



# *XII International Symposium on Antarctic Earth Sciences ISAES 2015*

*13 – 17 July 2015, Goa Marriott Resort & Spa*

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## XII International Symposium on Antarctic Earth Sciences

13 - 17 July 2015, Goa, India



Dear Fellow Delegates,

We extend a very warm welcome to you in the capital of the smallest state of India for the XII International Symposium on Antarctic Earth Sciences.

Goa with a very colourful history represents the twenty-fifth state of India and exhibits an amalgamation of multiple cultural influences, each positively contributing to the unique Goan identity. Its undulating and mountainous landscape forming part of the *Western Ghats* represents a biodiversity hotspot. Archean gneisses and granites, supracrustals, Deccan basalts, extensively developed regolith profiles and fluvial and coastal Quaternary deposits and landforms constitute the complex and very interesting geology of this state.

The symposium has a packed program in form of eleven plenary lectures and more than thirty sessions which have been organized in form of three concurrent sessions for five days from 13<sup>th</sup> to 17<sup>th</sup> July 2015 at Goa Marriott ReSørt. Exclusive poster sessions have been organized for one and a half hour each day for first four days of the symposium. Members of the Scientific Program Committee ensured a program representing wide range of interest in the Antarctic Earth Sciences through very active participation. We would like to make a special mention of Mike Sparrow in this context. Unfortunately he left SCAR a couple of months before this symposium. The collective efforts have led to participation of over 436 participants from 40 countries, ~202 oral presentations and ~234 poster presentations.

The effort of making this event possible and its organization is a collective effort. The support and inspiration from Dr. Shailesh Nayak, Secretary, Ministry of Earth Sciences & Chairman of Earth System Science Organisation (ESSO) and his officers made it possible to bring this symposium to India for the first time. National Centre for Antarctic and Ocean Research, Goa, entrusted with hosting of the symposium has worked as one unit to make this event possible. The untiring efforts of Local Organizing Committee members led by Mirza Javed Beg and ably supported by all have contributed greatly. We will like specially to mention Sweta, Anish, Mahesh, Sahina, Abhilash and Shramik who have coped with lots of pressure including occasionally unreasonable demands on their time.

An event as big as this symposium, cannot succeed without a strong support of sponSørs. SCAR support is the essence of this Symposium, which has been extended to the Early Career Scientists. ESSO institutes INCOIS, IITM, NIOT and NCAOR have supported the symposium as official partners. Besides, several members from ESSO-NCAOR and University of Delhi have contributed to the organization of the symposium.

The conference organization company, Planit!, led by Shri Rohit Kohli and represented by Rajiv Pande, Shwetha, Yogesh, Rahul, Prashant, Vishal, Pankaj, Shalini, Ragini and Samit are thanked for their efforts.

We share the blame for errors and problems faced by you despite our best efforts. We expect that XII ISAES 2015 at Goa will not only be a scientific success but will also leave long-lasting social impact. We hope that 'meeting of minds' amidst the Indian Summer Monsoon will blossom into new finds, new friendships and innovative ideas.

Rahul Mohan

M. Ravichandran

Naresh C. Pant

S. K. Tandon



## INDEX

Plenary Talks.....	2-14
S01-Geochronology of Antarctic Orogens .....	16-36
S02-Geodynamic Evolution of the Dronning Maud Land Mountains .....	37-55
S03-Crustal blocks adjacent to Antarctica- Sri Lanka, Mozambique and Antarctica .....	56-67
S04-West Antarctica: Problem Child of Gondwanaland - A Symposium Highlighting the Contributions of Ian W.D. Dalziel and David H. Elliot to Antarctic Tectonics .....	68-87
S05-The Rodinian Orogeny in East Gondwana- Implications for Supercontinent Evolution .....	88-116
S06-Large Igneous Provinces in Gondwanaland .....	117-148
S07-Evolution Of Antarctic Topography And Bathymetry: Understanding Links between Landscapes, Ice and Palaeoclimate .....	149-180
S08-Surficial Processes and Climate Change in Antarctic Terrestrial Environment: Changes and Impact on Permafrost, Erosion and Chemical Weathering.....	181-205
S09-ANTPAS - Antarctic Permafrost, Soils and Periglacial Environments .....	206-221
S10-The structure and evolution of the Antarctic continent in light of recent geophysical and geological investigations.....	222-278
S11-Cryosphere - Solid Earth Interactions.....	279-286
S12-Antarctic Geothermal Heat Flux, Subglacial Geology and Ice Dynamics .....	287-293
S13-Past Antarctic Ice Sheet Behaviour and Response to External Forcing .....	294-308
S14-The Himalayan Cryosphere - Global versus Regional climate forcing .....	309-351
S15-Palaeoclimate Records from Antarctic Drilling Projects.....	352-372
S16-Interactions between cryosphere, atmosphere and oceans in coastal Antarctica .....	373-407
S17-Southern Ocean Paleoclimatology .....	408-417
S18- Paleoenviromental changes in Antarctica and Southern Oceans since the last Glacial Maximum.....	418-436
S19-Lake Sediment Records of Past Changes in sea level and climate during the Late Quaternary .....	437-444
S20- Break up of Gondwana and Vertebrate evolution.....	445-463
S21- Key drivers of Antarctic biodiversity through the Cenozoic: the influence of climate, oceanography and tectonics .....	464-478



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13 - 17 July 2015, Goa, India



<b>S22- New Frontiers in Remote Sensing in Antarctic Earth Sciences: Cross-disciplinary advances .....</b>	<b>479-506</b>
<b>S24- Frontiers in Antarctic Earth Sciences .....</b>	<b>507-521</b>
<b>S25- Antarctic Meteorite and Micrometeorite.....</b>	<b>522-546</b>
<b>S26- General Antarctic Earth Science.....</b>	<b>547-583</b>



# PLENARY LECTURES



## Opportunities and Challenges in Solid Earth Research in India

**Shailesh Nayak**

Earth System Science Organisation, New Delhi, India

The Earth is almost 4.5 billion years old and behaves as a single and interlinked system. The mass and energy transfer within solid earth as well as across to other components such as ocean, atmosphere, cryosphere and biosphere are responsible for the evolution of the crust and its composition. These processes vary greatly in space from local to global scale and from few seconds to millions of years in time. The insight about Solid Earth structure and processes is critical in the context of geohazards, energy, natural resources, paleoclimate, environment, and ultimately to the sustainability of planet.

Advancing our knowledge and understanding of dynamic processes in the Earth's crust, mantle and core, and their linkages with observations and physical processes at the surface is a complex but are very significant. Through our knowledge about the composition of the Earth, its dynamic state has been advanced many fold in last few decades, there are several still scientific challenges to address. Some of major challenges are given below.

- i) Evolution of the Indian sub-continent and fragmentation and dispersal of the Super Continent Gondwanaland.
- ii) Onset of hotspot activity and wide spread volcanism over the Indian landmass.
- iii) Evolution of Himalaya and development of the Indus fan, the Bengal Fan.
- iv) Large scale transport of material their biogeochemistry, nutrient loading, biological productivity and impact of anthropogenic activity.
- v) Physical erosion and chemical dissolution and evolution of landscapes.
- vi) Coupling between climate change and surface uplift of mountain ranges.
- vii) Understanding low Geoid anomaly situated South of India.
- viii) Exploration of minerals, gas hydrates etc

Many such questions can be answered if we know what happens deep inside the Earth?

We need to probe what lies underneath of the Indian Plate. The following, is proposed.

- i) A network of seismic stations and OBS on land and surrounding Ocean to image deep interior continuously. This can be supported by seismic survey by ships and temporary stations on land. We have already initiated plan to set up about 100 stations next year in India including Myanmar, Nepal and Bhutan. All these stations are networked and real time data are available.
- ii) A network of GPS stations to measure rate of change having denser network at plate boundaries and to record building of strain along plate boundary. The network in A and N islands and in Himalayas is being set up.



- iii) A satellite-borne interferometric synthetic aperture radar to measure strain everywhere. Current radar satellite do not provide interferometric capability. Future satellites should have these capability.
- iv) Use of available data from SWARM, GRACE, and altimeters to probe interior of earth.
- v) A program for drilling deep boreholes. A deep borehole in Koyna has been planned. All preparatory activities have been completed. The drilling for pilot boreholes will be begin early next year. A drilling of borehole in the Laxmi basin has been initiated. The next bore hole planned is to investigate subduction zone around A and N Islands. This may start in 2017-18.
- vi) Setting up National Geochronological Facility to support above mentioned activities.



## **SCAR's perspective on Antarctic Earth Sciences**

**Jerónimo López-Martínez**

Department of Geology and Geochemistry, Faculty of Sciences, University Autonoma of Madrid, 28049 Madrid, Spain

The geological record in the Antarctic continental crust, the surrounding oceanic basins and the ice sheets is crucial to understand the Earth history. Consequently since the early times of the scientific research in Antarctica the Earth Sciences have been an important component of the scientific activity in the region. Geological, geophysical and glaciological studies have contributed to improve our knowledge of the Antarctic and Southern Ocean evolution from remote times and its consequences, in some cases with global implications. Extract the information from Antarctic rocks and structures is a challenge in a continent that is more that 99% covered by ice. Technological and new instruments developments are opening new opportunities and should improve in the future, including the access to samples and data below the ice and the seafloor, the use of new and more efficient measurement systems, satellites, and more accurate models. Antarctica is a significant piece in Gondwana and contains key information to reveal the breakup processes and their consequences from spatial and temporal perspectives in the context of plate tectonics. The Earth Sciences have contributed significantly to the Scientific Committee on Antarctic Research (SCAR) missions of promoting and coordinating international high quality scientific research in Antarctica and provide scientific advice to the Antarctic Treaty System and other bodies. The presence and role of the Earth Sciences in the context of Antarctic research, in particular within SCAR, will be commented. Since the establishment of SCAR in 1958 the Earth Sciences have had a presence in the organization's structure. This has been by means of different groups, projects and activities in this field. In the same way, have been produced many outputs from different initiatives and research programmes promoted by SCAR. The current situation of Earth Sciences in the SCAR structure will be commented as well as future perspectives in the light of new tendencies and possible scientific priorities for the coming years, including the results related to the Earth Sciences identified in the recent SCAR Antarctic Science Horizon Scan.



## **Antarctic Subglacial Exploration: First Results and Future Plans**

**Martin Siegert**

Grantham Institute – Climate Change and the Environment Imperial College London, Exhibition Road, London

Antarctic subglacial lakes have been regarded as extreme habitats for microbial life and keepers of important ice and climate records since 1996, when Lake Vostok was first shown to be a large deep body of water beneath central East Antarctica. We now know that there are nearly 400 Antarctic subglacial lakes; that some are connected hydraulically; and that the ice sheet's dynamics are affected by their presence in some places. After two decades of planning, involving the development of drilling techniques for lake access, environmental contamination protocols, instrument design and logistics set up, major progress has been made in attempts to directly measure and sample subglacial lakes, and to comprehend their role in ice-sheet flow. In March, an international meeting was held at the UK's Royal Society to share the results and experiences of the initial exploration programmes, and to plan future research. The scientific goals are ultimately to identify and understand life in these extreme environments and to acquire climate records from lake-floor sediments. In this plenary talk I will provide an overview of subglacial lake research based on findings presented at the Royal Society. I will also offer a vision for future exploration in the context of internationally-agreed scientific priorities, required engineering, enhanced logistics, environmental protection and international cooperation and collaboration. I will also discuss the role played by SCAR in building the research to its current state, and how it remains essential to the development of research in the coming decade.



## **Modern and Ancient Grounding Zone Systems– Mediators and Indicators of Ice Sheet Dynamics**

**Powell, R.D.**

Department of Geology and Environmental Geosciences, Northern Illinois University, DeKalb, IL 60115, USA

Grounding zones are those areas upstream and downstream of glacial grounding lines where ice moving over sediment or rock starts to interact with a lake or the ocean. The ice may end as a near-vertical cliff (tidewater face) or go afloat into a narrow floating glacier-tongue or larger ice shelf. Each type of grounding zone occurs in Antarctica today, as well as throughout its history. Through studies involving modeling, remote sensing and rare direct measurements, modern grounding zones have been recognized as being one of the key areas for potentially influencing grounded ice stability, especially if it is marine ice sheet with its bed sloping inland. Subglacial sediment and water delivery to these sedimentary systems are thought to be two of the parameters important in governing the degree of a system's influence over ice stability. Data from modern systems show temperate glaciers do have the capability of delivering sufficient sediment to the grounding line to enhance the possibility of its stabilization. Currently there are too few data from modern polar systems to fully assess their potential effects although models infer that they are also potentially capable of forcing at least temporary stabilization. Relict morphological forms built at grounding lines, such as grounding-zone wedges and morainal banks, have been increasingly documented and used to trace the timing, style and dynamics of the last retreat of glaciers and ice sheets across glaciated continental shelves. Successions representing grounding-zone systems in seismic reflection profiles and short and long sediment cores are recognized by their distinctive facies. Such successions can be used paleoglaciologically to help infer past glacial regime, and grounding zone and ice sheet dynamics. Once more quantitative data are available from modern systems it should be possible to constrain higher-resolution retreat rates from past glaciations. Investigations of modern grounding zones will be described to synthesize the current state of knowledge and examples of paleo-grounding-zone depositional systems will be discussed to demonstrate how modern studies can be used to infer ice sheet paleoglaciology and dynamics.



## Global Climate Change, ENSO and Black Swan Events: A Paleoclimate Perspective from the World's Highest Mountains

**Lonnie G. Thompson**

Distinguished University Professor, School of Earth Sciences; Senior Research Scientist, Byrd Polar and Climate Research Center; The Ohio State University

Glaciers serve both as recorders and early indicators of climate change. Over the past 37 years our research team at the Byrd Polar and Climate Research Center has recovered climatic and environmental histories from ice cores drilled in both Polar Regions and from low- to mid-latitude, high-elevation ice fields. The ice core-derived proxy records extending back over 25,000 years have made it possible to compare glacial stage conditions, as well as more recent highly resolved climate events, in the Third Pole Region with those in the tropical Andes of South America and the Polar Regions. The contrasting interpretations of stable isotopic ratios in high elevation ice core records and the lower elevation speleothem records in the Third Pole Region will be examined. The richness of the environmental archives preserved in ice cores will be explored to demonstrate how some "Black Swan" events have been recorded in ice cores around the world.

Tropical rainfall patterns influence the lifestyles of billions of people both north and south of the Equator. High resolution tropical ice core records allow precise examination of climate events on both sides of the Pacific Ocean Basin which are often connected by El Niño-Southern Oscillation. Tropical ice cores records are used to document two abrupt decadal-scale droughts centered on the mid-14th and late-18th centuries that are linked to El Niño and the migration of the Intertropical Convergence Zone near the onset and termination of the "Little Ice Age". In these Andean and the Himalayan ice cores, separated by 22,000 km, the oxygen isotopic ratio ( $\delta^{18}\text{O}$ ) is significantly correlated with NINO3.4 sea surface temperatures while large scale circulation regimes support aerosol transport from upwind source regions. Both events are contemporaneous with major societal disruptions. While uncertainty remains regarding how El Niño will change in a warmer world, recent studies have suggested an increasing frequency of extreme El Niño events and the associated hydroclimate variability in some regions including southern Asia.

Recent data on the already well-documented concomitant loss of ice on Quelccaya (Peru), Kilimanjaro (Tanzania) and the ice fields near Puncak Jaya (Papua, Indonesia) reinforce the hypothesis that large-scale tropical processes dominate recent tropical glacier retreat. This modern large-scale glacier retreat can be placed within a longer-term perspective. Radiocarbon dates on wetland plants exposed along the retreating margins of Quelccaya indicate that its surface area is now at its smallest extent in the last 6,000 years. The observed widespread melting of high-elevation low- to mid-latitude glaciers is consistent with model predictions of a vertical amplification of temperature, which is documented by increasing isotopic enrichment in ice cores from high elevation glaciers throughout the Tropics.



## Himalayan Glaciers: A Source of Water in North Indian Rivers

**Anil V. Kulkarni**

Distinguished Visiting Scientist, Divecha Center for Climate Change, Indian Institute of Science, Bangalore, INDIA

The Himalaya has one of the largest concentrations of glaciers and many rivers like Indus, Ganga and Brahmaputra originate from the glacier bound regions. However, this source of water may be influenced in future, as Himalayan cryosphere is constantly changing. Therefore, retreat of Himalayan glaciers are discussed extensively in scientific and public forum in India. The contribution of glacier melt in annual stream runoff is almost 72 % in the Upper Indus river basin and 59 % at Bhakra reservoir. The overall contribution is lower in the Ganga and Brahmaputra basins. However, well developed canal network in the Indus basin produces almost 96% and 26% of food production of Pakistan and India, respectively. Therefore changes in runoff pattern in Indus basin due to melting glaciers can significantly influence the water and food security of India and Pakistan.

Runoff pattern of the Himalayan rivers depends upon distribution of glaciers, which is influenced by the glacial mass budget. Mass budget estimates are available for relatively few glaciers and for short duration. The data suggest negative mass budget over past decades. The glaciers in Himalayan region are losing mass approximately at the rate of  $-6.6 \pm 1$  Gt per year. However, the loss in mass for many small glaciers located in low altitude range could be as high as  $1000 \text{ kg m}^{-2} \text{ y}^{-1}$ . These small glaciers and ice fields are important source of water for many mountain communities. In future, glacial retreat and mass budget will also be influenced local geomorphologic and climate changes. If more glacier lakes are formed due to increase in debris cover and if Black Carbon is transported in accumulation areas of the glaciers, it can significantly influence mass budget and distribution of glaciers. Therefore, continuous monitoring is needed to understand changing dynamics of Himalayan glaciers. In my talk, I will discuss these issues, present state and possible conservation of Himalayan glaciers, if Green House Gas (GHG) emission is shifted from RCP 8.5 to 2.6 pathways.



## Tracking Antarctica Back in Time through a Succession of Supercontinents

Ian W.D. Dalziel

Institute for Geophysics, Jackson School of Geosciences, The University of Texas at Austin Austin, Texas USA

Antarctica, Alex Du Toit's "keystone..... of Gondwana" is now known to have been an important element of at least one additional supercontinent in addition to Gondwana and Pangea, late Mesoproterozoic-early Neoproterozoic Rodinia. It is suspected to have been part of several other supercontinental entities, before, during and after the amalgamation of Gondwana. In this contribution I will discuss the evidence for Antarctica's role within a succession of supercontinents, thereby attempting to highlight critical unknowns and problems with our understanding of its role in Earth history.

The place of Antarctica within the Phanerozoic supercontinents of Pangea and Gondwana is now well established. Thanks to Mesozoic-Cenozoic seafloor spreading data, few questions regarding the late Paleozoic formation of Pangea remain outstanding. However, not least due our limited knowledge of the nearly entirely ice covered East Antarctic craton, the amalgamation of Gondwana at the end of Precambrian times is still imperfectly understood. That exacerbates the difficulty of achieving a satisfactory reconstruction of Rodinia. Unfortunately, the paleogeographic transition from Rodinia to Gondwana during the critical mid- to late Neoproterozoic interval of major planetary glaciations and the emergence of multicellular animal life has also proved difficult to reconstruct.

There is some evidence that Laurentia, the ancestral core of North America may still have been attached to southern South America, southern Africa and Antarctica as Gondwana amalgamated and did not become separated from them until the early Cambrian. This loose supercontinental arrangement has been called Pannotia, and the separation of Laurentia to break up this entity was an event that I have suggested may have been responsible for the initiation of early Paleozoic eustatic sea level rise and hence the Cambrian radiation of life. The presence of the Cuyania terrane in present-day northwestern Argentina with its benthic fauna of widely accepted Laurentian origin can be interpreted as the result of a Laurentian-Gondwana continent-continent collision in Ordovician times, briefly forming another supercontinental amalgamation of Laurentia and Gondwana that has been termed Artejia. The Cuyania terrane may have been juxtaposed to the margin of East Antarctica prior to the separation of Laurentia.

The role of Antarctica in supercontinental, or at least 'supercratonal', assemblies back into the ancient history of the planet before the amalgamation of Rodinia is very difficult to assess. Again this is mainly due to our limited knowledge of the structure and history of the East Antarctic craton. However, this has not deterred proposals that much of the craton was part of supercontinent 'Columbia' between 1.8 and 1.5 Ga, and that the Archean-Proterozoic Grunehogna terrane of Dronning Maud Land was part of 'Vaalbara', an entity comprising its parent Kapvaal craton of southern Africa and the Pilbara craton of northwestern Australia. Material acquired in the future from the bedrock of the East Antarctic Ice Sheet through the developing Rapid Access Ice Drilling (RAID) project should permit more robust understanding of the amalgamation of Rodinia and Gondwana as well as providing firmer clues to Antarctica's role in pre-Rodinia supercontinents.



## From Maps to Maximum Likelihood - Methodological Issues in the Analysis of Late Mesozoic Gondwanan Vertebrate Biogeography

Paul Upchurch

Dept. Earth Sciences, University College London, Gower Street, London, WC1e 6BT, UK

The break up of Gondwana during the Mesozoic and Cenozoic has prompted one of the most extensive research programmes in the field of historical biogeography. The biotic impact of Gondwanan fragmentation has been investigated using numerous analytical approaches, applied to a diverse array of neontological and palaeontological data sets. Continent-scale vicariance has frequently been identified as a major explanation for the distributions of Southern Hemisphere organisms, but more recent molecular studies have tended to favour an important role for trans-oceanic dispersal. One key problem for biogeographers is the lack of agreement concerning Gondwanan palaeogeography, such as the timing of the separation of Africa and South America, and the connectivity of South America, Antarctica and Indo-Madagascar during the Cretaceous. Many biogeographic analyses are based on the phylogenetic relationships, spatial distributions and divergence times of organismal lineages, with only an a posteriori comparison of the results with a single palaeogeographic history. Thus, it is often unclear to what extent biogeographic conclusions are sensitive to different palaeogeographies.

Recently developed biogeographic methods allow palaeogeographic data to be incorporated directly into the analysis. Such methods include the maximum likelihood approach implemented in the R package BioGeoBEARS. In order to examine the impact of palaeogeographic data on our understanding of Cretaceous biogeography, two dinosaurian groups with widespread Gondwanan representation (titanosauriform sauropods and abelisauroid theropods) were selected. Time-calibrated phylogenies for these groups were generated, using a variety of different assumptions about missing data. A review of the recent palaeogeographic literature was then used to develop five Cretaceous histories for the break up of Gondwana, with the differences focusing largely on the nature of the connection between South America and Antarctica. A series of BioGeoBEARS analyses were then undertaken, firstly with no constraints imposed by palaeogeography, and then with constraints based on each of the five competing palaeogeographic models.

The unconstrained analyses tended to favour a role for continent-scale vicariance. However, the application of palaeogeographic constraints resulted in a loss of support for vicariance (especially in the sauropod data set). Instead, the latter analyses indicate that sauropod distributions were determined by a combination of sympatry, geodispersal and regional extinction. One of the more puzzling aspects of Cretaceous dinosaurian biogeography is the repeated occurrence of closely related taxa in Asia and Australia during the early Late Cretaceous, despite the fact that these two areas had been separated by thousands of kilometres of ocean for tens of millions of years. The unconstrained BioGeoBEARS analyses support the view that this pattern is the result of trans-oceanic dispersal from Asia to Australia, which seems improbable for large-bodied terrestrial animals. However, the application of the palaeogeographic constraints produces a more plausible explanation. Essentially, it seems that at least two titanosauriform lineages became widespread across Pangaea during the Early Cretaceous, but subsequent regional extinctions resulted in relictsof this faunapersistingsolely in Asia and Australia (perhaps because these two regions retained similar environmental conditions). In contrast the history of the theropods requires a more major role for continent-scale vicariance driven by Gondwana fragmentation.

The main conclusions concerning the biogeographic histories of Cretaceous sauropods and abelisauroids are not strongly affected by different palaeogeographic constraints (though the details for particular lineages can vary markedly). However, failure to include any paleogeographic data at all has a profound impact. Although there are situations where it is appropriate to keep palaeogeographic and biogeographic data separate (e.g. when using biogeographic analyses to provide information on palaeogeography), it



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seems likely that the most accurate estimations of the biogeographic history of a clade are generated when a more holistic approach is employed.



## New Insights on Interactions between the Solid Earth and the Cryosphere

**Terry J Wilson**<sup>1</sup>; POLENET Team<sup>2</sup>

Ohio State University, United States<sup>1</sup>; polenet.org<sup>2</sup>

Arrays of geophysical and geodetic instruments deployed across broad expanses of the Antarctic interior, complemented by airborne geophysical surveys, have provided a wealth of new data on the evolution and dynamic behavior of the solid earth beneath the Antarctic ice sheets. New information on ice sheet dynamics and mass change patterns across the Antarctic ice sheet continues to emerge. New modeling efforts aim to better represent the heterogeneity in both the solid earth and ice sheets of Antarctica. Integration of new data and modeling initiatives is providing new understanding of the feedbacks between the solid earth and the cryosphere.

Crustal motions measured by GPS can provide a unique proxy record of ice mass change, due to the elastic and viscoelastic response of the earth to removal of ice loads. The POLENET/ANET project is acquiring data on crustal motion patterns, measured by GPS, and earth structure and rheological properties, mapped by seismology. For many sectors of Antarctica, the measured vertical and horizontal crustal motion patterns are not explained by glacial isostatic adjustment (GIA) models predicting displacements due to Last Glacial Maximum (LGM) ice loss. Within the Amundsen Sea Embayment, where seismic results document thin crust and low mantle viscosity, extremely high upward velocities are flanked by subsiding regions. The observed crustal motions can't be ascribed to an LGM ice loss signal, which would have already relaxed, and uplift is likely due to the elastic response to modern ice mass change and a viscoelastic response to ice loss on decadal-centennial time scales. Along the East-West Antarctic boundary in the Ross Embayment, GIA-induced horizontal crustal motions are toward, rather than away from, the principal ice load center in the Siple Coast region, correlating spatially with a strong lateral gradient in mantle viscosity mapped by seismology. In the Weddell Embayment region, where crustal thickness and mantle viscosity values change between East and West Antarctica and across crustal block boundaries, crustal motion patterns vary significantly and do not match GIA model predictions closely. It is clear that lateral variations in earth properties fundamentally influence the isostatic response to ice mass changes in Antarctica. Ongoing, integrated seismic-GPS studies are critical to developing the next generation of GIA models.

The nature of the bedrock below the ice sheets, particularly heterogeneity in lithology, topography, basal geothermal heat flux and hydrology, strongly influences ice sheet dynamics and are particularly important for the stability of marine-based ice sheets. Both the geologic boundary conditions and the type of substrate are linked with tectonic processes. Geophysical data and modelling studies show laterally varying heat flux and spatial associations between fast-flowing ice streams and underlying rifts. Seismic data have documented earthquake swarms associated with active subglacial magmatism. Seismic monitoring is providing important new information on conditions and processes at the ice/bedrock interface. Subglacial seismicity allows identification of regions of higher basal shear strength or of higher volumes of entrained debris, critical to controlling the sliding of glaciers.

Improved measurement and modeling of the links between the ice sheets and the solid earth below is essential for understanding ice sheet behavior and improving assessments of the contributions past and present of Antarctic ice sheets to global sea level change.



## Ocean Iron Fertilization – An Update based on the Results of LOHAFEX

S.W.A. Naqvi<sup>1</sup>; Victor Smetacek<sup>2</sup>

CSIR-National Institute of Oceanography, Goa, India<sup>1</sup>; Alfred Wegener Institute for Polar & Marine Research, Bremerhaven, Germany<sup>2</sup>

Ocean Iron Fertilization (OIF) is one of the potentially important means for sequestering CO<sub>2</sub> from the atmosphere, but the efficacy of this technique and its impact on the environment and ecology continue to be debated. In order to address the outstanding issues related to OIF, an international experiment LOHAFEX was jointly conducted by India and Germany in the Southern Ocean during January-March 2009. An anticyclonic eddy was fertilized with 20 tonne of ferrous sulphate and the “patch” created was successfully monitored for 38 days. The patch circulated around the eddy twice and was ejected out after three weeks. A bloom of phytoplankton developed, but unlike previous OIF experiments diatoms formed a minor component of the phytoplankton community due to low ambient silicate concentration. The phytoplankton biomass was limited by intense grazing by zooplankton. Primary productivity nearly doubled in response to fertilization, but bacterial biomass and production remained relatively low. CO<sub>2</sub> drawdown inside the patch was modest (< 15 matm). Most of the photosynthesized organic carbon accumulated in the surface layer in particulate and dissolved forms (about 80% of NCP) and export to deep sea measured with sediment traps was low, demonstrating low potential of recycling system for long-term CO<sub>2</sub> sequestration. Finally, OIF had little effect on the production of other climatically-important greenhouse gases (N<sub>2</sub>O, CH<sub>4</sub>, DMS, and haloalkanes).

LOHAFEX has provided new insights on physical, chemical and biological processes that govern the functioning of planktonic ecosystems. It was shown for the first time that a growing phytoplankton bloom could be kept in check by zooplankton. Hence the carbon cycle is not determined only by chemical factors. Only diatoms which are protected against grazing are able to transport large amounts of carbon to the deep sea. Hence the area where artificial iron fertilization will have a significant effect is restricted to the region with sufficient silicate concentrations. There also, bloom formation can be prevented by zooplankton grazing. Moreover, LOHAFEX demonstrated that although biological production in the Southern Ocean is iron-limited, iron supply alone cannot support unlimited phytoplankton biomass build-up (top-down control: grazers keep biomass in check and/or bottom-up control: limitation by Si and other micro-nutrient, e.g. vitamin B12). Because of low export of carbon to deep-sea in the silicate limited subantarctic region, which accounts for 2/3 of the high-nutrient, low-chlorophyll region of the Southern Ocean, potential of OIF as a means of CO<sub>2</sub> sequestration is substantially smaller than believed so far.



## **Geo-Conservation in Antarctica**

**Carson CJ**

Geoscience Australia GPO 378, Canberra, ACT, 2601, Australia

With improving accessibility to Antarctica, the need for proactive protection and management of sites of intrinsic scientific, historic, aesthetic or wilderness value is becoming increasingly important. Environmental protection and conservation practise in the Antarctic is globally unique and is managed by provisions contained within the Antarctic Treaty. Whilst these provisions have been primarily utilised to protect sites of biological or cultural significance, sites of geological or geomorphological significance may also be considered. However, in general, sites of geological and geomorphological significance are underrepresented in conservation globally, and, particularly, in Antarctica. Wider recognition of sites of geological significance in Antarctica can be achieved by development of a geo-conservation register, similar to geological themed inventories developed elsewhere in the world, to promote and recognise intrinsically valuable geological and geomorphological sites. Features on the register that are especially fragile, or otherwise likely to be disturbed, threatened or become vulnerable by human activity, can be identified as such and area management protocols for conservation, under the Antarctic Treaty, can be more readily invoked, developed and substantiated. Area management should mitigate casual souveniring, oversampling and accidental or deliberate damage caused by ill-advised construction or other human activity. The recognition of significant geological and geomorphological features within the Antarctic, and their protection, is identified under the current Australian Antarctic Science Strategic plan (under Stream 2.2; Vulnerability and spatial protection).



PARALLEL SESSIONS



## S01 – 28: Geochronology of Antarctic Orogens

### ***Geology and Geochronology of MacRobertson Land and Princess Elizabeth Land (East Antarctica): Successive Archaean to Cambrian Orogens and their Spatial Distribution***

Evgenii Mikhalskii<sup>1</sup>; Laiba, A.A. <sup>2</sup>; Kapitonov, I.N <sup>3</sup>; Presnyakov, S.L. <sup>3</sup>; Bayanova, T.B. <sup>4</sup>

Institute for Geology and Mineral Resources of the World Ocean (VNIIOkeangeologia), St.-Petersburg, Russia<sup>1</sup>; Polar Marine Geosurvey Expedition, St.-Petersburg Lomonosov, Russia <sup>2</sup>; All Russia Geological Research Institute (VSEGEI), St.-Petersburg, Russia <sup>3</sup>; Geological Institute of Kola Scientific Centre RAS, Apatity, Russia <sup>4</sup>

In this report we summarize geological and geochronological data acquired in MacRobertson Land and Princess Elizabeth Land. We accumulated new and previously obtained data for more than 270 samples studied for zircon chronology. This dataset provides a more detail insight into geological history and structure of this segment of the crust. In this report we present a new vision on its structure reflected in a new 1:1000000 tectono-geological map and emphasize new and yet unpublished data which reveal some important geological features. Punctuated orogenic activities occurred from ca 3500 Ma up to 500 Ma. The tectonic grid of the study region is defined by four tectonic provinces, two of which are the early Precambrian terrains in the southern Prince Charles Mountains (PCM) and in the east Prydz Bay coast.

The largest is the Meso- to early Neoproterozoic (Rayner) Province. A spatially minor and tectonically enigmatic the Cambrian Prydz Province is distinguished in the central Prydz Bay coast. The southern Prince Charles Mountains is known as the Ruker Province and comprises two zones of distinct geological history, which are the Ruker Zone (or Terrane), and the Lambert Zone (or Terrane). The Ruker Zone experienced major structure-forming events between ca 3400 Ma and ca 2800 Ma and is composed of the Archaean medium-grade basement covered with the Proterozoic lower-grade metamorphosed sedimentary sequences. Mawson Orogeny (ca 3400 to 3100 Ma) and Stinear Orogeny (ca 3000 to 2750 Ma) affected the basement of the Ruker Zone. Ca 2200 to 2100 Ma zircon growth event was countered in Mt Newton. Sedimentary covers comprise ca <2500 Ma Ruker Group, <1800 Ma Menzies Group and <1000 Ma Sodruzhestvo Group (detrital zircon study by Phillips et al., 2006). The Sodruzhestvo Group seems to comprise structurally varying rocks (psammite to crystalline schist and milonite) and metamorphic grade range from lower greenschist to amphibolite facies, thus questioning previous distinction of all medium-grade rocks as the Archaean. Our new chemical and Sm/Nd isotopic data on the Sodruzhestvo Group indicate it was sourced from the Proterozoic Rayner Province with negligible input from the Archaean basement.

The Lambert Zone refers to most of Mawson Escarpment and some other northernmost portions of the terrain. It comprises ca 3500 Ma orthogneisses which are thought to serve an infrastructure underlying mixed ortho- and paragneiss metamorphic complex enveloped between ca 2500 to 2100 Ma terminating with Newton (ca 2200 to 2100 Ma) orogenic episode. In Binders Nunataks paragneiss contains single detrital zircon population as old as ca 3500 Ma.

In the east Prydz Bay coast the early Precambrian rocks crop out in the Vestfold Hills and neighbouring Rauer Islands, the crustal blocks which may not have been conjugated before ca 550-530 Ma tectonic episode (Prydz Orogeny). Thus, Rauer Block experienced tectonomagmatic events between ca 3500 Ma and 2800 Ma with thermotectonic overprints at ca 2500 Ma and also subsequently. The Vestfold Block was largely formed at ca 2500 Ma (Vestfold Orogeny), and the timing from which both blocks evolved conjugated remains a matter of discussion. Nevertheless, both blocks reveal common and clearly distinct from the neighbouring Rayner Province magnetic anomaly field patterns suggestive of their connection before Rayner Orogeny.



Most of the study region is underlain by largely the Meso- to early Neoproterozoic rocks, which were defined as a part of much larger structure known as the Rayner Complex. This terrain (the Rayner Province) comprises three distinct litho-tectonic zones which somewhat differ in both geological history and rock composition: Fisher (central PCM), Beaver (northern PCM), and North-Lambert (the south-eastern Amery Ice Shelf fringe). The Fisher Zone and the Beaver Zone largely have not been structurally reworked during the Cambrian, unlike the North-Lambert Zone, but may be thermally overprinted in some areas. Our new detrital zircon data show that ca 2500 to 1600 Ma rocks contributed to some metasediments, e.g., in Mt Lanyon and Manning Nunataks, thus pointing out to yet unidentified the early Precambrian cryptic terrane or to derivation of these sediments from the Lambert Zone during the Mesoproterozoic. The Fisher Zone comprises rocks as old as ca 1400 to 1200 Ma (the Fisher orogenic phase), which experienced medium-grade metamorphism and deformations at ca 1200 to 1100 Ma. The Fisher Zone was tectonically inactive since that time and was intruded by only post-kinematic granites at ca 1020 to 950 Ma.

The Beaver Zone characteristically comprises rocks metamorphosed and deformed during ca 1150 to 930 Ma (the Beaver orogenic phase culminating in ca 1000 to 930 Ma Rayner structural episode). However, the Beaver Zone may include rock protoliths as old as ca 1500 to 1400 Ma (e.g., concordant zircon cores or upper intercepts) suggesting that Fisher-age precursors were involved. For instance, our new data reveal these ages from Taylor Platform and Summers Peaks in the northern PCM. Such association may be also distinguished in the area embracing the northern part of the eastern Amery Ice Shelf fringe and the western Prydz Bay coast and we correlate this terrain with the Beaver Zone, albeit this correlation is tentative because of a thermal overprint during the Cambrian.

The North-Lambert Zone characteristically comprises rocks which are not older than 1100 Ma in the terms of their protoliths, metamorphosed and deformed at ca 1000 to 900 Ma, and variously affected by thermal and structural processes during the Cambrian. This zone includes the Grove Mountains, southern part of eastern Amery Ice Shelf fringe, and some localities in the central Prince Charles Mountains.

In the central Prydz Bay coast largely the Cambrian (ca 550 to 530 Ma) metamorphic rocks are exposed, and we define this area as the Prydz Province characteristically different from other areas by syn-metamorphic pervasive structures. Many authors expand the Prydz Province toward Grove Mountains and eastern Amery Ice Shelf fringe, but we consider these areas being not adequately structurally reworked during the Cambrian. Anyway, the Prydz Province is an ensialic orogen.

Our new U-Pb data on detrital zircons from a paragneiss in Austin Nunatak (western Grove Mountains) yielded youngest population of ca 1000 Ma, indicating a Neoproterozoic age of these sediments, which may thus be a high-grade equivalent of Sodruzhestvo Group.



**S01 – 142: Geochronology of Antarctic Orogens**

***Zircon Geochronology of Metamorphic and Intrusive Rocks from the Eastern Amery Ice Shelf and South Western Prydz Bay, East Antarctica: Implications for the Rayner and Prydz Orogeny***

Liu Xiaochun<sup>1</sup>; Zhao Yue<sup>1</sup>; Song Biao<sup>1</sup>

Institute Of Geomechanics, CAGS, China<sup>1</sup>

The high-grade metamorphic rocks and intrusives from the eastern Amery Ice Shelf (E AIS) and southwestern Prydz Bay of East Antarctica represent the eastward extension of the Rayner Complex that was strongly reworked by a late Neoproterozoic/Cambrian metamorphic event. Therefore, these rocks can provide important information for the tectonic evolution of the Rayner and Prydz orogenises. Zircon U-Pb analyses of felsic orthogneiss and mafic granulite from these areas reveal their protolith ages ranging from 1380 to 1020 Ma. Subsequently, these rocks experienced two episodes of high-grade metamorphism at >970 Ma and between ~930-900 Ma, accompanied by intrusion of charnockite at >955 Ma and granite at 925 Ma. This suggests that the Rayner orogeny involved a long-lived (~360 Ma) magmatic accretion in a continental arc and a protracted or two-stage collision of the Indian craton with the western portion of East Antarctica leading to the formation the Indo-Antarctica continental block. Furthermore, most of the rocks, except for some from the Munro Kerr Mountains and Reinbolt Hills, were subjected to high-grade metamorphic recrystallization at ~530 Ma, accompanying the late- to post-orogenic intrusion of charnockite and granite at ~515-500 Ma. Therefore, the Prydz Belt may have developed on the eastern margin of the Indo-Antarctica continental block, and the late Neoproterozoic/Cambrian suture assembling Indo-Antarctica and Australo-Antarctica continental blocks should be located southeastwards of the E AIS-Prydz Bay region. Overall, although the new age data indicates the widespread existence of a late Mesoproterozoic to early Neoproterozoic high-grade metamorphic event in the E AIS-Prydz Bay region, the possibility that East Gondwana was not finally assembled until the Cambrian cannot be ruled out.



## S01 – 171: Geochronology of Antarctic Orogens

### ***Titanite and Zircon LA-ICPMS Dating of Granite Harbour Intrusive Complex Xenoliths sampled from western McMurdo Sound Cenozoic Lavas***

A.P.Martin<sup>1</sup>; A.F.Cooper<sup>1</sup>; R.C.Price<sup>1</sup>; R.E.Turnbull<sup>1</sup>; N.M.W.Roberts<sup>1</sup>

GNS Science, Dunedin, New Zealand<sup>1</sup>

**BACKGROUND:** In Southern Victoria Land Transantarctic Mountains the Ross Orogen was punctuated by voluminous Granite Harbour Intrusive Complex (GHIC) magmatism between the late Precambrian and early Paleozoic; the GHIC can be subdivided into four distinct suites. The DV1a Suite has calc-alkalic compositions with relatively low Sr/Y ratios (Low SY) whereas DV1b Suite plutons have alkali-calcic chemistry and high Sr/Y ratios (High SY), which has also been referred to as adakite-like. Both are interpreted to have been emplaced in a convergent margin setting. The DV2 suite is alkalic-calcic and associated with high-K and shoshonitic dyke swarms. The alkalic, Precambrian to Cambrian Koettlitz Glacier Alkaline Suite (KGAS) is considered to have been emplaced in an extensional tectonic setting that may either have been part of an extensional jog associated with oblique compression during the Ross Orogeny, or represent a period of more widespread extensional magmatism. The Transantarctic Mountains Front (TMF), marking the western boundary of the West Antarctic Rift System (between East and West Antarctica) is at the eastern edge of the Transantarctic Mountains. The TMF has been seismically mapped north of a prominent east-west trending lineament (the Blue Lineament) at approximately 78°S, but south of this the location of the TMF is poorly constrained. Here we report details of a suite of 46 crustal xenoliths and two in situ outcrops of GHIC rocks at Mount Morning. Mount Morning is a Cenozoic strato-volcano located in the Ross Sea that has been active for at least 18.7 Ma and probably from 24.1 Ma. Mount Morning forms part of the 2000 km long McMurdo Volcanic Group and is centred in the region of ambiguity regarding the location of the TMF south of the Blue Lineament.

**OBJECTIVES:** The objectives are i) to use geochronology, petrology and chemistry to link Mount Morning GHIC xenoliths with one or more of the four distinct GHIC suites ii) to advance understanding of the petro genesis of the crust beneath Mount Morning as it relates to the Ross Orogen and West Antarctic Rift System iii) to refine the inferred position of the TMF, and iv) to discuss the control, if any, of the TMF on the distribution of Cenozoic volcanism.

**METHODS:** The crustal sample suite has been examined using petrography and whole rock geochemistry and a sub-set of samples has been analysed for mineral geochemistry, geothermometry and geochronology to distinguish between an East Antarctica (Transantarctic Mountain-like) and West Antarctica (Ross Sea-like) affinity. Geochronology has been undertaken by laser ablation inductively coupled mass spectrometry (LA-ICPMS) on grains of zircon (sample OU78656) and titanite (sample OU78658) at the Australian National University and the NERC Isotope Geosciences Laboratory.

**RESULTS:** The xenolith and outcrop sample suite includes both metamorphic and igneous rocks. The metamorphic textural type (n = 13) has a calc-alkalic whole rock chemistry and are mineralogically lower crustal granulites. The granulite normative compositions overlap with the fields defined either for DV1 or DV2 suite granitoids. On N-MORB normalised extended element plots and on trace element discrimination diagrams the granulite xenoliths geochemistry overlaps with, or plots close to, DV1b rock types and may be described as adakite-like or Hi SY, and is comparable to some arc-like signatures. Geochronology on zircon grains from one granulite xenoliths yields a weighted average  $^{206}\text{Pb}/^{238}\text{U}$  age at  $545.2 \pm 4.4$  Ma. Petrography, mineral chemistry and geological context support this being a crystallisation age. Some of the igneous types of xenoliths with an alkalic whole rock geochemistry have normative compositions that overlap with the field defined for KGAS rocks. Their whole rock geochemistry on N-MORB normalised extended element plots is comparable to plutonic KGAS rocks of the Ross Orogen and dating of titanite grains from one specimen has yielded a  $^{206}\text{Pb}/^{238}\text{U}$  age at  $538 \pm 8$  Ma. Mineral chemistry



and petrography supports this being a primary crystallisation age but a cooling age interpretation cannot be ruled out.

**CONCLUSIONS:** A suite of crustal xenoliths, including lower crustal granulites, and two in situ outcrops has been analysed from Mount Morning, Southern Victoria Land, Antarctica. The lower crustal granulite xenolith petrography, whole rock geochemistry, normative mineralogy and geochronology are comparable to DV1b suite rocks in the adjacent Transantarctic Mountains. Furthermore, a sub-set of these rocks has adakite-like (or HiSY) compositions that can be explained by partial melting of, or modification by fluids derived from, subducted oceanic crust. Zircon grains from one granulite sample yield a  $545.2 \pm 4.4$  Ma age that is interpreted as a crystallisation age, comparable to the emplacement age of the Fontaine Pluton, and this supports the proposal for the existence of a magmatic arc during this period. The Mount Morning alkalic xenoliths are geochemically comparable to the Koettlitz Glacier Alkaline Suite (KGAS). Titanite grains in one alkalic xenolith yield a  $538 \pm 8$  Ma lower intercept age that may reflect cooling but is within the range of crystallisation and cooling ages reported for KGAS rocks. Based on the study of granulite xenoliths some workers have proposed a significant lower crustal discontinuity in the McMurdo Sound region separating continental crust of the East Antarctic Transantarctic Mountains from tholeiitic crust of the Ross Sea basement. The Transantarctic Mountain-like compositions in the Mount Morning granulite suite are consistent with the proposal that this lower crustal discontinuity occurs east of Mount Morning, perhaps cropping out along the trace of the Discovery Glacier. The Transantarctic Mountain Range bounding fault (TMF) may also pass along the trace of the Discovery Glacier if its location is controlled by the lower crustal suture, as hypothesised by previous workers. The extended Cenozoic magmatic history at Mount Morning (more than 24 my duration) could be the result of magma exploiting this lower crustal suture.



## S01 – 190: Geochronology of Antarctic Orogens

### *Role of the Nimrod Group, Central Transantarctic Mountains, In the Mawson Continent*

Fanning, C, Mark<sup>1</sup>; Goodge, John, W<sup>2</sup>

Research School of Earth Sciences, Australian National University<sup>1</sup>; Department Of Earth & Environmental Sciences, University Of Minnesota, Duluth, USA<sup>2</sup>

Archaean to Palaeoproterozoic components in the outcropping high-grade metamorphic and igneous rocks of the Nimrod Group, Transantarctic Mountains (TAM) are a key link in the Mawson Continent. These led to the linking of the Gawler Craton in South Australia, via the Terre Adelie craton in George V Land to the Shackleton Range of southern Coats Land.

Firstly, layered quartzo-feldspathic gneisses representing an Archaean basement initially formed between 3150-3000 Ma and are the core of the Mawson Continent. Long since recognized in the Nimrod Group (TAM), their presence had been proposed for the Gawler Craton on the basis of inherited zircon and Sm-Nd isotope systematics prior to more recent U-Pb zircon dating of similar gneissic rocks which cemented that primary connection. Such an Archaean basement is absent in the north Australian Craton (NAC) and so in keeping with the original Mawson Continent concept there is no link with northern Australia, as has been suggested by others.

A period of magmatic intrusion at ca.2500 Ma is the second major element recognized in the Mawson correlation. These are well documented in the Miller Range (Nimrod, TAM) and magmatic events of this age are also recorded in Gawler-Terre Adelie. An ensuing high-grade event in the latter, with prominent garnet paragneisses appears to be absent in the Nimrod, although similar events are present in the Shackleton Range. A minor but key magmatic event at 2000 Ma brings juxtaposition of deep crustal blocks with high-level granitoids in the southern Gawler. Whilst not cropping out in the Nimrod, recent evidence from glacial clasts shows that this component is present beneath the ice of East Antarctica, adjacent to the TAM. Similarly, prominent 1850 Ma granitoids in the southern Gawler are present as glacial clasts in the TAM and crop out in the Shackleton Range. An associated metamorphic event in marginal eastern Gawler is also indicated in Shackleton. Prominent metamorphism and magmatism at about 1700 Ma is a key element in all outcropping areas of the Mawson, although the tectonic style is not consistent across the proposed continent. Documented metamorphic signatures of ca.1700 Ma age indicate that some parts of the Mawson assemblage have characteristics of low-P/T metamorphic belts accompanied by magmatism (Gawler proper, Terre Adelie and Shackleton Range), including high-T granulites, whereas other areas are marked by eclogite/high-P granulite (high-P/T) signatures indicative of orogenesis and/or collision affecting older basement (Nimrod Group). These variations might reflect linked accretionary and magmatic signatures of Mawson consolidation or craton-margin activity.

A final 1600 Ma event is a major component late in the Gawler (Gawler Range Volcanics (GRV) and Hiltaba Granite suites) and is also seen along the Terre Adelie coast. It is yet to be recognized in the Nimrod, either as significant detrital zircon populations or as discrete magmatic rocks. This suggests that the Mawson, at least in terms of extending to the TAM, was no longer contiguous during Mesoproterozoic times. In part this is supported by the presence of significant 1440-1480 Ma detrital zircons in the Nimrod and Beardmore Groups and, importantly, as magmatic clasts clearly derived from proximal East Antarctica.

In summary, the Mawson Continent was initiated on a 3150-3000 Ma magmatic and gneissic basement that extended from the Gawler through Terra Adelie and the Transantarctic Mountains. Ensuing tectonic and magmatic events punctuated the continental history with key elements at 2500 Ma and 1700 Ma. Likely partial dispersal, at least of the Transantarctic Mountains sector occurred prior to 1600 Ma and the resultant collision of Gawler-Terre Adelie with the remainder of Australia gave rise to high-grade



## XII International Symposium on Antarctic Earth Sciences

13 - 17 July 2015, Goa, India



metamorphism along its northern margin and far-field magmatism within (i.e. the GRV and Hiltaba granites). The Transantarctic Mountains thereby had a separate. The Transantarctic Mountains has a separate 1440-1480 Ma magmatic event and this continued through Grenville times. Younger tectonic and magmatic events associated with the Delamarian-Ross-Pampean orogenies have variably affected and overprinted the earlier Mawson Continent elements.



**S01 – 194: Geochronology of Antarctic Orogens**

***Trilobite Biostratigraphy of the Cambrian Spurs Formation at Mariner Glacier, Northern Victoria Land, Antarctica: Implications for Stratigraphic Reconstruction***

Tae-Yoon Park<sup>1</sup>; Ji-Hoon Kihm<sup>1</sup>; Jusun Woo<sup>1</sup>; Young-Hwan Kim<sup>1</sup>; Jong-Ik Lee<sup>1</sup>; Insung Yoo<sup>1</sup>; Sangbum<sup>1</sup>

Korea Polar Research Institute<sup>1</sup>

Early Palaeozoic successions of northern Victoria Land, Antarctica, formed during the Ross Orogeny, are represented by an accretionary complex of sedimentary rocks from three different tectonic terranes: the Wilson, Bowers, and Robertson Bay terranes, from inboard to outboard. The Bowers Supergroup of the Bowers Terrane is divided into the Sledgers, Mariner, and Leap Year groups in ascending order, and spans the Cambrian Series 3 to the Lower Ordovician. The Mariner Group at Eureka Spurs comprises the Molar, Spurs, and Eureka Formation, in ascending order, which is unconformably overlain by the Lower Ordovician Camp Ridge Quartzite, and has served as the type section of the Mariner Group in northern Victoria Land. The Spurs Formation at Eureka Spurs is 716 m in thickness and is dominated by fissile mudstone with channelized breccias and diamictites, thin-bedded sandstone, and lenses of limestone. Despite the reports on the presence of trilobites from several horizons, trilobites from a single horizon of the Spurs Formation have been previously documented, thus providing limited information on the biostratigraphy. During 2012-2013, 2013-2014, and 2014-2015 Antarctic summer seasons, numerous trilobites have been collected from more than ten horizons of the Spurs Formation. The studied interval is characterized by re-occurrences of similar trilobite faunas, indicating that the stratigraphy at this section is somewhat repetitive. This indicates that the unusually thick Spurs Formation at Eureka Spurs in the previous stratigraphic reconstruction should be amended.



### S01 – 211: Geochronology of Antarctic Orogens

#### ***Detrital Zircon Geochronology of the Mariner Group, Bowers Supergroup, Northern Victoria Land, Antarctica: Implications on Sediment Source and the Tectonic Evolution***

Jusun Woo<sup>1</sup>; Kim, Y.H.G.<sup>1</sup>; Park, T.Y.S.<sup>1</sup>; Kihm, J.H.<sup>1</sup>; Lee, J.I.<sup>1</sup>; Kim, Y.<sup>6</sup>; Kim, T.H.<sup>1</sup>; Choe, M.Y.<sup>1</sup>

Korea Polar Research Institute<sup>1</sup>; CBNU, Republic of Korea<sup>6</sup>

The northern Victoria Land (NVL) consists of three terranes: Wilson, Bowers, and Robertson Bay terranes from inboard to outboard. The three terranes have been interpreted as exotic tectonic terranes accreted to the Antarctic continent by the arc-subduction during the Cambro-Ordovician Ross Orogeny. Recent petrographic and structural investigations on the terrane boundaries have provided new evidences which have supported this interpretation, e.g., existence of eclogite and structures indicating westward convergence during the accretion. In regard of stratigraphic aspect, however, few new stratigraphic data have been acquired since 70's and 80's reconnaissance investigations. This study aims at providing new geochronologic data of the Bowers Supergroup with the aid of detrital zircon geochronology. The Bowers Supergroup in Mariner Glacier area consists, in ascending order, of Glasgow Volcanics, Molar, Spurs, Eureka Formations, and Camp Ridge Quartzite. A total of 371 detrital zircon grains from six rock samples have been dated by SHRIMP U-Pb method. Detrital zircon ages from a tuff bed in the Glasgow Volcanics have the youngest grain of  $560 \pm 4$  Ma and major peaks at 550 Ma and 950 Ma. Detrital zircon ages from a sandstone bed in the Molar Formation have the youngest age of  $495 \pm 4$  Ma and major peaks at 550 Ma and 1050 Ma. Those from two sandstones from the Spurs Formation have the youngest ages of  $509 \pm 7$  Ma and  $517 \pm 7$  Ma with the major peaks in 800-700 Ma and 1500-1200 Ma intervals. Two sandstone samples from the Camp Ridge Quartzite have the youngest zircon grains of  $525 \pm 4$  Ma and  $471 \pm 5$  Ma. Two major peaks are distributed at 600-450 Ma and 1200 Ma. All samples yield minor peaks in the range of  $>1500$  Ma.

The zircon age peak of the Ross (480-550 Ma) and Grenville (900-1350 Ma) ages are evident in the Glasgow Volcanics, Molar Formation, and Camp Ridge Quartzite, with the Ross age peak being the most significant in proportion. This pattern is suggestive of inputs from heterogeneous source dominated by the late Neoproterozoic-Cambrian and Mesoproterozoic terranes. This is similar pattern to the coeval Byrd Group in the central Transantarctic Mountains. Minor peaks with ages older than 1500 Ma are interpreted as inputs from the cratonic source. Weak development of the Ross-age peak and a broad peak in the range of 1500-1200 Ma are unique characteristics of the detrital zircon ages of the Spurs Formation. This suggests that there was a change in sediment provenance or sediment dispersal system during deposition of the Spurs Formation.



## S01 – 271: Geochronology of Antarctic Orogens

### ***Neoproterozoic Basinal Deposition from Theschemacher Oasis, East Antarctica: Evidence From detrital Zircon U-Pb Ages in High-Grade metasedimentary Rocks***

Ravikant Vadlamani<sup>1</sup>; Böhn Bernhard<sup>2</sup>; Pimentel Marcio<sup>2</sup>

Indian Institute of Technology, Kharagpur India<sup>1</sup>; University Of Brasilia, Brazil<sup>2</sup>

The Lurio–Vijayan block along with adjoining crust of coastal central Dronning Maud Land, the Sør Rondane Mountains and Yamato-Belgica Mountains, eastern Dronning Maud Land, has been interpreted as consisting of independent exotic blocks/arcs that formed between 800-600 Ma in response to accretionary orogenesis during closure of the Mozambique Ocean. A key feature is the occurrence of deformed metasedimentary rocks intercalated with the high-grade magmatic rocks, the constraining of depositional age of which is attempted here. As detrital zircons represent sample of detritus into evolving sedimentary basins, the age distribution of zircons from granulite-facies metasedimentary successions has been conducted. The zircons separated were analyzed by LA-MC-ICPMS (<sup>206</sup>Pb/<sup>238</sup>U ages), and consist of mixed detrital and grains formed during younger granulite-facies metamorphic events. The Schirmacher Oasis comprises high- grade lithotectonic units that include felsic biotite-quartzofeldspathic gneiss (with two pyroxene granulite and sapphirine-orthopyroxene-garnet bearing granulite layers and pods) and enderbitic gneiss. The enderbitic gneiss contains enclaves of noritic gneiss and leucogabbro. Noritic gneiss-and foliated leucogabbro exposed in central Schirmacher contains enclaves of metamafic and ultramafic rocks comprising melanocratic gabbro, gabbroic anorthosite, pyroxenite and websterite, which preserve their pre-metamorphic (igneous) compositional layering despite a granulite facies mineralogy. Minor volumes of high- grade metasedimentary rocks include layered paragneiss comprising Fe-rich metapelite (quartz-garnet-sillimanite-perthite gneiss), garnet-sillimanite quartzite and minor calc gneiss with layers and boudins of metamorphosed noritic dykes.

The zircon age spectra from the Schirmacher Oasis pelite MS1/23 shows major peaks at 612 Ma and minor peaks at 1045 Ma, 700 Ma and 500 Ma, whereas this spectra from calcsilicate MS5/23 contains major peaks at 611 Ma, and minor peaks at 700 Ma, 750 Ma and 880 Ma. A leptynite sample SR4/23 (leucosome from the Western Schirmacher Oasis) contains major age peaks at 658 Ma and 724 Ma and minor peaks at 880 Ma, 830 Ma and 516 Ma.

Although similar, the Veteheia nunatak quartzite MS2/23 zircon age spectra contains major peaks at 1032 Ma, 933 Ma and minor peaks at 772 Ma, 600 Ma whereas a leucosome from Veteheia, sample MS4/23, contains zircons with major age peaks at 866 Ma and 648 Ma and minor peak at 970 Ma.

The total zircons include both detrital as well as those crystallized during high-grade metamorphic events; magmatic orthogneiss suite of eastern central and Schirmacher Oasis including enderbite, norite and gabbroic variants geochemically have calc-alkaline trends and preserve igneous zircons with ages of ~700-750 Ma. In contrast, the gabbroic enclaves show MORB-type trace element geochemistry and were emplaced earlier into the sedimentary successions at ~800 Ma. The 615 Ma and 648–658 Ma clusters in zircon U-Pb and garnet Sm-Nd dates clearly represent the age range of the pervasive UHT granulite-facies event coeval with the East African Orogeny. Relict high-grade metamorphism was also reported from garnet-bearing noritic dykes from the Veteheia nuntak at ~975 Ma.

A straightforward geodynamic interpretation is an early stage of rifting and emplacement of MORB-type magmas followed by a later stage of convergent tectonics which resulted in a collage of arc and micro-continent accretion to a continental margin. The first-order interpretation from the zircon age distribution patterns in metasedimentary granulites suggest a similar provenance and upper age depositional constraint to sedimentary rocks from both the Veteheia nunatak and the Schirmacher Oasis at either 850 Ma or ca. 1000 Ma. Importantly, the detrital zircon age spectra do not contain older grains derived from continental interior domains, in contrast to the detrital zircon age spectra from the metasedimentary



rocks of central Dronning Maud Land nunataks, supporting the concept of basin development in the collage of arcs and micro-continents and therefore would have been deposited in tectonically controlled basins.

This result, constraining the depositional ages of sedimentary succession, can be interpreted in two ways: either the basin can be correlated with the chemostratigraphic depositional ages reported for carbonates from the Montepuetz Complex, Mozambique, and the reported depositional ages spanning ~880 to 790 Ma for metacarbonate rocks from the Sir Rondane Mountains, that support the presence of contemporaneous marine platform depositional environment, probably in the now-consumed Mozambique Ocean; or that they represent ~1 Ga-aged basins being coeval and developed as a back-arc basin to the ~1 Ga orthogneiss-dominated arc terrains.



### S01 – 327: Geochronology of Antarctic Orogens

#### ***Continuous Sedimentation along the East Gondwana Margin - Implications from Detrital Zircon Ages of Ross-Orogenic Metasedimentary Units of Northern Victoria Land, Antarctica***

Läufer Andreas<sup>1</sup>; Estrada Solveig <sup>1</sup>; Eckelmann Katja<sup>2</sup>; Hofmann Mandy<sup>2</sup>; Linnemann Ulf<sup>2</sup>

Federal Institute For Geosciences And Natural Resources (BGR), Hannover, Germany<sup>1</sup>; Senckenberg Naturhistorische Sammlungen, Dresden, Germany<sup>2</sup>

Rodinia breakup led to the development of the passive margin of the Paleo-Pacific Ocean along the eastern side of the Australian-Antarctic sector of East Gondwana in the late Neoproterozoic. This passive margin stage terminated, when west-directed subduction of the Paleo-Pacific plate underneath the East Gondwana active continental margin initiated the Andean-type Ross-Delamerian orogeny in Cambrian times. In Antarctica, this ancient mountain belt constitutes the basement rocks of the modern Transantarctic Mountains.

Northern Victoria Land (NVL) is located at a central position of the Ross-Delamerian system. The Palaeozoic structural edifice of NVL is traditionally interpreted in terms of three fault-bounded lithotectonic units or terranes. These units comprise from west to east the Wilson Terrane (low- to high-grade metamorphosed sedimentary rocks and voluminous granitoids), the Bowers Terrane (low-grade metamorphic island arc-type volcanics of the Glasgow Formation and sedimentary rocks of the Molar Formation), and the Robertson Bay Terrane (very low- to low-grade turbidites). The tectonic evolution of NVL is still under debate. Some insights may be derived from detrital mineral dating of the thick metasedimentary sequences of the three terranes. However, the stratigraphic correlation between the isolated outcrops is rather difficult due to the regional and contact metamorphic overprint, the scarcity of fossil remains, and the juxtaposition of blocks of different ages and/or degrees of metamorphism during the Ross orogeny and by later tectonics of possibly late Palaeozoic and Meso-Cenozoic age.

In order to get information on provenance and depositional ages of the rock sand to compare them with metasedimentary units from other sectors of the Ross-Delamerian orogen as well as to test existing tectonic models, U-Pb LA-ICP-MS dating of detrital zircons from meta-sedimentary rocks of all NVL terranes was performed. Age dating was combined with petrographical and whole-rock geochemical studies. We analyzed 4 samples from the Priestley Formation (Wilson Terrane), 5 samples from the Molar Formation (Bowers Terrane), 2 samples from the Millen Schist belt along the Bowers-Robertson Bay terrane boundary, and finally 3 samples from the Robertson Bay turbidites.

The metasedimentary rocks of all lithotectonic units show very similar detrital zircon age spectra with two main age intervals, a Ross/Pan-African-age interval (470 to 700 Ma) and a Grenville-age interval (900 to 1300 Ma) as well as subordinate craton-related ages dispersed over a wide range of ca. 1600 to 3500 Ma. The Ross/Pan-African-age zircon population tends to get more dominant from the Priestley Formation in the Wilson Terrane in the W into the Molar Formation in the Bowers Terrane in the centre, and finally into the Robertson Bay Group in the E, whereas the amount of craton-related ages diminishes in this direction.

The concordia age of the youngest zircon population (interpreted as a maximum age of deposition) is ca. 592 Ma for the Priestley Formation (Neoproterozoic), whereas Ross-orogenic maximum depositional ages were derived from the Molar Formation (ca. 495 Ma), the Millen Schists (ca. 485 Ma) and the Robertson Bay Group (ca. 485 Ma).

These results imply (i) a common East Antarctic source area for all analyzed samples and (ii) the existence of a basement with Grenville- and early Pan-African-age signatures. The Priestley Formation is interpreted to have formed in a passive continental margin environment in late Neoproterozoic times, but



before the onset of subduction. It was later metamorphosed and intruded by the continental arc-type Granite Harbour Intrusives during the Ross Orogeny between c. 530 and 480 Ma. The 495 Ma depositional age of the Molar Formation contradicts earlier models that date the clastics into the middle Cambrian based on stratigraphic evidence that the Molar clastic rocks and the Glasgow volcanics interfinger and the contacts are of sedimentary nature. We interpret the Molar Formation as a turbiditic sequence deposited on the active continental margin and mixed with oceanic crustal materials and exotic island-arc-derived components to form a melange in an accretionary setting. The Glasgow volcanic rocks of the Bowers Terrane represent imbricate slices and fragments of an older exotic intra-oceanic island arc that formed in the Paleo-Pacific Ocean off the E Gondwana margin and became attached to the Ross-age active continental margin not later than c. 495 Ma. The thick, homogeneous sequence of the Robertson Bay turbidites was deposited in front of the now combined Wilson-Bowers terrane assembly during the early Ordovician after ca. 485 Ma as suggested by the ages from the Millen Schists and Robertson Bay turbidites. The basement of the Robertson Bay Group is unknown, but could probably consist of juvenile oceanic crust and/or thinned old continental crust as for example in the Australian section of the Ross-/Delamerian and Lachlan orogens. In this context, the geodynamic setting of NVL is consistent with a modified terrane model that consider the Bowers island arc as exotic terrane instead of a model that includes supra-subduction-zone forearc extension of the Wilson Terrane and the formation of an arc-/backarc-system.



## S01 – 404: Geochronology of Antarctic Orogens

### *Proterozoic Crustal History of Central East Antarctica*

Mark Fanning<sup>1</sup>; Goodge, J. W. <sup>2</sup>; Vervoort, J. D. <sup>3</sup>

Research School of Earth Sciences, Australian National University, Canberra, ACT 0200 Australia <sup>1</sup>;  
Department of Earth & Environmental Sciences, University of Minnesota, Duluth, MN 55812 USA <sup>2</sup>;  
School of the Environment, Washington State University, Pullman, WA 99164, USA <sup>3</sup>

The geotectonic history of the deep interior of East Antarctica is poorly known. Except for patchy geophysical datasets collected over the ice sheet, we are left to extrapolate geological information long distances from coastal outcrops or from rare exposures of Precambrian basement in the Transantarctic Mountains (TAM). Sampling of glacial moraines at the edges of large catchments eroding the interior and of crustally-interacting granitoids can, however, provide some valuable constraints on the otherwise covered subglacial geology. Together, these two approaches provide evidence for a rich, previously unknown Proterozoic crustal history of the East Antarctic shield and indicate the presence of fundamental crustal age boundaries.

New U-Pb zircon ages from a large suite of glacial igneous clasts collected from drainages crossing the TAM demonstrate that the crust in central East Antarctica was formed by a series of 2.00-1.90, 1.88-1.85, 1.75-1.73, 1.58-1.55, 1.48-1.43, and 1.20-1.10 Ga magmatic events. The dominant igneous populations are 1.85, 1.45 and 1.18 Ga, with some showing metamorphic overprinting at 1.15-1.18 Ga. Together, these disparate and unique lines of evidence indicate the presence in cratonic East Antarctica of a large, composite Proterozoic igneous province that reflects crustal growth across central East Gondwana, and they provide direct geologic support for a SWEAT configuration of the Nuna supercontinent to at least ~1.4 Ga. The persistence of ~1.1 Ga Grenville-age igneous and metamorphic signatures in the interior may reflect the latest stages of Rodinia assembly, and may provide the best sampling to date of crust underlying the Gamburtsev Subglacial Mountains.

Zircon Hf and O isotopic compositions of these igneous clasts help to further evaluate crustal history. Among the granitoid clast populations: (1) there is a general pattern of increasing  $\delta^{18}\text{O}$  with decreasing  $\epsilon\text{Hf}$ , both corresponding with increasing age; (2) granitoids of ~2.0 Ga age have positive Hf compositions ( $\epsilon\text{Hf} = +1$  to  $+4$ ) and mantle  $\delta^{18}\text{O}$ ; (3) rocks of ~1.57, ~1.79 and ~1.88- 1.85 Ga age show variable compositions with  $\epsilon\text{Hf} = +5$  to  $-8$ , and  $\delta^{18}\text{O} = 5.8$ - $8.3$  ‰, and the ~1.88-1.79 Ga granitoids require some involvement of Archean crust; (4) rocks of 1.50-1.45 Ga age have mantle signatures with  $\epsilon\text{Hf} = +5$  to  $+11$ ; and (5) rocks of ~1.2 Ga age have crustal  $\delta^{18}\text{O}$  signatures and  $\epsilon\text{Hf} = +2$  to  $+5$ . Together, these age and isotopic data provide the first glimpse of crustal growth in central East Antarctica and suggest a varied history of relatively juvenile Proterozoic magmatism.

In addition to the igneous clasts, metamorphic rock clasts from glacial moraines along the central TAM reveal previously unknown metamorphic events within the ice-covered shield. Abundant semi-pelitic leucogneiss clasts contain moderate- to high-P assemblages of Grt + Bt + Pl + Qz  $\pm$  Mc  $\pm$  Als  $\pm$  Ms, plus accessory Mnz and Zrn. In-situ SHRIMP U-Pb monazite analysis of two clasts gave Paleoproterozoic ages: one yielded an age of ~1190 Ma with older inherited components up to ~1900 Ma, and the other has a metamorphic age of ~1690 Ma with an older component at ~1870 Ma. Five other samples, from moraines near the Miller Range, yielded pre-Ross Neoproterozoic ages. Three have metamorphic ages of ~545-555 Ma whereas the others have ages between ~570 and ~595 Ma, the latter having an older component at ~660 Ma. These ages coupled with P-T analysis provide a greater understanding of the crustal and tectonic history of the East Antarctic shield. Together, they record previously unknown Paleoproterozoic tectonometamorphic events in central East Antarctica that may be related to assembly of the Nuna supercontinent (~1870-1900 Ma), a first record of this in Antarctica, and the younger Mesoproterozoic metamorphism corresponds to recently identified magmatic events, suggesting a



common tectonomagmatic origin. An age component of ~660 Ma may relate to Rodinia break-up recorded elsewhere in Antarctica and Australia. Ages from the younger samples (~545-595 Ma) precede metamorphic dates typically reported from the Ross Orogen (~470-540 Ma); these samples may therefore provide evidence that Ross metamorphism was initiated significantly earlier than previously thought.

Ross-age granitoids in the Transantarctic Mountains can be used as proxies of crustal age and evolution. New U-Pb age data, coupled with whole-rock geochemical compositions and zircon O- and Hf-isotope analyses, from a geographically diverse suite of granite samples provide a wealth of new geochronologic, tracer and inheritance information. SHRIMP U-Pb zircon ages from these samples range from ~475-550 Ma with several <490 Ma, which is typically considered the minimum age of Ross magmatism. Geochemically the Ross magmatic suite consists mostly of granites, with lesser granodiorites and tonalites that show major and trace element characteristics of Cordilleran-type, calc-alkaline volcanic-arc magmas. They have uniform peraluminous compositions of both ferroan and magnesian affinity. Trace-element patterns and oxide mineralogy show that both HFSE-enriched I-type compositions and S-type compositions occur along the length of the belt. SHRIMP zircon  $\delta^{18}\text{O}$  values range from +5.4 to +11.5‰ and are generally uniform within individual samples. The lower values are equivalent to those of mantle zircon and range to crustally-derived magmatic values. Initial  $\epsilon\text{Hf}$  compositions range from -16 to +7, and most samples are uniform in composition. Zircon xenocrysts indicate inheritance of older components of about 1.2, 1.6, 2.0 and 2.5 Ga, reminiscent of the igneous clast ages noted above. There is no apparent relationship between age and O- or Hf-isotope compositions, but a strong inverse correlation between  $\epsilon\text{Hf}$  and  $\delta^{18}\text{O}$  indicates that more crustal-like O-isotope compositions correlate with less radiogenic Hf. Four samples of S-type granites that intrude Archean basement lie off this trend and indicate greater contributions of older, unradiogenic crust. The isotopic compositions of this areally widespread granitoid suite indicates the presence of a fundamental crustal discontinuity along the Ross margin of East Antarctica at about the position of Shackleton Glacier, separating dominantly Mesoproterozoic crust to the south toward the Thiel Mountains from Archean-Proterozoic to the north in the direction of Victoria Land.



## S01 – 418: Geochronology of Antarctic Orogens

### ***An Investigation of Granitoid Sheets in the Hu Sverdrupfjella, Western Dronning Maud Land, Antarctica.***

Burger E.P.<sup>1</sup>; Grantham G.H.<sup>2</sup>; le Roux P.<sup>3</sup>; Roberts R.J.<sup>1</sup>

Department of Geology, University of Pretoria, Pretoria, South Africa<sup>1</sup>; Department Of Geology, University Of Johannesburg, Johannesburg, South Africa<sup>2</sup>; Department Of Geological Sciences, University Of Cape Town, Cape Town, South Africa<sup>3</sup>,

The HU Sverdrupfjella is a mountain range in Western Dronning Maud Land, Antarctica, between 72° S, 73° S and 00° 35' W, 01° 45' E. Sverdrupfjella has been subject to at least two orogenic events; an early top-to-the NW Mesoproterozoic (?) event and a later top-to-the SE Neoproterozoic/Cambrian event. Sverdrupfjella is composed predominantly of gneisses which are part of the Jutulrora, Fuglefjellet and Rootshorga complexes. These complexes are extensively intruded by large intrusions and veins/dykes with basic to acid to alkaline compositions with ages ranging from the Mesoproterozoic to the Jurassic.

Some of these intrusions show varying degrees of deformation and metamorphism. This study focuses on relatively thin granitoid sheets, which are common throughout Sverdrupfjella. The orientation, geochemistry and geochronology of these granitoid sheets are being studied in order to investigate their involvement in the tectonic evolution of the area and assembly of Gondwana.

Four granitoid phases are recognized and designated P0-P4. The oldest P0 phase comprises sub-horizontal folded sheets with axial planar foliations, the folding being consistent with D1 top-to NW deformation. Vein shapes are typically lenticular and anastomosing suggesting emplacement in a ductile environment.

Veins of the P1 granitoid phase are typically pegmatitic, crosscut most other phases including P0 and have been locally folded and boudinaged but typically have no planar fabrics. The P1 pegmatites typically have steep dips and strike ~NW-SE. At Kvitkjolen, a vein typical of P1 is truncated by a sub-horizontal thrust fault, indicating its intrusion during D1. The steep dip of the P1 veins indicates emplacement into an extensional environment and their morphologies indicate emplaced in a dominantly brittle environment. The P1 veins are very coarse grained, white in colour with the dominant minerals being quartz and plagioclase in approximately equal proportions, with some biotite occurring as large books. Alteration of plagioclase and interstitial (late-forming) K-feldspar is visible in thin section. The P1 pegmatites are generally metaluminous, and chondrite normalized REE plots show enrichment in LREE's and a pronounced positive Eu anomaly. Preliminary data show that the P1 granitoid phase is derived from a more juvenile source with distinct and higher <sup>143</sup>Nd/<sup>144</sup>Nd ratios than the other granitoids discussed here. The P2 phase veins and sheets are correlated with the Cambrian-age Dalmatian Granite (Grantham *et al*, 1991), are typically granitic, and show little deformation. They are clearly syn-tectonic (from field observations). The P2 granite sheets have dominantly shallow to near-horizontal dips and strike ~NW-SE. A sub-population within this group strike ~NE-SW. The shallow to near-horizontal dips and local conjugate intrusive pairs suggest a compressional emplacement setting. The veins were typically emplaced into a brittle environment. The P2 granites are medium to coarse grained and pink to buff in colour and locally exhibit tourmaline "spots", particularly in sheets intruded into carbonates in the Fuglefjellet Complex. The composition is: quartz, K-feldspar (dominant feldspar), some plagioclase, mica (biotite and some muscovite) limited partial alteration in thin section. P2 granites are typically peraluminous. Chondrite normalized REE plots show enriched LREE's and most samples have weak negative Eu anomalies. The P2 granites show more evolved <sup>143</sup>Nd/<sup>144</sup>Nd characteristics than the P1 granitoids and also show widely varying <sup>87</sup>Sr/<sup>86</sup>Sr isotopic signatures possibly suggesting genesis from older crust.



The P3 intrusions are typically pegmatitic and crosscut the other phases. P3 sheets strike ~NW-SE. The overlap in orientations and similar appearance (when grain sizes are similar) between P2 and P3 granitoids suggest that these intrusions may not be entirely distinguishable. The differences may indicate a change in emplacement conditions, involving a change in stress (producing different orientations) and an increase in volatile content (resulting in larger grain size). The P3 veins are typically very coarse grained, but have variable grain size (ranging from medium-grained to several cm long grains). P3 pegmatites are generally pink in colour, but do contain significant proportions of plagioclase at some localities. Quartz, feldspar (mostly K-feldspar), biotite, muscovite and some mafic accessory minerals make up P3 mineralogy. A single sample of P3 analyzed is peraluminous, enriched in LREE and has a positive Eu anomaly.

The P0 and P1 intrusions were emplaced during the early D1 top-to-NW deformation in Sverdrupfjella. Zircon geochronology from these intrusions will therefore constrain the age of D1. The P2 and P3 intrusions were emplaced during the D2 top-to-SE deformation which has been constrained at ~470Ma to ~500Ma. The data are compared with data from other areas in Dronning Maud Land.



**S01 – 475: Geochronology of Antarctic Orogens**

***Redox Condition of Granitoid Magmatism along an East-West Crustal Corridor of Bundelkhand Craton, Central India***

Gajender Kumar<sup>1</sup>; S. Kumar<sup>1</sup>; S. Raju<sup>2</sup>; S. Bora<sup>1</sup>; C. Mehra<sup>1</sup>; Saurabh Gupta<sup>1</sup>; M.S. Rawat<sup>1</sup>

Department Of Geology, Kumaun University, Nainital, India<sup>1</sup>; Geological Survey of India<sup>2</sup>

The northern most part of Indian Precambrian shield is occupied by Bundelkhand craton, which is located north of central Indian tectonic zone. U-Pb SHRIMP Zircon geochronology has suggested occurrence of five pulses of granitoid magmatism viz. diorite (2550±5 Ma), granodiorite (2544±5), fine grained syenogranite (2526±6 Ma) medium grained monzogranite (2522±8 Ma) and rhyolite (2526±6 Ma) constituting the Bundelkhand craton. Fine to coarse grained grey to pink coloured granodiorite, monzogranite, and syenogranite are the major lithounits exposed in the E-W crustal corridor of Bundelkhand craton. Magnetic Susceptibility (MS) measurement and biotite composition from representative granitoids have been carried out in order to understand redox condition, nature and tectonic environment of host granitoid melts. On the basis of MS measurement the granitoids are divided into magnetite ( $> 3 \times 10^{-3}$  SI units) and ilmenite ( $< 3 \times 10^{-3}$  SI units) series granitoids viz. fine grained pink to grey granodiorite ( $11.48 \times 10^{-3}$  SI units), medium grained pink granodiorite ( $8.18 \times 10^{-3}$  SI units) and medium grained pink syenogranite ( $7.99 \times 10^{-3}$  SI units), which are dominantly magnetite (oxidized) type while grey leucocratic monzogranite ( $0.05 \times 10^{-3}$  SI units) shows ilmenite series nature formed in reduced environment. Biotites from granodiorite are Fe-biotite, primary in nature and coexist with other ferromagnesian minerals. Biotites from pink to grey granodiorite are rich in Mg content and poor in Fe content ( $\text{FeO}_t/\text{MgO}=2.83\text{-}3.26$ ), and exhibit Mg-Fe<sup>+2</sup> substitution stabilizing at Fayalite-Magnetite-Quartz (FMQ) and Nickel-Nickel-Oxide (NNO) buffer, which mostly occurred in subduction-related, calc-alkaline magmas. Biotites from medium grained pink granodiorite are purely metaluminous (I-type) primary in nature though it is completely pinkish in colour which suggest that potassic hydrothermal fluid has not affected the primary composition of biotite. Biotite from leucocratic monzogranite are moderately enrich in Fe content ( $\text{FeO}_t/\text{MgO}=3.36\text{-}3.6$ ) and exhibit their crystallization and evolution in peraluminous (S-type) felsic melt. They are mostly stabilized at Fayalite-Magnetite-Quartz (FMQ) buffer which suggests lesser degree of oxidation state of host magma. It is further corroborated by the absence of Al-Fe<sup>+3</sup> substitutions. Biotites in medium grained pink syenogranite are highly enrich in Fe content and poor in Mg content ( $\text{FeO}_t/\text{MgO}=7.15\text{-}7.63$ ), which suggest typical A-type (anorogenic) alkaline nature of host magma, which evolved in rift setting. They lie below the Fayalite-Magnetite-Quartz (FMQ) with no substitution between Mg and Fe<sup>+2</sup> and Al and Fe<sup>+3</sup>, which are indicative of reducing environment. The obtained results suggested contribution of three types of granitoid melts in the evolution of Bundelkhand craton. Metaluminous to peraluminous felsic melts were formed in arc-related calc-alkaline subduction to syn-collisional tectonic environments. Later on, anorogenic anhydrous A-type syenogranite magma was formed, which most likely during an extensional tectonic regime.



**S01 – 479: Geochronology of Antarctic Orogens**

***Constraining the Pan-African High-Grade Metamorphism Time of the Larsemann Hills, East Antarctica***

Ren Liudong

Institute of Geology, Chinese Academy of Geological Sciences

Up to now, it is generally accepted that both the basement and cover sequences of the Larsemann Hills have been involved in the high-grade deformation and metamorphism during the Pan-African event, which peaked at 530 Ma and was responsible for the widespread granitic magmatism between 525-500 Ma, including emplacement of the Progress Granite at ca. 516 Ma. The Pan-African high-grade metamorphic time is mostly obtained through dating zircon rims dating occurring in various rocks. For zircons with complicated textures, it is rather difficult to discriminate the recorded ages of the rims as they could represent the time of magmatism, metamorphism or some period between events. If a geological body having a relative simple history and zircon with easily recognized textures are present, one can constrain the time of metamorphism of the target body through mutual field geological relations. The foliated garnet-bearing granite postdating the peak metamorphism in the Larsemann Hills has a crystallization age of  $551 \pm 15$  Ma, and presence of high-grade mineralogical relics in the granite, constrains the time of peak metamorphism of the host wall rock gneisses to be older than  $551 \pm 15$  Ma. Whereas the zircons with black CL images in the host garnet-biotite-plagioclase gneiss of the area give an average age of  $522.7 \pm 6.6$  Ma, suggesting that the zircons were severely disturbed and reset in the Pan-African metamorphic event, this time cannot represent the time of peak metamorphism. Combined with the heterogeneous deformation and the ubiquitous resetting of old zircons in various rocks, we deduce that the Pan-African metamorphism and associated granites in the Larsemann Hills appears to be caused by an intra-continental mechanism or reactivation, not inter-continental collision as conventionally considered.



**S01 – 480: Geochronology of Antarctic Orogens**

***In-situ U-Pb and Trace Element Analysis of Multistage Zircon Overgrowths of Pelitic Granulite from the Larsemann Hills, East Antarctica***

Wei-(RZ) Wang<sup>1</sup>; ZhaoYue<sup>1</sup>; Liu Xiaochun<sup>1</sup>

Institute Of Geomechanics, Chinese Academy of Geological Sciences, Beijing, China<sup>1</sup>

Cathodoluminescence images of zircons in thin sections of the pelitic granulite from the Larsemann Hills, East Antarctic reveal that many of them have two stages of overgrowth: the outmost gray rim and the inner dark mantle. The overgrowths vary in width, with some gray rims narrower than the dark mantles. In-situ Nano SIMS U-Pb analyses yielded Pan-African ages for both stages of overgrowth. The outermost gray rim have much less Y content than the inner dark mantle, reflecting the changing conditions during zircon crystallization. The textural relationships involving the inclusion of zircons with dark overgrowth in garnet suggest the dark mantle of the zircons should have grown earlier than the rapid growth of the garnet, consistent with their high Y feature. The outmost gray rims should have developed during later cooling after the major garnet growth.



**S01 – 482: Geochronology of Antarctic Orogens**

***In-situ U-Pb-Hf Isotope Analyses of the Ultra-High Temperature Metapelite from Mather Peninsula, East Antarctica***

WANG Yanbin<sup>1</sup>; Tong Laixi<sup>2</sup>; Ren Liudong<sup>1</sup>

Institute of Geology, Chinese Academy of Geological Sciences, China<sup>1</sup>; Guanzhou Institute of Geochemistry, Chinese Academy of Sciences, China<sup>2</sup>

U-Pb zircon geochronology from an ultra-high temperature (UHT, ~1000 °C) granulite-facies metapelite from the Rauer Group, Mather Peninsula, east Antarctica, has yielded evidence for two episodes of metamorphic zircon growth, at ~1.00 Ga and ~530 Ma. Two episodes of magmatism in the source region to the protolith sediment, at ~2.53 and ~2.65 Ga, were identified from the zircon cores. Successive zircon growth at ~1.00 Ga and ~530 Ma records a sequence of distinct, widely spaced high-temperature metamorphic and/or anatexis events related to Grenvillian and Pan-African orogenesis. These metamorphic events in the rocks from Rauer Group can be correlated with events previously reported from the adjacent southern Prydz Bay and northern Prince Charles Mountains. Archean-aged zircon cores have oscillatory growth zoning and possess  $\epsilon_{\text{Hf}}$  values between -10 and +4, suggesting derivation of their precursor magmas both from old crust and juvenile material from mantle. The metamorphic domains have negative  $\epsilon_{\text{Hf}}$  values, which this means that Archean crust was remelted to generate these domains. The metamorphic effect on zircon Lu-Hf and U-Pb isotope systems in UHT metapelite is evaluated.  $T_{\text{Hf}}$  DM ages from cores of zircon grains indicate the metapelite rocks share a common ca. 2.65-3.36 Ga source that is indistinguishable from that previously reported for parts of the Rauer Group. This study presents robust geochronological evidence for the timing of UHT metamorphism in the Rauer Group, supporting arguments that the peak UHT metamorphic event occurred at ~1.0 Ga and was overprinted by a separate high-grade event at ~530 Ma.

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**S02 – 129: Geodynamic Evolution of the Dronning Maud Land Mountains**

***Tectonic Evolution of Sør Rondane Mountains, East Antarctica, based on Sr-Nd Isotope Geochemistry of Metacarbonate Rocks***

Satish-Kumar, M.<sup>1</sup>; Otsuji, N.<sup>1</sup>; Kamei, A.<sup>2</sup>; Takazawa, E.<sup>1</sup>; Tsuchiya, N.<sup>3</sup>; Grantham, G.H.<sup>5</sup>; Kawakami, T.<sup>6</sup>; Ishikawa, M.<sup>7</sup>; Osanai, Y.<sup>8</sup>

Niigata University, Japan<sup>1</sup>; Shimane University, Japan<sup>2</sup>; Tohoku University, Japan<sup>3</sup>; Council for Geoscience, South Africa<sup>4</sup>; Kyoto University, Japan<sup>5</sup>; Yokohama National University, Japan<sup>6</sup>; Kyushu University, Japan<sup>7</sup>

Determination of depositional ages of metasedimentary sequences in orogenic belts and tectonic environments in which they were deposited are of prime importance in understanding the formation and evolution of supercontinents. Although depositional age bracket can be approximated between the youngest protolith age of detrital zircons and metamorphism, obtaining accurate age of deposition is a difficult task. In order to overcome this, strontium and neodymium isotope geochemistry of sedimentary rocks are widely used. Especially for chemically deposited rocks, Sr-Nd isotopes help to understand the depositional environment and tectonic setting, including source rock characteristics and paleo-ocean signature. These two isotopic systems have distinct residence and mixing time in seawater, and are also largely controlled by surrounding continents. In this study, we have carried out a comprehensive study of Sr and Nd isotopic systems of metacarbonate and metamorphosed silicate rocks, such as pelitic, felsic, mafic and ultramafic rocks, from several important outcrops throughout the Sør Rondane Mountains, East Antarctica. We attempt to develop a model on the tectonic evolution prior to the final amalgamation of Gondwana supercontinent.

The Sør Rondane Mountains (SRMs), East Antarctica, situated in the junction of the N-S East African Antarctic Orogen and E-W Kuunga orogeny, is a key area to understand the final amalgamation of Gondwana Supercontinent exposed a suite of highly deformed medium- to high-grade metamorphic rocks in association with various types of igneous rocks. Metasedimentary rocks in this terrain were supposed to have formed in the paleo-ocean between East and West Gondwana. Based on recent geological studies, SRMs are divided into two terranes, the SW and NE terranes, by the Main Tectonic Boundary. In the SW terrane, metaigneous rock of ca. 1000 Ma intrusive ages occur along with metasedimentary rocks, which underwent metamorphic evolution along a clockwise P-T path. The NE terrane is dominated by metasedimentary rocks, with a characteristic anticlockwise P-T path. Additionally, metapelitic rocks in the SW terrane have similar detrital age population with the nearby meta igneous rocks, in contrast to those in the NE terrane show older detrital ages (ca. 3300 Ma). Both these terranes were subjected to regional metamorphism during the amalgamation of Gondwana. Twenty-four different metacarbonate layers were sample from seven regions within the Sør Rondane Mountains. Most of these layers occur as conformable units associated with gneisses of both sedimentary and igneous origins. Thickness of the layers varies from several decimeters to over ten meters, within which thin layers of pure and impure marbles crops out as alternate bands parallel to the regional trend of the major deformation. Skarn layers are developed between marble and gneiss in some units. In the impure marble layers, calc-silicate minerals such as olivine, spinel, clinohumite, phlogopite, diopside and tremolite are observed, in addition to accesSøry amounts zircon and graphite.

An extensive geochemical screening for post-depositional alteration, using oxygen isotopes, trace elements and REE + Y patterns, strontium isotope chemostratigraphy was applied to the metacarbonate rocks from SRMs and depositional ages of 880-850 Ma and 820-790 Ma (late-Tonian and early-Cryogenian age) were estimated. A detailed evaluation of Sr and Nd isotopic evolution was carried out. The metacarbonate rocks in the SW terrane are showing typical seawater-rock mixing relationship in a  $\epsilon_{\text{Sr}}$  vs.  $\epsilon_{\text{Nd}}$  cross-plot indicating the deposition of metacarbonate rocks nearby meta-tonalitic and



orthogneiss dominated continental arc. By contrast, the metacarbonate rocks in the NE terrane show a signature of depositional setting surrounding a continent, based on the comparison of metacarbonate rocks with continental and oceanic derived rock units.

We obtained evidence for the existence of an Oceanic Island arc system and peripheral Oceans before the formation of Gondwana supercontinent in the Neoproterozoic. Applying a multi-element isotope geochemical approach on chemostratigraphically well-constrained metacarbonate rocks collected from the remote Sør Rondane Mountains in East Antarctica, we model carbonate deposition surrounding an island arc system, mid-ocean volcanic islands and shallow marine continental shelf of a yet unidentified interior Antarctic continent, all of which accreted and amalgamated in the late Neoproterozoic to early Paleozoic to form the Gondwana supercontinent. We also compared the metacarbonate data with basement rocks from various neighbouring Gondwana continents, wherein some regional affinities could be established. Nd model ages of cratonic basements from East Africa (Kalahari) and India (Dharwar) is obviously different from Balchen carbonate rocks from Sør Rondane in East Antarctica, and the possible existence of a cratonic nucleus within the East Antarctic continent is speculated, surrounding which the carbonate rocks of the Balchen region might have deposited. Thus, geochemical proxies such as Sr and Nd isotopic compositions provide important information about depositional setting of sedimentary rocks and provide key information about the surrounding rocks of oceanic crust (basement) and continental crust during the time of deposition, which can lead us to a better understanding of paleo-tectonic setting of crustal fragments that assemble to form supercontinents.



## S02 – 161: Geodynamic Evolution of the Dronning Maud Land Mountains

### *Spatial and Temporal Influences on the Geochemical Signature of Pan-African Magmatism in the Sør Rondane Mountains (East Antarctica)*

Elburg, M.<sup>1</sup>, Andersen, T.<sup>2</sup>, Jacobs, J.<sup>3</sup>, Läufer, A.<sup>4</sup>, Le Roux, P.<sup>5</sup>, Ruppel, A.<sup>4</sup>, Harris, C.<sup>5</sup>, Krohne, N.<sup>6</sup>, Damaske, D.<sup>4</sup>

Department of Geoscience, University of Johannesburg, South Africa<sup>1</sup>, Department of Geosciences, University of Oslo, Norway<sup>2</sup>, Department of Earth Science, University of Bergen & Norwegian Polar Institute, Tromsø, Norway<sup>3</sup>, Federal Institute of Geosciences and Natural Resources (BGR), Germany<sup>4</sup>, Department of Geological Sciences, University of Cape Town, South Africa<sup>5</sup>, Department of Geosciences, University of Bremen, Germany<sup>6</sup>

The Sør Rondane Mountains, Western Dronning Maud Land, have been proposed to comprise two distinct terranes, an older amphibolite to granulite facies NE terrane with a clockwise PTt path and a younger greenschist to granulite facies SW terrane with a counter-clockwise PTt path that collided along the Main Tectonic Boundary.

New U-Pb zircon data, in combination with published analyses, show that Pan-African magmatism in the Sør Rondane Mountains occurred between ca. 650 and 500 Ma. Within this period, three magmatic (-metamorphic) pulses are observed, at 650-600 Ma, 575-550 Ma and 530-500 Ma.

Magmatism during the 650-600 Ma period was restricted in spatial extent and intermediate-felsic in composition, with the only pluton (Dufek) for which geochemical data is available showing a subduction signature in its trace element pattern. Zircon U-Pb and Lu-Hf data indicate contamination with local ca. 950 metatonalites, and the Hf-Nd isotopic signature can be explained by reworking of this pre-existing Neoproterozoic crust; the trace element "subduction signature" could therefore have been inherited. This magmatic episode occurred concurrently with high-grade metamorphism, that was most pronounced in the NE terrane.

The 575-550 Ma period is characterised by minettes, syenites and A-type granites. The minettes are similar in age as well as Sr and Nd isotopic composition to the syenites, with initial epsilon values close to 0. They are highly enriched in trace elements, and generally silica-undersaturated, which is different from the older exposed rocks in the area. However, mantle-normalised diagrams show negative Nb-Ta and Ti anomalies, suggestive of melting of subduction-modified lithospheric mantle. A-type granites display isotopic compositions similar to those of the syenites and minettes, which might indicate that minor crustal contamination drove the derivative liquids to quartz saturation.

The last magmatic period witnessed the intrusion of A-type granites and, presumably associated but yet undated, (quartz-) monzodiorites. Whole rock Nd and zircon Hf isotopic ratios extend to lower values than for the previous phases of magmatism, with little distinction between the mafic and felsic intrusives. Quartz <sup>18</sup>O values are similar to those observed for the earlier magmatic episodes, suggesting that the amount of crustal contamination is unlikely to be the main influence on the radiogenic isotopic ratios. The samples with the lower epsilon values are derived from more north-easterly areas showing that previously defined metamorphic and structural zones may coincide with boundaries between sectors with different average crustal ages.

The 150 Ma duration of igneous activity within the Sør Rondane Mountains suggests that its tectonic history is more complicated than simply the collision of two terranes along the Main Tectonic Boundary. It is more likely that successive collisions of smaller crustal fragments resulted in the collage that now constitutes the Sør Rodane Mountains. The presence of mafic and silica-undersaturated rock types



## *XII International Symposium on Antarctic Earth Sciences*

*13 - 17 July 2015, Goa, India*



suggests the involvement of the (lithospheric) mantle, arguing against intracrustal melting after crustal thickening as the only mechanism for melt generation.



**S02 – 207: Geodynamic Evolution of the Dronning Maud Land Mountains**

***Neoproterozoic 650-550 Ma Geologic Events at Sør Rondane Mountains, East Antarctica***

Hokada, T.<sup>1</sup>; Hori, K.<sup>1</sup>; Osanai, Y.<sup>2</sup>; Toyoshima, T.<sup>3</sup>; Baba, S.<sup>4</sup>; Nakano, N.<sup>2</sup>; Adachi, T.<sup>2</sup>

National Institute of Polar Research, Japan<sup>1</sup>; Kyushu University, Japan<sup>2</sup>; Niigata University, Japan<sup>3</sup>; Univ. Ryukyus, Japan<sup>4</sup>

The Sør Rondane Mountains in Dronning Maud Land preserve multiple tectonothermal events in the age range of c. 650-520 Ma (e.g., Shiraishi et al., 2008; Osanai et al., 2013; Adachi et al., 2013; Hokada et al., 2013), and has attracted interest as key region for understanding of the final amalgamation of Gondwana supercontinent. Generally the reported ages of Gondwana collision zones are in the range of 750-500 Ma (e.g., Jacobs et al., 2003; Grantham et al., 2003; Meert, 2003). From East Antarctica, a number of Neoproterozoic to Cambrian high-grade metamorphic terranes are distributed, and pervasive 550-520 Ma metamorphic ages have been reported from most of these terranes (e.g., Fitzsimons, 2000; Harley, 2003; Shiraishi et al., 2003) with minor >650-550 Ma ages (e.g., Shiraishi et al., 2008). The Sør Rondane Mountains is one such area where older c. 640-600 Ma high-grade metamorphic rocks along with pervasive 550-500 Ma age events have been obtained. Hokada et al. (2013) discussed based on the zircon and monazite U-Th-Pb and REE analyses by using ion microprobe (SHRIMP) and electron microprobe (EMP) applying to garnet-biotite-sillimanite gneiss and associated multiple generations of leucocratic veins in the central part of the Sør Rondane Mountains, and suggested multiple (at least three stages) of metamorphic and fluid (intrusion of leucocratic vein) events at >700 Ma, 640-630 Ma and 550-520 Ma with main granulite-facies event at c. 637 $\pm$ 6 Ma. Geologic records of the Sør Rondane Mountains, combined with the other available and newly obtained age data, could provide constraints for decoding Neoproterozoic-Cambrian metamorphic-fluid regimes in the Gondwana collision zone.



## S02 – 250: Geodynamic evolution of the Dronning Maud Land Mountains

### ***Hydrous Plutonic Magmatic Rock from Dg Snout, Schirmacher Oasis, East Antarctica: Implications and Significance***

Randive, K. R.<sup>1</sup>; Beg, M. J.<sup>2</sup>; Asthana, R.<sup>3</sup>

Rashtrasant Tukadoji Maharaj Nagpur University, Nagpur, India<sup>1</sup>; National Centre for Antarctic and Ocean Research, Goa, India<sup>2</sup>; Geological Survey of India, Faridabad India<sup>3</sup>

Hydrous plutonic magmatic rocks form discrete suites such as appinites, sanukitoids, adakites, dubrachites, etc; each suite comprises several individual rocks types; for e.g. Caledonian appinites include rocks such as cortlandite (a hornblende peridotite) and kentallenite (an olivine + pyroxene + alkali feldspar + plagioclase monzonite) among others. Main features of these suites are the abundance of hydrous minerals (amphiboles and micas), elevated large ion lithophile elements (LILE) and light rare earth elements (LREE) concentrations, and many of the lithologies of the above suites show chemical affinities to high-K calc-alkalic shoshonites. The appinites and dubrachites are considered to be parental magmas for the calc-alkaline lamprophyres such as vogesite, spessartite, kersantite and minnette.

The above suites of rocks can form where the mafic magma becomes anomalously enriched in water. Such environments are likely to occur in several specialized subduction related settings.

An unusual looking magmatic rock is observed in the DG Snout area of Schirmacher Oasis, Antarctica. Dimension of this outcrop is about 15 m wide and 25 m long. The rock is coarse-grained and composed of almost equal proportions of felsic and mafic minerals, mica being most prominent. The rock is intruded by pegmatites which also occur profusely at the contact of intrusion. Microscopic and EPMA studies indicate presence of mica, amphiboles and feldspars as major minerals along with zircon, apatite, monazite, quartz and thorite. The rock has intermediate composition with high silica, low magnesia and LILE-enriched and HFSE-depleted trace elements pattern. The chondrite normalized REE spidergram shows LREE-enriched HREE-depleted pattern with only meagre Eu anomaly. Amphiboles are actinolite and tremolite; feldspars are Ba-rich potassic feldspars and sodic plagioclase and micas are biotites. This rock is mineralogically and geochemically analogous with the lamprophyre dykes of the Schirmacher Oasis and other nunataks in the proximity. It is apparent that the hydrous plutonic magmatic rock of the DG Snout is either a part of the one of the suites of a hydrous plutonic magmatic rocks or the metasomatised enclave within a granitic batholith or a “peri-batholithic” rock mass.



## S02 – 304: Geodynamic evolution of the Dronning Maud Land Mountains

### ***Pan-African Strike-Slip Tectonics in the Sør Rondane Region, Dronning Maud Land, and Lateral Extrusion of the East African-Antarctic Orogen***

Ruppel, A.<sup>1</sup>; Läufer, A.<sup>1</sup>; Jacobs, J.<sup>2</sup>; Elburg, M.<sup>3</sup>; Krohne, N.<sup>4</sup>; Eagles, G.<sup>5</sup>; Mieth, M.<sup>5</sup>; Jokat, W.<sup>5</sup>; Damaske, D.<sup>1</sup>; Lisker, F.<sup>4</sup>

Federal Institute for Geosciences and Natural Resources (BGR), Hannover, Germany<sup>1</sup>; University of Bergen & Norwegian Polar Institute, Norway<sup>2</sup>; University of Johannesburg, South Africa<sup>3</sup>; University of Bremen, FB 5 Geoscience, Germany<sup>4</sup>; Alfred Wegener Institute (AWI), Helmholtz Centre for Polar and Marine Research, Bremerhaven, Germany<sup>5</sup>

Sør Rondane occupies a key position for reconstructing the late Neoproterozoic to early Paleozoic geodynamic evolution in eastern Dronning Maud Land (DML) since it appears to be located close to the supposed intersection of the East African-Antarctic Orogen (EAAO) and the Kuunga Orogen. The western part of Sør Rondane is dominated by two distinct terranes. The amphibolite to granulite-facies NE terrane is mainly composed of metasedimentary rocks, showing Pan-African overprint provided by new SHRIMP zircon data from metamorphic rims with ages of ca. 560 Ma. The SW terrane is subdivided by the Main Shear Zone (MSZ) into two lithotectonic units, i.e. Pan-African greenschist- to granulite-facies metamorphic rocks with “East African” affinities in the N and a Rayner-age early Neoproterozoic gabbro-tonalite-trondhjemite-granodiorite (GTTG) complex with “Indo-Antarctic” affinities in the S. The GTTG complex has suffered Pan-African greenschist- to lower amphibolite-facies thermal overprint but also contains large domains with only weak deformation except for its northern margin affected by the MSZ. New zircon crystallisation ages cluster around 1000-930 Ma. Oceanic affinities are reported for the GTTG terrane and its wide age range might indicate a long-lasting accretionary orogen.

The MSZ is characterized by a right-lateral sense of movement and high-strain ductile deformation under peak amphibolite-facies conditions. The structure can be traced over a distance of ca. 120 km between Lågakollane in the W and Lunckeryggen in the E and reaches several hundred meters in width. The MSZ cannot be traced further to the W where it seems to terminate at the north-eastern border of the NW-SE oriented prominent magnetically defined SE DML Province. This structure may coincide with a significant dextral shear zone that runs from the Schirmacher Oasis into the region S of Sør Rondane (Schirmacher-Rondane Lineament). The SE DML Province most likely consists of Rayner-age (1000-900 Ma) crust with evidence of intense Pan-African reworking indicated by new geochronological data. The continuation of the MSZ into eastern Sør Rondane and beyond is not clear either, since it appears to terminate at a N-S oriented region with low magnetic signatures (central Sør Rondane corridor) that is possibly related to extensional tectonics. Crosscutting relationships with dated magmatic rocks bracket the activity of the MSZ between Latest Ediacaran to Cambrian times (c. 560-530 Ma). Based on new combined aeromagnetic and structural results from a four-seasons survey of the greater Sør Rondane region, we propose that the crustal structural architecture of eastern DML and is strongly influenced by N-directed (with Africa/Antarctica restored to its original position in Gondwana) lateral extrusion of the EAAO. This process was likely driven by the combination of (i) indentation of the SE DML block towards the conjugate stable Kalahari-Grunehogna cratonic foreland, (ii) extensional collapse of the previously (c. 580-550 Ma) thickened and gravitational unstable crust of central DML, and (iii) large-scale tectonic escape of crustal blocks in eastern DML along major shear zones such as the Schirmacher Rondane Lineament and MSZ towards an unconstrained yet unknown region at a lateral position of the EAAO.



## S02 – 321: Geodynamic evolution of the Dronning Maud Land Mountains

### *The Evolution of an Antarctic Landscape at the Weddell Sea Margin of Gondwana? An Example from the Shackleton Range*

Lisker, L.<sup>1</sup>; Krohne, N.<sup>1</sup>; Läufer, A.<sup>2</sup>; Kleinschmidt, G.<sup>3</sup>; Spiegel, C.<sup>1</sup>

University of Bremen, Germany<sup>1</sup>; Federal Institute for Geosciences and Natural Resources, Germany<sup>2</sup>; Goethe University, Frankfurt, Germany<sup>3</sup>

The Shackleton Range adjacent to Dronning Maud Land represents a landscape of elevated plateaus bound by high escarpments. It forms a continuation of the Transantarctic Mountains towards the Weddell Sea. The geological architecture of the Shackleton Range consists of Precambrian igneous and (meta-) sedimentary rocks of an early Paleozoic nappe stack, post-orogenic red beds and patchy Permo-Carboniferous glacial deposits. An occurrence of ~180 Ma Ferrar volcanoclastics is discussed controversially, while younger sedimentary rocks are not preserved.

Hence, low-temperature thermochronological techniques are the only tool to resolve the geological evolution and landscape development of the region within late Gondwana and Antarctica. Fission-track and (U-Th-Sm)/He analyses were conducted on apatites and zircons from a locally sediment covered paleosurface across the basement of the Shackleton Range. A first challenge was to conclude on the original age of this surface by means of geochemical and petrographic analyses of clastic remnants. Fine-grained deposits from the eastern Shackleton Range with a K/Ar whole rock age of ~180 Ma have been discussed to be either a diamictite or volcanoclastic rock. The geochemical signature of these rocks refers to a rhyolitic rock composition with a fingerprint similar to the ~180 Ma dolerite dikes in the neighboring Theron Mountains and Whichaway Nunataks. Moreover, thin section analysis recognized fiamme-like textures and subhedral crystal fragments within a dense devitrified matrix, whereas well-rounded clastic components or rock fragments are absent. By analogy, the combined geochronological, geochemical and petrographic data identify the deposits of the eastern Shackleton Range as Jurassic pyroclastic rocks related to the Ferrar event.

The thermochronological data set of the Shackleton Range consists of 32 published and new zircon fission-track ages of 160 - 210 Ma, apatite fission-track ages of 95 - 230 Ma (mean track lengths 12.4 - 13.9  $\mu\text{m}$ , standard deviations 1.0 - 2.9  $\mu\text{m}$ ) and apatite (U-Th-Sm)/He ages of 108 - 155 Ma. Thermal history modelling of these combined data from 13 samples and geological and geomorphological constraints produced a consistent thermal history of early Jurassic cooling to (near-) surface temperatures followed by re-heating to temperatures up to 100°C and final cooling since ~105 Ma.

This cooling scenario delineates the complex transition from an ancient orogen to the hinterland of an active continental margin, and finally to a passive margin setting, interfered by (super-) continental extension and dispersal. The earliest phase detected by the present data is the uplift and erosion of a Neoproterozoic early Cambrian Pan-African mountain range. The remaining paleosurface or peneplain was established at least during the Permo-Carboniferous when the deposition of glacial sediments marked basement exposition followed by long-lasting subsidence and burial within a back-arc basin behind the active Panthalassan margin of Gondwana. An at least 6 km thick sedimentary sequence accumulated during late Paleozoic - early Mesozoic times and was exhumed rapidly prior to the emplacement of the Ferrar magmatic suite at ~180 Ma at surface or shallow crustal depths, apparently related to regional extension and eventually Gondwana breakup. Thermal history models infer subsequent burial up to depths of 4 km, associated with the mid-Jurassic initiation of the Weddell Sea. Basin evolution continued until Late Cretaceous times when the little consolidated sedimentary strata were exhumed suddenly and completely. This episode of basin inversion was probably triggered by tectonic reorganization of the terranes around the Weddell Sea. However, final uplift and the formation of the present-day landscape may not have occurred prior to the Neogene. In general, the Shackleton



## *XII International Symposium on Antarctic Earth Sciences*

*13 - 17 July 2015, Goa, India*



Range region was occupied for most of Gondwana time by sedimentary basins that probably formed part of an extensive intracontinental basin system within the supercontinent.



**S02 – 346: Geodynamic evolution of the Dronning Maud Land Mountains**

***The Geology and Geochronology of a Tonian Oceanic Arc Super Terrane (TOAST) in Eastern Dronning Maud Land***

Jacobs, J.<sup>1</sup>; Elburg, M.<sup>2</sup>; Läufer, A.<sup>3</sup>; Kleinhanns, I.C.<sup>4</sup>; Henjes-Kunst, F.<sup>3</sup>; Estrada, S.<sup>3</sup>; Ruppel, A.<sup>3</sup>; Damaske, D.<sup>3</sup>

Department of Earth Science, University of Bergen & Norwegian Polar Institute, Norway<sup>1</sup>; Department of Geology, University of Johannesburg, South Africa<sup>2</sup>; Federal Institute for Geosciences and Natural Resources (BGR), Hannover, Germany<sup>3</sup>; Eberhard Karls Universität, Tübingen, Germany<sup>4</sup>

We report the field geology, geochronology and geochemistry of an important and previously unstudied region between eastern (Sør Rondane Mountains) and central Dronning Maud Land (DML). The area allows the characterization and ground-truthing of a large and mostly ice-covered area that is geophysically distinct and which was previously interpreted as a potentially older cratonic block south of a Late Neoproterozoic/Early Paleozoic mobile belt, exposed in the Sør Rondane Mts. SHRIMP/SIMS zircon analyses of 20 samples together with new geochemistry indicate that the exposed basement consists of a ca. 1000-900 Ma juvenile terrane that is very similar to the juvenile rocks of the SW-Terrane of Sør Rondane, a characteristic gabbro-trondhjemite-tonalite-granodiorite suite, with normalised trace element patterns typical for subduction-related magmas and mostly positive initial epsilon Nd values. The area shows strong Late Neoproterozoic/Early Paleozoic crustal reworking, migmatization and melt production, including 560-530 Ma A-type magmatism. Therefore, this area is very similar to the SW-Terrane and differs only in the degree of Late Neoproterozoic/Early Paleozoic reworking. We interpret the SW-Terrane of Sør Rondane as a mega-boudin sandwiched in between rheologically weaker portions of similar oceanic arc terranes. Therefore, the study area, and thereby the aeromagnetically distinct SE DML province does neither represent the foreland of a Late Neoproterozoic/ Early Paleozoic mobile belt, nor a craton, as has previously been speculated, based on geophysical data alone. Instead, a large Tonian Ocean Arc Super Terrane (TOAST) with significant extent emerges. Its western limit is represented by the Forster Magnetic Anomaly, which represents a suture to the Grenville-age Maud Belt. East of the TOAST, the Rayner Complex is similar in age but otherwise distinctly different. The Rayner Complex has a much long history of island arc accretion with continent-continent collision at ca. 950 Ma and has markedly more evolved crust. In contrast, the TOAST has a pronounced juvenile character without significant inheritance and lacks metamorphic overprint immediately following crust formation. This indicates that it has not been an integral part of Rodinia. The eastern boundary of the TOAST is probably in the vicinity of the Yamato Mts., whilst its northern extension might be seen in the Vohibori Terrane (SW Madagascar), which in turn could correlate with the Arabian Nubian Shield. The Late Neoproterozoic/Early Paleozoic tectono-metamorphic overprint of the TOAST shows a slight decrease in ages from W to E, possibly indicating that it first amalgamated on its Kalahari side before it was attached to Rukerland/Indo-Antarctica.



**S02 – 347: Geodynamic evolution of the Dronning Maud Land Mountains**

***Western Australia-Kalahari (WALAHARI) Connection in Rodinia: Not Supported by U/Pb Detrital Zircon Data from the Maud Belt (East Antarctica) and the Northampton Complex (Western Australia)***

Ksienzyk, A. K.<sup>1</sup>; Jacobs, J.<sup>1,2</sup>

Department of Earth Science, University of Bergen, Norway<sup>1</sup>; Norwegian Polar Institute, Tromsø, Norway<sup>2</sup>

The Kalahari Craton is an important building block of the supercontinent Rodinia, but its position with respect to other cratons is still controversially discussed. The Maud Belt in East Antarctica is part of the extensive Namaqua-Natal-Maud Orogen along which Kalahari collided with another continent during Rodinia assembly. One of the continents that have been suggested as collision partners for Kalahari is Western Australia, with the Pinjarra Orogen as the counterpart to the Maud Belt. We investigate this connection from a geochronological point of view. SHRIMP U/Pb zircon analyses of three metasedimentary samples from the Maud Belt date Grenville-age metamorphism within the orogen at ca. 1100-1060 Ma. One sample was later affected by Pan-African metamorphism at ca. 540 Ma. A second sample is interpreted as a molasse of the Maud Belt and was deposited in the Neoproterozoic. Detrital zircons from all three samples are consistent with derivation of the sediments predominantly from within the Namaqua- Natal-Maud Belt, with minor contributions from the Kalahari Craton. No clear Western Australian fingerprint could be detected in the detrital ages and a direct comparison between detrital zircon ages from the Maud Belt and the Northampton Complex (Pinjarra Orogen, Western Australia) showed distinct differences in the age spectra. Altogether, we consider a collision between Kalahari and south-western Laurentia a more likely scenario.



**S02 – 352: Geodynamic evolution of the Dronning Maud Land Mountains**

***A New Compiled Geological Map of Dronning Maud Land, Antarctica: Progress and Challenges***

Abu-Alam, T.S.<sup>1</sup>; Elvevold, S.<sup>1</sup>

Norwegian Polar Institute, Tromsø, Norway<sup>1</sup>

Geological mapping and investigation of the mountain chain in Dronning Maud Land has been carried out by a number of geologists from South Africa, Japan, India, Germany, Russia and Norway over the last 40-50 years. The existing geological maps of Dronning Maud Land are, for a large part, based on fairly old data which makes these maps inhomogeneous. The maps are at different scales, contain different levels of details, and the standards for classification of the rock units may also differ between the maps. This limits the ability to use these map to draw an overview tectonic model of the evolution of Dronning Maud Land. This limitation is extended to understanding the evolution of the southern parts of the Gondwana supercontinent since the Dronning Maud Land is the southern geographical link between South Africa, Australia and Indian subcontinent. Moreover, the existing topographic dataset from Dronning Maud Land is based on fairly old topographic maps (1960s), and there is a discrepancy between the topographic dataset and the more recent Landsat images. As a result of the discrepancy between these datasets, some of the outcrops are not mapped at all. For all these reasons, a new geological map of the Dronning Maud Land, for the area between 20°W and 45°E, is being compiled to the scale 1:250 000 (11 sheets) at the Norwegian Polar Institute but in collaboration with other national and international institutes. The goal is to integrate existing maps into a new seamless, digital uniform geological GIS database. This new geological map will be a descriptive map based on the new topographic dataset of the Landsat 8. This abstract aims to present the progress in the compilation project and open it to the public discussion.



**S02 – 372: Geodynamic evolution of the Dronning Maud Land Mountains**

***Formation, Extension and Exhumation Recorded by High-Grade Rocks, Central Dronning Maud Land, Antarctica***

Elvevold, S.<sup>1</sup>; Engvik, A. K.<sup>2</sup>; Hendriks, B. W. H.<sup>2</sup>

Norwegian Polar Institute, Tromsø, Norway<sup>1</sup>; Geological Survey of Norway, Trondheim, Norway<sup>2</sup>

A deep-seated metamorphic complex is exposed in Filchnerfjella in central Dronning Maud Land. The metamorphic evolution of the complex has been recovered through a study of textural relationships, conventional thermobarometry and pseudosection modelling. Relics of an early, high-P assemblage are preserved within low-strain mafic pods. Subsequent granulite facies metamorphism reached 850-885 °C and 0.55-0.70 GPa. Peak conditions were followed by near-isothermal decompression recorded by a variety of reaction textures. The decompression was accompanied by partial melting and intrusion of voluminous bodies of quartz syenite. The regional foliation of the metamorphic complex is cut by extensional shear bands and shear zones. The extensional structures show a progressive evolution from ductile through semiductile towards brittle conditions. The quartz syenites post-date formation of the main gneiss fabric, but contain narrow semiductile to brittle shear zones illustrating that the extension continued also after their emplacement dated at 521±4 Ma.

<sup>40</sup>Ar/<sup>39</sup>Ar data on hornblende, biotite and K-feldspar provide constraints on the cooling path of the gneisses. Hornblende ages are c. 480 Ma, biotite ages range from c. 465 to c. 435 Ma, whereas K-feldspar ages yield c. 437 Ma. The <sup>40</sup>Ar/<sup>39</sup>Ar ages indicate an initial rapid cooling rate of ~10 °C/Ma between 480 and 465 Ma, followed by a lower cooling rate of ~6 °C/Ma during the subsequent 30 million years. The K-feldspar <sup>40</sup>Ar/<sup>39</sup>Ar ages place a lower time limit on the duration of the uplift, by the time of thermal relaxation to a stable continental geotherm. Extensional structures combined with the near-isothermal decompressional P-T path indicate tectonic unroofing of the high-grade complex. The <sup>40</sup>Ar/<sup>39</sup>Ar-ages demonstrate that the cooling took place during the later stage of the Pan-African orogeny.



## S02 – 373: Geodynamic evolution of the Dronning Maud Land Mountains

### ***Modeling of Late-Magmatic Fluid Infiltration into a Metamorphic-Plutonic Complex, Dronning Maud Land***

Elvevold, S.<sup>1</sup>; Engvik, A. K.<sup>2</sup>; Austrheim, H.<sup>3</sup>; Engvik, L.<sup>4</sup>; Stöckhert, B.<sup>5</sup>

Norwegian Polar Institute, Tromsø, Norway<sup>1</sup>; Geological Survey of Norway, Trondheim, Norway<sup>2</sup>;  
University of Oslo<sup>3</sup>; Sør-Trøndelag University College<sup>4</sup>; Ruhr-University Bochum, Germany<sup>5</sup>

Excellent outcrops in Dronning Maud Land, Antarctica, provide unique insights into the mode and extent of fluid infiltration into metamorphic and plutonic rocks in the middle crust. The nunataks of Mühlig-Hofmannfjella and Filchnerfjella comprise a deep-seated metamorphic-plutonic rock complex, dominated by a dark colour due to anhydrous, charnockitic and granulitic mineral assemblages including perthite, plagioclase, orthopyroxene and garnet. The area was affected by a late-magmatic fluid infiltration outcropping as conspicuous light alteration halos around granitoid veins, probably originating from underlying magma chambers. The alteration halos were formed by CO<sub>2</sub>-H<sub>2</sub>O volatiles emanating from the veins into the host rock causing hydration of the granulite facies assemblage such as breakdown of orthopyroxene to biotite and sericitisation of plagioclase. The marked colour change is caused by the transformation and microcracking of feldspar, and the spread of dusty opaques and fluid inclusions.

The high density of microcracks in quartz and feldspar exceeds that observed in the unaltered host rock by an order of magnitude. The field relations indicate that the veins originated as melt driven hydraulic fractures, sealed by pegmatite and aplite crystallising from volatile-rich melts, with the alteration halo being the wake of the process zone formed at the tip of the propagating fractures. It is proposed that the damage zone is characterised by a transient state of high permeability which was short-lived due to rapid healing and sealing of microcracks. Based on a set of assumptions, numerical modelling explores the time scales of the infiltration processes, taking into account the combined effects of fluid flow, heat transfer and temperature dependent decay of interconnected porosity due to microcrack healing. Assuming an initial magma temperature of 700°C, a far field temperature in the host rock of 300°C, an initial porosity in the damage zone of 0.5% and 2%, a permeability of 10-16 m<sup>2</sup>, and a pressure difference of 300 MPa, we find that the fluid infiltration into the damage zone proceeds within seconds to minutes and that the fluid flow contributes significantly to the heat transfer into the host rock. Assuming an initial microcrack aperture of 1 µm, the model predicts that the crack healing time scale is significantly longer than that of fluid infiltration in the case of thin veins with narrow damage zones. In this case crack healing does not hinder fluid infiltration. Only for thick veins with high heat content and prolonged crystallization history, permeability may become reduced by crack healing during progressive fluid infiltration. The results indicate that the formation of the alteration halos flanking pegmatitic veins may be a quasi-instantaneous process on geological time scales.



**S02 – 379: Geodynamic Evolution of The Dronning Maud Land Mountains**

***Deglaciation History of Sør Rondane Mountains in Dronning Maud Land, East Antarctica Deduced by Geomorphology, Exposure Ages, and GIA Modelling***

Suganuma, Y.<sup>1</sup>; Miura, H.<sup>1</sup>, Zondervan, A.<sup>2</sup>; Okuno, J.<sup>1</sup>

National Institute of Polar Research, Japan<sup>1</sup>; GNS Science, Japan<sup>2</sup>

Recent studies have reported a significant decrease in thickness of the East Antarctic Ice Sheet (EAIS) during the last several million years. However, the geographical extent of this decrease and subsequent isostatic rebound remain uncertain and a topic of debate. In this study, we reconstruct magnitude and timing of ice sheet retreat at central part of the Sør Rondane Mountains in Dronning Maud Land, East Antarctica, based on detailed geomorphological survey, cosmogenic exposure dating, and glacial isostatic adjustment modelling. Three distinct deglaciation phases during the Quaternary for this sector of the EAIS are identified, based on rock weathering and <sup>10</sup>Be surface exposure data. In this study, we adopt the single-disk model to estimate the effective total uplift induced by ice sheet thinning at the Sør Rondane Mountains. Based on these data, we estimate that during the Plio-Pleistocene the ice sheet thinned by at least 500 m. This thinning is attributed to the reorganization of Southern Ocean circulation associated with the global cooling into the Pleistocene, which reduced the transport of moisture from the Southern Ocean to the interior of EAIS.



## S02 – 405: Geodynamic Evolution of the Dronning Maud Land Mountains

### ***Recent Development of the Low-Temperature Thermal History of the Dronning Maud Land Mountains, Evidence from (U-Th)/He Dating***

Sirevaag, H.<sup>1</sup>; Jacobs, J.<sup>2</sup>; Ksienzyk, A. K.<sup>3</sup>; Dunkl, I.<sup>4</sup>

Department of Earth Science, University of Bergen, Norway<sup>1</sup>; Norwegian Polar Institute, Tromsø, Norway<sup>2</sup>; Ksienzyk Department Of Earth Science, University Of Bergen<sup>3</sup>; Geoscience Center, University of Göttingen, Germany<sup>4</sup>

The Dronning Maud Land Mountains form a 1500 km long, continental margin parallel mountain range, stretching from Heimefrontfjella in the southwest, along Penckgraben and Jutulstraumen towards Gjelsvikfjella in the northwest and towards Sør Rondane to the east. The Dronning Maud Land Mountains formed due to flexural uplift during the early Jurassic rifting between East and West Gondwana. Synchronously to the rifting, substantial amounts of continental flood basalts from the Karoo mantle plume were emplaced, covering parts of western Dronning Maud Land. Remnants of these basalts are present in i.e. Vestfjella. The Dronning Maud Land Mountains are characterized by a relatively young, alpine topography with a significant relief, with mountain tops above 3000 MSL. and the Jutulstraumen incision with a depth of ca. 1900 mbsl. Low-temperature thermochronological methods (i.e. fission track and (U-Th)/He dating of apatite, zircon and titanite) can be used for estimating exhumation histories. By covering temperatures between ca. 50 and 300°C, these methods can be used to reveal the timing of mid-crustal to surface processes, including erosional exhumation. By combining apatite fission track (AFT) dating with (U-Th)/He dating, we can improve the preglacial low-temperature tectonothermal evolution of the Dronning Maud Land Mountains, and provide more sophisticated input parameters for the East Antarctic ice sheet models.

Previous thermochronological studies in the Dronning Maud Land Mountains have mainly focused on fission track analyses of apatites (AFT), however titanite fission track (TFT) and zircon fission track (ZFT) analyses have also been carried out. The AFT ages from vertical profiles in Heimefrontfjella range between 230 and 80 Ma, with AFT ages of similar altitude increasing towards the SE. In Gjelsvikfjella further north, AFT ages range between 365 and 185 Ma, generally increasing from Jutulsessen (W) to Hochlinfjellet (E). Vertical profiles further east yield AFT age ranges between 265 and 155 Ma (eastern Mühlig-Hofmannfjella), 310 and 170 Ma (Conradfjella), 295 and 265 Ma (Zwieselhöhe) and between 220 and 145 Ma (Gruberfjella). All samples, except for samples from Zwieselhöhe, show a positive age-elevation correlations. The TFT analyses from four samples from Gjelsvikfjella range between 515 (Festninga) and 325 Ma (Jutulsessen), indicating a general increase from west to east. Fourteen ZFT analyses from Conradfjella and Schneidegebirge give ages between 365 and 285 Ma (Conradfjella) and between 290 and 235 Ma (Schneidegebirge). A steep, positive age-elevation correlation is present for the ZFT ages. Additionally, (U-Th)/He analyses of apatites (AHe) have been published from Mühlig-Hofmannfjella (370-210 Ma), Conradfjella (305-135 Ma), Zwieselhöhe (275-140 Ma) and Gruberfjella (180-105 Ma).

New (U-Th)/He analyses of apatites (40 samples) and zircons (5 samples) between Heimefrontfjella to the west and Sør Rondane to the east have recently been carried out. On the basis of the AHe ages, the Dronning Maud Land Mountains can be divided into four main provinces:

#### 1. Heimefrontfjella

Four AHe ages from Heimefrontfjella yield range between 60 and 110 Ma, with the majority ranging from 60 and 85 Ma. Additionally, three single grain ZHe ages between 440 and 450 are also present.

#### 2. Jutulstraumen

The AHe ages around Jutulstraumen are widely scattered with ages between 40 and 350 Ma. Two distinct populations at Sistefjell are represented by seven grains in two samples with AHe ages of 75-120



Ma and 250-350 Ma. Samples from the west of Jutulstraumen yield ages between 45 and 160 Ma, with the younger component derived from Ahlmannryggen and the older one from Annandagstoppene. Four samples from the center of Jutulstraumen (Holane, Midbresrabben and Straumsvola) have AHe ages between 45 and 165 Ma, where the oldest component is represented in a sample from Midbresrabben. Additionally, three ZHe ages from Holane scatter between 280 and 305 Ma.

### 3. Hinterland of the DML escarpment

Samples from the hinterland of the escarpment give AHe ages between 40 and 310 Ma, however, the majority of the samples are older than 75 Ma. In addition, three zircons from Sverdrupfjella range between 200 and 345 Ma.

### 4. Continental wedge

The analyses of samples in the continental wedge (the region between the coastline and the mountain range) yield scattered AHe ages between 30 and 90 Ma. Along a coast-perpendicular profile, these samples are progressively younger towards the coast.

By applying low-temperature thermochronology, four major post-Pan- African cooling phases have been detected: 1) A Carboniferous cooling phase related to the compressive tectonics (recorded in cDML), 2) a Jurassic phase connected to passive margin evolution during Gondwana break-up (recorded in cDML), 3) a Mid-Late Cretaceous phase resulting from rapid uplift (~75- 100 m/Ma) and the establishment of a new erosional base level (recorded in Heimefrontfjella, cDML and Schirmacheroase) and 4) a Cenozoic phase related to intensive erosion, coeval with the onset of glaciation.



**S02 – 449: Geodynamic Evolution of the Dronning Maud Land Mountains**

***A Relook at the Nature of Magmatism in CDML in the Context of Extension of the East African Orogeny in Antarctica***

Pant, N. C.<sup>1</sup>; Roy, S.<sup>2</sup>; Joshi, A.<sup>2</sup>; D'Souza, M. J.<sup>2</sup>

University of Delhi, India<sup>1</sup>; Geological Survey of India<sup>2</sup>

The East African Orogeny (EAO) marks the suture between East and West Gondwana. Subsequently the passage of EAO into Antarctica was opined by many workers and therefore areas like Central Dronning Maud Land (cDML), previously considered to be Mesoproterozoic, are now interpreted to be part of the Pan-African Belt System. The passage of EAO into Antarctica is considered through a NNW-SSE trending narrow linear tract of suture zone through the granulitic terrane of Schirmacher which was subsequently extended up to 110 km south into the Wohlthat Mountains in cDML.

Post Orogenic magmatic suits (A-Type granites) are common to many orogens and in many cases closely follow the cessation of deformation. The known characters of postorogenic magmatism includes high temperature magmatism with enhanced silica content, negative Eu anomaly, isotopically primitive nature ( $^{87}\text{Sr}/^{86}\text{Sr} < 0.705$ ) compared to the orogenic granites ( $^{87}\text{Sr}/^{86}\text{Sr} > 0.705$ ). A map of magmatic rocks associated with extension of EAO in cDML has been compiled. The major magmatic rocks include granite, anorthosite, charnokite and mafic dykes with reference to the extension of EAO. Towards West of the projected suture zone through Wohlthat Mountains the extensive magmatic rocks were mapped. The Western part of the suture comprises parts of cDML known as Orvinfjella and Mühlig-Hoffmannfjella series of mountains. The Orvinfjella comprises of Dallmannfjellet, Conradfjellet, Kurzeffjellet, Holtedahlfjellet, Drygalskifjella and Filchnerfjellet mountain ranges. They appears as an arcuate shape E-W oriented mountain ranges covering longitudes from 10°E to 7°E. The plutonic rocks (e.g. in Holtedahlfjellet) are characterized by coarse grained, undeformed granitoids like charnokite, biotite granites and quartz syenites. The granite is light coloured containing fayalite while the charnokites have Opx with high ferrosilite content. The mineral assemblage of granite is Qtz+Kfs+Pl+Bt+Hbl+Ap+Fa+Zrn+Fe-Ti oxide. Sometimes hornblende in granite preserves relict orthopyroxene, Mesoperthitic K-feldspar occurs as phenocrysts. Mesoperthite is at times mantled by myrmekite. Granites are visibly undeformed and unmetamorphosed although discrete shears are present. Geochemically these are meta-aluminous to per-aluminous monzogranite to quartz monzonite with SiO<sub>2</sub> content going upto 74% in some of the rocks. This paper proposes a model of crustal thinning on the western side of the suture zone in East Antarctica i.e., in the Orvinfjella and Mühlig Hofmannfjella areas for generation of these magmatic bodies. Crustal thinning as a consequence of trans-extensional regime in the area adjacent to suture zone leading to emplacement of post orogenic plutonic rocks are common to many orogens. These magmatic activities generally give rise to A-Type rocks in space and time. It explains the cessation of deformation activity followed by high temperature, LREE enriched, highly siliceous granitoids arising from a perceived thinning of crust.



## **S02 – 514: Geodynamic Evolution Of The Dronning Maud Land Mountains**

### ***The East African – Dronning Maud Land Orogen – Passive Margin System***

Jacobs, J.<sup>1,2</sup>; Bauer, F.<sup>1</sup>; Ksienzyk, A.K.<sup>1</sup>; Sirevaag, H.<sup>1</sup>

Department of Earth Science, University of Bergen, Norway<sup>1</sup>; Norwegian Polar Institute, Tromsø, Norway<sup>2</sup>

The conjugate East African and Dronning Maud Land continental margins form part of an Orogen – Passive Margin System. The conjugate margins reactivated the rheologically weakest part of the ca. 600-500 Ma East African-Antarctic Orogen. In northern Mozambique, the margin zig-zags and structural inheritance plays a significant role for the margin architecture. In this presentation we compare the existing thermochronological data sets from northern Mozambique and Dronning Maud Land in order to unravel the style of pull-apart rifting between East and West-Gondwana at ca. 160 Ma.

In northern Mozambique, the Lurio Belt is an important lineament that has blocks with contrasting thermochronological ages on either side. At the same time, the Lurio Belt is the most prominent tectonic feature of the East African-Antarctic Orogen in northern Mozambique; it separates a southern part of the orogeny, which appears to have lost its orogenic root from a northern part that probably still has its lithospheric root. South of the Lurio Belt, thermochronological data are Cretaceous and therefore are significantly younger than the initial Gondwana break-up and are also much younger than to the N of the Lurio Belt. This is consistent with a protracted exhumation history to the S of the Lurio Belt and the presence of voluminous Cretaceous sediments found in the Mozambique Basin.

In Dronning Maud Land, the Dronning Maud Land Mts. form a coastal parallel mountain chain that resembles an escarpment. Here, the oldest apatite fission-track ages that predate Gondwana break-up are known from the high part of the mountain range and from the back-side of the escarpment. Thermochronological data younger than Gondwana break-up are known from the coastal wedge, in the vicinity of the Bouvet mantle plume and around the Jutulstraumen rift. Here, apatite fission-track analyses are as young as Late Cretaceous.

The asymmetric distribution of thermochronological data on either side of the initial Gondwana rift with an escarpment on the Dronning Maud Land side might suggest that initial pull-apart Gondwana rifting resulted in an upper plate margin on the Mozambique side and a lower plate margin on the conjugate Antarctic side.



**S03 – 208: Crustal Blocks Adjacent to Antarctica- Sri Lanka, Mozambique and Antarctica**

***Mesoproterozoic (1100-1040 Ma) A-Type Granitoid Magmatism in the Namaqua-Natal and the Maud Belts***

Tomokazu Hokada<sup>1</sup>; Geoffrey Grantham<sup>2</sup>; Makoto Arima<sup>3</sup>; Satoshi Saito<sup>4</sup>; Richard Armstrong<sup>5</sup>; Kazuyuki Shiraishi<sup>1</sup>

National Institute of Polar Research, Japan<sup>1</sup>; Council for Geoscience, South Africa<sup>2</sup>; Yokohama National University, Japan<sup>3</sup>; Ehime University, Japan<sup>4</sup>; ANU, Australia<sup>5</sup>

Sensitive high-resolution ion microprobe (SHRIMP) U-Pb zircon dating was applied on A-type granitic intrusions from Natal Province, South Africa and from Sverdrupfjella in Western Dronning Maud Land (WDML), Antarctica. Zircons from the seven granitoid intrusions analyzed in this study suggest 1100-1040 Ma ages, which confirm widespread Grenville-age A-type granitic magmatism in these regions. No older inherited zircon grains were seen, consistent with the interpretation that these granitoid intrusions were formed through juvenile magmatism (Grantham et al., 2001). The sample from Sverdrupfjella, Antarctica shows a ~530Ma metamorphic rim whereas none of the Natal samples show any younger overgrowths. In the Natal region, mean  $^{207}\text{Pb}/^{206}\text{Pb}$  ages apparently decrease from north (1100-1090 Ma at Nthilimbitwa Pluton) to south (1060 Ma from Mvoti and Glendale Plutons to 1040 Ma from Kwalembe and Ntilbankulu Plutons). The sample from Sverdrupfjella, Antarctica has ~1093Ma old zircons. The limited metamorphic age data available from country rocks to the intrusions suggest that the intrusions have been generated and emplaced syn- or post-metamorphic of the Namaqua-Natal-WDML regions. Our data, therefore, can constrain the termination of high-grade metamorphism to be no younger than 1040 Ma. The available chronological data of the A-type granites show a crude spatial-age relationship with the younger ages <~1060Ma being restricted to the southern and western margins of the Kalahari Craton (southern Natal and Namaqualand) whereas the older ages >1060Ma are restricted to the eastern margin (Mozambique, Antarctica and northern Natal) of the Kalahari Craton.



**S03 – 309: Crustal Blocks Adjacent to Antarctica- Sri Lanka, Mozambique and Antarctica**

***A Geochemistry of the Straumnsnutane Lavas (Jutulstraumen Group), Western Dronning Maud Land, Antarctica and the Espungabera Lavas (Mkondo Group, Central Mozambique): Evidence for Comagmatic and Continental Emplacement***

Neo Moabi<sup>1</sup>; Geoffrey Grantham<sup>1,2</sup>; James Roberts<sup>3</sup>; Petrus le Roux<sup>4</sup>

Council for Geoscience, Pretoria, South Africa<sup>1</sup>; Dept of Geology, University of Johannesburg, Auckland Park, Johannesburg, South Africa<sup>2</sup>; Department of Geology, University of Pretoria, Pretoria, South Africa<sup>3</sup>; Department of Geological Sciences University of Cape Town, Rondebosch, Cape Town, South Africa<sup>4</sup>

The Straumnsnutane lavas overlie the sedimentary platform sequence of the Ahlmannryggen Group in western Dronning Maud, Antarctica while the Espungabera lavas overlie the Umkondo group in Mozambique and Zimbabwe. The volcanic units are thought to be in the same stratigraphic position in both localities, and are believed to form part of the ~1100 Ma Umkondo Igneous Province in southern Africa. This study presents a comprehensive geochemical survey of these lavas, and will contribute to a better understanding of the ~1100 Ma Umkondo Igneous Province in southern Africa and Antarctica. Geochemical data of the Straumnsnutane lavas were compared with the data obtained from Espungabera lavas. Radiogenic isotope data for both lavas were also obtained. Both these lavas are very fine grained, moderately weathered and slightly to moderately amygdaloidal. These lavas are dominantly basaltic andesites, basalts, minor basaltic trachyandesites and trachyandesites. The petrographic studies indicate that the Straumnsnutane lavas are dominated by clinopyroxenes, Fe-Ti Oxides and plagioclase which show some saussurization from moderate to severe. Metamorphic mineral assemblages indicate greenschist facies conditions, followed by prehnite-pumpellyite facies conditions on a retrograde path for both the Straumnsnutane lavas similarly to the Espungabera lavas. Very similar trace element ratios values of Nb/U and La/Yb for both the lavas suggest a cogenetic origin. The REE data for Straumnsnutane and Espungabera lavas have comparable LREE and HREE distributions and slopes, with both being characterised by weak negative Eu anomalies. Also similar between Straumnsnutane and Espungabera lavas are negative Nb anomalies and enrichment in large ion lithophile elements (LILEs). The  $^{87}\text{Sr}/^{86}\text{Sr}$  isotopic data calculated at 1100Ma and negative  $\epsilon\text{Nd}$  values (-2.83 to -3.49) for the Espungabera lavas suggest contamination by continental crust during their genesis. The  $^{87}\text{Sr}/^{86}\text{Sr}$  vs.  $^{143}\text{Nd}/^{144}\text{Nd}$  isotopic modelling calculated at 1105Ma shows that both lavas may have been formed from mixing of a MORB-like source and about 5% of older crust. The similarities seen in major, trace elements and rare earth element geochemistry indicate that the Espungabera and the low Ti Straumnsnutane lavas have the same magmatic origin and emplacement in a continental environment.  $^{87}\text{Sr}/^{86}\text{Sr}$  and  $^{143}\text{Nd}/^{144}\text{Nd}$  isotope analyses suggest that the lavas experienced contamination by continental crust during their genesis. The craton-based tholeiitic Umkondo Igneous Province is broadly co-eval with tonalitic calc-alkaline and granitic gneisses in the Nampula and Maud Terranes in Mozambique and Antarctica respectively, immediately east of the Kalahari Craton in a re-constructed Gondwana. These data can be interpreted to indicate that the Espungabera and Straumnsnutane lavas form part of a back-arc complex, west of a volcanic arc/subduction zone along the eastern margin of the Kalahari Craton at ~1100Ma.



**S03 – 400: Crustal Blocks Adjacent to Antarctica- Sri Lanka, Mozambique and Antarctica**

***Metamorphic and Isotopic Evidence for the Continuation of the Arabian-Nubian Shield into Antarctica***

Boger, S.D.<sup>1,2</sup>; Pastohov, M.<sup>1</sup>; Maas, R.<sup>1</sup>; Hirdes, W.<sup>3</sup>

School of Earth Sciences, The University of Melbourne, Victoria, 3010, Australia<sup>1</sup>, GAF AG, Arnulfstrasse 199, 80634 Munich, Germany<sup>2</sup>, Bundesanstalt für Geowissenschaften und Rohstoffe, Stilleweg 2, 30655 Hannover, Germany<sup>3</sup>

The Arabian-Nubian Shield represents a vast tract of mostly juvenile Neoproterozoic crust that is exposed on either side of the Red Sea in northeast Africa and Arabia. The geochemical and isotopic composition of the protolith rocks from this region suggest it was built via the long-lived accretion of intra-oceanic arcs within the Mozambique Ocean prior to the amalgamation of Gondwana. The rocks of the Arabian-Nubian Shield narrow along strike to the south and at present are inferred to terminate along the coast of east Africa in southern Kenya and northern Tanzania. We explore the possibility that this belt can be traced southwards into the Sør Rondane region of East Antarctica via southwest Madagascar and Sri Lanka. The proposed correlations between these regions rest upon a distinctive phase of pre-600 Ma deformation and metamorphism, juvenile Nd isotopic compositions, and the commonly observed intra-oceanic geochemical character of the exposed igneous rocks. These characteristics are shared with the protolith rocks of the Arabian-Nubian Shield. If the suggested correlations are correct, the continuity of the Arabian-Nubian Shield into Antarctica has profound implications for the way in which we view the accretion of the Africa-India-Antarctica sector of Gondwana.



**S03 – 410: Crustal Blocks Adjacent to Antarctica- Sri Lanka, Mozambique and Antarctica**

***Gondwana Assembly in Sri Lanka and Dronning Maud Land: Constraints from Zambia, Madagascar and Southern India***

Fitzsimons, I.C.W.<sup>1</sup>; Clark, C.<sup>1</sup>; Collins, A.S.<sup>2</sup>

Curtin University, Australia<sup>1</sup>; University Of Adelaide, Australia<sup>2</sup>

Madagascar is located between the Congo Craton of Africa and the Dharwar Craton of India in Gondwana reconstructions. It is likely to contain one or more sutures that trend north-south in present-day African coordinates and which developed during Neoproterozoic ocean closure and collision of the Congo and Dharwar cratons to form the East African Orogen. Madagascar also lies north of rocks in Mozambique and Sri Lanka with structural trends parallel to the east-west Zambezi Belt of south-central Africa. These latter trends are near orthogonal to structures in the East African Orogen, and are interpreted by some as reflecting another collisional suture. The spatial, temporal, and tectonic relationships between these two orogenic trends remain highly controversial, but detailed geochronological work in Zambia, Madagascar, and southern India has provided a framework for understanding at least some of these issues. It is widely accepted that a major suture passes immediately west of Madagascar in Gondwana reconstructions, close to the Vohibory Unit of southwest Madagascar, which has an oceanic arc affinity and correlates with the juvenile Eastern Granulites of Tanzania metamorphosed at 0.65-0.60 Ga. This suture separates basement rocks of Madagascar from the Congo Craton, but more controversial is a proposed suture in eastern Madagascar separating Malagasy basement from the Dharwar Craton. Some workers have used the presence of 2.52-2.48 Ga basement in both central Madagascar and the Dharwar Craton to argue that Madagascar had been contiguous with the Dharwar Craton since the Neoproterozoic. If correct, then there is no Neoproterozoic suture in eastern Madagascar and there is only one oceanic suture in the East African Orogen. Others have focused on 2.2-1.8 Ga detrital zircons in the metasedimentary Itremo Group of central Madagascar, which correspond closely with detrital zircon ages from the Muva Supergroup of Zambia, deposited at c. 1.8 Ga onto the Bangweulu Block of the Congo Craton. This detrital correlation has been used to argue that central Madagascar has an African provenance, supporting the presence of a suture in eastern Madagascar between these rocks and the Dharwar Craton, and requiring the existence of two oceanic sutures in the East African Orogen. These relationships suggest that central Madagascar was part of a microcontinental block that rifted away from Africa and was subsequently sandwiched between Africa and India during Neoproterozoic ocean closure and continental collision. Proterozoic metasedimentary units with distinctive 2.2-1.8 Ga detritus have since been identified in northern Madagascar, southern Madagascar and the Southern Granulite Terrane of India, extending the lateral extent of this proposed microcontinent. Controversies surrounding the status of this second suture thus reflect two differing opinions for the tectonic affinity of Madagascar, one based on a Neoproterozoic basement that correlates closely with the Dharwar Craton and the other based on a Palaeoproterozoic cover sequence that correlates with the Congo Craton. These two viewpoints are difficult to reconcile given evidence that the cover sequence was deposited directly onto the basement at c. 1.8 Ga and the widespread belief that the Congo and Dharwar cratons were first juxtaposed in the Neoproterozoic. However, recently reported U-Pb ages collected from south-central Madagascar as part of a major international mapping program help resolve this contradiction. This work has identified two new basement units in Madagascar: meta-igneous rocks with 2.0-1.8 Ga granitic and gabbroic protoliths and meta-igneous rocks of the Dabolava Suite with 1.04-0.98 Ga calc-alkaline protoliths. Both units are interleaved with metasedimentary rocks that contain 2.2-1.8 Ga detrital zircons, and in some cases a younger zircon population at 1.1-1.0 Ga consistent with erosion of Dabolava Suite rocks. The older 2.0-1.8 Ga basement units of Madagascar closely match 2.0-1.8 Ga basement gneiss of the Bangweulu Block that forms the basement to the Muva Supergroup of Zambia, while the 1.04-0.98 Ga Dabolava Suite is of similar age and chemistry to 1.05-0.94 Ga Irumide plutons that intrude the Muva Supergroup. This demonstrates that south-central Madagascar preserves all three elements of the Irumide Orogen that developed on the south-eastern margin of the Congo Craton,



namely 2.0-1.8 Ga basement gneiss overlain by a thick 1.8 Ga sedimentary sequence and intruded by 1.0 Ga plutons. These correlations are further supported by the recent identification of 2.0 and 1.0 Ga protoliths interleaved with metasedimentary sequences of the Southern Granulite Terrane of India, supporting earlier correlations of these rocks with south-central Madagascar and Zambia. These conclusions support arguments for a Neoproterozoic suture in eastern Madagascar, which is likely to continue through southern India between the Dharwar Craton and the Southern Granulite Terrane, and are consistent with the existence of an African-derived microcontinent in the centre of the East African Orogen. More detailed geochronology is now needed in Sri Lanka and Droning Maud Land to determine whether comparable rock units can be identified further south, which will help constrain the crustal architecture in the region where east-west Zambezi trends appear to intersect the East African Orogen.



**S03 – 432: Crustal Blocks Adjacent to Antarctica- Sri Lanka, Mozambique and Antarctica**

***Neoproterozoic to Cambrian Granitoids of Northern Mozambique and Dronning Maud Land Antarctica: Timing, Genesis and Tectonic Implications for Gondwana Amalgamation***

G.H. Grantham<sup>1,4</sup>; P.H. Macey<sup>2</sup>; M.P. Roberts<sup>3</sup>; B.A. Ingram<sup>4</sup>; R.A. Armstrong<sup>5</sup>; B.M. Eglington<sup>6</sup>; T. Hokada<sup>7</sup>; K. Horie<sup>7</sup>; K. Shiraishi<sup>7</sup>; C. Jackson<sup>8</sup>; V. Manhica<sup>9</sup>

University of Johannesburg, South Africa <sup>1</sup>; Council For Geoscience, Bellville<sup>2</sup>; Council For Geoscience, Port Elizabeth<sup>3</sup>; Council For Geoscience, Pretoria<sup>4</sup>; ANU, Canberra, Australia<sup>5</sup>; University of Saskatchewan, Saskatoon, Saskatchewan, Canada<sup>6</sup>; NIPR, Tachikawa, Tokyo, Japan<sup>7</sup>; Private<sup>8</sup>; DNG, Maputo, Mozambique<sup>9</sup>

Granites with ages ~570Ma to ~490Ma are seen in the Namuno and Nampula Terranes of northern Mozambique, Malawi and southern Irumide Belt in northern Mozambique as well as in Dronning Maud Land, Antarctica. Their compositions vary from rare andalusite-bearing peraluminous types to dominantly biotite and/or hornblende bearing metaluminous types. The latter also include “syenitic charnockites” which are dominantly exposed in central Dronning Maud Land. In northern Mozambique, western Dronning Maud Land and eastern Dronning Maud Land (Sør Rondane) charnockites are extremely rare but are common in Central Dronning Maud Land. In western Dronning Maud Land, granites are seen in Sverdrupfjella, but not in Kirwanveggen to the south. Their distribution is therefore limited to from just north of the Lurio Belt, in northern Mozambique to southern Sverdrupfjella, Antarctica.

No significant major and trace element differences are seen between the charnockitic and non-charnockitic types between southern Africa and Antarctica. Most intrusions have A2 type compositions after Eby (1992) and are typical of melts of thickened crust in continental collisions or areas of extension and typical of Cordilleran compositions after Frost et al. (2001). The mineralogical differences involving dominantly biotite/hornblende bearing varieties in N.Mozambique and orthopyroxene-bearing varieties in CDML are interpreted to be the result of T and p<sub>H<sub>2</sub>O</sub> differences resulting in subsolvus granites and hypersolvus charnockitic “syenites” respectively, rather than significant differences in bulk chemistry. The granites are late- to syn-kinematic to post-tectonic. In eastern and western Dronning Maud Land, the granites typically form shallowly inclined sheets, locally conjugate, consistent with compressional emplacement as well as larger pluton intrusions. In Sør Rondane the granites are clearly syn-kinematic to the ~500Ma transpressional Main Shear Zone. In Mozambique, both sheet-like veins and plutons are seen. Radiogenic isotope data (Rb/Sr and Sm/Nd) from Mozambique and Antarctica and inherited zircons indicate partial melting of Mesoproterozoic basement and, locally, Archaean Kalahari-craton basement in western Dronning Dronning Maud Land. No juvenile isotopic contributions consistent with a juvenile extensional setting are recognised.

Granitoids with ages between ~490Ma and ~525Ma, mostly seen south of the transpressional Lurio Belt of N. Mozambique but not south of Sverdrupfjella, Antarctica, are inferred to result from partial melting in the footwall of a mega-nappe emplaced southwestwards from N. Mozambique, over much of Dronning Maud Land, during Gondwana amalgamation. Their younger age is consistent with post tectonic heating in the footwall of the mega-nappe structure. Granitoids with ages >~550Ma, dominantly seen N of the Lurio Belt in northern Mozambique and in central and eastern Dronning Maud Land, are interpreted to be related to de-compression driven partial melting in the hanging wall of the mega-nappe structure, possibly assisted by fluid ingress from the footwall.

Published gravity data over central Dronning Maud Land is consistent with thickened crust in that area.



**S03 – 433: Crustal Blocks Adjacent to Antarctica- Sri Lanka, Mozambique and Antarctica**

***The Structural Evolution of the Straumnsnutane area, Western Dronning Maud Land, Antarctica - Implications for the Amalgamation of Gondwana***

G.H. Grantham<sup>1,3</sup>; A. Bumby<sup>2</sup>; N. Moabi<sup>3</sup>

University of Johannesburg<sup>1</sup>; University of Pretoria, Pretoria, South Africa<sup>2</sup>; Council for Geoscience, Pretoria, South Africa<sup>3</sup>

The Straumnsnutane Formation lavas underlying the Straumnsnutane area of western Dronning Maud Land, Antarctica form the uppermost sequence of the Ahlmannryggen Group. They are correlated with the Espungaberra Formation of the Umkondo Group exposed in central Mozambique and eastern Zimbabwe. In contrast to the relatively undeformed Espungaberra Formation, the Straumnsnutane Formation shows a complex structural history. Early planar and linear fabrics, thrust faulting and folding suggest top-to-NW tectonic transport under greenschist facies conditions. Younger folding, faulting, and quartz veining suggest conjugate top-to-ESE and WNW transport. The later deformation also occurred under greenschist facies conditions.

Comparison of the tectonic history of the Straumnsnutane area with that of the adjacent Maud Belt to the east in Sverdrupfjella suggests that the early deformation is correlatable with D1 Mesoproterozoic structures in the Maud Belt characterised by top to the NW thrust faulting and folding. The later deformation can be correlated with top-to the SE D2 structures of Cambrian age in the Maud Belt.

The latter deformation implies that the cratonic Ritscherflya Supergroup was at least partially submerged in the footwall of a mega-nappe structure formed during the amalgamation of Gondwana, involving collision between N and S Gondwana in the Kuunga Orogeny ~550-600Ma ago. The tectonic evolution is supported by published geochronological data which suggests deposition of the Ritscherflya Supergroup at ~1125Ma. Discordant zircons and Ar-Ar data indicate metamorphism and alteration at between 600-480Ma probably related to D2. No evidence of strike-slip deformation previously reported in Ahlmannryggen was recorded in Straumnsnutane.



**S03 – 468: Crustal Blocks Adjacent to Antarctica- Sri Lanka, Mozambique and Antarctica**

***Comparison of Sr-Nd isotope data from southern Africa and Dronning Maud Land and Sør Rondane, Antarctica***

G.H. Grantham<sup>1</sup>; M. Satish Kumar<sup>2</sup>; N. Otsuji<sup>3</sup>; E.Burger<sup>4</sup>; T.Kawakami<sup>5</sup>; M.Ishikawa<sup>6</sup>; N.Tsuchiya<sup>7</sup>; P. Le Roux<sup>8</sup>

University of Johannesburg<sup>1</sup>; Department of Geology, Niigata University, Japan<sup>2</sup>; Graduate School of Science and Technology, Niigata University, Japan<sup>3</sup>; Department of Geology, University of Pretoria, South Africa<sup>4</sup>; Department of Geology and Mineralogy, Kyoto University, Japan<sup>5</sup>; Graduate School of Environment and Information Sciences, Yokohama National University, Japan<sup>6</sup>; Department of Geoscience and Technology, Graduate School of Engineering, Tohoku University, Japan<sup>7</sup>; Department of Geological Science, University of Cape Town, South Africa<sup>8</sup>

A recently proposed mega-nappe model for the Neoproterozoic? Cambrian-age Kuunga Orogeny involves collision between N. and S. Gondwana. S.Gondwana is interpreted to have comprised southern Africa (consisting of the Kalahari Craton and parts of adjacent metamorphic belts including the Barue and Nampula complexes of the Mozambique Belt), western Dronning Maud Land (WDML), Antarctica (consisting of the Grunehogna Craton and the Maud Belt) and Sri Lanka (consisting of the Vijayan Complex).

N. Gondwana is inferred to have comprised parts of south central Africa, Sri Lanka, Madagascar and India (consisting of the Tanzanian Craton and parts of adjacent metamorphic belts including the Xixano Complex of Cabo Degado Complex, the Highlands and Wannu Complexes in Sri Lanka, Central Dronning Maud Land, Sør Rondane and Lutzo Holm Bukta areas in Antarctica).

Differences in published geochronological data from the metamorphic belts of the various areas are fundamental to defining the various components of the mega-nappe model. Comparison of published and unpublished Sr and Nd radiogenic isotope data, calculated at 500Ma from the metamorphic belt basement gneisses of the mega-nappe component areas, show broad differences between the different areas from N and S Gondwana.

Neoproterozoic to Cambrian-age granitoids which intrude the various areas mostly mirror their host country rocks suggesting localised anatexis without significant juvenile input. Sr and Nd isotope data from some of these intrusions suggest that they were sourced in the footwall but intrude the hanging wall components of the mega-nappe. The Sr-Nd data from the North Gondwana correlated areas dominantly show marginally negative, less evolved Nd characteristics but similar, positive, wide ranged Sr characteristics compared to the South Gondwana correlated areas.

Comparison of the Sr-Nd isotopic provinces show broad similarities with various geophysical domains defined by recently published aeromagnetic and gravity data sets from Antarctica.

The data are evaluated in terms of their implications for the mega-nappe model for the Kuunga Orogeny.



**S03 – 506: Crustal Blocks Adjacent to Antarctica- Sri Lanka, Mozambique and Antarctica**

***Neoproterozoic to Neoproterozoic Crustal Domains in the Lutzow-Holm Complex, East Antarctica***

Daniel J. Dunkley<sup>1,2</sup>; Kazuyuki Shiraishi<sup>2</sup>; Yoichi Motoyoshi<sup>2</sup>; Yoshikuni Hiroi<sup>3</sup>; Chris J. Carson<sup>4</sup>; Tomoharu Miyamoto<sup>5</sup>; Toshiaki Tsunogae<sup>6</sup>

Department Of Applied Geology, Curtin University, Perth, Western Australia<sup>1</sup>; National Institute of Polar Research, Tachikawa, Japan<sup>2</sup>; Department of Earth Sciences, Chiba University, Japan<sup>3</sup>; Geoscience Australia, Canberra, Australian Capital Territory<sup>4</sup>; Department of Earth And Planetary Sciences, Kyushu University, Fukuoka, Japan<sup>5</sup>; School of Life And Environmental Sciences, University of Tsukuba, Japan<sup>6</sup>

In long-lived, hot orogens the nature of pre-existing crust and the early stages of continental crust assembly and orogenesis is commonly obscured by late-stage ductile deformation and high-grade metamorphism. The Lutzow-Holm Complex (LHC) was assembled and metamorphosed at amphibolite-facies (eastern section along the Prince Olav Coast, POC) to UHT granulite-facies (western section in southern Lutzow-Holm Bay, LHB), during the final Cambrian assembly of East and West Gondwana. The first SHRIMP studies indicated a variety of protoliths assembled and metamorphosed at 550-530Ma, contrary to earlier studies that assigned formation to syn-Grenvillean events. There is evidence from multiple sources, however, that the orogenic construction of the complex was either prolonged or multistage in nature, and that the timing of high-grade metamorphism was in places decoupled from the timing of continent-continent collision and peak deformation. Strands of evidence include the preservation of moderate-high pressure (>10kbar) relict assemblages in high-T, moderate-P granulites; decompression reaction textures both before and after peak metamorphism; the lack of clear tectonic boundaries between lithological units that could represent sutures between exotic crustal blocks; the obscuration of syn- or intra-tectonic magmatic relationships by intense ductile reworking, and the preservation of metamorphic zircon growth at multiple stages during the Ediacaran and Cambrian Periods, especially in the south western, higher-grade section of the LHC. A sharp transition of the dominant orientation of major tectonic features and lithological types occur along the Telen Glacier, with charnockite-dominated lithologies to the north wrapped into westward-verging recumbent folds and shear zones, whereas south of the glacier tectonic intercalations of supercrustal lithologies and charnockitic basement show reworking by steep to vertical E-W strike-slip shearing, with a dextral sense in most localities. Similar relationships were observed between the south and central parts of Austhovde, on the western side of Lutzow-Holm Bay. The absence of discrete structural features that might identify a tectonic suture along the Telen Glacier - Austhovde boundary suggests that this transition is instead the reworking of a pre-existing lithological boundary, and that the steep ductile fabric in the south represents pervasive tectonic reworking that has widely obliterated pre-orogenic lithological relationships. Despite this, domains of crustal provenance can be identified through a combination of distinctive lithological assemblages, protolith geochronology from new and published zircon U-Pb ages, Nd model crustal ages and aeromagnetic maps. The following magmatic groups are identified by region, lithology, and protolith age:

-ca. 2.5Ga felsic to intermediate orthogneisses (in the vicinity of the Shirase Glacier between Sudare Iwa, Austhovde and Botnnuten, and possibly of great extent below the East Antarctic ice sheet, as suggested by aeromagnetic mapping and by boulders well represented in southern LHB moraines).

-ca. 1.85Ga felsic to mafic orthogneisses (S Coast from Berrodden to Telen).

-ca. 1Ga felsic to mafic orthogneisses, varying from charnockite orthogneiss to pyroxenite. Probably comprises contemporaneous but unrelated magmatic suites, including island arcs (on the west side of Lutzow-Holm Bay, along the Prince Harald Coast between Karamete Point and Padda Island).



-ca. 1Ga felsic to mafic orthogneisses, varying from charnockite to garnet-bearing porphyritic orthogneiss to pyroxenite. Probably comprises contemporaneous but unrelated magmatic suites, including island arcs (Kjuka to Ongul Island and east along the POC to Akarui Point).

-ca. 630Ma felsic to intermediate orthogneiss (East Ongul Island and Okulwa), derived from remelting of 1Ga protoliths. Probable combination of plutonic and volcanic magmatism.

-ca. 610-580Ma syn-orogenic felsic orthogneiss and metagranites (in localities associated with ca. 2.5Ga and 1.85Ga magmatic protoliths)

-ca. 530Ma late orogenic metagranites (in localities associated with ca. 2.5Ga and 1.85Ga magmatic protoliths)

In addition to these lithotypes, metasediments with distinctive compositions and detrital zircon age signatures are found in association with the orthogneisses. The most distinctive assemblage is found exclusively at localities near the boundaries of Paleoproterozoic (ca. 2.5 and 1.85Ga). lithofacies and Mesoproterozoic (ca. 1Ga) lithofacies, from Telen to Austhovde, and consists of scapolite-diopside calc-silicates, dolomitic marbles, metabasalts, metapelites and metacherts, and is interpreted as a sedimentary succession deposited on a passive continental margin. Similar dolomarmarbles and calc-silicates are common in moraines in the south of Lutzow-Holm Bay, suggesting a wider subglacial extent of these lithologies. Detrital zircon age signatures from these metasediments and others at Rundvagshetta are dominated by 1.8Ga, 2.5Ga and 2.7Ga sources, and younger zircons are absent. Metapsammites and metapelites are commonly found in localities with 1Ga orthogneisses, along with minor calc-silicates; however, detrital signatures contain a dominant Mesoproterozoic component, with few Paleoproterozoic and Archean ages that do not correspond to those from south Lutzow-Holm Bay. On East Ongul Island, metapelites are variably graphite and carbonate-bearing, and contain a dominant ca. 630Ma detrital source, suggesting a volcanoclastic component. In addition to these lithologies, granitic and mafic intrusions could be identified in southern LHB that were emplaced between episodes of ductile deformation, especially in relatively low-strain domains between steep E-W transverse ductile shear zones. These low strain domains with inter-tectonic intrusions are found in LHB at Innhovde, Austhovde, Vesleknausen, south Rundvagshetta, Berrodden, Telen and Kjuka. Zircon growth peaks around 590Ma and 540Ma, with early magmatism around 620Ma and late, post-deformational high-grade metamorphism, metasomatism and magmatism around 520Ma are seen. Slow cooling in the orogen to K-Ar closure temperatures continues until about 450Ma.

A model of orogenesis is proposed that involves an initial stage of continent-continent collision, possibly with the entrainment of small, diverse crustal blocks, from about 600Ma, an age closer to the peak of orogenesis in the adjacent terrane of the Sør Rondane Mountains. Peak metamorphism and ductile strain is not co-incident with initial collision, but occurs in crustal blocks in a very large, long-lived orogen, where upper to middle crustal blocks have become horizontally decoupled from the lower lithosphere, obscuring original plate boundaries. A similar model has been proposed for the Grenvillean orogen of North America. It provides a concept that can be tested by the identification of prolonged or polystage orogenesis in other parts of the Pan-African orogen that assembled East and West Gondwana. In other regions with high-grade Cambrian metamorphism, in Mozambique, Madagascar, India and Sri Lanka, evidence of additional Ediacaran collisional orogenesis is beginning to emerge.



**S03 – 508: Crustal Blocks Adjacent to Antarctica- Sri Lanka, Mozambique and Antarctica**

***Linking High-Temperature Metamorphism of Southern India and Sri Lanka***

K. Sajeev<sup>1</sup>; D.J. Dunkley<sup>2</sup>; P.L. Dharmapriya<sup>3</sup>; Sanjeeva P.K.Malaviarachchi<sup>3</sup>

Centre for Earth Sciences, Indian Institute of Science<sup>1</sup>; Department of Applied Geology, Curtin University, Western Australia<sup>2</sup>; Department of Geology, University of Peradeniya, Sri Lanka<sup>3</sup>

The P-T-t evolution of ultrahigh-temperature granulites from the Cauvery Shear Zone, central Madurai Block in southern India, and central Highland Complex of Sri Lanka have significant bearing in understanding the high-grade metamorphism and lower crustal processes during the Neoproterozoic-Cambrian orogeny in eastern Gondwana. In the Cauvery Shear Zone region garnet-kyanite rock that contains inclusions of gedrite-spinel-quartz as well as sapphirine-spinel assemblages within garnet, together mark the prograde formation of garnet from lower to higher pressure conditions. Garnet surrounding gedrite reveals the later formation of garnet. The garnet-corundum-staurolite-kyanite assemblage formed at high-pressure represents the peak metamorphism. Garnet cores have a Fe-rich composition and Mg-rich rim. The REE chemistry of zircon rims is comparable with that of garnet cores except for a significant absence of Eu. Staurolite in the investigated samples has moderate to high Mg-content, which again indicates high-pressure stability. Thermodynamic modelling results show that the P-T peak of this gedrite-bearing granulite was at UHT conditions (ca. 19 kbar and ca. 925°C). The petrographic and phase diagrams together demonstrate the evolution of this granulite, having a tight hairpin-type anticlockwise P-T path. The U-Pb ages and REE analyses suggest that the metamorphic rims on zircon grew at ca. 537 ± 5 Ma, i.e., in equilibrium with the garnet cores. The garnet-core-zircon equilibrium was stable during the ultrahigh-temperature conditions. Samarium-Nd mineral data suggests a cooling age of ca. 511 Ma. The biotite in garnet-kyanite rock has a K-Ar cooling age of ca. 519 Ma, which can be interpreted as the time of uplift. Comparison of the present results with other published petrographical and geochronological datasets from the Cauvery Shear Zone enables the determination of a realistic P-T-t evolution of this terrane during the Neoproterozoic-Cambrian orogeny. In contradiction the P-T-t evolution of central Madurai Block as well as the central Highland Complex have a clockwise prograde path with multistage decompression and uplift after ultrahigh-temperature peak metamorphism. The central Madurai Block as well as the central Highland Complex preserve records of Neoproterozoic tectonothermal events associated with the final assembly of the Gondwana supercontinent. The U-Pb zircon geochronological results of ultrahigh-temperature rocks from these regions provide convincing geochronological evidence for late Neoproterozoic UHT metamorphism. Comparing the present results with available datasets from Antarctica and Madagascar could provide important information on a precise eastern Gondwana correlation.



**S03 – 509: Crustal Blocks Adjacent to Antarctica- Sri Lanka, Mozambique and Antarctica**

***Evolution of the Kolli-Massif Southern India***

K. Sajeev<sup>1</sup>; P.M. George<sup>1</sup>

Centre for Earth Sciences, Indian Institute of Science Bangalore, India<sup>1</sup>

Southern India is a collage of crustal fragments which formed and were subjected to crustal evolutionary processes through geological history. Broadly the geology of southern India is divided into the Dharwar Craton (DC), which consists of Archean granites and greenstone belts, and the Proterozoic granulites of the Southern Granulite Terrain (SGT). The relationship between these two geological entities has been much discussed and debated over many decades. Previous studies from the region had considered the SGT as 1) a lower crustal manifestation of Dharwar Craton or 2) multiple crustal blocks that were accreted onto the Dharwar Craton in the Archean and the Neoproterozoic. Although there are arguments for and against both proposals, it is clear that the formation and evolution of crust in DC and SGT are as yet not unravelled, with only sporadic studies. Hence it is important to study the individual history of each crustal fragment.

We focus on the region within the Palghat Cauvery Shear System (PCSS), between the Salem Attur Shear Zone (SASZ) and the Cauvery Shear Zone. The evolution of PCSS is also highly debated with various proposed models as 1) a suture zone 2) reworked Archean crust or 3) a central part of the Neoproterozoic Pandyan mobile belt. However, an extensive study of the region was lacking. We have investigated about 500 samples including ultramafics, metagabbros, charnockite, hornblende biotite-gneiss, pyroxene granulites and metasediments. The evidence gathered from field, geochemical and geochronological studies suggests that there was a major crustal growth event ca. 2600 Ma, followed by granulite-grade regional metamorphism ca. 2480 Ma. The southern margins of the region have imprints of Neoproterozoic reworking from 800 to 500 Ma. We propose a two-stage evolution for the region with Neoproterozoic marginal reworking of the newly defined Kolli massif, and Neoproterozoic marginal reworking resulting in the formation of the Cauvery Shear Zone.



**S04–30: West Antarctica: Problem Child of Gondwanaland - A Symposium Highlighting the Contributions of Ian W.D. Dalziel and David H. Elliot to Antarctic Tectonics**

***Detrital Zircons from the Triassic Sediments in Horn Bluff (George V Land): An East Australia rather than Antarctic Provenance***

Mikhalsky, E.V.<sup>1</sup>; Leichenkov, G.L.<sup>1</sup>; Kapitonov, I.N.<sup>2</sup>

Institute for Geology and Mineral Resources of the World Ocean (VNIIOKeangeologia)<sup>1</sup>; All Russia Geological Research Institute (VSEGEI), St.-Petersburg, Russia<sup>2</sup>

Horn Bluff is an isolated outcrop in George V Land. It is composed of presumably Triassic 80-m thick clastic sediments overlain by Jurassic hypabyssal dolerites. These sediments occupy the westernmost exposed section of the mid-Palaeozoic to early Mesozoic (Beacon) cover overlaying early Paleozoic Ross Orogen. However, the remote position of this locality from most Beacon sequences exposed in the Transantarctic Mountains and its proxy to the Neoproterozoic to Palaeoproterozoic Terre Adalie Craton enables an inquiry of the source of the Horn Bluff sediments. Samples utilized in this study were collected by D.S. Soloviev in 1958.

The exposed section was in much detail described by Ravich et al. (1965, *The Precambrian of East Antarctica*, Moscow, Nedra, 470 pp. [In Russian]). Grey fine- to coarse-grained quartzitic or polymictic sandstones and minor conglomerates make up the section. Garnet, pyroxenes, hornblende, kyanite, staurolite, muscovite, biotite, tourmaline, etc., are minor but common constituents of polymictic sandstones. Shallow-water continental environments were revealed by cross-bedding and mud cracks. The clasts are poorly rounded and badly sorted, indicating immature character of these sediments with proximal source region. Ravich et al. proposed the Precambrian basement served the sediment source.

A medium-grained polymictic sandstone (layer 5 in Ravich et al., 1965, p. 372-373) yielded abundant detrital zircons. Laser ablation local U/Pb analyses on 45 grains were obtained in the Centre of Isotopic Research (VSEGEI, Russia). The recovered grains have varying size and morphology, implying their polygenic origin and likely derivation from different source rocks. Most grains showed two coherent clusters of concordant analyses with an average mean  $^{206}\text{Pb}/^{238}\text{U}$  of  $255 \pm 6$  Ma and  $602 \pm 8$  Ma (spread of individual analyses between ca 520 Ma and ca 670 Ma). Single analyses showed concordant ages of ca 1000 Ma, ca 1250 Ma, ca 1450 Ma, ca 2000 Ma. Five discordant analyses define a regression line with an upper intercept at ca 2750 Ma and a lower intercept at ca 500 Ma. The youngest (ca 255 Ma) age group is defined by short- or long prismatic crystals (length/width up to 6) with oscillatory zoning and well developed unrounded facets. These grains clearly have not experienced transport abrasion and must have been derived from a proximal source. On the contrary, the second age group (ca 600 Ma) comprises well-rounded short-prismatic to oval and ball-shape grains. Some of these grains display prominent abrasion with grain boundaries cutting zoning, while others are just ball-shaped crystals likely of metamorphic origin. Such ball-shaped crystals show relatively low Th/U (0.1-0.2), while other crystals have Th/U = 0.5-1.2. Thus ca 600 Ma grain population reveals a pronounced transport from a distal source region and continuous sedimentary recycling. The older (>700 Ma) grains are mostly well-shaped crystals suggestive of one-cycle sedimentation.

Our finding of ca 255 Ma detrital zircons, on the one hand, proves the Triassic age of the sedimentary strata in Horn Bluff, and on the other hand, provides direct evidence of the latest Permian magmatic activity affected (or provided material to) the Australo-Antarctic segment of the East Antarctic Craton margin.

A mixed volcanic and cratonic provenance of Late Permian and Triassic braided stream deposits within the Permian Triassic Transantarctic Basin has been encountered by D. Elliot, and many authors attributed this volcanic input to a ca 250 Ma subduction in the Palaeo-Pacific beneath New Zealand Marie



Byrd Land Antarctic Peninsular blocks (e.g., Torsvik et al., 2008 and references therein). Indeed, K/Ar, Rb/Sr, and U/Pb zircon ages in the range 225-290 Ma have been reported from the Marie Byrd Land and Thurston Island to Antarctic Peninsula. However, a less remote and more firmly defined source of the latest Permian zircons may be found within the New England Orogen of north-east Australia where Carboniferous–Permian Kennedy Igneous Province comprises various granitoid suites dated, in particular, between ca 290 Ma and ca 255 Ma. Basically similar detrital zircon age spectrum has been found in some samples from the Permian Triassic Sydney Basin. In particular, some sediments from East Australia yielded detrital zircon age spectra of ca 250-260 Ma, ca 500-700 Ma, ca 900-1200 Ma, ca 2000 Ma, ca 2700 Ma, which is very similar to our data. A prominent distinction of these sediments is the presence of ca 450-350 Ma zircon population, lacking in our data. It may also be noted that ca 600 Ma zircon population from Horn Bluff is essentially older than Ross Orogeny ages commonly observed in the Transantarctic Mountains, and hence may be better correlated with the east Australia rather than Antarctic sources. Thus we suggest that Horn Bluff sediments represent a part of the late Palaeozoic-early Mesozoic basins in east Australia. Of course, yet unidentified late Palaeozoic intraplate magmatism within the neighboring sub-ice Antarctic depressions might have served a source for zircons recovered from the studied sample.

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**S04-92: West Antarctica: Problem Child of Gondwanaland - A Symposium Highlighting the Contributions of Ian W.D. Dalziel and David H. Elliot to Antarctic Tectonics**

***U-PB SHRIMP Inherited Zircon Age Patterns of Magmatic Rocks from the South Tasman Rise (Australia)***

Fioretti A.M.<sup>1</sup>; Tunesi A.<sup>2</sup>; Korsch R.J.<sup>3</sup>; Bergomi M.<sup>2</sup>; Visona D.<sup>4</sup>

CNR - Istituto Geoscienze e Georisorse<sup>1</sup>; Dipartimento Di Scienze Dell'Ambiente E Del Territorio EDi Scienze Della Terra, Milano Bicocca, Italia<sup>2</sup>; Geoscience Australia, Canberra, ACT, Australia<sup>3</sup>; Dipartimento Di Geoscienze, Universita' Di Padova, Via-Gradenigo, 35131 Padova, Italy<sup>4</sup>

The South Tasman Rise (STR), composed of a western and an eastern part, is a submerged continental fragment located between Tasmania and Antarctica. It was part of the East Gondwana Continent that formed during breakup between Antarctica and Australia. Because of its central location in the plate boundary framework that developed within East Gondwana, the STR underwent all the major tectonic events that led to the dispersal of Gondwana. A petrological and geochronological study was carried out on magmatic rocks dredged during AGSO (now Geoscience Australia) cruise 147. The oldest sample yielded a Grenville age, one sample is a granite gneiss of late Proterozoic crystallization age (ca. 740 Ma); seven samples yielded Cambrian crystallization ages in the range 487-507 Ma and are thus coeval with the Ross-Delamerian orogen; one sample is Early Devonian (412 Ma), and one is Late Devonian (ca. 363 Ma).

To gain further information on the origin of these granites we investigated the ages of discordant zircon cores within magmatically-zoned zircon. These cores likely represent zircons that were inherited from the source region and therefore provide information on its age and composition.

In the E-STR, at DR44, zircon from a Late Proterozoic (ca. 745 Ma) garnet-bearing granite gneiss shows rare younger metamorphic overgrowths and several older cores with main ages at 960; 1040; 1170; 1250; 1320; 1450; 1580; 1700; 1800 and 2315 Ma. Cambrian age granodiorite from DR31 (ca. 511 Ma) shows no obvious zircon inheritance. Zircon cores from Early Devonian (412 Ma) granite at DR48 show inheritance ages pattern with prominent peaks at ca. 1460; 1540; 1610; 1660; 1770 and individual ages ranging from ca. 1400 to 2500 Ma. A similar pattern is also observed in the Late Devonian granite at DR30A, which shows core ages between 1400 and 1900 Ma, and rare younger than 1400 Ma core zircon. Inheritance age spectra of Late Proterozoic to Devonian granitoid rocks from the E-STR show patterns similar to those of some Devonian granites from western Tasmania, pointing to a common crustal source component and provide further constraints to the stratigraphy of the South Tasman Rise and to it being part of the Western Tasmanian Terrane.

In the W-STR, zircon from six samples of Cambrian ages (543-487 Ma) show no inherited zircon ages. Apparent cores, visible on optical and cathodoluminescence images, yielded the same age as the rims and are therefore interpreted as early nuclei.



**S04–155: West Antarctica: Problem Child of Gondwanaland - A Symposium Highlighting the Contributions of Ian W.D. Dalziel and David H. Elliot to Antarctic Tectonics**

***Eocene Organized Oceanic Spreading during the Initial Development of the South Western Scotia Sea (Antarctica)***

Andrés Maldonado<sup>1</sup>; Manuel Catalán<sup>2</sup>; Jesus Galindo-Zaldívar<sup>3</sup>; Yasmina M. Martos<sup>1</sup>; Anatoly A. Schreider<sup>4</sup>

Instituto Andaluz de Ciencias de la Tierra (CSIC/UGR), Spain<sup>1</sup>; Real Instituto Y Observatorio De La Armada, Spain<sup>2</sup>; Departamento De Geodinamica, Universidad De Granada, Spain<sup>3</sup>; P.P. Shirshov Institute Of Oceanology, Russia<sup>4</sup>

The Scotia Arc is one of Earth's major ocean gateways and is critical for understanding behavior of the Antarctic Circumpolar Current (ACC) and its influence on the development of global climate, the evolution and stability of Antarctic ice-sheets and Southern Hemisphere biodiversity. This arc embraces the Scotia Sea, an ocean basin that connects the Pacific and Atlantic oceans across Drake Passage, which was formed by the tectonic dispersion of the continental blocks that constituted the bridge between South America and the Antarctic Peninsula. The opening age of this sea is a subject of considerable controversy since conflicting ages spanning more than 20 Ma, from Eocene to Oligocene, have been proposed. The precise timing and tectonic mechanisms of this region is of crucial importance due to its implications for the instaurations of a proto-ACC.

A general consensus exist in the interpretation of magnetic anomaly profiles crossing the west Scotia Sea, which show chrons 8 and 3 (26.5 Ma) on both branches of the spreading corridors of the West Scotia Ridge (WSR). These studies also make isolated identifications of chrons 9 and 10 at the extremes of the flanks on some of these corridors. Recent studies also identify the occurrence of chrons 11 and 12 from anomalies west of Terror Rise. The magnetic anomalies become younger, until chron 5C, in the spreading corridors of the northeastern region of the WSR, which suggest that the spreading center had propagated northwards. Most models of these magnetic anomalies show that spreading started at intermediate rates (~26 mm/yr half rate), which later dropped to slow (~12 mm/yr) at around chron 5C.

A grid of geophysical profiles, including total intensity magnetic field data were obtained during the SCAN2013 cruise on board of the BIOHESPERIDES from the southwestern Scotia Sea, in a region called the Ona Basin. Data were filtered in order to eliminate spikes and smoothed using a running mean. The magnetic anomalies were calculated taking into account the Definitive Geomagnetic Reference Field (DGRF). In addition, diurnal corrections were applied considering the Spanish magnetic observatory located in Livingston Island (South Shetland Islands). The top of the acoustic basement oceanic Layer 2 identified in the region MCS profiles was considered the upper boundary of the magnetized layer. These profiles were integrated with magnetic data taken from our previous profiles and the datasets available in the region.

The oceanic crust of the Ona Basin is thrust northward by the continental blocks, as revealed by the MCS profiles. The continent/ocean boundary (COB), marked by a set of reversal faults, is depicted by a sharp increase of the magnetic field, which reaches up to 120 nT. This strong anomaly is associated with the Pacific Margin Anomaly (PMA). Previous studies of the basin floor in this region support the occurrence, although subdued, of C9 and part of C10 close to the continental margin. It has been suggested that the small amplitudes characterizing C9 and C10 result from the combined effect of several polarity intervals at very slow spreading rates. An unusual magmatic regime with reduced emplacement of igneous rocks associated with the early phase of oceanic crustal accretion was proposed, moreover, to explain the low amplitude of these magnetic anomalies. A recent study of the distribution of the magnetic anomalies in the Ona Basin by Maldonado et al. (2014) suggests the occurrence of older anomalies than previously identified, although their precise recognition is elusive. They suggest in the model of profile HESANT 92/93 M-05 a spreading center in the southern region of the western Ona



Basin, spanning chrons C11r to C12r. A mean full spreading rate of ~8 mm/yr was envisaged for this early 3 Ma period, where the dissymmetry of the magnetic anomalies between the two flanks was attributed to the normal faults affecting the northern flank of the ridge. These authors, however, fail to recognize a consistent pattern of the magnetic anomalies in the profiles available in the region. These older anomalies identified in the Ona Basin are not documented in the conjugated margin off Tierra del Fuego.

The presently available data set of magnetic profiles reveals, however, a consistent pattern of maxima and minima oceanic reversals, with a NW trend in the southwestern corner of the Ona Basin, slightly oblique to the Shackleton Fracture Zone. The magnetic seafloor anomalies of the model of profile HESANT 92/93 M-02 are tentatively identified considering a process of regular seafloor spreading. We suggest a spreading center spanning chrons C9r to C16n.1n (~28 Ma to 35 Ma), in the southern branch of the spreading center, although the short length of the profile does not fully cover the northern branch. The same pattern of maxima and minima oceanic magnetic anomalies is observed in the eastern Ona Basin, between the Ona High and the Terror Rise. In this basin the trend of the anomalies is NW, slightly rotated in a clockwise direction in respect to the anomalies of the western Ona Basin. The best fit of the magnetic anomalies model of profile L20\_01, suggest a spreading center spanning chrons C18n.1r to C20n (~39 Ma to 43Ma), although its short length does not allow a definitive identification of the anomalies. The signature of the anomalies and the pattern of distribution, however, are consistent in all the profiles analyzed. Since a clearly organized pattern of magnetic anomalies was not initially identified in the Ona Basin, a chaotic, preliminary episode of opening associated with the early stages of continental fragmentation of the South America-Antarctic Peninsula Bridge was suggested. Based on the available data we conclude, in contrast to previous studies, that the initial phase of oceanic spreading in the Ona Basin was the consequence of organized spreading from single, migrating spreading centers, which were affected by successive ridge jumps, which begins in Eocene times, several million years earlier than traditionally considered.

Maldonado et al., 2014. *Global and Planetary Change*, 123:152-173



**S04–168: West Antarctica: Problem Child of Gondwanaland - A Symposium Highlighting the Contributions of Ian W.D. Dalziel and David H. Elliot to Antarctic Tectonics**

***The Roadmap towards Gondwana Break-Up via Continental Rifting and Microplate Motion in the Weddell Sea Region***

Tom Jordan<sup>1</sup>; Fausto Ferraccioli<sup>1</sup>

NERC-British Antarctic Survey, United Kingdom<sup>1</sup>

The Weddell Sea (WS) is underlain by a major Jurassic continental rift system and separates several inferred West Antarctic microplates from East Antarctica. Most tectonic reconstructions based on geological and paleomagnetic data indicate that the Haag-Ellsworth-Whitmore (HEW) microcontinent was located in the Natal Embayment between East Antarctica and South Africa prior to Gondwana break-up. A major unresolved issue is however how such a far-travelled HEW microcontinent was transferred and rotated to its present position at the southeastern edge of the WS in West Antarctica, and how this links to continental rifting processes within the WS rift system.

Here we analyse new magnetic and gravity anomaly data compilations that cover both the WS rift system and its flanking blocks in West and East Antarctica and combine these with data from the World Digital Magnetic Anomaly Map (EMAG-3) to re-assess Gondwana breakup reconstructions. To examine variations in crustal architecture and magmatic patterns within the WS, we combine digitally enhanced magnetic and gravity imaging, depth to magnetic source estimation and, 2D joint magnetic and gravity modelling tied to the only deep seismic profile available.

Using GPlates, we then examine both existing and new reconstructions scenarios that incorporate different amounts of microplate motion, continental extension and differing kinematics. We conclude that a new model that predicts ca 400 km of E-W extension in the southern WS and a possible component of oblique extension induced by strike-slip reactivation of a potentially more distributed plate boundary between East and West Antarctica is permissible.

If our preferred model is correct, then block rotation and microplate movement may be more closely related to the tectonic evolution of the Gondwanide Orogen than to Weddell Sea rifting and Gondwana break-up.



**S04–175: West Antarctica: Problem Child of Gondwanaland - A Symposium Highlighting the Contributions of Ian W.D. Dalziel and David H. Elliot to Antarctic Tectonics**

***South Georgia Microcontinent? Another Problem Child?: Preliminary Results of RVIB Nathaniel B. Palmer Cruise NBP1408***

Ian Dalziel<sup>1</sup>; Lawrence A Lawver<sup>1</sup>

The University of Texas at Austin, USA<sup>1</sup>

South Georgia, a rugged, mountainous island, is the emergent part of a microcontinent ca. 375 km long and 175 km wide located near the eastern end of the North Scotia Ridge. It is over 1500 km east of Isla de los Estados, the termination of the Andean Cordillera at the southeasternmost tip of South America. Prior to the plate tectonics paradigm, it was clearly a tectonic problem child in the same sense as the crustal blocks of West Antarctica. South Georgia is comprised mostly of Lower Cretaceous turbidites, including a formation with dominantly siliceous detritus, an ophiolitic complex, Mesozoic granitic plutons, and calc-alkaline arc volcanics. It is clearly not a typical oceanic island. During the 1970's, through mapping on the island as well as in southernmost South America, it was determined that the geology of South Georgia exactly matched that of the Andean hinterland to the south of the Beagle Channel in Tierra del Fuego. Moreover, it was noted that if the South Georgia microcontinent could be restored to the embayment in the South American continental margin, immediately east of Cape Horn, there is an obvious source, the Upper Jurassic rhyolitic Tobifera Formation, for the siliceous detritus in the Lower Cretaceous turbidites of the Sandebugten Formation on the northeastern coast of the island. A source is conspicuously absent at its present day location. An alternative original position for the microcontinent was proposed in 2010, namely the southeastern corner of the Falkland/Malvinas Plateau, now to the NNE of South Georgia's present location. However, recent U-Pb detrital zircon studies have confirmed the status of the South Georgia microcontinent as having been a part of the Andean Cordillera in Tierra del Fuego, 1500 km to the west.

In other senses, however, the island and its surrounding microcontinent remain a tectonic problem child. How did it reach its present location over 1500 km east where it must have been at the tip of the Andes in eastern Tierra del Fuego, and when? How did it reach its height of ca. 3 km, which is three times as high as the mountains in Tierra del Fuego from which it is now separated? What role did the island and subjacent microcontinent play in the onset and development of the Antarctic Circumpolar Current? Cruise NBP1408 of the United States National Science Foundation's RVIB Nathaniel B. Palmer, 22 September to 22 October 2014, was planned to address these questions.

The underway geophysical data currently being worked up include, gravity, magnetic, swath mapping and seismic reflection profiling data. The seismic profiles include the first to be acquired across both the northeastern and the southwestern margins of the South Georgia microcontinent. In addition, underway data acquired south and east of the microcontinent bear on the debate regarding the age of onset of seafloor spreading in the east Scotia Sea backarc basin. Results obtained and conclusions reached up to the time of the meeting will be presented.



**S04–180: West Antarctica: Problem Child of Gondwanaland - A Symposium Highlighting the Contributions of Ian W.D. Dalziel and David H. Elliot to Antarctic Tectonics**

***Age of the East Scotia Sea and its Implications for the Scotia? South America Plate Boundary***

Lawrence Lawver<sup>1</sup>; Ian W.D. Dalziel<sup>1</sup>; Marcy Davis<sup>1</sup>; Steffen Sastrup<sup>1</sup>

University of Texas at Austin, USA<sup>1</sup>

The western boundary of the recently formed East Scotia Sea has been based on the identification of marine magnetic anomalies, indicative of true ocean crust. Anomalies as old as Chron C5C? (16.7 Ma to 16 Ma) to the south of the eastern end of South Georgia Island have been published with an unquestioned Chron C5B (15.2 Ma to 14.8 Ma) located at approximately 35°W. On the eastern side of the distinct present day spreading center in the East Scotia Sea, only magnetic anomalies as old as Chron C5? (10.9 Ma to 9.7 Ma) are identified but that particular anomaly is either to the east of the present day active island arc (59°S), or is overlain by the active arc (57.5°S). On the recent NBP1408 cruise of the R/V IBN Palmer, we investigated whether lineated magnetic anomalies older than 10 Ma could actually be found where they are suggested to the south and southeast of the South Georgia microcontinent. Using a magnetometer, a gravimeter, multichannel seismic reflection, and multibeam data, we were able to obtain a cohesive data set that suggests that anomaly Chron C4A (9.6 Ma to 9.1 Ma) is clearly identifiable just to the east of 34°W with Chron C5n.2n (10.9 Ma to 9.9 Ma) prominent at 34°W. The oldest lineated magnetic anomaly to the west of the active spreading center may be the final part of Chron C5r (11.36 Ma to 11.05 Ma). Magnetic anomalies older than Chron C5r are very low amplitude compared to the younger East Scotia Sea anomalies and cannot be correlated between the two recent NBP1408 tracks. In addition the seismic reflection and multibeam data indicate that the low amplitude anomalies are produced by seafloor disruptions, unrelated to recent oceanic seafloor creation. Such identifications would mean that the east and west sides of the present day active East Scotia Sea spreading center are nearly identical in age and do not suggest the need for a significant amount of island arc erosion and a rapid retreat of the island arc with respect to an actively eastward migrating South Sandwich trench.

If the true oceanic seafloor of the East Scotia Sea is in fact no older than 11.4 Ma then this would fit with the assumed time of collision of the South Georgia microcontinent with the Northeast Georgia Rise, an oceanic plateau, produced about 101 Ma to 92 Ma with the concurrent formation of Maude Rise, the Agulhas Plateau and the Northeast Georgia Rise. South Georgia's rapid eastward movement with respect to Tierra del Fuego stopped abruptly with its collision with Northeast Georgia Rise resulting in the extrusion of the East Scotia Sea and a significant change in seafloor spreading direction along the America-Antarctica Ridge. As a result of the collision, the Scotia-South America plate boundary may now be switching from left lateral transform motion originally occurring north of the South Georgia microcontinent to south of the microcontinent as witnessed by recent teleseismic earthquakes recorded along the southeastern margin of the microcontinent.



**S04–195: West Antarctica: Problem Child of Gondwanaland - A Symposium Highlighting the Contributions of Ian W.D. Dalziel and David H. Elliot to Antarctic Tectonics**

***Provenance of the Palaeozoic Siliciclastic Rocks of the Ellsworth Mountains, West Antarctica, Determined by Detrital Zircon Geochronology***

Castillo, P.<sup>1</sup>; Fanning, C.M.<sup>1</sup>; Fernandez, R.<sup>2</sup>; Poblete, F.<sup>3</sup>

Research School Of Earth Sciences, The Australian National University, Canberra, Australia<sup>1</sup>; University of Texas Institute For Geophysics, The University Of Texas At Austin, Austin, Texas, USA<sup>2</sup>; Geosciences Rennes, Université De Rennes 1, Rennes, France; Departamento De Geología, Universidad De Chile, Santiago, Chile<sup>3</sup>

The Ellsworth-Whitmore Mountains block (EWM) is one of the most isolated fragments forming West Antarctica. This block, largely ice covered, is most extensively exposed in the Ellsworth Mountains, where there is an extensive record of sedimentation from early Cambrian to Permian times. However, the tectonic history and the palaeogeographic significance of the EWM remain enigmatic. Current models suggest that the EWM originated in a position adjacent to southern Africa and the Coats Land coast of Antarctica. This position implies that the EWM would have a record of the Cambro-Ordovician orogenic event that occurred along the palaeo-Pacific margin of Gondwana. However, evidence for this tectonic event is lacking and the EWM rather shows indications of a continental rift setting during the Cambrian.

In this contribution, 9 recently collected sandstone samples from the Ellsworth Mountains were analysed for their U-Pb detrital zircon age spectra using SHRIMP II and RG. They belong to the early Cambrian to Carboniferous sequences and record up-stratigraphy provenance variations comparable with similar sedimentary sequences in Antarctica and South Africa.

The active continental rift sediments of the Cambrian Heritage Group are dominated by igneous zircons of Grenville age (1.0-1.2 Ga). Detrital zircons from two different localities of the Middle Cambrian Liberty Formation identify a change in provenance up-stratigraphy. The lower level yields younger detrital zircons of ca. 850 Ma whilst the upper level (close to the contact with the Upper Cambrian Minaret Formation), records younger zircons at ca. 530 Ma. Samples from the Upper Cambrian Springer Peak Formation and the upper part of the Liberty Formation have a second igneous and metamorphic zircon component of Pan-African age (530-650 Ma). The Heritage Group samples have U-Pb detrital zircon patterns similar to those from the Pensacola Mountains and South Africa, with sources in the Namaqua-Natal and Mozambique/Maud Belts; this probably also restricted contributions from older cratons.

At upper stratigraphic levels, the passive margin sediments of the Upper Cambrian to Devonian Crashsite Group are conformable. Sandstone samples from the base of this Group yield dominant igneous zircon components with a Ross/Pan-African provenance (500-620 Ma) and scattered older ages. Detrital zircons from the Devonian Mt Wyatt Earp Formation are principally in the range of 480-610 Ma, with major peaks at ca. 500 and 530 Ma, indicating likely sources in the Transantarctic Mountains and Dronning Maud Land, Antarctica.

The Whiteout Conglomerate conformably overlays the Crashsite Group. It is a diamictite that marks the Permo-Carboniferous Gondwana glaciation in the Ellsworth Mountains. Although both sampled areas are quite different (north-upper and south-lower parts respectively) their detrital zircon age patterns are very similar. They are dominated by a 500-650 Ma zircon component, lacking detrital zircons younger than Cambrian. Comparison of the Whiteout Conglomerate with other glaciogenic strata in southern Gondwana suggests deposition related to that in the Transantarctic Mountains.

From the continuous record of early Cambrian to Permian sedimentation in the Ellsworth Mountains, new detrital zircon dating indicates typical Gondwana margin signatures. However, variations up



section/sequence in zircon provenance suggest a restricted depositional basin during the Cambrian; probably common to that in South Africa and separated from the Transantarctic Mountains sedimentary basin by the Mozambique/Maud belt. This configuration changed in the Ordovician and continued during the late Palaeozoic, when the South African basin had an influx of detritus from Ordovician to Devonian exotic sources, whereas the EWM only received detritus from the Ross/Pan-African orogenic belts.



**S04–296: West Antarctica: Problem Child of Gondwanaland - A Symposium Highlighting the Contributions of Ian W.D. Dalziel and David H. Elliot to Antarctic Tectonics**

***Tectonics Approach from Mass Transport Deposits Analysis: The Scotia-Antarctic Plate Boundary***

Lara F. Perez<sup>1</sup>; Fernando Bohoyo<sup>2</sup>; David Casas<sup>2</sup>; F. Javier Hernandez Molina<sup>3</sup>; Galindo-Zaldavar, J.<sup>4</sup>; Andrés Maldonado<sup>4</sup>; Patricia Ruano<sup>5</sup>

Geological Survey of Denmark and Greenland (GEUS)<sup>1</sup>; Geological Survey of Spain (IGME)<sup>2</sup>; Royal Holloway University of London (RHUL)<sup>3</sup>; Instituto Andaluz de Ciencias de la Tierra (CSIC-Universidad de Granada), Armilla, Granada, Spain<sup>4</sup>; University of Granada, Spain<sup>5</sup>

The Scotia and Sandwich plates accommodate the present left-lateral displacement between the major South American and Antarctic plates. The Scotia plate southern boundary is located along the South Scotia Ridge (SSR). The deformation and stretching of continental blocks occurred during the Scotia Sea evolution have been particularly relevant along this boundary that at present shows restraining and releasing bends structures compatible with the present-day stress field. Northern of the SSR the southern Scotia Sea is formed by deep intra-oceanic sedimentary basins (Ona, Protector, Dove and Scan, from west to east) developed since late Eocene up to middle Miocene between stretched continental morpho-structural highs. The main aim of this study is to characterise and determine the vertical and spatial distribution of Mass Transport Deposits (MTDs) in the infill of the basins and highs near the Scotia-Antarctic plate boundary for establishing their link with major tectonic instability events.

Several works highlight the tectonic complexity of the Scotia Sea region, especially along its southern margin, coinciding with the Scotia-Antarctic plate boundary, where oceanic and continental domains are bounded by faults of different character. The sedimentary record covering these domains has been divided in two main sequences limited by a regional chronostratigraphic limit attributed to the middle Miocene. With a variable distribution inside both, pre-middle Miocene and post-middle Miocene sedimentary record, a number of sedimentary bodies have been interpreted as MTDs. They are characterized by a lenticular to irregular morphology and internal transparent or weak chaotic seismic facies. MTDs size, considering apparent length and thickness, is highly variable even though the greater are located in the eastern most basin, Scan Basin.

The spatial distribution of the MTDs reveals a preferential position in the eastern continental margin of the basins. This is indicative of higher margin instabilities that may be related to the local deformation due to the influence and evolution of both the Scotia-Antarctic plate boundary and the East Scotia Ridge (ESR). The preferential vertical distribution of the MTDs in the sedimentary record evidences a greater tectonic-related instability period in the margin evolution from the middle Miocene to the Quaternary. It started at about 15 Ma when the ESR substitutes to the West Scotia Ridge (WSR) as the main oceanic spreading centre in the Scotia Sea. However, the WSR continued still active until ~6.5 Ma. Coevally an increasing in the spreading rates of the ESR occurred and the faster spreading in its northern segment onset, respect to the central and southern segments. This tectonic activity is then the most plausible candidate for triggering the observed MTDs, through earthquakes or increment of the slope steepness. Also the high occurrence of MTDs during the Pliocene is related to an intensification in the tectonic activity, due to the Shackleton Fracture Zone the western intraoceanic transpressive boundary between Scotia and Antarctic plates uplift period and the Phoenix Ridge extinction. In addition, this period is also influenced by a general warm and the subsequent West Antarctic Ice Sheet melting that may influence a higher sedimentary input and favour sediments instabilities.



**S04-306: West Antarctica: Problem Child of Gondwanaland - A Symposium Highlighting the Contributions of Ian W.D. Dalziel and David H. Elliot to Antarctic Tectonics**

***Age, Geochemistry, and Sr-Nd-Pb Isotopic Compositions of Volcanic Rocks from Mt. Melbourne and the Western Ross Sea, Antarctica***

Lee, Mi Jung<sup>1</sup>; Kim, T.H<sup>1</sup>; Lee, J.I.<sup>1</sup>; Nagao, K.<sup>1</sup>

Korea Polar Research Institute, South Korea<sup>1</sup>

New K/Ar ages and geochemical and isotope data (Sr, Nd, Pb) of submarine samples from the Terror Rift Region and subaerial lavas from Mt. Melbourne Volcanic Field (MMVF) in the western Ross Sea, are presented. The MMVF samples are classified into Groups A and B based on their temporal and spatial distribution. All samples are alkaline, ranging from basanite to trachybasalt, and exhibit the Ocean Island Basalt (OIB)-like patterns of trace element distribution, with a prominent depletion in K and Pb. They exhibit an HIMU-like isotopic signature ( $^{206}\text{Pb}/^{204}\text{Pb} = 18.510\text{-}19.683$ ,  $^{87}\text{Sr}/^{86}\text{Sr} = 0.70300\text{-}0.70398$ ,  $^{143}\text{Nd}/^{144}\text{Nd} = 0.51284\text{-}0.51297$ ) and trace element affinities (Ce/Pb = 25-35, Nb/U = 45-60, Ba/Nb = 5-13, La/Nb = 0.5-0.9). New K/Ar ages and geochemical data, combined with published data, show no correlations between age and composition of Cenozoic basalts in NVL. The Terror Rift submarine lavas (0.46-0.57 Ma) display a distinct trend, with more primitive geochemical characteristics (higher MgO (7.2-9.8 wt.%) and CaO (9.9-11.9 wt%) and stronger HIMU signature (higher  $^{206}\text{Pb}/^{204}\text{Pb}$  and less radiogenic  $^{87}\text{Sr}/^{86}\text{Sr}$  and  $^{143}\text{Nd}/^{144}\text{Nd}$  ratios) than those of MMVF basalts. Results from a rare earth element (REE) model suggest that the Terror Rift submarine lavas are derived from small degrees (1-2%) of partial melting of an amphibole-bearing garnet peridotite mantle source. Despite the distinctly different ages and locations of the MMVF Group A (0.16-0.33 Ma) and B (1.25-1.34 Ma) basalts, they show similar geochemical and isotopic features, indicating the sharing of common mantle sources and magma processes during magma generation. Incompatible trace element ratios (e.g., Ba/Nb = 6.4-13.2, La/Yb = 14.4-23.2, Dy/Yb = 2.2-3.0) and isotopic compositions of the MMVF Group A and B volcanics suggest derivation from higher degrees (2-5%) of partial melting of a garnet peridotite source and strong influence of an EMI-type mantle source. The stronger HIMU signature of the Terror Rift submarine lavas appears to be related to smaller degrees of partial melting, suggesting preferential sampling of the HIMU component in the less partially melted rocks from the Cenozoic NVL magmatism. In contrast, the higher degree of MMVF A and B magmas can be explained by greater interaction with heterogeneous lithospheric mantle, resulting in a diluted HIMU signature compared with that of the Terror Rift submarine lavas.



**S04–326: West Antarctica: Problem Child of Gondwanaland - A Symposium Highlighting the Contributions of Ian W.D. Dalziel and David H. Elliot to Antarctic Tectonics**

***Reconstructing Gondwana: A Global Perspective***

Lawver, L.A.<sup>1</sup>; Norton, I.O.<sup>1</sup>; Davis, J.<sup>1</sup>; Gahagan, L.M.<sup>1</sup>

University of Texas at Austin, USA<sup>1</sup>

In April 1982, Ian Dalziel and David Elliot organized a remarkable Penrose Conference, The Antarctic Plate: a global perspective, held at the Skyland ReSørt in the Shenandoah National Park, Virginia, USA. Wegeners Entstehung der Kontinente, first published a century ago in 1915, alluded to the separation of Africa from South America and Australia from Antarctica. In 1937, DuToit published his book Our Wandering Continents that built upon the idea of the southern continents having been organized as a supercontinent, Gondwana, the land that contained the Indian Land of the Gonds, an idea first proposed by Suess in the late 19th century. Earlier flora work dating to the early 19th century discussed the southern occurrence of Glossopteris and it was hypothesized then that the southern continents were originally grouped together even though the Glossopteris flora was not found on Antarctica until Scotts ill-fated expedition in 1912. Fossils found on Seymour Island and recent advances in retroposon data from various fossils have led to new constraints on when mammals found in Antarctica diverged from their cohorts in South America and Australia.

A paper by Norton and Sclater in 1979 systematically looked at the marine magnetic anomalies found in the southern oceans and it became very apparent that a single, rigid, present day Antarctic continent produces an unacceptable overlap of the Antarctic Peninsula with the Falkland Plateau when the Gondwanide plates are reconstructed. Thus the problem of where to fit West Antarctica took on new urgency and hence the Penrose meeting organized by Dalziel and Elliot. Since the Norton and Sclater paper, various hypotheses have been proposed to solve the overlap problem. While much new data have been collected by ship, plane and satellite in the southern oceans and from geology and geophysics on land, there is yet to be an accepted, single solution to the original location of West Antarctica in a global perspective through time. It is widely accepted that the several crustal blocks that comprise West Antarctica have moved relative to each other and to the East Antarctic craton during Gondwana break up, but their original locations are still debated and there is no consensus concerning how they might have gotten from their original pre-break up positions to their present configuration.

Satellite altimetry data have been remarkably useful in reconstructing Africa and Australia to East Antarctica although less useful in reconstructing India to East Antarctica. Magnetic anomaly data collected by Bergh from South Africa, Segoufin and Patriat from France and more recently by Jokat and his students have produced a solid fit for Africa and East Antarctica. While magnetic anomalies mostly constrain the location of Australia with East Antarctica, only a tight space remains to fit Sri Lanka and India between there constructed Africa and the reconstructed Australia. The resulting space does align charnokite localities on India with those on East Antarctica. Even with all the new data and interpretations, it is still problematic as to where the Antarctic Peninsula fits into a coherent Gondwana. Different scenarios will be explored highlighting their positives and negatives. Advances in computer graphics presentation makes reconstruction scenarios look very good but they are only as good as the data input. The final solution for the break-up of Gondwana and in particular the motion of the Peninsula with respect to the southern tip of South America is still enigmatic.



**S04–370: West Antarctica: Problem Child of Gondwanaland - A Symposium Highlighting the Contributions of Ian W.D. Dalziel and David H. Elliot to Antarctic Tectonics**

***Calculation and Interpretation of Isostatic Gravity Anomalies in Antarctica and its Surroundings***

Gao Jinyao<sup>1</sup>; Yang Chunguo<sup>1</sup>; Zhang Tao<sup>1</sup>; Wu Zhaocai<sup>1</sup>; Shen Zhongyan<sup>1</sup>; Wang Wei<sup>1</sup>

Second Institute of Oceanography, SOA, China<sup>1</sup>

Seeing that there is a lack of ideal data of terrain and isostatic gravity correction to be available in Antarctica and its surroundings, we have used BEDMAP2 (a recently published regional model for the Antarctic continent and its surrounding oceans) and JGP95E (a global digital terrain model) to calculate the global terrain effects and the Airy isostatic effects on the gravity field of the Antarctic continent and its surrounding oceans south of 60°S. We compute gravity effects of three mass layers: ice, water and bedrock. The Airy isostatic compensation model used to calculate gravity isostatic effects assumes an average compensation depth of 30 km and a mantle density of 3.27 g/cm<sup>3</sup>. We can derive the root thickness compensating for density differences of ice, water and bedrock to normal crust with density of 2.67 g/cm<sup>3</sup>. The terrain and isostatic gravity correction data are given at 1 nautical mile by 1 nautical mile grid of rectangular coordinates of the polar azimuth projection.

In order to gain a tradeoff between computational accuracy and speed, the global relief needs to be divided into near zones and far zones using the outer limit of the Hayford-Bowie zone O (166.7 km) (Heiskanen and Moritz, 1967) surrounding each computation point, which is restricted by 1 nautical mile by 1 nautical mile grid of rectangular coordinates of the polar azimuth projection. The BEDMAP2 is fully used for the near-zone calculation. The global digital topographic model JGP95E (Arabelos, 1999) south of 60°S is replaced by BEDMAP2, and this reconstructed JGP95E is used for the far-zone calculation. Gravity effects of both the near zone and the far zone are computed by the same formula for the gravity effect from a truncated spherical shell block in a spherical coordinate system (Lei, 1984; Gao and Jin, 2003; Mikuka et al., 2006). BEDMAP2 and the reconstructed JGP95E are rearranged into rings around each computation point. DTU10 is a satellite altimetry derived global marine free-air gravity anomaly model (Andersen, 2010), with land filled by EGM2008. We have obtained Bouguer gravity and isostatic gravity anomalies in Antarctica and its surroundings by subtracting gravity terrain and isostatic effects from the DTU10 free-air gravity anomaly.

A combination of gravity terrain and isostatic effects is in the range of 15 mGal to 18.5 mGal over about 90% of the entire region. It suppresses regional variations of gravity terrain effects but preserves local highs and lows. As a result, isostatic gravity anomalies are similar to free-air gravity anomalies, but have relatively small undulating amplitudes. Isostatic gravity anomalies have values between 29.6 mGal and 23.5 mGal in about 90% of the region, are closer to zero in the Antarctic continent and its surrounding oceans, and have a standard deviation of 23.7 mGal. This implies that the Airy isostatic model is generally reasonable for Antarctica and its surroundings, but locally imperfect for bedrock rises and falls, especially in East Antarctica. Along the outer shelf uplift zone surrounding Antarctica, the positive gravity belt has higher values in free-air gravity anomalies than those in isostatic gravity anomalies. Meanwhile, the positive gravity belt of isostatic gravity anomalies almost disappears in the background anomalies of 20 mGal to 10 mGal facing the Pacific ocean between 105°E and 70°W. These negative background anomalies may be an over-compensation phenomenon or related with thick sedimentation. Moreover, the lithosphere of Ross Sea and offshore Wilkes Land near the Pacific-Antarctic Ridge are intensively broken by transform faults, its strength becomes weak, and this favors a local equilibrium adjustment with the Airy isostatic model. Within the Ross Sea sector area, including its outer ocean, isostatic gravity anomalies are smoothly lowest in the entire region. These transform faults may cut through lithosphere to induce the mantle thermal turbulence, which further reduces the lithospheric strength and brings about an over-compensation phenomenon. Local relatively high anomalies along the basin axes in Ross Sea may imply that the mantle magmas are likely pulled into crust or underplated beneath crust. These



geodynamic characteristics of RossSea might deepen in understanding of the West Antarctic Rift System. We may pay attention to the difference between the Airy isostatic model and a real isostatic equilibrium status. A better understanding of this difference may be pursued from two perspectives. Firstly, we will check a correlation between gravity terrain effects and free-air gravity anomalies. We thus obtain gravity isostatic effects that uncorrelate with free-air gravity anomalies and then invert these gravity effects for undulations of the Moho. Secondly, we would invert Bouguer gravity anomalies for Moho undulations, with constraints of deep seismic sounding data. If the above two results of Moho undulations agree with each other, their unveiling isostatic characteristics tend to be objective and independent to any prior isostatic compensation model. Relating to the flexure isostatic model, Moho undulations can be further used to analyse wax and wane of the Antarctic ice sheet. If we also study geoid undulations (or gravity potential anomalies), there may be a clearer relation of mantle dynamic response to changes of the ice sheet and lithospheric rigidity in Antarctica.

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**S04–408: West Antarctica: Problem Child of Gondwanaland - A Symposium Highlighting the Contributions of Ian W.D. Dalziel and David H. Elliot to Antarctic Tectonics**

***Tectonic Evolution of the South Shetland Island - Antarctic Peninsula System: A Preliminary Study***

Joaquin Bastias<sup>1</sup>; Richard Spikings<sup>1</sup>; Francisco Herve<sup>2</sup>

Universite De Geneve, Switzerland<sup>1</sup>; Universidad Andres Bello, Chile<sup>2</sup>

The rocks of the South Shetland Islands and the northern Antarctic Peninsula were formed within a Mesozoic and Cenozoic arc, as a consequence of subduction at the Pacific margin of northern West Antarctica. Geochemical analyses of the intrusive and extrusive magmatic rocks at the South Shetland Islands show that they formed within an island arc, and were derived from a depleted MORB mantle source. The Antarctic Peninsula was assembled via terrane accretion and autochthonous magmatic processes through the Paleozoic and Tertiary. Distinct terranes within West Antarctica are referred to as Filchner Block, Central Domain, Western Domain, Eastern Domain, and the Ellsworth Whitmore Mountains, of which the origin and time of accretion are only loosely constrained. The autochthonous magmatic products are mainly the Antarctic Peninsula volcanic group and the Antarctic Peninsula batholith. The first consist in Mesozoic through Tertiary volcanic rocks composed of calc-alkaline basic, intermediate and silicic lavas, volcanoclastic deposits, and ignimbrites. The second comprehends Triassic through Miocene plutonic complexes and related hypabyssal rocks of variable composition, including granites, granodiorites, diorites, tonalites and gabbros. The subduction directions are considered to be east-dipping (subduction of the proto-Pacific oceanic lithosphere), and west-dipping (subduction of the proto-Weddell Sea lithosphere).

Prevailing paleogeographic models place the Antarctic Peninsula outboard of Patagonia during the Early Jurassic. The opening of the Weddell Sea accompanied the separation of both continental land masses during the Jurassic. The formation and evolution of the Scotia Plate over the past 40 Ma finally separated the Antarctic Peninsula from Patagonia, allowing the Antarctic Circumpolar Current to form.

This project aims to develop a geological model for the South Shetland Islands Antarctic Peninsula system for the Paleozoic-Tertiary, spanning between the possible existence of an Ordovician arc, to the Late Miocene and younger opening of the Bransfield Strait and the formation of the South Shetland Islands. A field study (February, 2015) will be combined with numerous geochronological, isotopic, geochemical and thermochronological methods. Numerous studies within Patagonia have been completed, although there is a paucity of numerical data published from West Antarctica.

The objectives are currently broad and general because the project is in a juvenile stage, and they are:

- i) The nature of Jurassic magmatism, and how this relates to the Pacific (Terra Australis) margin of Gondwana: The Andean Jurassic arc, located from northern Chile to Colombia (with a gap in northern Peru), has been studied in detail. Comparisons will be made between the Andean Jurassic arc (e.g. magma sources, chemistry and periods of compression and extension) and the Jurassic intrusive rocks of the northern Antarctic Peninsula. This comparison will facilitate correlating subduction zones along southern and western Gondwana during the Jurassic.
- ii) Antarctic Peninsula basement: To constrain the age (e.g. are there Ordovician and Carboniferous arcs?), and determine the tectonic environment within which it formed. Where were these terranes situated within the Terra Australis margin and when did they rift away from the core of Gondwana.
- iii) Cretaceous arc evolution: What is the distribution, crystallization age range and geochemical character of the Cretaceous Arc within the northern Antarctic Peninsula? Did it form during alternating periods of compression and extension, as it did throughout the Andes?



- Quantitative information from the Cretaceous margin will increase the accuracy of correlations with Patagonia within South America.
- iv) Tertiary arc evolution, the formation of the Bransfield Strait and its relationship with the cessation of spreading within the Phoenix Plate: The rocks of the South Shetland Islands and the Antarctic Peninsula have been affected by subduction of the oceanic Phoenix Plate since the early Mesozoic. Subduction gradually terminated diachronously northwards along the Antarctic Peninsula, and it is currently only active beneath the South Shetland Islands. Extensional processes during the last 4 Ma have developed the Bransfield Strait, a narrow extensional basin (65 km wide) that separates the South Shetland Island on the west of the Antarctic Peninsula, although the beginning of the extension of the Bransfield basin is been assumed to start in the Oligocene-Miocene. It is attempted to measure and determine an age for the beginning of the extension and with this provide with significant insight for the recent tectonic evolution in the region.
- v) Paleogeographic reconstructions from the Jurassic through the Paleogene: Correlations will be made between the geology of the Cape Fold Belt (southern Africa), southern South America and the South Shetland Islands Antarctica Peninsula. The main objective is to improve paleogeographic reconstructions of the Terra Australis margin within Gondwana, until the formation of the Drake Passage at approximately 40 Ma.

We will use geochronological (U-Pb zircon, LA-ICPMS, ID-TIMS;  $^{40}\text{Ar}/^{39}\text{Ar}$ ) geochemical (major oxides, traces and REE), thermochronological (apatite U-Pb, alkali feldspar  $^{40}\text{Ar}/^{39}\text{Ar}$ , apatite and zircon fission track and (U-Th)/He) and isotopic tracing (Hf in zircon, Nd whole rock and O in quartz) methods. These techniques will provide accurate measurements of the age of crystalline rocks, and will constrain magma sources and the tectonic environment within which the rocks formed. The thermochronological data will be combined with the sedimentation history to constrain exhumation, which provides quantitative insights on the timing of extension and terrane accretion.

**Acknowledgements:**

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**S04-439: West Antarctica: Problem Child of Gondwanaland - A Symposium Highlighting the Contributions of Ian W.D. Dalziel and David H. Elliot to Antarctic Tectonics**

***Crustal Blocks and Large Igneous Provinces within Gondwana***

Bryan Storey<sup>1</sup>

Gateway Antarctica, University of Canterbury, New Zealand<sup>1</sup>

It is now thirty three years since Ian Dalziel and David Elliot published their seminal paper in 1982 on West Antarctica: problem child of Gondwanaland. It was appropriately the first 16 pages to be written within what has now become the well-established Tectonics Journal. As their thought provoking paper stimulated many years of active research within both West Antarctica and Gondwana resulting in many related publications, it is timely to review and ask the question if West Antarctica remains a problem child within Gondwana? Crustal blocks, some of which behaved as independent micro plates during Gondwana breakup have been clearly defined, and large igneous provinces have been identified. However, some of the fundamental questions about Gondwana breakup and the reasons why the supercontinent for the most part disintegrated into large continental blocks (today's continents of South America, Africa, India, Australia and New Zealand) together with an array of micro-continents within the Weddell Sea region remain unanswered. It has long been recognized that the location of the crustal blocks corresponded with centres of magmatic activity and with the Permo-Triassic Gondwanide fold belt. Inevitably many models sought related processes to explain these phenomena. Undoubtedly, questions remain but it appears to be no coincidence that in broadly the same geographical area, the Scotia Sea region, a similar array of micro-continental blocks were formed during the Cenozoic opening of Drake Passage and the final separation of Antarctica from South America. Perhaps some fundamental processes, that we are not fully aware of, exist within the Earth's mantle controlling such events.



**S04-442: West Antarctica: Problem Child of Gondwanaland - A Symposium Highlighting the Contributions of Ian W.D. Dalziel and David H. Elliot to Antarctic Tectonics**

***Ian W. D. Dalziel and David H. Elliot: Contributions toward our understanding of the Paleo-Pacific Margin of Gondwanaland***

Mukasa, S. B.<sup>1</sup>

College of Engineering and Physical Sciences, University of New Hampshire, United Kingdom<sup>1</sup>

As a tribute to the tremendous contributions made by polar scientists Ian W.D. Dalziel and David H. Elliot to our understanding of the paleo-Pacific margin of Gondwanaland, this abstract and the talk to follow will attempt to summarize highlights of their work through the years on Gondwanaland assembly and break up, humbled by the fact that much has to be left out. Besides keen observation and enviable prose, the greatest strength of their respective bodies of work has to be early recognition of the importance of multidisciplinary. While Dalziel trained as a structural geologist and tectonicist – a seasoned practitioner of measuring geologic structures with a Brunton compass – his many publications have drawn on geochronology, geochemistry, paleontology, paleomagnetism, petrology and GPS-campaign surveys. Elliot trained as an igneous petrologist, but his publication record shows an appreciation for geochronology, geochemistry, paleontology, stratigraphy, and volcanology.

Over the past fifty years, Dalziel and Elliot have arguably made the most important discoveries about the evolution of Gondwanaland and its margins. In joint publications beginning in the early 1970s, they unraveled the tectonic evolution of the Scotia Arc, introducing plate tectonic concepts in the region, which have survived the test of time. They next turned to the bedrock geology of Antarctica – much of it concealed by ice sheets – and deduced the presence of several crustal blocks or microplates, each with a distinct kinematic and magmatic history. Years of observations and a variety of measurements made by Dalziel and Elliot along with their collaborators led to recognition of the Antarctic Peninsula, Ellsworth-Whitmore Mountains, Haag Nunatak, Marie Byrd Land, and Thurston Island as microplates, not only distinct from each other, but also allochthonous with respect to the East Antarctic Craton. Furthermore, they recognized widespread evidence for deformation, metamorphism and magmatic activity termed the Gondwanide Orogeny, which has since been linked to subduction zone jump in the 300-230 Ma timeframe, and subsequent development of a continental arc extending from eastern Australia to the Andean margin of South America during much of the mid Mesozoic.

A short interlude from research along the paleo-Pacific margin of Gondwanaland allowed Dalziel to ponder Precambrian rocks in the Shackleton Range and other areas of East Antarctica, which led to completely new thinking about the Neoproterozoic world. He, along with other colleagues, soon recognized that the global patchwork of ~1.0-Ga orogens, now far from each other, represented dispersed fragments of a Neoproterozoic supercontinent – subsequently named Rodinia – which linked North America with East Antarctica in reconstructions at 1.0 Ga. This became known as the SWEAT hypothesis, meaning juxtaposition of the southwestern United States and East Antarctica. The demise of Rodinia by rifting in the late Neoproterozoic resulted in a reconfiguration of the southern landmasses (Africa, Antarctica, Australia, India and South America) into the supercontinent Gondwanaland during collisional events identified as the Pan-African and Brasiliano orogenies, depending upon locality. Subsequent studies along the paleo-Pacific margin documented the timing of Gondwanaland breakup – with dispersal of Zealandia (Campbell Plateau, Challenger Plateau, Chatham Rise, Lord Howe Rise, North Island, South Island) from West Antarctica – leading to formation of the modern southern Pacific Ocean.

When serendipitous opportunity presented itself during the 1969 Antarctic field season in the form of stumbling upon a massive cache of fossil remains exposed close to his field camp at Beardmore Glacier, Elliot did not hesitate to set aside his petrologist's hat and don one of a vertebrate paleontologist. Comparing that season's fossil finds to earlier finds on other southern continents provided one of the



most important and compelling forms of evidence that Antarctica was in the distant past connected to Africa, Australia, India and South America for at least 60 Myr.

Elliot and associates have also devoted much effort to understanding the timing and mechanisms of emplacement for the Ferrar Large Igneous Province (FLIP). This is a voluminous province of intrusions, differentiated sills, lavas and volcanoclastic rocks tied to magmatic activity at 182 Ma in a narrow belt parallel to the Transantarctic Mountains, and extending for 4,000 km, from the Weddell Sea to Tasmania and eastern Australia. Ferrar magmatism has been tied to the inception of Gondwanaland breakup. Impressed by contemporaneity and geochemical similarities of Ferrar intrusions, sills and lavas over vast distances, Elliot and associates proposed origination of magma in this LIP from a point source and then rapid dispersal by lateral flow in dikes and sills that appear to have exploited weak zones in the upper crust.

With such significant contributions, it is very fitting that Dalziel and Elliot have both been immortalized with naming of several Antarctic features and fossil finds. Dalziel Ridge is the prominent western ridge of the Columbia Mountains in Palmer Land on the Antarctic Peninsula. Several organisms bear Elliot's name: *Oreochimaellioti* – fish; *Cryolophosaurusellioti* – dinosaur; *Cucullaeaellioti* – bivalve mollusk; *Antarctodarwinellaellioti* – gastropod; and *Plectilospermumelliotii* – gymnosperm seed.



**S05–39: The Rodinian Orogeny in East Gondwana- Implications for Supercontinent Evolution**

***Geological Studies in Baalsrudfjellet Nunatak between Schirmacher Oasis and Wohlthat Mountains to Establish the Continuation of East African Orogen (EAO) in cDML***

Sandip Roy<sup>1</sup>; Naresh C. Pant<sup>2</sup>; A.D. Dharwadkar<sup>1</sup>; P.K. Kumar<sup>1</sup>

Geological Survey of India, Faridabad, India<sup>1</sup>; University of Delhi, Delhi, India<sup>2</sup>

The granulite facies rocks of Northern Mozambique as well as the Central Dronning Maud Land (cDML) represent the southernmost segment of the 8000km long East African-East Antarctic Orogen (Jacobs and Thomas, 1994). However the seemingly logical extension of EAO towards south of Mozambique belt into Antarctica through cDML (Harley et al., 1997; Jacobs 1999, Jacobs et al. 2003, Yoshida et al., 2003) using the continent- continent collision orogenic model (Collins et al., 2012) is beset with certain inherent problems and gaps in information (Pant et al., 2013). This is partly due to the fact that unlike the northern segment of this Orogenic belt where the ophiolite sequence is well preserved (e.g., Arabian Nubian Belt) the southern segment is represented by deep seated exhumed terrain. Several studies have attempted to address the issues (Jacobs et al., 2003; Mikhalasky et al., 2006). However additional and detailed data on lithological continuity, identification and characterization of suture zone and geochronological characterization is required in this context.

The 600-660Ma EAO granulites of Mozambique belt (Stern 1994) was correlated and extended into coastal margin of Antarctica through the 17km long NNW-SSW trending granulite bearing Schirmacher Oasis (Ravikant et al., 2004, 2007; Baba et al., 2006). Tracing the similarity in lithological association, granulite grade metamorphism pattern and geochronological data, the 640 Ma EAO event was extended to another 110km south of Schirmacher in Humboldt Mts in cDML (Pant et al., 2013). Based on the presence of younger anorogenic magmatism in East and West of Humboldt Mts they assumed as few 10's of km wide linear corridor of EAO from the Schirmacher to the Humboldt Mountains.

There are eight nunataks between the Schirmacher and the Humboldt Mountains which stands out projected above the ice sheet. These nunataks are very strategically placed because they represent the entire in between geology of the area. Baalsrudfjellet is one of these nunataks which is located just outside the eastern most margin of the assumed EAO corridor and, therefore, a significant outcrop to validate the passage of EAO between Schirmacher and Humboldt Mountains. Granulite grade conditions similar to those reported from the Humboldt Mountains have been established in this nunatak. The geochronological constraints have been obtained using chemical dating of monazite from metapelites and the data validates continuation of EAO in between the Schirmacher and the Humboldt Mountains.



**S05–51: The Rodinian Orogeny in East Gondwana- Implications for Supercontinent Evolution**

***MESO- To Early Neoproterozoic Terranes of East Antarctica: Continuity through Steady Accretion or Random Neighbors through Continental Collisions?***

Mikhalsky, E.V.<sup>1</sup>

Institute for Geology and Mineral Resources of the World Ocean (VNIIOkeangeologia) <sup>1</sup>

Summarized are published and new geological and geochronological data acquired in the Circum-East Antarctic Mobile Belt (CEAMB), which experienced major crust-forming and orogenic events mainly during the Meso and/or early Neoproterozoic. Many authors believed the CEAMB included most of the Antarctic coastal area from Dronning Maud Land in the west, through Enderby Land, Prince Charles Mountains, and Princess Elizabeth Land, to Windmill Islands in the east. Many workers consider the CEAMB to have formed during continent-continent collision(s), which resulted in the amalgamation of Rodinia at ca 1000 Ma. However, it was found that the CEAMB includes areas of different tectonic evolution (from east to west: Wilkes, Rayner, and Maud Provinces) and was locally affected by a major high-grade event at ca 550-500 Ma. These findings supported the idea of Cambrian collision(s) of separate continental blocks, which led to the final amalgamation of Gondwana.

The Wilkes Province includes rocks crystallized at ca 1700-1500 Ma and ca 1370-1100 Ma. A geological link has been well established between the Wilkes Province and the Albany Fraser Orogen (AFO) of Western Australia. In Wilhelm II Land straddling the boundary between the Wilkes and Rayner Provinces, Ua/Pb zircon ages and Sm/Nd isotopic compositions for rocks in Mirny oasis, Mt Brown and Gaussberg volcano show that this region is underlain by isotopically coherent crust which experienced a high-grade event at ca 980-920 Ma. Indications of ca 500 Ma event in coastal areas, together with the lack of such indications in Mt Brown, point to a concentration of ca 500 Ma processes (roughly co-eval with the Prydz Orogeny) in the coastal part of Wilhelm II Land and their attenuation inland. We also determined ca 1480 Ma age for mafic magmatic protolith in Mt Brown, which may be correlated with roughly co-eval orthogneiss in the Wilkes Province.

These observations suggest the conjugated positions of these crustal blocks in the early Mesoproterozoic and argue against a Cambrian suture running between them.

The eastern Rayner Province in the Prince Charles Mountains (PCM) includes rock protoliths as old as ca 1500 Ma. It experienced major orogenic activity at ca 1400-1200 Ma (the Fisher Phase), and ca 1150-930 Ma (the Beaver Phase, culminating in the ca 1000-930 Ma Rayner Structural Episode). ESE-WNW trending mafic dykes intruded at ca 850 Ma. Thus, the Rayner Province in the PCM has many features in common with the AFO. These include: nearly contemporaneous formation of juvenile crust in convergent settings at ca 1400-1250 Ma, mantle sources with very similar Nd isotope compositions, and similar, but not co-eval, subsequent evolution in intra-continental environments (ca 1215-1140 Ma in the AFO and ca 980-950 Ma in the PCM). The composition and history of the PCM argue for continuation of the Fraser ocean further west into the Rayner Province. The younger age of final tectonothermal activity in the PCM supports a suggestion that closure of the Fraser-Fisher ocean and continent collision occurred steadily from east to west.

Newly obtained Ua/Pb (SHRIMP-II) zircon ages and whole-rock chemical data from western Rayner Province (Thala Hills in western Enderby Land) show that three high-T tectonomagmatic events affected this area at ca 970 Ma, ca 830 Ma, and ca 545 Ma. The ca 970 Ma event corresponds very well to the Rayner Structural Episode which affected much of East Antarctica, including the Sir Rondane Mountains to the west and Kemp Land and PCM to the east. This correlation argues for a conjugated geological evolution of these regions in spite of the late Neoproterozoic to Cambrian Lutzow-Holm orogen between them. The ca 830 Ma event probably involved some mantle-derived precursors, while the ca 970 Ma and



545 Ma events were largely of within-crust nature. The ca 830 Ma orogenic event has not been encountered within the PCM or Wilkes Province, where tectonothermal activity ceased long before this time and mafic dykes swarms were emplaced at ca 1150 Ma and 850 Ma. The ca 830 Ma event is roughly co-eval with mantle superplume activity in the Australian segment of Rodinia, and may be related to such a process.

At the boundary with the Maud Province Lutzow-Holm Bay coast was a focus of high-temperature metamorphism and deformation (Lutzow-Holm Orogeny) at ca 550-500 Ma, and there is evidence for previous tectonothermal activity (mainly ca 1000 Ma). From Yamato Mountains of eastern Dronning Maud Land major groups of zircon ages between ca 1000 Ma and 600 Ma were reported and subordinate ca 800-700 Ma nearly concordant ages were found. In the Sir Rondane Mountains the main phases of magmatic activity, which involved voluminous subduction-related igneous rocks, were dated at 995-975 Ma and 770 Ma.

In central Dronning Maud Land Neoproterozoic tectonomagmatic activity was concentrated within different crustal blocks at ca 750-710 Ma and/or 650-570 and Early Palaeozoic activity at ca. 530-480 Ma. These activities were largely of within-crust nature, and only anorthosites and charnockites represent derivatives of mafic lower crust or upper subcontinental mantle. Thus the late Tonian to early Cryogenian tectonothermal processes found in eastern Rayner Province do not seem to have co-eval equivalents in Maud Province, where major tectonothermal activity occurred somewhat later in late Cryogenian to Ediacaran times. The CEAMB reveals a heterogeneous structure and prolonged and complex geological evolution, which is evidenced by pin-point zircon ages either between 1400-1300 Ma or 1000-970 Ma. The geological histories of Wilkes, Rayner, and Maud provinces suggest their derivation and evolution during successive (essentially from east to west) accretion collision events, rather than their existence as independent crustal entities before the Cambrian. A continuation and steady closure of the Fraser Fisher Mauda ocean (or smaller independent basins) may explain consistently younger ages in the westernmost terranes. Ensialic nature of most Meso- to Neoproterozoic terranes should be noted. Going further (in both senses), a link to the Cambrian ophiolites in Shackleton Range could be suggested. However, in this scenario the nature of the ca 550-500 Ma intraplate events remains problematic.



**S05–66: The Rodinian Orogeny in East Gondwana- Implications for Supercontinent Evolution**

***India- East Antarctica Connection Re-Visited***

Somnath Dasgupta<sup>1</sup>; Sankar Bose<sup>2</sup>; Santanu Kumar Bhowmik<sup>3</sup>

Indian Institute of Science Education & Research, Kolkata, India<sup>1</sup>; Presidency University, Kolkata, India<sup>2</sup>;  
Indian Institute of Technology, Kharagpur, India<sup>3</sup>

The Eastern Ghats Belt (EGB), India has been known to be an important link in understanding the evolutionary history of Rodinia since last 25 years. In particular, it is construed the EGB and parts of East Antarctica shared a common tectonothermal history as integral part of Rodinia since last one billion years, till the breakup of India from Antarctica. Recent geological investigations in the EGB, particularly isotopic data, although broadly supporting such a correlation, brought out significant differences in details in the geological histories of the two erstwhile partners that reveal a substantially more complex history of correlation. The EGB itself was found to be a collage of different isotopic domains and provinces with distinct tectonothermal histories. It became increasingly clear that no single model can explain the tectonothermal evolution of the entire EGB. The unique ultrahigh temperature metamorphism in the EGB actually occurred at different times in different domains, and was found to be not precisely analogous to that in East Antarctica. Further, new isotopic and geological data point out pre-Rodinia juxtaposition of parts of EGB and East Antarctica, possibly as a part of Columbia. Similarly, the post-Rodinia (as part of East Gondwana) history of the two continents has to be re-looked in the light of recent petrological and geochronological data obtained from the northernmost part of the EGB. Interestingly, orogenic activities associated with the assembly and break-up of both Columbia and Rodinia have been traced well within the Indian continent, which point to new configurations of the transcontinental orogens. The revised path of propagation of the Grenvillian orogen in the Indian continent has particular bearing on Indo-Antarctic correlation during the time of Rodinia. The prolonged period spanning Columbia to East Gondwana witnessed complex history of assembly and dispersal of microplates in the Indian continent, leading finally to the development of the crustal architecture. This requires a reappraisal of the models of intercontinental correlation. We present here an updated synthesis of available information from the EGB and other temporally equivalent orogens in India to bring out the inherent complexities in India- Antarctica correlation, identifying the gaps in knowledge, and thereby suggesting avenues of future investigations.



**S05–104: The Rodinian Orogeny in East Gondwana- Implications for Supercontinent Evolution**

***New Ua/Pb Zircon Age Data from the Bunger Hills? Denman Glacier Area: Prominent Orogeny at Ca 1190? 1140 Ma and Possible Link to the Mawson Palaeocontinent***

Mikhalsky, E.V.<sup>1</sup>; Belyatsky, B.V.<sup>2</sup>; Presnyakov, S.L.<sup>2, 3</sup>

Institute for Geology and Mineral Resources of the World Ocean (VNIIOkeangeologia)<sup>1</sup>; Russian Geological Research Institute (VSEGEI)<sup>2</sup>; Polar Marine Geosurvey Expedition<sup>3</sup>

In this study we present SHRIMP-II Ua/Pb zircon (VSEGEI, St. Petersburg) data from four specimens. Three of those charnockitic granites from two different nunataks and a metasedimentary xenolith from one of them) were sampled by P.S. Voronov and L.V. Klimov in 1957 from Mt Strathcona and nearby outcrop located at western side of upper Denman Glacier and one was eventually sampled from the Bunger Hills (mafic granulite dyke).

Orthopyroxene-bearing biotite granite contains abundant short- to long-prismatic zircon grains showing prominent oscillatory zoned internal structure with rare cores. Analyses of seven grains form a concordant group and yielded a weighted mean  $^{206}\text{Pb}/^{238}\text{U}$  age of  $1181\pm 11$  Ma. This is interpreted to date granite crystallization. Two core analyses are nearly concordant and have  $^{207}\text{Pb}/^{206}\text{Pb}$  ages of ca 2650 Ma and 1800 Ma which date inherited matter.

Weakly gneissose two-pyroxene-biotite mesocratic tonalite contains fragmented long-prismatic oscillatory zoned zircon grains. Eight concordant analyses gave a weighted mean  $^{206}\text{Pb}/^{238}\text{U}$  age of  $1174\pm 14$  Ma which is thought to date tonalite crystallization. This intrusion contains xenoliths of sillimanite-biotite-bearing paragneisses. Zircons from a paragneiss vary from short-prismatic to oval abraded grains arguing for their detrital origin. Some grains consist of core with Th/U = 0.5-1.0 and mantle/overgrowth with Th/U = 0.1-0.2. Two groups of nearly concordant analyses have been obtained on ten grains: ca 2000-1750 Ma (three analyses yielded  $1744\pm 24$  Ma) and ca 2500-2360 Ma. Three analyses on mantles have given a weighted mean  $^{206}\text{Pb}/^{238}\text{U}$  age of  $1189\pm 18$  Ma which we interpret as the age of metamorphism.

Granulitic mafic dyke from the Bunger Hills contains irregular shaped or rare oval zircon grains with rough igneous zoning. Small cores were observed in a few grains. Eight analyses have given a concordant age of  $1179\pm 14$  Ma which is thought to date the minimum time of dyke injection. Two core analyses yielded individual nearly concordant ages of ca 1661 Ma and ca 1356 Ma. A charnockite intrusion from the Obruchev Hills was dated at ca  $1140\pm 4$  Ma (Alexeev et al., 2011). This rock contained inherited zircons with ca 1800-1600 Ma ages. Our data demonstrate that granitoid (charnockitic) emplacement occurred at ca 1180-1140 Ma immediately following ca 1190 Ma metamorphic event. Inherited material was mostly dated at ca 2650-2360 Ma and ca 2000-1600 Ma with prominent age peak at ca 1750 Ma. Within the uncertainties these data are in a good agreement with the data presented by Sheraton et al. (1992) for the Bunger Hills: peak metamorphism at ca 1190 Ma and gabbro to granite intrusions at ca 1170-1150 Ma. This indicates that Mt Strathcona and Bunger Hills separated by Denman Glacier and Scott Glacier may have experienced very similar geological evolution, hence arguing against a major suture between these areas. It is noteworthy that the Pan-African events were not recognised at Mt Strathcona. The Palaeoproterozoic ages reported here (ca 2360 Ma, ca 1750 Ma) may find roughly co-eval counterparts in some other Antarctic regions, particularly within those included with the assumed Mawson Palaeocontinent (the Terre Adlie Craton, Miller Range) along with the Gawler Craton in Australia (Fanning et al., 1995). The Mawson Palaeocontinent experienced ca 2550-2430 Ma, ca 2000 Ma, ca 1850, ca 1700 Ma, and ca 1600-1550 Ma tectonomagmatic activities best evidenced within the Gawler Craton. Some authors considered the Wilkes Province of East Antarctica as ca 1500-1400 Ma juvenile crust accreted to the Mawson Palaeocontinent and included it with the latter thus expanding it towards the Denman Glacier area (e.g., Payne et al., 2009). Our data confirm this suggestion and argue for the late Palaeoproterozoic connection of Wilkes Province (particularly the Bunger Hills and Denman Glacier area)



and the Mawson Palaeocontinent. Moreover, the Palaeoproterozoic ca 2000-1800 Ma zircons were found entrained by Gaussberg volcanic rocks (Mikhalsky et al., 2015), ca 2000-1600 Ma zircons were found in accreted ice from Vostok Station borehole (Leichenkov et al., 2011), and in the southern Prince Charles Mountains ca 2500-2450 Ma and ca 2200-2000 Ma events with a subordinate episode at ca 1750 Ma have been encountered (Mikhalsky et al., 2006). These and our present data point to possible continuation of the Mawson Palaeocontinent (or roughly co-eval separate blocks) in vast Antarctic sub-ice interiors maybe composing most of it. The mid- to late Mesoproterozoic zircon ages are also common and apparently even more pronounced in most areas including the Ross Orogen hinterland (Goodge et al., 2010). Thus the proposed hypothetical Greater Mawson Palaeocontinent must have been reworked by an intraplate orogeny or dismembered and eventually amalgamated in convergent tectonic settings in the course of the Mesoproterozoic evolution.



**S05–196: The Rodinian Orogeny in East Gondwana- Implications for Supercontinent Evolution**

***The Ca. 780 Ma Reworking Of the Uht Metamorphosed Lower Crust of the Eastern Ghats Belt and Its Implication for the Breakup of Rodinia***

Sankar Bose<sup>1</sup>; Kaushik Das<sup>2</sup>; Makoto Arima<sup>3</sup>; Junji Torimoto<sup>4</sup>

Presidency University, Kolkata, India<sup>1</sup>; Hiroshima University, Japan<sup>2</sup>; Yokohama National University, Japan<sup>3</sup>; Hokkaido University, Japan<sup>4</sup>

The Eastern Ghats Belt (EGB) witnessed orogenic activities during the Proterozoic time. The northern part of EGB is characterized by ca. 1000 Ma UHT metamorphic event followed by ca. 950 Ma reworking during compressive regime. This latter event also in EGB also provides crucial link to model the India-east Antarctica connection during the final amalgamation of Rodinia. However, the exhumation of UHT metamorphosed deep crust is an unresolved issue and it requires a comprehensive deformational-petrological-geochronological (P-T-t-D) study. The present work is done on the granulites exposed near the Chilka Lake anorthosite complex, northern EGB. The grossly migmatite rock association comprises of high-grade paragneisses and orthogneisses showing complex and multiple stages of folding and foliation/lineation development. The metamorphic history of the granulites is best recorded in the aluminous granulite that contains two contrasting mineral assemblages. The earliest (M1-D1) stage of metamorphism is identified by the development of a sillimanite-quartz-plagioclase-biotite foliation within garnet porphyroblasts. Subsequent M2-D2 event produced the peak granulite assemblages represented by Opx+Grt+Pl+Crd+Kfs+Qtz+Rt and Grt+Sil+Kfs+Pl+Qtz in two different bulk compositions at T = 900-950°C, P = 8.0-8.5 kbar. The gneissic foliation is further folded during the M3-D3 event and the axial planar S3 fabric is tectonically transposed parallel to S2 to form the regional structure of the area. Garnet porphyroblasts show decomposition to symplectic intergrowth of Opx+Crd+Spl and Spr+Crd in the former assemblage whereas Spl+Crd+Bt is formed in the latter; all attest to near-isothermal decompression to T = 700-800°C, P = 6.0-6.5 kbar. The appearance of contrasting intergrowth assemblages during M3-D3 stage can be explained by the variation of the bulk composition as evident from the chemistry of garnet and associated intergrown phases. M4 stage cooling produced late biotite-bearing assemblages. Local occurrence of intergrowth consisting granular Opx+Crd+Kfs replacing late biotite implies incipient granulite-grade reworking during M5 stage. Fluid-inclusion data suggest the presence of high-density CO<sub>2</sub>-dominated fluid during the peak M2-D2 stage, while the fluid regime changed to low-density mixed CO<sub>2</sub>-H<sub>2</sub>O (-N<sub>2</sub>-CH<sub>4</sub>) one during the M3-D3 stage. Zircon U-Pb SHRIMP data show prominent event of zircon growth during ca. 780 Ma (within a spread of 760-800 Ma) followed by a spread of near-concordant data in the time span of ca. 740-600 Ma. Texturally constrained monazite U-Th-Pb EPMA data, on the other hand, show two distinct ages for monazite growth. Monazite occurring within garnet porphyroblasts yield a group age of ca. 988±23 Ma from the data point analyzed from the grain interior, whereas the exterior part in contact of garnet show younger spot ages. Monazite occurring within quartzofeldspathic matrix also yields spot ages in the latter mentioned range and combining both sets of data, a group age of 742±15 Ma is obtained. Few spots with younger dates in the range of 550-500 Ma are also noted. We interpret that the ca. 990 Ma could possibly imply the timing of the M2-D2 event the signatures of which is not preserved in the analyzed zircon grains. The M3-D3 event is the most prominent event that occurred in the time frame of ca. 780 Ma. The spread of <740 Ma zircon as well as monazite data possibly implies large-scale redistribution of U, Th and Pb isotopes due to interaction with aqueous fluid. This interpretation is in sharp contrast to the suggested tectonothermal event in Chilka during 690-660 Ma as argued by earlier workers. Our data further show that the two adjacent crustal domain of EGB (Domains 2 and 3) shared similar histories at least up to ca. 1000 Ma after which the tectonic development of the northern EGB witnessed a paradigm shift. The ca. 780 Ma decompression event in the northern EGB opens up new possibilities for interpreting the breakup of Rodinia.



**S05–197: The Rodinian Orogeny In East Gondwana- Implications For Supercontinent Evolution**

***Meso-Neoproterozoic Mid-Crustal Metamorphism from the Ajmer-Srinagar Section, Rajasthan, India and its Implication to Assembly of Greater Indian Landmasses During The Grenvillian Orogenesis***

Sankar Bose<sup>1</sup>; Pritha Seth<sup>1</sup>; Nilanjan Dasgupta<sup>1</sup>

Presidency University, Kolkata, India<sup>1</sup>

The Delhi-Aravalli Mobile Belt (ADMB) of western India juxtaposed the south Indian against the north Indian cratonic landmass. The Srinagar-Ajmer section of the South Delhi Fold Belt (SDFB) exposes a package of medium-grade metamorphic rocks along with synkinematic granite and the entire litho-ensemble was thrust on top of the basement gneisses occurring farther east. The metasedimentary package includes conglomerate, quartzite, pelitic schist and calc-silicate schist and gneiss. The pelitic schist shows development of garnet-zone followed by staurolite- and kyanite-zone close to the granite. Textural study show eastward progressive development of the Barrovian sequence reaching the peak conditions within the kyanite zone. The emplacement of the granite occurred during to the peak metamorphic stage (kyanite-zone) and the entire sedimentary package along with the granite were subsequently deformed. The coarsening of staurolite, garnet and kyanite grains in close proximity to the granite indicates enhanced material and heatflow from the crystallizing magma. Monazite grains within the pelitic schist are present in the foliation-forming assemblage and grew synkinematically with garnet and staurolite porphyroblasts. U-Th-Pb chemical data from such monazite grains yield mean age of 980±11 Ma which implies the timing of the peak metamorphic event. Few spots from the exterior part of the matrix monazite yield lower values (<900 Ma) and possibly implies Pb-loss by subsequent events, or, a separate orogenic pulse. Monazite grains within the granite show complex zoning with at least three age clusters (~ 1790 Ma, ~ 990 Ma, ~ 820 Ma). It appears that the granite contains fragments of the basement and was emplaced during the Grenvillian orogeny and subsequently got deformed. The style and timing of metamorphism in the Srinagar-Ajmer section closely match with the granulite facies reworking (M2) of the basement. We argue that the Grenvillian orogeny with its characteristic collisional setting involved deep to mid-crustal sections. Our results further vindicate the fact that the Greater Indian landmass was assembled during the formation of the supercontinent Rodinia.



**S05–205: The Rodinian Orogeny in East Gondwana- Implications for Supercontinent Evolution**

***Inferring a Neoproterozoic Orogeny Preceding Therodinia Break-Up in NW India***

Devsamridhi<sup>1</sup>; Pant, Naresh. C.<sup>1</sup>; Fareeduddin<sup>2</sup>; Sharma Surbhi<sup>1</sup>

University Of Delhi, India<sup>1</sup>; Geological Survey of India, Bangalore, India<sup>2</sup>

An orogeny is essentially a result of lateral compression caused by large scale directional stresses. Characterization of orogenic events and their sequence can provide a synoptic view on the Supercontinent amalgamation and breakup and hence can build up our understanding related to continental evolution. The Grenvillian Orogeny marks the assembly of supercontinent Rodinia which is Meso- to Neo- Proterozoic in age. The Rodinia supercontinent formed at about 1300 Ma and reached its maximum size at 1000 Ma, as proposed by its archetypal model. Its fragmentation started ~750 Ma along a rift between Western Laurentia and East Antarctica and Australia.

In Indian shield, the remnants of Grenvillian Collision event are reported from the Aravalli Craton, which covers an area of over 0.1 million sq. km. in the northwestern part of India. The craton consists of prominent fold belts represented by Aravalli and Delhi Supergroup the protolith of which were unconformably deposited on the Archaean gneissic basement i.e. Banded Gneissic Complex (BGC or Mewar Gneiss) prominently in the east. The linear NNE-SSW trending Delhi fold belt is around 700 Km in length and variable in width. It shows a double fan structure, which flare out in north and south and joined together in the middle along a narrow belt. This gives way to the principal division of this belt as North Delhi Fold Belt (NDFB) and South Delhi Fold Belt (SDFB). Recent studies indicate the Delhi-Orogeny to be Grenvillian age collision event during which the closure of Delhi depositional basin on the fringes of the Bundelkhand Gneissic Complex occurred by collision with a continental block towards west. No record of pre-Delhi basement adjacent to the Delhi Fold Belt towards west is known where post Delhi sedimentary succession (Marwar Supergroup) and a felsic volcanic large igneous province (Malani Igneous Suite) is reported. The major thermal event that followed the Delhi Orogeny was Malani Volcanism which has been reported Anorogenic (A-type) magmatism and is dated around 730Ma.

Towards the southern end of Delhi Fold Belt a NW-SE trending magnetic anomaly, at high angle to the Delhi trend, is recorded which is also supported by broad gravity signatures. We examined an argillaceous-calcareous metamorphosed sequence west of Mount Abu to characterize this anomaly. Our investigation of metapelites indicate presence of low- to medium grade metamorphic assemblage developed at  $822\pm 29$  Ma which was partially reset at  $723\pm 65$  Ma as estimated from chemical geochronology of texturally constrained monazite. The partial reseeded can be ascribed to the Malani eruption. This metasedimentary sequence is deposited over a granitic basement. The granites are dated to be  $892\pm 10$  Ma and this age was partially reset at  $815\pm 43$  Ma i.e. around the time of this younger orogeny. The high angle structural relationship between the younger metapelites and Delhi fold belt is suggestive of a post Delhi orogenic activity. It is contended that the Rodinia break-up marked by MIS was preceded by anorogenic event which we report for the first time.



**S05–209: The Rodinian Orogeny in East Gondwana- Implications for Supercontinent Evolution**

***Supercontinent Reconstructions via Paleomagnetic and Geochronological Studies of Mafic dykes in Peninsular India***

Manoj K Pandit<sup>1</sup>; Joseph GMeert<sup>2</sup>; Mercedes Belica<sup>3</sup>

University of Rajasthan, India<sup>1</sup>; Department of Geological Sciences, University Of Florida<sup>2</sup>; University of Western Australia, Crawley, Perth<sup>3</sup>

Recent advances in plate tectonics have identified numerous supercontinents in the Earth's history, such as Columbia, Rodinia, Gondwana, and Pangaea. The general makeup of the most recent supercontinent, Pangaea, is well constrained from seafloor magnetic anomaly, paleomagnetic, geological and faunal data, however there are still vigorous debates regarding the exact configuration. Given the controversies surrounding the different Pangaea reconstructions establishing the makeup of earlier supercontinents is far more difficult. In part, this is due to the lack of adequate geologic, isotopic, geophysical and paleontological data. In attempting to decipher past continental configurations during the Precambrian times using paleomagnetism, the major constraint is the availability of unaltered sequences of igneous and sedimentary rocks. Peninsular India is one such region, and previous work indicates a high potential for generating useful data from India that can be used in conjunction with other regions to produce paleogeographic maps for the Proterozoic.

Previous Proterozoic supercontinents have been established using geologic similarities and the alignment of features such as orogenic belts, dyke swarms, or rapakivi pulses in order to establish contiguity; however, paleomagnetic techniques remain the only quantitative test of such reconstructions. As an example, the geologic record present in Precambrian terranes suggests a major global rifting event from 2.2 to 2.0 Ga followed 100 million years later by global widespread orogenesis from 1.9 to 1.7 Ga. The orogenic belts that formed during this event were used to generate the Columbia supercontinent model. In spite of the fact that high quality paleomagnetic data are being generated more rapidly in recent years, there is no current consensus on the exact make-up and geometry of Columbia. In addition to paleomagnetic data, the Large Igneous Province (LIP) record is also used for continental reconstructions. LIPs are large volume and geologically brief magmatic events that typically occur in an intraplate setting and commonly accompany the rifting or assembling of supercontinents. A LIP typically has a focal point (plume source) that can be identified by the convergence of the associated radiating dyke swarms. Coeval radiating dykes can be used as piercing points between different continental nuclei, where the focus of each swarm overlaps in the correct reconstruction. Radiating dyke swarms around Cuddapah Basin in south India have been evaluated and have provided two separate paleomagnetic directions from NW-SE ( $D=3.2^\circ$ ,  $I=56.4^\circ$ ,  $\alpha_{95}=17.9^\circ$ ,  $\lambda=37^\circ$ ) and N-S ( $D=240^\circ$ ,  $I=-65.5^\circ$ ,  $\alpha_{95}=10.9^\circ$ ,  $\lambda=47.7^\circ$ ) trending ~2.2 Ga dykes related to separate magmatic pulses at 2.18 and 2.21 Ga. New paleomagnetic results from E-W and NW-SE trending 2.37 Ga dykes yield a Grand Mean dual polarity paleomagnetic pole at  $15.1^\circ\text{N}$  and  $62.2^\circ\text{E}$  ( $\alpha_{95}=4.0^\circ$ ) for Dharwar Craton, placing India at polar latitudes ( $D=88.7^\circ$ ,  $I=-81.7^\circ$ ,  $\alpha_{95}=4.8^\circ$ ,  $\lambda=73.7^\circ$ ).

In this talk, we examine a number of paleomagnetic and geochronologic studies on mafic dyke swarms within India and their possible extensions into other continents including East Antarctica.



**S05–216: The Rodinian Orogeny in East Gondwana- Implications for Supercontinent Evolution**

***Grenville-Age Suturing of the Eastern Ghats Province with the Paleoproterozoic Singhbhum Craton***

Dewashish Upadhyay<sup>1</sup>; S. Chattopadhyay<sup>1</sup>; J.K Nanda<sup>2</sup>; S.N Mahapatro<sup>3</sup>; K.L Pruseth<sup>1</sup>

Department of Geology And Geophysics, Indian Institute Of Technology, Kharagpur, India<sup>1</sup>, Geological Survey Of India<sup>2</sup>; Geological Survey of India Training Institute, Hyderabad, India<sup>3</sup>

**Background:**

Based on paleomagnetic data from the 771-751 Ma Malani Igneous suite in north western India, Torsvik et al. (2001, Precambrian Research, 108, 318-333) proposed that India was either not a part of Rodinia or was adjacent to the northwestern margin of Australia. This is in contrast to conventional paleogeographic reconstructions of Rodinia at ca. 1.0 Ga which link proto-India with east Antarctica, the two cratons having been welded together along the Grenville-age Eastern Ghats Province-Rayner complex orogen. Implicit in these correlations is the assumption that the Eastern Ghats Province had amalgamated with proto-India during the Neoproterozoic Grenville-age orogeny.

While most authors support a Grenville-age suturing of proto-India and east Antarctica, Dobmeier et al. (2006, Precambrian Research, 146, 165-178) argue that the Eastern Ghats Province-Rayner complex crustal block constituted an exotic terrane that became a part of peninsular India only in the early Paleozoic during the Pan-African orogeny, a view supported by Das et al. (2008, Precambrian Research, 162, 70-85) and Biswal et al. (2007, Tectonics 26, 1-21) who correlate the Pan-African high-grade metamorphism and ductile deformation along the contact between cratonic India and the Eastern Ghats Province with the amalgamation of the two terranes. If this were true, the Eastern Ghats Province-Rayner complex terrane was a part of Rodinia while the rest of the Indian subcontinent was not, in accordance with models that place India outside Rodinia.

However, Tucker et al. (1999, Geol. Soc. Am. 31, A317, Colorado, Denver, Abstracts with Program), based on correlatable Neoproterozoic silicic magmatism in the Malani Igneous suite, Seychelles and northern part of Madagascar, suggested that NW India, Seychelles and North Madagascar was a separate terrane in the Neoproterozoic. The 771-751 Ma paleopole of the Malani Igneous suite may not be representative of India and therefore, cannot be used to infer the position of proto-India in Rodinia. Thus, the timing of amalgamation of the Eastern Ghats Province with the Indian shield is central to the correlation between proto-India and east Antarctica in Rodinia reconstructions. A Grenville-age for the juxtaposition would support the conventional paleogeographic reconstruction models that position proto-India adjacent to east Antarctica while an early Paleozoic amalgamation of the two terranes would be consistent with the hypotheses that India was not a part of Rodinia.

**Objectives:**

The main objective of the study is to constrain the suturing of the Eastern Ghats Province with the Singhbhum craton. This has been done by characterizing the metamorphic and geochronological evolution of the Malayagiri supracrustal belt in the Rengali Province, which represents a wedge-shaped Neoproterozoic cratonic terrane located between the Paleo-Mesoproterozoic Singhbhum cratonic nucleus and the Eastern Ghats Province.

**Methods:**

U-Pb dating of zircons was done using a Laser Ablation-Sector Field-Inductively Coupled Plasma-Mass Spectrometer (LA-SF-ICP-MS). In-situ Th-U-Pb chemical dating of monazites was done using a Cameca SX-100 Electron Probe Micro Analyzer. The major element compositions of minerals were measured with the same Electron Probe Micro Analyzer.



Results and conclusions:

The Malayagiri supracrustal rocks were deposited in the Neoproterozoic between 2.79 Ga and 2.42 Ga. The ca. 2.78 Ga Pal Lahara-Kamakhyanagar Gneiss served as the basement to the supracrustal sequence. The sediments were derived from the gneissic basement as well as from adjacent older Banded Iron Formations. The supracrustal rocks were affected by three major tectonothermal events at ~2.42 Ga, 0.98-0.94 Ga, and 0.57-0.54 Ga and a minor thermal event at ~0.82 Ga. The Grenville-age metamorphism reached upper amphibolite facies conditions with a clockwise sense of metamorphic evolution. The Eastern Ghats Province granulites in the vicinity of the Malayagiri supracrustal belt are characterized by major tectonothermal events at ca. 1.22 Ga, ~0.98 Ga, ~0.81 Ga, and ~0.67 Ga. The Malayagiri supracrustal rocks and the Eastern Ghats granulites had a common geological history since the early Neoproterozoic with both terranes sharing the 0.98-0.94 Ga, 0.85-0.80 Ga and 0.62-0.50 Ga tectonothermal events. The earliest event shared by the two terranes corresponds to the suturing of the Eastern Ghats Province granulites with the southern margin of the cratonic Rengali Province. Thus, the docking of the Eastern Ghats Province with cratonic India took place during the Grenvillian and not during the Pan-African orogeny implying that proto-India was welded together with east Antarctica along the Grenville-age Eastern Ghats Province-Rayner complex orogen.



**S05–258: The Rodinian Orogeny in East Gondwana- Implications for Supercontinent Evolution**

***Contact Relations between the Eastern Ghats Province, the Rengali Province and the Singhbhum Cratonic Block: Implications for Indo-Antarctica Correlation in Rodinia***

J.K.Nanda<sup>1</sup>; S.N.Mahapatro<sup>1</sup>

Geological Survey of India<sup>1</sup>

Recent geodynamic models suggest that the Rodinia Supercontinent came into existence in late Mesoproterozoic to early Neoproterozoic by assembly of continents and again dispersed in Mid-Neoproterozoic with the resulting fragments reassembling to form Gondwana in Early Paleozoic. In the reconstruction of Rodinia, proto-India is positioned adjacent to east Antarctica and it is believed that the two cratons were welded together along the Grenville-age Eastern Ghats-Rayner complex orogen. The Eastern Ghats Belt (EGB) occurs in juxtaposition with the Singhbhum and Bastar cratonic blocks in the eastern India. Mainly two types of boundary relations were described between the EGB and the adjoining cratonic blocks in different sectors, which is characterised either by thrust tectonics (nappe) with terrane boundary shear zones or by a zone of metamorphic transition. Recent studies assume that the EGB is a composite terrain/terrane comprising several litho-structural Provinces separated by crustal scale shear zones. In the architecture of the EGB, the largest of all provinces representing the sensu-stricto Grenvillian orogen of the EGB is named as the Eastern Ghats Province (EGP). In the north, a wedge-shaped Neoproterozoic terrane - the Rengali Province is located between the Paleo-/ Mesoarchean Singhbhum cratonic nucleus and the Eastern Ghats Province.

The Neoproterozoic Eastern Ghats Province is a polycyclic granulite facies terrane comprising metasedimentary successions (khondalite, quartzite and calc-silicate granulite) along with charnockitic gneisses, enderbites, mafic granulites, megacrystic garnet- and/or orthopyroxene-bearing granitoid plutons (0.98-95 Ga) and massif-type anorthosite (0.98-0.92 Ga). This orogen is widely considered to have been at the forefront of collisions and amalgamation involving the Indian shield with those of east Antarctica and Australia.

The Rengali Province is a fault bounded complex lithotectonic domain comprising banded granite gneiss and migmatite (Pal Lahara-Kamakhyanager Gneiss) with meta-volcanosedimentary supracrustal successions (Deogarh, Tikra and Malyagiri Groups) consisting of quartzite, pelitic and psammopelitic schist (St+Grt+Bt and Ky+St+Bt, And+Grt+Bt schists) and amphibolites (Cpx±Grt). Besides, Neoarchean (2.9 Ga) massifs of charnockite-enderbite orthogneiss, interlayered mafic granulite and felsic leucogneiss occur around Badarama extending discontinuously eastward through Riamal, Rengali, Bhuban upto Jenapur in east. Thus, rocks of both low- and high- metamorphic grade occur juxtaposed within this Province. A series of E-W trending strike ridges of recrystallised quartzite ( $\pm$ Mus  $\pm$ Sil/Ky) interlayered with pelitic and psammopelitic schists(+Grt+St+polymorphs of aluminosilicate) and minor amphibolite occur interleaved between the dispersedly located charnockite-enderbite-leucogneiss massifs to the north and the EGP in the south. Deformed gneissic nepheline syenite bodies (~1.45 Ma) are intrusive into these quartzites. The Rengali Province is bound in the north by the Barakot shear zone/Akul fault zone which separates it from the Singhbhum craton. The WNW-ESE trending North Orissa Boundary Fault (NOBF) reportedly marks the boundary between the Rengali Province and the EGP. Permo-Carboniferous coal bearing Gondwana sediments laid down in fault bounded basins cover part of the contact zone. The Mahanadi tectonic zone has been correlated with the Lambert rift of the east Antarctica. A segment of the NOBF, referred to as the Kerajang Fault, defines the northern boundary of the Talchir Gondwana basin. The nature, extension, disposition of the Rengali Province and its relation with the adjoining EGP and the Singhbhum craton has been a topic of debate in recent years. In the eastern segment of the contact zone the Singhbhum craton, the Rengali Province and the EGP come closer separated by zones of prominent shear zones characterised by southerly dipping mylonite foliation with down dip to north easterly plunging lineation. The Rengali Province becomes narrow eastwards and closes to the west of Bhuban. Although



the regional trend of the EGP is NE-SW, the structural trend of the northern EGP, northwards from the Mahanadi Shear Zone and that of the Rengali Province is EW. A mylonite fabric is superimposed on the earlier fabrics in the gneisses close to the contact zone. Between Parjang and Kamakhyanagar in the central part of the contact zone, the Malaygiri supracrustals (IOG) also get dragged and intertwined into this tectonic zone with E-W trend. The Rengali Province has been inferred variously viz(i) as a dilational step-over zone within a continental strike-slip system, and interpreted as a rotated fragment of the Bastar craton, (ii) a part of the Singhbhum craton, (c) a disparate block unrelated to the EGP, SC and BC. Geochronological data reported from the Rengali Province and in its eastern segment indicates an Archaean lineage. The ages of  $\sim 3.06$  Ga and  $\sim 2.78$  Ga from monazites in metasedimentary granulites from around Bhuban,  $\sim 3.2$  Ga Sm-Nd model ages for the Rengali enderbites,  $\sim 2.80$  Ga for the Pal Lahara - Kamakhyanagar Gneiss at Bhuban,  $\sim 2.90$ - $2.75$  Ga Rb-Sr whole rock ages for granites and charnockites point towards extensive Meso / Neoproterozoic magmatism and metamorphism in the province. The Udaygiri anorthosite in the northern fringe of the EGP emplaced after the fabric-defining Grenvillian metamorphism in the EGP could be coeval with the other Grenvillian massif-type anorthosite complexes in the EGP and may correspond with a Grenvillian collision between the EGB and the Rayner Complex of East Antarctica, and may be related to the assembly of Rodinia.



**S05–261: The Rodinian Orogeny In East Gondwana- Implications For Supercontinent Evolution**

***Felsic Volcanism from Two Mesoproterozoic Sedimentary Basins of India: Signature for Subduction-Related Outgrowth in Supercontinent? Columbia??***

Subhojit Saha<sup>1</sup>; Partha Pratim Chakraborty<sup>1</sup>; Kaushik Das<sup>2</sup>

Department of Geology, University of Delhi, Delhi, India<sup>1</sup>; Hiroshima University<sup>2</sup>

Precambrian era (2500-540Ma) represents most dynamic time period in the Earth history and still remains a challenge in our understanding as it registered crucial and irreversible changes in lithosphere, atmosphere, hydrosphere and biosphere. Many such changes are conjoined in nature, transect boundaries between different geological provinces viz. craton, mobile belt and sedimentary archives and need to get established with robust geochronology. The well-received 'Supercontinent' model attempts collation and correlation between signatures from different geological provinces and aims at identification of events which are transcontinental in character. Increasing availability of high-resolution analytical techniques and growing international collaborations in last five decades have enriched geochronological database on Indian Precambrians with employment of high precision Sm-Nd dating, U-Th-Total Pb monazite EPMA, U-Pb zircon SHRIMP dates over the traditional Rb-Sr whole rock and K-Ar/Ar-Ar authigenic mineral dates. In general, these studies took into purview major rift systems, cratonic cores, orogenic (mobile) belts and to a lesser extent sedimentary basins and aimed at addressing issues related to timing of regional-scale magmatism (rift-related or granitic plutonism), metamorphism vis-vis orogeny or provenance for sedimentary basins. Besides, these studies also contributed in fitting Indian craton in different supercontinent architecture models viz. Columbia, Rodinia etc. although it is felt that data from yet unattended geological provinces can make these models more robust. A cluster of small sedimentary basins and detached outcrop belts in east Indian craton, despite their strategic geotectonic position, i.e. girdling the boundary between the craton and mobile belt viz. Eastern Ghat Mobile Belt (EGMB) and unmetamorphosed character, escaped attention of workers due to their complex deformation pattern and lack of well-constrained stratigraphy. The present work takes into its purview two such basins viz. Singhora and Ampani and discusses results obtained from i) geochronology (U-Th- Total Pb EPMA monazite) of conformable porcellanites present within these basin successions (at the lower part of Singhora succession and at the upper part of Ampani succession) and ii) detrital geochronology of sedimentary packages of both the basins in the backdrop of supercontinent Columbia. U/Th total Pb electron probe microanalysis data of monazite grains from the Ampani tuff revealed several age data clusters: c. 2400, c. 2130, c. 1600, c. 1450 and c. 1000 Ma. An age of  $1446 \pm 21$  Ma is proposed as the depositional/crystallization age for the Ampani tuff, considering its maximum probability. Comparable ages of  $1437 \pm 50$  Ma (strongest peak after deconvolution of a broad peak around ~1500 Ma) is also recorded from the tuffaceous units of the Singhora basin. The results allowed us to infer a major felsic volcanic event during ca. 1450 Ma at the eastern margin of the Indian Craton. Conformable ages from the felsic volcanics ( $1450 \pm 31$  Ma) in south China craton allowed workers to conceive subduction-related outgrowth of continents with the formation of several accretionary zones along the margins of Laurentia, Amazonia and Australia during the time frame encompassing the last phase of the Supercontinent Columbia. Besides, a shift in sediment provenance in course of depositional histories of both Ampani and Singhora basins is inferred from detrital zircon geochronology and sediment geochemistry; although the provenance shift would not have been contemporaneous on a regional scale. While the provenance shift is recorded in the Singhora basin after the volcanic event (i.e. immediately above the Saraipalli Fm. Bhalukona Fm. boundary), in case of Ampani basin the shift is registered prior to the event. From the results it seems that although the two basins are contemporaneous in broad sense, there may be a time lag between the initiations of the two.



**S05–277: The Rodinian Orogeny in East Gondwana- Implications for Supercontinent Evolution**

***Geochronological Evidence from Granites of the Bathani Volcano Sedimentary Sequence of Chotanagpur Gneissic Complex and Implications for Growth of the Greater Indian Landmass***

Ashima Saikia<sup>1</sup>; Mansoor Ahmad<sup>2</sup>; Bibhuti Gogoi<sup>1</sup>

University of Delhi, Delhi, India<sup>1</sup>; Geological Survey of India, Patna, India<sup>2</sup>

The hypothetical position of India within the Columbian supercontinent has been a debatable issue due to lack of robust palaeomagnetic and geochronological data. The Indian subcontinent is known to comprise of several cratonic blocks that may or may not have been continuous throughout Proterozoic time. Reliable data of magmatic activities or deformation events are reported from the cratonic blocks south of Central Indian Tectonic Zone (CITZ). However, data from the cratons north of CITZ and from the Chotanagpur Gneissic Complex (CGGC), a part of the CITZ, is only beginning to come. Age data is a prerequisite to understand various tectono-thermal events leading to amalgamation and fragmentation of Indian cratonic blocks before incorporation within supercontinents. Position of India has been an integral part of all hypothetical models of reconstruction of supercontinents.

The CITZ which is a 1500 km long E-W to ENE-WSW trending orogenic domain running through the heart of peninsular India marks the suture zone where the North and South Indian blocks amalgamated to form the Great Indian Landmass. It consists of three broad domains from west to east, viz., the main CITZ occupying the central region of mainland India; the CGGC lying east of the main CITZ juxtaposed between two mobile belts namely the North Singhbhum Mobile belt (NSMB) in the south and the Mahakoshal mobile belt (MMB) in the north and the easternmost Shillong Plateau Gneissic Complex (SPGC). The Mahakoshal belt is confined to the central CITZ and in the western portion of the CGGC. Its eastern continuation in the CGGC domain was untraceable. CGGC has been mostly described as a Proterozoic high-grade metamorphic terrain experiencing multiple episodes of metamorphism and deformation. No preserved magmatic protolith for the CGGC was known before the reported occurrence of Bathani volcano sedimentary sequence (BVSs) by Ahmad and Wanjari (2009).

The BVSs is exposed at the northern fringe of CGGC extended over an aerial distance of ca 40 km with the type area located at Bathani village of Gaya District, Bihar, India. Ahmad and Paul (2013) divided the belt into three distinct litho-domains: northern (ND), central (CD) and southern domain (SD). The northern litho-domain comprises of granitoids which intrude the volcano sedimentary sequence of central domain. The central litho-domain preserves pillows in basalt, pillow breccia, volcanic breccia and bombs, Banded Iron Formation, Banded Carbonate Chert. The southern litho-domain includes folded Rajgir metasediments, viz., phyllites and quartzites of Rajgir Group.

Geochronological investigation has been carried out on granites of the BVSs sequence from the northern margin of CGGC. The Rb, Sr, Sm and Nd isotopic ratios were measured using multi-collector TIMS-Triton (Thermo Fisher) on 9 granite samples using isotope dilution technique. Ages have been calculated using Isoplot 3 (Ludwig, 2003). This has yielded Rb-Sr whole rock isochron age of  $1673 \pm 130$  Ma, a Meso-Proterozoic crystallization age for these granites. The granites also yield well constrained early Paleo-Proterozoic Nd model ages (2266 to 2496 Ma) averaging 2355 Ma, which approximately represent the extraction age of the granitic melt from the source.

The obtained crystallization age of the granites corresponds to the 1.9-1.6 Ga bracket when the Columbia supercontinent assembled. Chatterjee and Ghose (2011) and Bora et al. (2013) have reported  $1697 \pm 17$  Ma monazite age of porphyritic granite and  $1753 \pm 9.1$  Ma U-Pb SHRIMP age for granitoids respectively from the MMB. Rb-Sr isochron age of  $1673 \pm 130$  Ma for the granites from BVSs confirm that it is an eastern continuation of the MMB which has remained unaffected by Grenvillian Orogeny. This suggests that Indian proto continent was a single unit at the time of incorporation within Rodinia. In order to



## *XII International Symposium on Antarctic Earth Sciences*

*13 - 17 July 2015, Goa, India*



understand the assembly, configuration and disintegration of the Great Indian Landmass vis-a vis the Columbia and Rodinia supercontinents we need to look for continuation of the mobile belts of CITZ in the proposed adjoining proto-continental blocks to position them in the hypothetical supercontinental models.



**S05–286: The Rodinian Orogeny in East Gondwana- Implications for Supercontinent Evolution**

***The Brahmani Shear Zone in the Eastern Indian Shield - An Additional Aid to Indo-Antarctica Correlation?***

Amol Dayanand Sawant<sup>1</sup>; Saibal Gupta<sup>1</sup>

IIT Kharagpur, India<sup>1</sup>

India-East Antarctica collision during assembly of the supercontinent Rodinia is believed to have occurred around 1 Ga, based on structural, metamorphic and geochronological evidence. Orogenesis associated with this collisional event is supposed to have resulted in granulite metamorphism in the middle and lower parts of the thickened crust. In India, parts of these 1 Ga granulites are presently exposed in the Eastern Ghats Province (EGP); this province is bounded by Archaean Indian cratons to the west and north. After the 1 Ga collision, the EGP and the adjacent part of East Antarctica (probably the Rayner Province) are together believed to have shared similar deformation and metamorphic histories, including thermal overprints at 550-490 Ma followed by Gondwana basin formation at 250 Ma rifting. Indian and East Antarctica rifted apart at around 100 Ma during the breakup of Pangaea. Correlation of structural and metamorphic episodes between the EGP and East Antarctica is complicated as most of the latter is covered by an ice sheet, and hence the rock exposure level is low. The structural and metamorphic record of the EGP shows that the 1 Ga collision affected the entire EGP, while the later events were localized to terrane boundaries, and hence their structural and metamorphic record can only be seen in these localized domains. Nevertheless, Rodinia reconstruction models are contingent upon the correlation of lineaments with similar structural, metamorphic and geochronological signatures. Here, we report a shear zone where the Cambro-Ordovician record can be seen from the northern boundary of the EGP, which we refer to as the Brahmani Shear Zone (BSZ) in this study. The BSZ comprises strongly foliated alternating bands of garnetiferous quartzofeldspathic gneisses, khondalites and charnockites; the foliation is consistently east-west trending and subvertical. Only one set of persistently down-dip lineations are observed in the field. Maximum asymmetry is observed in horizontal section, implying that the down-dip lineation is not a stretching lineation, and that the material transport vector must have been horizontal during the last shearing event. This is supported by textural analysis using Electron Back Scattered Diffraction (EBSD) analysis. From microstructural and geothermobarometric analyses, the BSZ is interpreted to be a dextral strike-slip fault that operated under greenschist facies conditions and separates 1 Ga EGP granulites from a 2.8 Ga granulite terrane to the north. The western extension of the BSZ is the Kerajang shear zone that separates the EGP granulites from the 2.8 Ga amphibolites of the Rengali Province. Based on structural-metamorphic-geochronological studies, the Kerajang shear zone and the BSZ can be correlated with the 550-490 Ma remobilization.

Traditionally, the Mahanadi rift (south of the BSZ) in the EGP has been considered to be the conjugate of the Lambert rift in East Antarctica. Based on the spatial constraints, the BSZ should have a conjugate further south along the Antarctica coastline, in all likelihood in the Prydz Bay coast area. However, this part of East Antarctica appears to be an amalgam of terranes of disparate ages. Three major Antarctica terranes are of importance in this context – the Prydz Bay region, the Rauer Group of northern Prydz Bay and the Vestfold Hill block. The Prydz Bay region is characterized by a strong Pan-African granulite facies metamorphism that overprints an earlier Grenvillian (~ 1.0 Ga) imprint. This sequence of events appears to be correlatable with the Eastern Ghats Province. On the other hand, the Rauer Group appears to comprise an interleaved sequence of Archaean orthogneisses (3.3-2.8 Ga) and Mesoproterozoic intrusives (~ 1.0 Ga) that are inferred to have shared a tectonothermal event only at 0.5 Ga. On the other hand, the Vestfold Hills block is dominated by ~ 2.5 Ga orthogneisses, though there are also some reports of a c. 1.0 Ga thermal event in this block. Major terrane boundaries, whose structural character is undetermined, must therefore exist between these terranes in the Antarctica. A comparison with the structural boundaries in eastern India suggests that the newly characterized BSZ, that separates Archaean and Proterozoic components by a dextral strike-slip system that operated at ~ 490 Ma, may



## XII International Symposium on Antarctic Earth Sciences

13 - 17 July 2015, Goa, India



actually constitute one of the major boundaries that continue into this part of East Antarctica, in all probability within the Rauer Group, or between the Rauer Group and the Vestfold Hills block. Indeed, given the nature of strike-slip systems, and the possibility of transporting exotic terrane slivers over considerable distances in such systems, the confusing amalgam of terranes in the Prydz Bay area can possibly be explained.



**S05–330: The Rodinian Orogeny in East Gondwana- Implications for Supercontinent Evolution**

***The C. 1.0 Orogeny in the Eastern Ghats Province, India? Is it Really Related to Indo-Antarctica Collision?***

Saibal Gupta<sup>1</sup>

Indian Institute of Technology Kharagpur <sup>1</sup>

It is commonly assumed that India was attached to East Antarctica in the supercontinent Rodinia, and that this amalgamation was effected through a major collisional orogeny at around 1.0 Ga. At present, the imprints of this orogen are seen in the form of granulite facies metamorphic rocks in the Eastern Ghats Province (EGP) of India, and similar grade, coeval metamorphic rocks in the Rayner Province of East Antarctica. The 1.0 Ga event is widely correlated with ultrahigh (> 900°C) to high temperature metamorphism, and the associated P-T path has been postulated to one in which cooling from peak temperatures preceded decompression. Prolific magmatism, in the form of between 980-950 Ma closely followed peak temperature; many of these melts have an intracrustal origin, consistent with thermal relaxation after crustal thickening that can be correlated with collisional orogeny.

Although the 1.0 Ga event is likely related to collision, there are a few problems associated with this interpretation. The first appears to be the relative timing of penetrative deformation with peak metamorphism, with the former clearly post-dating the latter in most parts of the orogen. This must either mean that compressive stresses persisted significantly after the metamorphic peak for almost 100 million years, suggesting that the later parts of the orogeny may be dominantly intracontinental. Secondly, an overthickened crust that must result from this orogeny must have created significant topography. This must then have been removed, so that the presently exposed granulites are exhumed at the surface. In most modern orogens, such large topographic loads create major foreland basins that ultimately become the repositories of detritus derived from the orogen. Since the granulites are overthrust to the west over the craton, the expected basins should occur in the foreland to the west. This is a major problem for the collision model, since none of the basins adjacent to the granulites in the foreland region are known to host sedimentary detritus of the appropriate age. A final issue is the source of the intracrustal melts that intruded the granulites during the late stages of the c. 1.0 Ga orogeny. These melts must have been derived from domains underlying the present-day crustal surface of the EGP. This has implications for the nature of the present-day crust that underlies these granulites post-metamorphism, these domains must have become extremely anhydrous and dense. Detailed gravity investigations, and results of some seismic studies in the northern part of the EGP indicate that low density, upper crustal material appears to underlie the granulites at the surface. It appears that the present-day middle and lower crust of the EGP may not have undergone this extremely high temperature metamorphism. In other words, the granulites may have been thrust onto adjacent low density, cratonic upper crust after granulite metamorphism, implying that significant crustal shortening may have occurred even after this event. This opens up the possibility that the c. 1.0 Ga metamorphism may not be related to the collision of East Antarctica with the Indian craton, at least in its present configuration. Unroofing of the granulites may also have occurred elsewhere, thereby explaining the lack of 1.0 Ga detritus in the adjacent Indian craton. As stated, this is only a possibility, but it is one that cannot be overruled.



**S05–337: The Rodinian Orogeny in East Gondwana- Implications for Supercontinent Evolution**

***The Kerajang Shear Zone in the Eastern Indian Shield and the Neoproterozoic to Early Palaeozoic Indo-Antarctica Story***

Surajit Misra<sup>1</sup>; Saibal Gupta<sup>2</sup>

Borehole Geophysics Research Laboratory (ESSO-MoES), India<sup>1</sup>; Department of Geology and Geophysics, IIT Kharagpur, India<sup>2</sup>

In the Neoproterozoic time, the contact between granulites of the Eastern Ghats Belt (EGB) and the Archaean cratons of the Indian shield was the site of a major continent-continent collision between India and Antarctica. The collisional interface along the western boundary of the EGB and the Bastar Craton is commonly characterized as a thrust. However, the nature of the northern boundary of the EGB with the Singhbhum Craton is controversial, with proposed models ranging from thrusting and strike-slip shearing to transpressional tectonics. The primary cause of the controversy regarding the northern margin is the presence of a structurally complex lithotectonic domain called the Rengali Province (RP), distinct from both the bounding terranes, i.e. Singhbhum Craton (SC) in north and EGB in south. We have recently identified the Rengali Province as being bound by two WNW-ESE trending strands of a strike-slip system, that enclose a multiply deformed (deformations D1 to D3) intervening domain, with D3 representing dextral shearing. The D1 and D2 deformation events are interpreted as a deformation continuum characterized by recumbent isoclinal folding and refolding about parallel fold axes with associated penetrative fabric formation. In a granulite (charnockite) lens within the province, the penetrative fabric retains a cylindrical geometry. In the surrounding quartzofeldspathic gneisses, quartzites and mica schists of the province, superimposition of syn-D3 shortening on D1-D2 folds generated complex non-cylindrical geometries while the granulites escaped D3 strain. Low D3 strain domains within the province preserve an annealed granoblastic mosaic texture, with a mineralogy characteristic of the amphibolite facies. In the province-bounding shear zones, D3 deformation was associated with mylonitization, dynamic recrystallization and greenschist facies metamorphism. Strain analyses and Anisotropy of Magnetic Susceptibility studies in the quartzites indicate that post-D2 strain ellipsoids are characterized by sub-vertical axial planes and extrusion directions consistent with crustal shortening.

Samples from high D3 strain zones are associated with sub-horizontal extrusion parallel to the inferred direction of strike-slip shearing. D3 strike-slip shearing was associated with a limited pure shear component, indicating that it is unrelated to the widespread shortening structures documented from the region. Quantitative estimates of peak metamorphic temperature are about ~ 750°C in the pressure range 6-10 kb, obtained from post-D2, pre-D3 assemblages in charnockites and amphibolites. SHRIMP ages from zircons within the charnockite unit are identical from the surrounding hornblende orthogneiss, with c. 2.8 Ga magmatic cores overgrown by c. 2.5 Ga rims. Chlorite bearing syn-D3 assemblages within the mica schists yield ages of 490-470 Ma, indicating that greenschist facies metamorphism in the Rengali Province operated 2000 Ma after the amphibolite facies event. Since the province-bounding shears form a step-over zone, the structural complexity within the Rengali Province arises from superposition of syn-D3 shortening structures on initially asympathetically oriented, inherited cylindrical D1-D2 folds. Hydrous fluid channeling causing greenschist facies metamorphism and quartz vein emplacement accompanied D3 as the step-over zone was dilational in nature. Interpretation of the structural set-up as a step-over zone suggests that the Rengali Province is probably a fragment of the eastern fringe of the Bastar Craton, equivalent to the Jeypore Province that has charnockites of identical ages. This c. 2.5 Ga orogen may extend along the eastern boundary of the Bastar Craton to the southern part of the Eastern Dharwar Craton.

The Rengali Province is apparently devoid of any record of the Grenvillian orogeny (~1 Ga), but preserves a Neoproterozoic history. The EGP and its counterpart in East Antarctica (the Rayner Province) were juxtaposed together during this orogeny, and shared common deformation and metamorphic



## XII International Symposium on Antarctic Earth Sciences

13 - 17 July 2015, Goa, India



histories along the interface between these two continental blocks. Major thermal imprints at  $\sim 2.5$  Ga, 550-490 Ma and 250 Ma have been recorded within the Rauer Group and Vestfold Hills in the Prydz Bay Region of East Antarctica. India and Antarctica rifted apart during breakup of Pangaea at around 100 Ma. Thus, the Kerajang Shear Zone that separates the Archaean RP in north and the Proterozoic EGP in south by a major dextral strike-slip system, and operated at around 490 Ma, may continue into East Antarctica. If the Indo-Antarctica correlation model is accurate, effects of the strike-slip deformation should be observed in the Antarctica segment, possibly in the regions mentioned above.



**S05–425: The Rodinian Orogeny in East Gondwana- Implications for Supercontinent Evolution**

***Petrology And U-Pb Geochronology Of Zircon In a Suite of Charnockitic Gneisses from Parts of the Chotanagpur Granite Gneiss Complex (Cggc), East Indian Shield: Evidence for Reworking of a Mesoproterozoic Basement during the Formation of Rodinia Supercontinent***

Mukherjee, Subham<sup>1</sup>; Dey, A.<sup>1</sup>; Sanyal, S.<sup>1</sup>; Ibanez-Mejia, M.<sup>1</sup>; Sengupta, P.<sup>1</sup>

Jadavpur University, Kolkata, India<sup>1</sup>

Archean and early Palaeoproterozoic rocks of the Indian shield are dissected by a c. 1500 km long, EW to ENE-WSW trending belt that stretches from the Central Indian Tectonic Zone (CITZ) in the west to Shillong Plateau in the NE exposing the Chotanagpur Granite Gneiss Complex (CGGC) in the central part of the belt. Recognition and characterization of the magmatic and tectonothermal events in this linear belt are crucial to understand the formation of Rodinia Supercontinent in general and formation of Greater Indian Landmass in particular. Paucity of state-of-the art petrological data and robust geochronology are the main hindrance in tracing the tectono- magmatic evolution of this important belt. The regions in and around Deoghar, Jharkhand, India that occupy the central region of CGGC expose a sea of charnockitic gneisses that are variably retrogressed to hornblende-biotite gneiss. A prominent migmatitic banding in charnockite is defined by patchy to laterally continuous bands of garnet-orthopyroxene (rare) bearing leucosomes that are set in orthopyroxene-garnet rich melanosome. In most places, orthopyroxene is hydrated to amphibole and biotite whereas garnet remains virtually inert in the process of retrogression. This suggests that retrogression occurred in upper amphibolite facies where the assemblage garnet+amphibole+biotite are stable. The charnockitic gneisses are interlayered with and contain xenoliths of khondalite (garnet-sillimanite-gneiss with little or no primary biotite), calc-granulite (garnet-clinopyroxene-plagioclase-scapolite-titanite with retrograde epidote and calcite) and volumetrically minor mafic granulite (garnet-ortho- and clino-pyroxenes, plagioclase with retrograde amphibole). The khondalite shows prominent migmatitic structures that are at high angle to and transposed by the migmatitic banding of the charnockitic gneisses. A set of mafic dykes cut the migmatitic banding of the charnockitic gneiss. The migmatitic banding and the mafic dykes show superposed folding with roughly N-S axial trace. Conventional geothermobarometry and numerical analyses of mineralogy of charnockitic gneisses (and its retrogressed counterparts) indicate that migmatization of the protolith of the charnockitic gneiss occurred in the narrow pressure-temperature range of ~6.5-7.5 kbar and 820°C-850°C which was followed by near isobaric cooling and hydration. Although a prograde clock-wise P-T path could not be resolved from the studied rocks, certain features such as (a) absence of any syn-metamorphic magmatic rocks (advective heat source), (b) development of garnet-bearing leucosomes in profusion and (c) complex deformation accompanying metamorphism and partial melting are all consistent with a tectonothermal evolution of the protolith of charnockitic gneisses in a continent-continent collision setting. The inferred peak P-T conditions corresponds to a dT/dZ of ~ 34°C/km, which is a typical gradient is recorded from many collisional orogens formed during the assembly of the Rodinia and Gondwana Supercontinents. Zircon grains in the charnockitic gneiss show oscillatory zoned core regions that are truncated by featureless rims. LA-ICPMS U-Pb dating of zircon grains yields concordant results with <sup>207</sup>Pb/<sup>206</sup>Pb dates cluster around ~1450 Ma and ~950 Ma for the cores and rims of zircon respectively. In view of the foregoing analyses, we suggest that the older dates reflect the crystallization age of the protolith whereas and the younger ages are likely to indicate the age of migmatization (i.e. timing of collisional event) of these charnockitic gneisses. Geochemically the charnockitic gneisses show typical A-type granitoid chemistry and hence are likely to have formed in an extensional setting (continental rift zone). This geochemical signature and the field relations are consistent with the view that the protolith of the charnockitic gneisses were emplaced in a continental basement dominated by supracrustal rocks (khondalite and calc-granulite). Massif-type anorthosites which are also a proxy for crustal extension have been found intrude into the supracrustal rocks (khondalite and other granulite facies rocks) from the southern part of the CGGC. Compared to the studied charnockitic gneisses, U-Pb zircon data from the massif-type anorthosite yield a distinctly older crystallization age (~1550 Ma) but contemporaneous



metamorphic overprint (~950 Ma). Despite the limitations imposed by the still sparse geochronological data set, impress of Palaeoproterozoic activities tectonothermal (~1800Ma-1600Ma) is recorded in the supracrustal rocks. Existing geological and geochronological data base suggest that the last high grade event that affected the rocks of the CGGC occurred in the time span of 1025-923 Ma. Integrating all the geological information and geochronological data it is proposed that the Palaeoproterozoic crust of the CGGC that was rifted apart and intruded by felsic and anorthositic magmas during Mesoproterozoic time remained stable for more than 500 Ma until it was reworked by the Stenian-Tonian orogenic event associated with the assembly of Rodinia Supercontinent (~1100-900Ma). The style and age of high grade metamorphism as recorded in the charnockitic gneisses are in good agreement with the style and age of terminal high grade metamorphism documented from the CITZ. This study therefore supports the view that the Stenian-Tonian tectonothermal process(es) eventually fused the northern and southern blocks of the Indian shield along the 1500km long belt. This contribution seeks to discuss the implications of our new geologic, thermobarometric and geochronologic dataset for understanding the formation of Greater Indian Landmass and its role within the assembly of the Rodinia Supercontinent.



**S05-467: The Rodinian Orogeny in East Gondwana- Implications for Supercontinent Evolution**

***U-Pb Shrimp Zircon Geochronology of Granitoids from Meghalaya Plateau, NORTHEAST INDIA: Evidence of Columbian and Gondwanian Supercontinental Assembly***

Santosh Kumar<sup>1</sup>; Yasutaka Hayasaka<sup>2</sup>; Vikoleno Rino<sup>3</sup>; S. Raju<sup>4</sup>; Kosuke Kimura<sup>2</sup>; Kentaro Terada<sup>5</sup>; Sita Bora<sup>1</sup>; Manjari Pathak<sup>6</sup>

Department of Geology, Centre of Advanced Study, Kumaun University, India<sup>1</sup>; Department of Earth and Planetary Systems Science, Hiroshima University, Higashi-Hiroshima, Japan<sup>2</sup>; Department of Geology, Nagaland University, Kohima, India<sup>3</sup>; Geological Survey of India, Chennai, India<sup>4</sup>; Department of Earth and Space Science, Osaka University, Osaka 565-0871, Japan<sup>5</sup>; Geological Survey Of India, Gandhi Nagar, Ahmedabad, India<sup>6</sup>

The Meghalaya plateau is dominantly composed of basement granite gneisses, migmatites, granulites and rocks of Mesozoic-Tertiary Groups. Cambro-Ordovician granitoid plutons of variable dimensions intrude the granite gneisses and Shillong Group of rocks all across the plateau including the Mikir Hills. Mafic to hybrid microgranular enclaves are hosted in some granitoid plutons, which indicate mafic magma ponding, evolution of mafic-felsic magma, and crustal growth in the interior of plateau. These granitoid bodies represent high-K, metaluminous to peraluminous, post-collisional, fracture-controlled diapiric plutons, which were formed by a protracted thermal event, related to mantle upwelling during Pan-African orogeny. Oxidizing nature of mafic and felsic magma interacting system typical to open magma chamber has also been recognized based on magnetic susceptibility mapping of granitoids and its biotite composition. Zircons from representative samples of basement and intrusive granitoids have been treated for U-Pb SHRIMP chronology in order to understand contribution of global thermal events and supercontinent cycles during crustal growth of Meghalaya plateau through time. Zircons from granite gneiss of Rongjeng locality record oldest magmatic age and exhibit varied textural features. Most zircons are euhedral and strongly zoned over which rounded to sub-rounded narrow rims are developed because of metamorphic fluid action. Some zircons display sieved texture in the core and chaotic patchy-zoned rims with very high U-content because of metamictization. Zircons of granite gneiss yield an upper intercept concordant age of  $1778 \pm 37$  Ma and lower intercept age of  $258 \pm 20$  Ma, which represent primary crystallization age and secondary hydrothermal activity respectively. Patchy zoned rims of zircons yield a range of  $^{207}\text{Pb}/^{206}\text{Pb}$  ages from  $531 \pm 44.3$  Ma to  $479.2 \pm 41.4$  Ma, which are considered age of metamorphism of granite gneiss. An inherited core of zircon yields  $^{207}\text{Pb}/^{206}\text{Pb}$  age of  $2566.4 \pm 26.9$  Ma, which strongly suggest recycling of Neoproterozoic crust in the evolution of basement granite gneiss. It is interesting to observe that Neoproterozoic inherited core of zircon has developed a wide metamorphic zone of  $531 \pm 44.3$  Ma and has escaped the Palaeoproterozoic to Mesoproterozoic magmatic growth. Fine grained granite from Songsak pluton yields two broad groups of zircon. One group of zircons exhibits euhedral, strongly zoned texture with high Th/U ratio and yields  $^{207}\text{Pb}/^{206}\text{Pb}$  primary age of  $523.4 \pm 7.9$  Ma whereas another group has rounded to subrounded zircons with very low Th/U ratio yielding  $^{207}\text{Pb}/^{206}\text{Pb}$  age of  $1620.8 \pm 9.2$  Ma. The latter age is considered the age of basement granite gneiss, and the zircons of which were extensively assimilated while ascent and emplacement of granitoid melt forming Songsak pluton at  $523.4 \pm 7.9$  Ma. Zircons from granite gneiss of Mikir Hills sampled from Longvalley are rounded to subrounded with zoned cores and yield  $^{207}\text{Pb}/^{206}\text{Pb}$  primary age of  $1430.4 \pm 9.6$  Ma. Rim of a zircon crystal yields  $^{207}\text{Pb}/^{206}\text{Pb}$  age of  $514 \pm 18.6$  Ma, which is most likely a result of fluid regime evolved during Pan-African granite magmatism.

Cambro-Ordovician granitoid plutons intruding the basement gneissic and Shillong Group of rocks are well exposed in several localities across Meghalaya plateau, and can be classified as medium to coarse grained phenocryst-free equigranular granitoids, and porphyritic granitoids containing megacrysts of K-feldspar embedded in medium to coarse grained matrix mainly composed of bt( $\pm$ hbl)-pl-Kf-qz-mag-ttn-ap assemblage. At places aplite and mineralized to unmineralized pegmatite veins intrude these granitoids. Occasionally some sulphide minerals are also observed hosted in the granitoids. Zircons separated from



representative granitoid samples have yielded weighted  $^{207}\text{Pb}/^{206}\text{Pb}$  mean age for Kaziranga ( $528\pm 5.5$  Ma), south Khasi ( $519.5\pm 9.7$  Ma;  $516\pm 9.0$ ), Kyrdem ( $512.5\pm 8.7$  Ma), Nongpoh ( $506.7\pm 7.1$  Ma), and Myllem ( $484.7\pm 8.9$  Ma;  $496\pm 9.4$  Ma;  $508.2\pm 8.6$  Ma) granitoids, which are products of global Pan-African tectono-thermal event and remarkably coincide with the later stage of East Gondwana assembly occurred at 570-500 (Kuunga orogen) culminating the formation of Gondwana (Pannotia). Inherited core of a zircon hosted in Kyrdem granitoid yields  $^{207}\text{Pb}/^{206}\text{Pb}$  age of  $1758.1\pm 54.3$  Ma, and a rim grown over the core yields an age of  $750.6\pm 35.6$  Ma. A large-sized inherited core of zircon from Myllem granitoid gives an age of  $1134\pm 15$  Ma. These older ages of inherited zircon cores imply timescale recycling of basement gneissic which played significant role in the generation of Cambro-Ordovician granitoids. Zircons from microgranular enclave hosted in Myllem granitoid yield weighted  $^{207}\text{Pb}/^{206}\text{Pb}$  mean age of  $529\pm 22$  Ma whereas enclave in south Khasi granitoid provides weighted  $^{207}\text{Pb}/^{206}\text{Pb}$  mean age of  $515\pm 13$  Ma, which are similar to the ages noted for zircons of respective host granitoids. This feature underlines that mafic (enclave) and felsic (host) magmas were coexisting, and hence both the mafic and felsic magmas must be product of same thermal events, however, their sources and depth of origin may be different. Some zircons in hybrid microgranular enclave have rounded (partially dissolved) cores, which appear inherited from protolith but interestingly determine the same ages as observed for magmatic rims grown over the cores. It is therefore inferred that these zircon cores were formed originally in granitoid melt and then transferred mechanically from host granitoid magma to a hybrid magma environment during mixing event. Partial dissolution of zircons occurred in high-T hybrid melt as a result of thermal rejuvenation and subsequently rims were grown over the cores in hybridizing magma system. In this case resident time of zircons in host hybrid melt should be sufficiently enough, which may have favoured partial dissolution. It is worthwhile to mention that such cores are not common in the zircons of granitoids.

Meghalaya plateau thus records four major magmatic episodes, which occurred extensively at ca 1800 Ma, ~1600 Ma, ~1400 Ma, ~500 Ma with clear signature of Neoproterozoic (~2560 Ma) component forming the basement gneissic complex, and later partial contribution of basement gneissic rocks in the generation of Cambro-Ordovician granitoid plutons with a small input of mafic to hybrid magmas in the evolution of some granitoid plutons (South Khasi, Myllem and Kyrdem). Based on evidences it is suggested that Meghalaya plateau encompasses the Columbian and Gondwanian continental affinities during its crustal growth history. Evidences of Columbian supercontinent assembly are also preserved in the crystalline rocks of Eastern Ghat Mobile Belt, Mahakoshal Belt, Aravalli Belt and Arunachal Himalaya of India.



**S05–502: The Rodinian Orogeny in East Gondwana- Implications for Supercontinent Evolution**

***Cordierite-Forming Reactions in a Suite of Ultra High Temperature Mg-Al Granulites from Parts of the 'Eastern Ghats Province' India: Evidence for Breakdown of Rodinia (?)***

Das E<sup>1</sup>; Karmakar S<sup>1</sup>; Dey A<sup>1</sup>; Sengupta P<sup>1</sup>

Department of Geological Sciences, Jadavpur University, Kolkata, India<sup>1</sup>

We present P-T-D-t evolution of a suite of Mg-Al granulites exposed along the stretch Araku – Anantagiri, Andhra Pradesh, India. In Araku-Anantagiri area which falls in the Domain 2 of the Eastern Ghats Province bluish coloured aluminous granulites occur as patches / lenses within garnetiferous quartzofeldspathic gneisses (leptynite) that are enclosed by charnockitic orthogneisses. On the basis of mineralogy two associations viz. sapphirine bearing (Group A) and sapphirine free (Group B) are identified. Group A that presumably formed in Mg-rich bulk composition develop the association sapphirine (peraluminous, MgO + FeO : Al<sub>2</sub>O<sub>3</sub> : SiO<sub>2</sub> ~ 7 : 9 : 3 with X<sub>Mg</sub> = 0.78) + sillimanite + orthopyroxene (X<sub>Mg</sub> = 0.69, Al<sub>2</sub>O<sub>3</sub> up to 9.4 wt%) + garnet (X<sub>Mg</sub> = 0.52) + cordierite (X<sub>Mg</sub> = 0.91) + quartz + plagioclase (X<sub>An</sub> = 0.35) + alkali feldspar + rutile + ilmenite ± spinel ± retrograde biotite (X<sub>Mg</sub> = 0.76).

Textural features suggest that sapphirine + garnet (porphyroblastic, grt1) + quartz ± spinel ± sillimanite (with accessory rutile and ilmenite) developed during peak metamorphism. Subsequently, this assemblage became unstable to form successive coronae of orthopyroxene + sillimanite and garnet (grt2) + sillimanite around sapphirine ± spinel. Finally, aggregates of coarse cordierite containing two or more inclusions of the aforesaid minerals developed in the rock. Locally, thin rims of cordierite separates the coronitic orthopyroxene from sillimanite. Rarely, biotite develops along with cordierite.

In contrast to Group A, mineralogy of Group B (spinel<sub>ss</sub> + sillimanite + orthopyroxene [X<sub>Mg</sub> = 0.65, Al<sub>2</sub>O<sub>3</sub> up to 7.12] + garnet [X<sub>Mg</sub> = 0.5] + cordierite [X<sub>Mg</sub> = 0.87] + quartz + plagioclase [X<sub>An</sub> = 0.34] + alkali feldspar + ilmenite) is conspicuous by the absence of sapphirine and rutile. Spinel<sub>ss</sub> is an aggregate of hercynite (X<sub>Mg</sub> = 0.45), hemo-ilmenite and magnetite with an outline that suggest one pristine phase. Interpreting the texture and mineral compositions we demonstrate that spinel<sub>ss</sub> represents break down product of a Fe-Mg-Ti-Al spinel. Spinel<sub>ss</sub> + cordierite + garnet (porphyroblastic, grt1) + quartz ± sillimanite were stabilized during peak metamorphic condition which subsequently became unstable to form coronitic orthopyroxene + sillimanite and garnet + sillimanite around spinel. Like Group A, second generation cordierite was formed at the expense of orthopyroxene + sillimanite + quartz.

The earliest foliation (S<sub>1</sub>) presumably developed at D<sub>1</sub> is defined by stretched grains of spinel, sillimanite and sapphirine (only in group A) that are found as inclusions in porphyroblastic garnet. However, garnet-bearing peak metamorphic assemblage defines a granoblastic texture in both the groups (S<sub>2</sub>, D<sub>2</sub>) that obliterated the S<sub>1</sub> fabric. Geometrical analyses of the mineralogy in parts of the system KFMASH (+ Ca, Mn), topology of numerically computed phase diagrams for representative bulk compositions (pseudosection) and quantitative geothermobarometry all suggest that the peak mineral assemblages in Groups A and B were formed under extreme condition at lower crustal depth (~1000 °C and ~9 kbar, M<sub>1</sub> metamorphism) due to extensive partial melting. Such extreme temperature of metamorphism is consistent with stability of spinel + sillimanite + quartz and sapphirine + sillimanite + quartz and Ti-Al spinel. Near isobaric cooling from the M<sub>1</sub> produced coronitic sillimanite, garnet and orthopyroxene. Cordierite that consumed the coronitic phases were formed due to steeply decompressive P-T path with a pressure drop of ~5 kbar (M<sub>2</sub>). Extant geochronological data dates the timing of ultra high temperature metamorphism and near isobaric cooling which is ~1100 Ma. This event can be correlated with Rayner orogeny in east Antarctica during the formation of Rodinia. However, a post-Rodinia thermal reworking event is recorded by texturally constrained EPMA monazite dating in spinel granulites at ca. 750 Ma with a weak overprinting of Pan African orogeny though metamorphic re-equilibration of mineral assemblage is not conspicuous.



**S05–513: The Rodinian Orogeny in East Gondwana- Implications for Supercontinent Evolution**

***Evolution of Mesoproterozoic Kumta and Mercara Suture Zones in Western India: Constraints on India-Madagascar Correlations***

K. Sajeev<sup>1</sup>, C. Ishwar-Kumar<sup>1</sup>

Indian Institute of Science <sup>1</sup>

The understanding of exact position of continental fragments in various supercontinent assemblies and relationship between various shear/ suture zones and crustal blocks across the continental fragments through various time periods have significant implication in understanding the tectonic processes through geological time-scale. The period between the assembly of Rodinia and its break-up to form the Gondwana supercontinent in the Neoproterozoic marks an important stage in the tectonic history of southern Peninsular India. India and Madagascar occupied the central position in the eastern Gondwana assembly, and the correlation between them is important to understand the tectonics of eastern Gondwana. The tectonic linkage between India and Madagascar is one of the most debated problems in the field of paleogeography of eastern Gondwana.

Palaeomagnetic studies reveal that India and Madagascar were contiguous prior to the breakup of Gondwana supercontinent. Before the breakup of eastern Gondwana, India and Madagascar had several deep crustal shear zones which were continuous across these continental fragments. These shear/suture zones are used as one of the major criteria for the continental correlation. The Kumta and Mercara suture zones in western Peninsular India offer critical insights into the crustal evolution of eastern Gondwana. The Kumta suture zone is situated on the western margin of southern India (Ishwar-Kumar et al., 2013). The suture zone is c. 15 km-wide, westward dipping and contains garnet-biotite, fuchsite-haematite, chlorite-quartz, quartz-phengite schists, biotite augen gneiss, marble and amphibolite. The textural evidences, phengite composition and phase diagram estimations of quartz-phengite schist suggest a near-peak pressure-temperature conditions of c. 18 kbar at c. 550°C, followed by near-isothermal decompression. The detrital SHRIMP U-Pb zircon ages from quartz-phengite schist give four age populations ranging from 3280 to 2993 Ma and for garnet-biotite schist ranges from 2580-3420 Ma. Phengite from quartz-phengite schist and biotite from garnet-biotite schist have K-Ar metamorphic ages of ca. 1326 and ca. 1385 Ma respectively. The Karwar block towards the west of Kumta suture zone consists of ca. 3200 Ma tonalite trondhjemite-granodiorite and amphibolites. The Bondla arc in the north west of the Kumta suture zone consists of gabbro and ultramafic rocks such as peridotite, chromitite, serpentinite. The chromian spinel chemistry from the serpentinite and chromitite indicates its origin in supra-subduction arc tectonic setting. The Sirsi shelf is located towards the eastern side of the Kumta suture zone is about 60-80 km wide and contains weakly deformed and unmetamorphosed shallow westward-dipping sedimentary rock. The Sirsi shelf consists of pebbly quartzite/sandstone, turbidite, magnetite iron formation, and limestone. The quartzite in the farther east has an unconformable contact with ca. 2571 Ma quartzo-feldspathic gneisses of the Dharwar block. The Mercara suture contains mylonitic quartzo-feldspathic gneiss, garnet-kyanite-sillimanite gneiss, garnet-biotite-kyanite-gedrite-cordierite gneiss, garnet-sillimanite gneiss, garnet-hornblende gneiss, calc-silicate granulite and metagabbro. The c. 20 km wide, curved Mercara suture zone containing highly sheared and deformed gneisses strikes EW, NW to NS (southwards), dips W and has dextral kinematic indicators. At its southern end the NS-trending Mercara suture terminates discordantly against the EW to NW trending Moyar suture zone. The southern part of the Coorg block is separated from the Nilgiri block by the western segment of the Moyar shear zone and it mainly consist of garnet-biotite gneiss, hornblende-biotite gneiss with amphibolite enclaves, quartzite and younger granite. The textural evidence, mineral chemistry and thermodynamic modeling of garnet-biotite-kyanite-gedrite-cordierite gneiss from the Mercara suture zone indicates peak metamorphic pressure-temperature conditions of c. 13 kbar at 825°C followed by isothermal decompression and cooling. The lower intercept age of detrital zircons in the metasedimentary rocks from the Kumta suture zone ranges from 1000-1200 Ma and those from the Mercara suture zone



varies from 1106-1464 Ma. These ages are interpreted as the timing of peak metamorphism which is related to the suturing event. Garnet-biotite schist from the Kumta suture zone has zircons with  $\Sigma Hf$  (t) values ranges from -9.2 to 5.6, and TDM model age from 2747 to 3546 Ma, whereas pelitic gneisses from the Mercara suture have  $\Sigma Hf$  (t) values that vary from -18.9 to 4.2 and TDM model age from 3214 to 3647 Ma, respectively.

Integration of the above results indicates that the sediments in Kumta and Mercara suture zones have age ranges from Paleoproterozoic to Mesoproterozoic and the sediments were underwent high-pressure metamorphism during the Mesoproterozoic. The sediments were mainly derived from provenances containing juvenile crust, together with mixing of material derived by recycling of older crust. The Mesoproterozoic Kumta and Mercara suture zones separate the Archean Karwar block and Coorg blocks from the Dharwar block. The Betsimisaraka suture in north-eastern Madagascar divides Mesoarchean Antongil and MaSøra blocks from the Antananarivo block. Based on the interpretation of published geochronology results from north-eastern Madagascar we interpret that the Betsimisaraka suture is late Mesoproterozoic in age. By the compilation of above results with the published data we propose that the Kumta and Mercara suture zones as the extension of Betsimisaraka suture of north-eastern Madagascar into western India.



**S06 – 35: Large Igneous Provinces in Gondwanaland**

***Petrogenesis of the Butcher Ridge Igneous Complex, A Unique Layered Glassy Silicic Intrusion Within the Ferrar Large Igneous Province***

Demian Nelson<sup>1</sup>; John Cottle<sup>1</sup>; Melanie Barboni<sup>2</sup>; Blair Schoene<sup>3</sup>

University of California, Santa Barbara, United States<sup>1</sup>; University of California, Los Angeles, United States<sup>2</sup>; Princeton University, United States<sup>3</sup>

Mafic sills and lavas of the Jurassic Ferrar Large Igneous Province are assumed to have originated from the same parental magma source with minor differentiation during magma transport, storage, and emplacement. However, a ~6000 km<sup>3</sup> layered glassy hypabyssal intrusion in the Cook Mountains of southern Victoria Land, the Butcher Ridge Igneous Complex (BRIC), is reputed to be a highly differentiated intrusion of the Ferrar LIP. At present, the temporal relationship between BRIC and Ferrar LIP magmatism is poorly constrained and the origin of evolved compositions and meter scale layering is unknown. Here we present new high-resolution U-Pb ID-TIMS geochronology on zircon and baddeleyite from both the BRIC and a Ferrar sill that confirms BRIC magmatism occurred during the main phase of Ferrar magmatism (184-182 Ma). Furthermore, new isotopic, major- and trace-element data for BRIC samples (n=130) indicate that the BRIC contains the most highly evolved, 73 wt. % SiO<sub>2</sub>, rocks of the Ferrar LIP and that differentiation was likely driven by crustal contamination of a mafic Ferrar parental magma. Ongoing geochemical modeling explores the local granite/metamorphic basement, lower crustal xenoliths, and Beacon Supergroup sediments as possible end member assimilants. Furthermore, petrographic observations and evidence for alkali-ion exchange suggest that devitrification and secondary hydration resulted in meter-scale layering throughout the BRIC and may represent a previously undescribed igneous layering process. These new data are synthesized into a petrogenetic model for the BRIC and provide an opportunity to compare silicic magmatism within the Ferrar LIP with other LIPs globally.



## S06 – 40: Large Igneous Provinces in Gondwanaland

### ***Provenance of Detrital Zircons from the High Atlas of Morocco Deciphered by SHRIMP U-Pb Dating***

A.M. Fioretti<sup>1</sup>; A. Marzoli<sup>1,2</sup>; R. Merle<sup>3</sup>; N. Youbi<sup>4</sup>; D.J. Dunkley<sup>3</sup>; J. Dal Corso<sup>2</sup>; B. Andreucci<sup>2</sup>; E. Font<sup>5</sup>; G. Bellieni<sup>2</sup>

National Council of Researches (CNR) - Istituto di Geoscienze e Georisorse, Italy<sup>1</sup>; Dipartimento Di Geoscienze, University of Padova, Italy<sup>2</sup>; Curtin University, Perth, Australia<sup>3</sup>; Cadi Ayyad University, Marrakech, Morocco<sup>4</sup>; Faculdade de Ciências da Universidade de Lisboa (FCUL), Lisbon, Portugal<sup>5</sup>

Continental basins developed during the Triassic in the central High Atlas and Argana basins of Morocco. Sedimentation occurred in a shallow marine or lagoonal environment. Possible sources of sediment include the Meseta region to the north, from predominantly Paleozoic formations, or the Anti Atlas region to the south, from Proterozoic to Paleozoic formations. Siltstones of latest Triassic age sampled at the base of the End-Triassic CAMP (Central Atlantic Magmatic Province) basaltic flows on the southern margin of the High Atlas contain abundant detrital zircon.

Cathodoluminescence imaging reveals magmatic textures in most zircon grains. Grains analysed by Sensitive High Resolution Ion Microprobe (SHRIMP) yielded ages ranging from the Cambrian to the Archean. Probability distributions display a prominent peak at ca. 0.6 Ga, corresponding to the Pan-African orogenic event. A lesser concentration occurs at about 2 Ga, corresponding to the Eburnian event. Both the Pan-African and Eburnian events are well represented in the geology of southern Morocco (Anti Atlas), but are absent in present-day outcrops of northern Morocco (Meseta). The zircon ages indicate that late-Triassic sediments largely derive from the Anti Atlas. However, some of the analysed zircons yield ages of ca. 1.1 Ga, which are not known in the presently exposed rocks of the Anti Atlas and the southern Morocco in general. This may indicate that the source rocks of such Mid-Proterozoic zircons may be now eroded terrains of possibly allochthonous origin (maybe deriving from the Avalonia or Laurentia continents). Furthermore, a few analysed zircons yield Archean ages (2.5-3.1 Ga) suggesting that they derived from the West African craton, which is presently occurring at almost 300 km to the South of the Central Atlas.



## S06 – 62: Large Igneous Provinces in Gondwanaland

### ***Evidence of Magma Mixing and Mingling in Neoproterozoic-Cambrian Granitoids of Meghalaya and Its Correlation with Pan-African Activity***

Sadiq Md<sup>1</sup>; Umraob R.K.<sup>2</sup>

Geological Survey Of India, Faridabad, India<sup>1</sup>; Geological Survey Of India, North Eastern Region, Shillong, India<sup>2</sup>

The Meghalaya plateau is an uplifted horst-like feature covering an area of about 40000 km<sup>2</sup> and bounded on all sides by major structural discontinuities viz; by the E-W trending Dauki and Brahmaputra fault systems in the south and the north respectively. The west and the east sides are abutted by the N-S Yamuna fault system and the NW-SE trending Kopili fault. Nongchram fault and Um Ngot lineaments are another N-S trending structures that traverse the Shillong plateau. Several syn- to late tectonic granitoids (Nongpoh, Kyrdem, Myllem, South Khasi, Rongjeng, Sindhuli granitoids isolated granitic pluton around Samingiri Dilsekgiri in West Garo Hills), occur as discordant plutons cross-cutting the Shillong Group of metasedimentary rocks and gneissic complex of Meghalaya plateau and their emplacement is controlled by pre- existing fractures and lineaments. Present study focused on calc-alkaline, metaluminous Nongpoh and Kyrdem plutons and South Khasi batholith which are, in parts intrusive into the Precambrian Gneissic Complex and Umsning Schist Belt of the Meghalaya Plateau. The Nongpoh granitoids contain three types of enclaves viz, xenolith of country rock, dark grey porphyry and black biotite rich microgranular enclaves. Mafic magmatic enclave (MME) has been identified in igneous provinces around the world. MME are of various shapes including circular, rounded, ellipsoidal, rectangular, angular to sub angular and as stretched bodies are produced by evolving nature and kinematics of interacting felsic and mafic magmas. Mineralogical composition of porphyritic granite hosting mafic enclaves is similar except the modal percentage of accessory minerals in the MME and country rock. MMEs are rich in titanite and allanite. Field observations, textural assemblages viz; rapakivi texture, mixed apatite morphology, resorbed plagioclase xenocrysts, inclusion zones in feldspar, irregular anorthite profile across the plagioclase crystals, titanite-feldspars ocellar relation, quartz-hornblende, biotite ocelli, poikilitic- microcline, plagioclase, hornblende, quartz and biotite, zoned titanite and allanite and sub-linear variations between silica and major oxides, chemical mixing and element diffusion suggest that multistage magma hybridization was the main process in the evolution of Meghalaya granitoids. Neoproterozoic-Cambrian granitoids emplacement is known to be the major phase of granitic activity in Meghalaya plateau and corresponds to Pan-African activity. These calc-alkaline granitoids originated due to tensional stress and thermal upwell associated to the collisional extensional episode of the Gondwana supercontinent.



**S06 – 100: Large Igneous Provinces in Gondwanaland**

***Do Large Igneous Provinces Exist In Terrestrial Planets? A Comparative Planetology Through Basalt Geochemistry***

Ray D<sup>1</sup>; Misra S<sup>2</sup>

Physical Research Laboratory Ahmadabad, India<sup>1</sup>; SAEES, University of KwaZulu-Natal, Durban-4000, South Africa<sup>2</sup>

The Large Igneous Provinces (LIPs) on our terrestrial planet represent high magmatic flux over a short geological timescale and mainly include Continental flood basalt (CFB) provinces and Oceanic Plateau Basalts (OPBs). Unlike Earth, the LIPs in other terrestrial planets are relatively unknown, however, the possibilities of existence of gigantic basaltic provinces in rocky planetary bodies in our inner Solar System cannot be ruled out. One of the growing evidences favouring the existence of LIPs in terrestrial planets largely based upon the fact that terrestrial planets are mostly comprised of basaltic crust, the most common rock type found in the terrestrial LIPs. Moreover, the enormous basaltic plains of Moon, Mars, Mercury and Venus often resemble with flat terrain “plateau volcanism” similar to terrestrial CFBs or OPBs. Recent results from MESSENGER mission on Mercury, furthermore, revealed that flood basalt-type volcanism might be present in northern latitude of Mercury with a variable composition between basalt and komatiite. In the present work, we compare the geochemistry of CFBs and MORBs from Earth with the mare basalts (high-Ti and low-Ti) from Moon, Martian basaltic meteorite and in-situ X-ray data and surface composition of Mars, Mercury and Venus (orbiter and/or in situ data) using some common geochemical parameters and try to show that the terrestrial MORB-like basalts could be the more common rock type on the planetary surfaces in our inner Solar system.

The geochemical data of mare basalts are collated from literature. The database for Mercury and Venus are sparse as compared to Moon and Mars. The Martian basaltic meteorite data are compiled from the Mars Meteorite Compendium and also from some recent compilations. The in-situ APXS data of Martian surface are also taken into consideration for the present comparison. Surface compositions of Mercury and Venus are limited as compared to Moon and Mars, however, a few were obtained by different interplanetary missions and collated for this study. In terms of terrestrial basalts, we incorporated here the Deccan Trap CFB and terrestrial MORBs as a reference. In the TAS (Total alkali Silica) diagram, the terrestrial MORBs form a cluster within the ‘basalt’ field close to an average SiO<sub>2</sub> ~50 wt%. The total alkali content of these basalts varies over a considerable range between ~ 2.5 and 5 wt%. The terrestrial CFBs form an overlapping cluster within MORBs and show a limited variation in total alkali between ~2.5 and 3.5 wt%. In contrast, total alkali of mare basalts is extremely low (~1 wt%), although these rocks vary in composition between ultrabasic to basic fields. On the other hand, the majority of the in-situ analyses of the basaltic rocks from the Martian surface show a restricted SiO<sub>2</sub> (~46 wt%) and total alkali (~3.3 wt%) and partly overlapping the field of the terrestrial MORBs. However, SiO<sub>2</sub> variability of the Martian basaltic meteorites are relatively higher (~45 and 51 wt%) with characteristically low total alkali content (<2 wt%) in majority of cases. Interestingly, the composition of the majority of Martian basaltic meteorites does not match with either terrestrial MORBs or with the CFBs, instead shows similarity in composition with the L-Ti Mare basalts. The two out of three surface composition of Venus fall under the terrestrial CFB field, while Mercury composition is more similar to basaltic andesite.

In more sensitive MgO versus Al<sub>2</sub>O<sub>3</sub>/TiO<sub>2</sub> bivariate plot, the terrestrial MORBs show a continuous linear/slightly curvilinear trend between very restricted MgO of 5 and 9 wt%, their Al<sub>2</sub>O<sub>3</sub>/TiO<sub>2</sub> ratio is highly variable between ~2.5 and 25. The terrestrial CFBs are also plotted on this trend with very restricted Al<sub>2</sub>O<sub>3</sub>/TiO<sub>2</sub> ratios around 5. The high-Ti mare basalts are exclusively basaltic, while low-Ti mare basalts show composition variation over the basalt and komatiitic basalt fields. The majority of the mare basalts have Al<sub>2</sub>O<sub>3</sub>/TiO<sub>2</sub> ~5, but none of these members show overlapping composition with any terrestrial examples. Though majority of the in situ Martian surface compositions overlaps with the terrestrial



MORBs, a few of them and the Martian basaltic meteorite data show komatiitic basalt and low-Mg komatiite composition. The available Mercury surface compositions resemble with low-Mg komatiite, while the rocks from Venus surface are more representative of basalt with MgO ~12 wt%. In  $Al_2O_3/TiO_2$  versus  $CaO/Al_2O_3$  plot, the examples of terrestrial CFBs and MORBs show a restricted  $CaO/Al_2O_3$  ratio close to ~0.8. The in-situ Martian surface chemical data have  $CaO/Al_2O_3$  ratio mostly vary between 0.5 and 0.8 and overlapping with the field of terrestrial MORBs, whereas the Martian basaltic meteorites have a wide variation in  $CaO/Al_2O_3$  between 0.8 and 2. The in-situ Martian APXS data also show an overlapping composition with the terrestrial MORBs. The mare basalts, however, are different in composition to the terrestrial and Martian basalts, and characteristically have relatively low  $Al_2O_3/TiO_2$  (<5) and high  $CaO/Al_2O_3$  ~1.1. The Mercurian and Venusian rocks mostly resemble with in situ Martian surface data in this diagram. Our previous studies on the mare basalts show that these basalts were similar to the terrestrial MORBs in terms of trace element chemistry although some important differences exist. Our present observation suggests that the martian in-situ rocks also resemble with the terrestrial MORBs in terms of their bulk composition. So it can be concluded that the terrestrial MORB-like basalts are more abundant on the planetary bodies close to the Earth.



## S06 – 101: Large Igneous Provinces in Gondwanaland

### ***Trace of the Mid-Ocean Ridge Basalt (MORB) - Like Component: Evidences from a Tholeiitic Flow of Anjar, Deccan Volcanic Province, India***

Ray D<sup>1</sup>; Shukla A D<sup>1</sup>

Physical Research Laboratory Ahmedabad, Gujarat, India<sup>1</sup>

Continental flood basalt volcanisms is mostly related to continental rifting and generally preceded the seafloor spreading, offer unique opportunity to examine the sub crustal mantle geochemistry. The Deccan Volcanic Province (DVP ~67-64 Ma) is well known as rifted continental flood volcanism and widely spread over northwestern and central peninsular India. We examine here a tholeiite flow ( $\text{Na}_2\text{O}+\text{K}_2\text{O}$ : 2.36-2.37) (estimated age ~ 61 Ma  $\pm$  1.6 Ma by Ar-Ar chronology) associated with several flows of alkali basalts ( $\text{Na}_2\text{O}+\text{K}_2\text{O}$ : 3.5-4.9 wt%) (~68 Ma) from Anjar area near Gandhidham in Kutch district of Gujarat, India. Earlier studies discussed that the alkali volcanic plug in Kutch region was emplaced in a half graben structure and possibly erupted prior to peak of the Deccan volcanic activity (~65 Ma). In this work, our aim is to identify the igneous process(es) resulting the evolution of alkali and tholeiitic lavas and thereafter using trace element geochemistry to assess the mantle geochemistry. We, finally, compare the Deccan tholeiite with Indian Ocean MORB (modern and older MORB) in order to understand whether any MORB-like mantle component exists beneath the rifted lithosphere or not. We used the incompatible trace elements data and their ratios as they are very useful to infer the igneous process(es) and mantle geochemistry and also they have considered as least affected either by crystal fractionation or partial melting. Our comparisons of modern MORB glass compositions from Central Indian Ridge (CIR) characteristically show both enriched and depleted character ( $\text{Ba}/\text{Yb}_N$ : 0.10-1.69). The trace element geochemistry of tholeiite flow closely resembles with enriched Mid-Ocean Ridge Basalt (E-MORB) composition, however, their compositions differ from the modern CIR MORB (Anjar tholeiites are higher in  $\text{Ba}/\text{Nb}$  ~15-16,  $\text{Ba}/\text{Th}$  ~158-182 and lower in  $\text{Nb}/\text{U}$  ~25-32 ratios as compared to CIR MORB ~4-8, 66-177, 41-60). Interestingly, trace element ratios of Anjar tholeiite closely resemble with one of the older (~60 Ma) "enriched" Indian Ocean seafloor basalt (DSDP site 223,  $\text{Ba}/\text{Nb}$ ~17,  $\text{Ba}/\text{Th}$  ~181 and  $\text{Nb}/\text{U}$ ~34.). Furthermore, Anjar tholeiite lacks the typical strong fractionated trace element pattern ( $\text{Ba}/\text{Yb}_N$ : 3.54-3.65) unlike the alkali flows ( $\text{Ba}/\text{Yb}_N$ : 5.41-9.14). Moreover, the chondrite normalized REE pattern of tholeiite is also relatively flat ( $\text{La}/\text{Yb}_N$ : 2.34-2.60) as compared to the steeping REE pattern of alkali basalt ( $\text{La}/\text{Yb}_N$ : 5.79-13.34). In process identification plot (in incompatible element ratios versus least compatible bivalent plot), Anjar tholeiite along with the CIR MORBs argue against the major role of crystal fractionation during its evolution, instead, favouring partial melting-dominated processes. By contrast, alkali basalts were evolved through a process dominated by crystal fractionation. We, further, tested the effect of crustal contamination using the trace element ratios. Our bivariate plots suggest alkali basalt and the least contaminated Ambenali basalt of DVP closely fall in a curvilinear mixing trend of Ocean Island Basalt (OIB)-Lower Continental Crust (LCC). By contrast, tholeiite chemical compositions are predominantly MORB-like and fall along the similar compositional field occupied by the CIR MORB (Anjar tholeiite:  $\text{Nb}/\text{La}$ ~ 0.95-0.98; Global MORB:  $\text{Nb}/\text{La}$  ~0.98). In fact, this particular Anjar tholeiite lacks the evidences of typical crustal contamination signature ( $\text{Th}/\text{Yb}$  PM: 1.74-1.84) unlike other tholeiites reported from Kutch region ( $\text{Th}/\text{Yb}$  PM: 5.42-6.04). The Anjar tholeiite appears as the least affected by crustal component even while comparing to the Ambenali formation basalt ( $\text{Th}/\text{Yb}$  PM: 2-2.69). In conservative trace element ratio plot ( $\text{Ti}/\text{Yb}$  vs  $\text{Nb}/\text{Yb}$ ), Anjar tholeiite interestingly fall parallel to global MORB-OIB array, in fact, more similar to MORB and therefore accounting distinct mantle characters as compared to the alkali counterpart.

Based on the observed remarkable geochemical resemblance, we, therefore, suggest that the tholeiite flow of Anjar may have been derived from Indian Ocean MORB-like mantle component similar to 60 Ma old "Enriched" Indian seafloor basalts and attributed the least crustally contaminated member of DVP (even lesser contaminated than the Ambenali formation). Lithospheric thinning due to continental rifting



might have facilitated the dispersal of Indian-MORB like asthenosphere during the post-Gondwana break-up. By contrast, alkali lavas are composite in nature, i.e. resemble more to Reunion and OIB-like mantle component and contaminated variously by LCC as well. The geochemical dissimilarity between tholeiite and alkali basalt also led us to conclude two different parental magmas viz. for tholeiite magmatism there is significant involvement of nonplume mantle where the latter correspond to plume interferences. Isotopic studies are in progress.



**S06 – 111: Large Igneous Provinces in Gondwanaland**

***East Antarctic Volcanic Provinces Linked to Mesozoic Plumes and the Gondwana Break-Up***

Sushchevskaya, N.M.<sup>1</sup>; Belyatsky, B.V.<sup>2</sup>; Krymsky, R.Sh.<sup>2</sup>; Laiba, A.A.<sup>3</sup>

Vernadsky Institute of Geochemistry, RAS, Moscow, Russia<sup>1</sup>; A. P. Karpinsky All-Russian Geological Institute (VSEGEI), St.-Petersburg, Russia<sup>2</sup>; Polar Marine Geosurvey Expedition, St.-Petersburg Lomonosov, Russia<sup>3</sup>

East Antarctic Mesozoic igneous provinces as old as 180-110 Ma manifested in the areas of Queen Maud Land (QML), Schirmacher and Jetty Oasises are associated with different tectonic events of the time. The first major event occurred about 180 million years ago, when the large plume Karoo-Ferrar-Maud has been appeared and led to a split in the eastern Gondwana [Jokat, 2003]. In the eastern part of QML revealed numerous basic dikes of different geochemical characteristics. Eastward in the area of Schirmacher Oasis magmatism associated with a time interval 170-160 Ma is represented by NE dike series often coinciding with the direction of more ancient dikes [Sushchevskaya, Belyatsky 2011].

Finally, in the Lambert Glacier area magmatism of ultra-alkaline composition generated about 120-110 Ma magmatic field along a major rift system - Lambert fault zone [Sushchevskaya et al., 2011]. The impact of Karoo-Maud plume on the lithosphere had a long multistage character. Magmatism lasted at least 20 - 30 million years during which a series of dikes and flows radially-distributed from the center of the plume and covered an area of about 145 000 km<sup>2</sup> along the coast of Antarctica (QML) had been formed [Leat, 2007]. Plume impact within Antarctica distributed to the South and to the East, leading to the formation of extended igneous provinces along Transantarctic Mountains and along the east coast (Queen Maud Land province and Schirmacher Oasis). Moreover, this plume activity may be continued later on, after about 40 million years cessation, as Kerguelen plume within the newly-formed Indian Ocean, significantly affects the oceanic rift magmatism [Sushchevskaya et al., 2011].

Plume influence from 130 to 110 million years ago enveloped the coast of Australia, India and Antarctica, forming magmatic province of the oceanic framework. At 110 million years ago Kerguelen-plume focused near the ancient spreading zone of Wharton Ridge in the eastern part of the incipient Indian Ocean. On the eastern flank of the plume within India (Rajmahal) and Antarctica (Jetty Oasis) continental landmasses, ultra-basic alkaline magmatism associated with low degrees of lithospheric mantle melting manifested at 117-110 Ma [Kent et al., 2002; Laiba et al., 1987]. A broken chain of 6 stock-like bodies of alkaline-ultramafic dikes and sills within oasis Jetty stretches for 15 km along the eastern shore of Beaver Lake located opposite the Kerguelen Archipelago. Compositions of olivine grains separated from the alkaline-ultramafic rocks of the Southern and Northern bodies, from lamprophyre dikes near Beaver Lake, as well as from biotite picrites of Meredite massif located 100 km from the oasis Jetty show a large variation range for individual samples (75 to 91). The high proportion of pyroxenite component for the mantle source estimated on Ni and Mn content in the liquidus olivines averages up to 60-80%. The huge dispersion in Ni and Mn for olivine composition with the same Mg numbers testifies for significant heterogeneity of melting source. Unlike Raniganj ultrapotassic intrusives (basalt; trachybasalt; tephriphonolite; phonolite; picrite; basanite) [Paul, 2005] basalts from the Lambert area are enriched in magnesium and sodium. At the same time these basalts are close to previous in relation lithophile elements and isotopic characteristics. Kerguelen-plume impact significantly affected the formation of enriched tholeiitic magmas within the spreading zone (Wharton Ridge) and continued until the Quaternary when the Heard Island was formed within the Kerguelen plateau and Gaussberg volcano on the coast of the East Antarctica as well. Distribution of plume material along weak zones reflects the possibility of deep flows - plume movements occurring at different lithosphere levels and sublithospheric mantle [Foley, 2008]. In all cases, basaltic magmas enriched source according to lithophile element contents and Pb-Sr-Nd isotope data can be attributed to the melting of the Gondwana lithospheric mantle metasomatized at



the earlier stages of tectonic development and involved in the melting process during the Karoo-Maud and Kerguelen-plume activities.



**S06 – 217: Large Igneous Provinces in Gondwanaland**

***An Overview of Geochemistry and Petrology of Cretaceous Mafic Dykes In and Around Nongchram Fault Zone of the Shillong Plateau, NE India: Implications for Genetic Link to Kerguelen Plume***

Niva Rani Devi

Arya Vidyapeeth College, Guwahati, Assam, India

The present study highlights an overview of petrological and geochemical signatures of the Early Cretaceous mafic dykes from Shillong plateau of NE India. These dykes are emplaced in the Precambrian Gneissic Basement Complex in the western part of the Shillong plateau and are directionally parallel to the N-S trending deep-seated Nongchram fault. Best exposures of these dykes are found from Swankre-Rongmil area in South Khasi and East Garo Hills districts of Meghalaya respectively. Field evidences indicate very sharp contact with the host rocks and absence of any imprints of assimilation. Petrographically, these mafic dykes are classified as basalts and dolerites. The whole rock geochemistry suggests that these dykes are genetically related to each other and probably derived from the same parental magma. On AFM and total alkali and silica (TAS) diagrams these dykes show sub-alkaline basaltic andesite/andesite geochemical characteristics. Trace element and REE behaviour hint that possibly the melt responsible for these mafic dykes had undergone differentiation before its emplacement. These mafic dykes show similar geochemical signatures to mafic rocks recovered from the Kerguelen plateau.

It is widely accepted that Kerguelen plume is responsible for the eruption of basaltic magma in and around Kerguelen plateau, Broken ridge, Naturaliste plateau, Rajmahal-Sylhet province and ultramafic-alkaline-carbonatite rocks of Shillong plateau. Earlier workers have established that Kerguelen hotspot was active since 130 Ma and is responsible for mafic and alkaline magmatism in the Shillong plateau. It has also been suggested that Kerguelen hot spot was very close to Shillong plateau between 100 Ma and 115 Ma. Thus the emplacement of studied mafic dykes seems to have genetic link to the Kerguelen mantle plume.

Key words: Shillong plateau, Nongchram fault, Kerguelen plume.



**S06 – 260: Large Igneous Provinces in Gondwanaland**

***Contemporary Felsic and Orthopyroxene-bearing Basalt and Andesite Volcanism in the Eastern Margin of Rajmahal Basalts (India): Genesis of High-Mg Andesite by Magma Mixing***

N. C. Ghose<sup>1</sup>; Biswajit Ghosh<sup>2</sup>

Formerly Department of Geology, Patna University, India<sup>1</sup>; Department of Geology, University of Calcutta, India<sup>2</sup>

The Indian sub-continent is known for the occurrence of two Large Igneous Provinces (LIP) during the Cretaceous period called the Rajmahal basalts (115-118 Ma) in the eastern continental margin and the Deccan basalts (65 Ma) in the central and western India. The two massive volcanic edifices were generated due to plume activity located at present below the Kerguelen and Reunion Islands respectively, in the Southeastern Indian Ocean. The Rajmahal volcanic event in Lower Cretaceous, coincides with widespread magmatism in the Shillong Plateau in northeast (Sung valley, Sylhet), east coast basins (Bengal, Mahanadi and Krishna-Godavari) and emplacement of alkali/tholeiite dyke swarms in the Gondwana basins and southern Peninsular India. They belong to rift related magmatism in the Bunbury Province of Western Australia, Prince Charles Mountain of East Antarctica, Naturalist Plateau of the Southeast Indian Ocean, coinciding with fragmentation of the Gondwana.

The Rajmahal Basalt Province (RBP) is dominantly composed of basalts and basaltic andesites with minor amounts of hypersthene basalt, andesite, trachyandesite, high-Mg (enstatite-bearing) andesite, rhyodacite, dacite and pitchstone of rhyolitic composition (TAS). It is apparent from AFM, that the parent magma was well differentiated prior to eruption which is characterized by moderate enrichment of iron followed by pronounced fractionation of alkali. The Rajmahal basalts show remarkable similarity with those of the Columbia River and the Siberian Platform in major element composition. However, they are richer in silica, alumina and magnesia, but poorer in iron and titania as compared to the Deccan basalts. Higher silica (<54 wt%) and Sr-isotopic (0.70831-0.70977) ratios of basalts, andesites and trachyandesite of Rajmahal are related to contamination of the Proterozoic basement of the Chotanagpur gneiss-granulite terrain and the Gondwana trough sediments (Upper Paleozoic-Triassic). Presence of fragments of gabbro, websterite and silt in basalts and andesite supports crustal contamination. However, cognate fragments of gabbroid may represent accumulation of crystals in a subcrustal magma chamber, later ripped up by fresh surge of magma.

The lavas were erupted through several craters and mega-fractures of the shield margin, and along N-S trending arm of E-W running Gondwana basins that dissect the Chotanagpur plateau into two equal halves. It is established that early eruptions are confined to the western margin and is thickest, composed essentially of coarse- to medium-grained plagioclase phyric basalts. The thickness of lava flow decreases towards north, south and the eastern parts of RVP. The felsic rocks - trachyandesite, enstatite-bearing andesite, rhyolite and tuff, are usually confined to the eastern margin. They are closely associated with siliceous pyroclastic rocks including ignimbrite and bentonite (devitrified tuff/glass) that give evidence of violent eruptions at least in the early phase.

Early flows are separated by volcanoclastic and/or clastic sedimentary inter-beds, rich in fossil flora. Fine- to very-fine grained younger flows are largely sub-aerial with higher glass contents and are usually devoid of sedimentary/pyroclastic inter-beds. Presence of illite in bentonite, quenched clinopyroxene in crystal-tuff and oolites in sandstone in the basal part of lava profile, gives evidence of volcanism possibly in shallow marine environment. Correlating these features with the age of Rajmahal volcanism and contemporary magmatic events of Bunbury in Western Australia, Naturalist Plateau and Kerguelen in the Indian Ocean, connection of the former with juvenile Indian Ocean cannot be ruled out.



The felsic volcanic are largely limited to northeastern margin of RVP, has erupted through vents located between Dudkhol in the north and Chandola Pahar (including Berhait and Tinpahar) in the south, towards the waning phase of volcanic activity. The pitchstone contains tridymite and cristobalite, high-temperature polymorphs of quartz, and sharp euhedral orthopyroxene and minor opaque (Ghose and Chatterjee, 2015), indicating probable derivation by partial melting of lower crust. Occurrence of hypersthene basalt (En<sub>81</sub>) and high-MG enstatite-bearing andesite (En<sub>84</sub>) in this milieu at Tinpahar, bears petrological significance, as the two events, viz., felsic magmatism and the formation of orthopyroxene-bearing basalts and andesites, are found to be inter-related and coeval.

The hypersthene basalt and enstatite-bearing andesite are characterized by the presence of orthopyroxene, the former shows intergranular texture while the latter is vitrophyric (~50 vol %). The hypersthene basalt is composed of hypersthene (En<sub>81</sub>), fine needles of plagioclase, clinopyroxene, titaniferous magnetite and discrete grains of quartz. Besides enstatite (En<sub>84</sub>), the enstatite-bearing andesite consists of serpentine and low-Ca amphibole as secondary alteration products. Other minerals like plagioclase, oxidized magnetite and pyrite occur as accessories. Thus orthopyroxene remains stable at high temperature under steep thermal gradient for a large variation of silica between basalt-andesite and pitchstone, similar to distribution of fayalite in lithosphere. The andesite shows identical silica contents between the groundmass glass (SiO<sub>2</sub> = 57.41 wt %) and the whole rock (57.3 wt %).

Chemically, enstatite-bearing andesite is characterized by high Mg# 70 compared to basalts 47- 63 or trachyandesites 37-41. The former is poorer in incompatible elements (viz., Zr, Y, Sr, Ba, Rb and REE), but enriched in compatible trace elements (viz., Ni, Cr and V) than the latter. High Sr-isotopes of enstatite-bearing andesite (0.70689) and trachyandesite (0.70977) is comparable to late aphyric basalts (0.70541-0.70773). However, phyric basalts of early eruptions are usually less contaminated (0.70385-0.7042). The contrasting behaviour of the two subalkali basalts, i.e. early and late eruptions, supports variable crustal contamination of mantle-derived parent magma. It is concluded that the hypersthene basalt and the high-Mg enstatite-bearing andesite were derived possibly due to mixing of two magmas – a mantle derived basalt and the other felsic magma, generated by partial melting of lower crust at high temperature. The presence of modal quartz and sedimentary xenolith (silt particles rimmed by quartzofeldspathic vein) in hypersthene basalt confirms the above contention.



**S06 – 278: Large Igneous Provinces in Gondwanaland**

***Mineralogical and SR-ND Isotopic Signatures of Flows and Dykes from the Northeastern and Western-Central Part of the Deccan Large Igneous Province***

Kumar R.<sup>1</sup>; Ahmad T.<sup>1</sup>; Pant N.C.<sup>1</sup>

Department of Geology, Centre of Advanced Studies, University of Delhi, India<sup>1</sup>

“Large Igneous Provinces (LIPs) are magmatic provinces with areas of  $>0.1 \text{ Mkm}^2$ , igneous volumes  $>0.1 \text{ Mkm}^3$  and maximum life spans of  $\sim 50 \text{ Myr}$  that have intraplate tectonic settings or geochemical affinities, and are characterized by igneous pulse (s) of short duration ( $\sim 1\text{-}5 \text{ Myr}$ ), during which a large proportion ( $>75\%$ ) of the total igneous volume has been emplaced”. LIPs are found to occur in both continental and oceanic settings and most are of Mesozoic-Cenozoic age. LIPs are important geological events as they offer spatial and temporal insights into the compositional similarities and/or differences in the earth's interior.

Continental flood basalt (CFB) provinces are continental LIPs which consist predominantly of flood basalt lavas (tholeiitic basalt). Three phases of eruptions have been interpreted in most CFB provinces. It usually begins with outpouring of limited picritic basaltic lavas followed rapidly by episodic outbursts of large volume of tholeiitic lavas (acme stage). The late stage eruptions in some CFBs are associated with more evolved, explosive magmatism.

Three phases of eruptions in the Deccan CFB province of western-central India are reflected by the occurrences of (i) near-primitive picritic basalt in the northwestern Deccan Trap, (ii) thick pile of tholeiitic basalt in the northeastern, central and southwestern Deccan Trap, and (iii) tuffs associated with basalt in Bassein area of the western-central Deccan Trap.

In this light, the present study intends to highlight mineral and Sr-Nd isotopic similarities and/or differences between the northeastern (Jabalpur and Betul regions) and the western-central (Bassein region) part of the Deccan CFB province. Sampling details are as follows: (i) basalt flows from Jabalpur region, (ii) basalt flows and dykes from Betul region, and (iii) basalt flows and dolerite dykes from Bassein region.

Basalt flows of Jabalpur, Betul and Bassein regions are fine-grained with porphyritic and glomeroporphyritic textures. They all have a broad common mineralogy containing micro-phenocrysts of lamellar euhedral plagioclase (60-70%) and prismatic anhedral clinopyroxene (30-40%). These micro-phenocrysts commonly appear to float in a groundmass of very fine-grained plagioclase laths and anhedral clinopyroxene. Basalt dykes of Betul region are fine-grained with aphyric texture containing plagioclase laths and anhedral clinopyroxene. Dolerite dykes of Bassein region are medium-grained with aphyric texture containing euhedral to subhedral plagioclase and clinopyroxene. All flows and dykes contain titanomagnetite and ilmenite in groundmass. It is to be noted that 2-5 % olivine micro-phenocryst occurs in basalt flows of Jabalpur region as well as in basalt flows and dykes of Betul region. However, olivine is absent in basalt flows and dolerite dykes of Bassein region. This suggests a more evolved nature of the lava during the last phase of Deccan CFB eruption in and around Bassein area.

Plagioclase of Jabalpur flow exhibit solid solution from bytownite to labradorite, where anorthite content of micro-phenocryst range from  $\text{An}_{78-59}$  and that of groundmass from  $\text{An}_{56-54}$ . Plagioclase of Betul flow falls mainly within labradorite field with very limited solid solution, where the anorthite content of micro-phenocryst range from  $\text{An}_{64-42}$  and that of groundmass  $\sim \text{An}_{40}$ . Plagioclase of Betul dykes fall within labradorite field with very limited solid solution, where the anorthite content of micro-phenocryst range from  $\text{An}_{69-53}$  and that of groundmass from  $\text{An}_{67-50}$ . Plagioclase of Bassein flows falls within labradorite field with very limited solid solution, where the anorthite content of micro-phenocryst range from  $\text{An}_{69-53}$  and



that of groundmass from  $An_{50-48}$ . Plagioclase of Bassein dolerite dyke exhibits solid solution from labradorite to andesine, where the anorthite content of micro-phenocryst range from  $An_{75-28}$  and that of groundmass from  $An_{67-35}$ .

Clinopyroxene micro-phenocrysts of Jabalpur flows, Betul flows and dykes, and Bassein flows and dolerite fall within augite field showing increasing iron enrichment from core to rim as well as in groundmass. Few grains of clinopyroxene from Bassein dolerite are of pigeonite composition. Olivine micro-phenocrysts seen in Betul flows and dykes as well as in Jabalpur flows exhibit solid solution from hortonolite to hyalosiderite, where fosterite content range from  $Fo_{66-29}$ .

On the basis of Sr-Nd isotopic signature, Jabalpur flows can be distinctly divided into two groups: (i) upper flows with  $^{87}Sr/^{86}Sr$  (t) from 0.7041 to 0.7059 and  $\epsilon_{Nd}$  (t) from -1.4 to +4.4, thus showing close affinity to the Mahabaleshwar formation of the Southwestern Deccan stratigraphy, and (ii) lower flows with  $^{87}Sr/^{86}Sr$  (t) from 0.7079 to 0.7085 and  $\epsilon_{Nd}$  (t) from -2.5 to -1.3 showing close similarity with the common signature of Peng et al., 1994. The lower and upper flows are separated by a hiatus represented by the presence of 0.5 cm to 0.5 m thick red bowl.

The  $^{87}Sr/^{86}Sr$  (t) of Betul flows range from 0.7057 to 0.7063 and  $\epsilon_{Nd}$  (t) from -1.5 to +1.5, thus showing close affinity to the upper Poladpur formation. The dykes of Betul fall into two general types. (i)  $^{87}Sr/^{86}Sr$  (t) ranging from 0.7043 to 0.7048 and  $\epsilon_{Nd}$  (t) from +1.4 to +3.0, thus showing close similarity with the Mahabaleshwar formation, and (ii)  $^{87}Sr/^{86}Sr$  (t) ranging from 0.7046 to 0.7066 and  $\epsilon_{Nd}$  (t) from +0.9 to +2.3, thus showing close affinity to the upper Poladpur formation.

The  $^{87}Sr/^{86}Sr$  (t) of Bassein flows and dolerite dykes range from 0.7042 to 0.7055 and  $\epsilon_{Nd}$  (t) from -2.6 to +2.7, thus showing close affinity to the Mahabaleshwar formation.

It is inferred here that Jabalpur lower flows with MIX isotope signature may belong to the lower formations (Lonavala or Kalsubai) of the southwest Deccan CFB, whereas the upper flows show close resemblance to the Mahabaleshwar formation. Betul flows and one set of Betul dykes fall in the upper Poladpur formation field and these dykes are probably feeders to the associated flows. The Bassein flows and dolerite dykes, with similar Sr-Nd isotopic signatures, probably represent the last phase of Deccan CFB eruption. The Bassein dolerite dykes appear to be feeders to the Bassein flows.



**S06 – 295: Large Igneous Provinces in Gondwanaland**

***Alteration and Submergence of the Deccan Traps of Kachchh, Gujarat, India: Implications for the Role of Flood Basalt Volcanism in the India-Seychelles Break-up***

Souvik Mitra<sup>1</sup>; Saibal Gupta<sup>1</sup>; Satadru Bhattacharya<sup>2</sup>; Santanu Banerjee<sup>3</sup>; Prakash Chauhan<sup>3</sup>; Nirmala Jain<sup>3</sup>

Department of Geology and Geophysics, IIT Kharagpur, India<sup>1</sup>; Space Applications Centre (ISRO), Ahmedabad, India<sup>2</sup>; Department Of Earth Science, IIT Bombay, Mumbai, India<sup>3</sup>

The Deccan Trap volcanics are presumed to have originated from the Reunion hotspot 65 million years ago, and cover a major part of western and central India, particularly the states of Maharashtra and Gujarat. One of the most fascinating ongoing geological debates related to the Deccan Traps has been the relative role of a plume vs. tectonic component in driving the final phase of Gondwanaland break-up, and the creation of the western continental margin of India.

Proponents of the plume hypothesis have suggested that impingement of the Reunion plume at the base of the Indian continental lithosphere ultimately resulted in the break-up of India from Seychelles, thus culminating the dismemberment of India from the last vestiges of Gondwanaland. Opponents of the plume model and its role in the break-up have commonly cited the absence of any evidence of pre-volcanism uplift along the Indian west coast that is expected in active, plume-driven rift settings. Indeed, it has been argued that much of the uplift now noted along the western coast of India happened subsequent to the Deccan eruption, as lateritised basalt tops, representing palaeo-surfaces, testify to uplift subsequent, and not prior to, the eruption of the Deccan.

In the present study area in the district of Kachchh, Gujarat, basaltic flows of the Deccan Traps overlie the Late Jurassic Bhuj Formation and are unconformably overlain by the Palaeocene Matanumadh Formation. The unconformity is expressed in the form of a deeply weathered profile in the upper part of the basalt. This study is based on the alteration pattern in the uppermost basalt layers, and in some of the overlying sediments, as a monitor of the Cenozoic tectonics of the Indian west coast. The study concentrates on an E-W trending traverse extending from the village of Matanumadh to Lakpat. Many of the flows are extensively altered, forming the 'onion shells' characteristic spheroidally weathered basalts, with the unaltered parts of the traps occurring generally further south. The unaltered basalts initially contain olivine, plagioclase and pyroxene. Spectroscopic studies show that successively, the igneous mineralogy is replaced by smectites, and then by kaolinite, and finally by a laterite layer on top. This sequence of clay minerals appears to indicate a warm and humid climatic regime in the interregnum that followed Deccan volcanism. The weathered basalts are subsequently overlain by tuffaceous shales and sandstones of the Matanumadh Formation, and then in turn by the lignite-rich Naredi Formation. While the Matanumadh Formation is believed to have formed in sparsely distributed swamps, the Naredi formation was deposited in shallow lagoonal environments of early Eocene age. Overlying sedimentary successions suggest deeper water facies, indicating further deepening of the basin, till uplift and re-emergence of Kachchh occurred in the post-Pliocene time, possibly driven by compressional tectonics related to the India-Eurasia collision.

Lateritisation of basalt tops occurs under sub-aerial conditions with minimal erosion. In Kachchh, it appears that subsidence, and not uplift, occurred after a phase of minimal erosion and sedimentation. This is in complete contrast to what apparently happened elsewhere along the western Indian coast, where uplift, rather than subsidence, predominated. What caused this subsidence in the Kachchh region? Since this subsidence did not take place immediately following the volcanism, but after a period of quiescence that allowed lateritisation to take place, it cannot be related to the flood basalt volcanism. Recent age data for the break-up of India from Seychelles vis-a-vis Deccan volcanism appear to indicate two stages of rifting; one occurring prior to (~ 71 Ma), and possibly also continued into the acme of flood



basalt magmatism (~ 65 Ma), and another phase that occurred 2-3 Ma after cessation of Deccan volcanism (~ 62 Ma). This last phase has been correlated with the final rifting off of Seychelles from the Laxmi Ridge, which is believed to be a continental sliver off the Indian west coast. It is possible that rifting related to this final phase of break-off continued into the Kachchh basin, which was inherently susceptible owing to its inherited Mesozoic rifting history. Other parts of the Indian west coast had already rifted off from the Laxmi Ridge during the earlier phase of extension, and were therefore not affected by the rift system associated with the later phase of break-off. The geographic configuration of this later rifting, and how it relates to the Laxmi Ridge-Seychelles break-off remain uncertain, but this remains the only explanation for the variable topography and Cenozoic geological history of the Kachchh region of the Deccan Volcanic Province and the remainder of the Trap-occupied Indian west coast.



**S06 – 300: Large Igneous Provinces in Gondwanaland**

***The Links between Large Igneous Provinces and Environmental Change; Evidence Reviewed from Antarctica***

Bryan Storey

Gateway Antarctica, University of Canterbury, New Zealand

Earth history is punctuated by events during which large volumes of predominantly mafic magmas were generated and emplaced by processes that are generally accepted as being, unrelated to 'normal' sea-floor spreading and subduction processes. These events form large igneous provinces (LIPs) which are best preserved in the Mesozoic and Cenozoic where they occur as continental and ocean basin flood basalts, giant radiating dyke swarms, volcanic rifted margins, oceanic plateaus, submarine ridges, and seamount chains. The Mesozoic history of Antarctica is no exception in that a number of different igneous provinces were emplaced during the initial break-up and continued disintegration of Gondwana, leading to the isolation of Antarctica in a polar position. The environmental impact of large igneous province formation on the Earth System is debated. Large igneous province eruptions may be capable of causing environmental and climatic effects including global warming, oceanic anoxia and/or increased oceanic fertilization, calcification crises, mass extinction and release of gas hydrates. This review explores the links between the emplacement of large igneous provinces in Antarctica and related environmental and climatic changes during the Mesozoic and Cenozoic.



**S06 – 338: Large Igneous Provinces in Gondwanaland**

***Morphometric Analysis, Drainage Pattern and Degradation Status for the Quaternary and Older Cinder Cones in the Large Igneous Province, Saudi Arabia***

Manoj Mukhopadhyay<sup>1</sup>; Faisal K Zaidi<sup>1</sup>; Abdulaziz Laboun<sup>1</sup>

King Saud University, Riyadh, Saudi Arabia<sup>1</sup>

Volcanic eruptions in the Large Igneous Province (LIP) in western Saudi Arabia are mainly found in two distinct tectonic settings: a rather well defined, less than 10 Ma old volcanic line in an extensional setting, extending north-south for ~300 km, called the Makkah-Madinah-Nafud LINE (MMNL) that contains mildly alkaline lavas (AOB). MMNL lies adjacent to primitive but more alkaline lavas in the harrats (volcanic fields) of Kishb, Hadan and Buqum (HKHB). Detailed morphometric estimates for fairly large-sized 87 scoria cones for MMNL and HKHB are given here first. The estimated parameters are: cone height (Hco), cone basal diameter (Wco), crater diameter (Wcr), average cone slope angle (S), their mutual inter-relations plus the cone volume. The parameters are estimated using the classical method. Their respective regression relations are also established and their gross results compared between MMNL and HKHB. Larger cinder cones are characterized by angular asymmetry at their base angles that generally varies in N-S direction for MMNL. This is supportive for a hot spot trace model for LIP. Results demonstrate that the cinder cone character for MMNL is more akin to an extensional setting, which helps identifying the ongoing process of the juvenile continental rift formation. GIS-based river drainage pattern and representative elevation profiles taken across both MMNL and HKHB are taken up next to demonstrate the exerting relationship of the scoria cone morphometry on the drainage network. Drainage network is wider eastward for MMNL; this is mostly synchronous to gentler topography as compared to that washing its western slopes. River drainage network for HKHB typically shows concentric pattern for its north and south parts but is drastically different for the older Hadan Volcanic Field (~28-15 Ma). Combined analysis of the scoria cone morphometry, elevation character and drainage network lead us to speculate for an initial relationship between the age of cinder cones and their degradation status for this part of LIP, Saudi Arabia. Finally, based on the above results we also estimate both the drainage frequency and texture for the volcanic fields in MMNL and HKHB. These results have potential applications in geothermal reserve estimates.



**S06 – 345: Large Igneous Provinces in Gondwanaland**

***Reverse Volcanic Stratigraphy In the ~2.5 Ga Dongargarh Large Igneous Province, Central India: Implications for Rift History***

Sarajit Sensarma<sup>1</sup>; D Paul<sup>2</sup>

University of Lucknow, Lucknow, India<sup>1</sup>; Indian Institute of Technology (IIT), Kanpur, India<sup>2</sup>

The temporal changes in magma composition, spatial distribution, and volume within the same tectonothermal event, as in large igneous provinces (LIPs), can provide powerful geodynamic constraints. The mafic horizons in volcanic sequences in rift-related LIPs are particularly useful to study the mode and temporal evolution of magma in an extensional regime and associated rifting. The ~2.5 Ga Dongargarh bimodal large igneous province (LIP) in the central Indian Craton is one of the rarest bimodal LIP known to date, previously considered absent from the geological record (Bryan et al., 2002). The stratigraphic, geochemical and petrological characteristics, combined with some understanding of sedimentary processes in the Dongargarh province suggest close relation between magmatism and extension, consistent with the transition from progressive opening of continental rifts that failed to open into sea.

The Dongargarh bimodal LIP comprise sub-equal volumes of near-coeval rhyolites ( $\text{SiO}_2 > 74$  wt%, ~ 4 km thick) and basalts in a zone of tectonomagmatic extension. The two main basaltic horizons (Pitepani and Sitagota volcanics), interspersed with sedimentary horizons, occur successively towards top. The top most horizon (Mangikhuta volcanics) containing Fe-rich tholeiitic andesite, compositionally similar to icelandite, represents the terminal phase of mafic volcanic activity in the province. Intrinsic similarities of the high Mg- low Mg basalts suites that have erupted in repetition, i.e. similar batch of two different mantle-derived magmas of two main basaltic units, are remarkable. The  $\text{SiO}_2$  and incompatible trace elements contributions from near-coeval rhyolite melt decline from 15-20% in early high-Mg basalts (MgO ~7.5 wt % at a given  $\text{SiO}_2$  54.5 wt% ; ~ 1 km thick) to ~10% in the younger (~3 km) and more MgO-rich basalts/picrite (MgO > 10 wt%,  $\text{SiO}_2$  48-50 wt %). Picritic rocks are characterized with pyroxene spinifex textures. The low-Mg tholeiite in the province may have crystallized at a lower magma temperature of ~1160°C, whereas the picritic parental magma (highest MgO ~ 15.3 wt %) may have crystallized at 1370°C. This indicates a well developed magmatic system beneath Dongargarh, where progressively younger and more voluminous mafic magmas erupted before undergoing significant fractionation (to produce Fe-rich andesites) with increasing opening of the rift.

Typically, high magnesian rocks are found in early basalts of mafic LIP successions such as Karoo, Deccan, West Greenland and East Greenland. However, a "reversed stratigraphy" characterized by low to high magnesian basaltic units in the sequence is observed in the Dongargarh province. This feature is not commonly known except for the Baltic Shield and the Siberian Traps. The temporal changes in volume and composition of lavas in the Dongargarh province is related to progressive thinning of crust during the transition from continental rifting to incipient sea-floor opening in a single, continuous extensional event at or about the Neoproterozoic-Palaeoproterozoic transition. We suggest that volume of rift-related LIP magmatism depends not only on the mantle temperature but also on the rift history.



**S06 – 361: Large Igneous Provinces in Gondwanaland**

***Tectonic History of the Conrad Rise and Magnetic Anomalies in the Southern Indian Ocean***

Nogi Y.<sup>1</sup>; Sato H.<sup>2</sup>; Sato T.<sup>3</sup>

National Institute of Polar Research, Tokyo, Japan<sup>1</sup>; School of Business Administration, Senshu University, Japan<sup>2</sup>; National Institute Of Advanced Industrial Science And Technology, Japan<sup>3</sup>

The Conrad Rise is regarded as one of the LIPs (large igneous provinces) in the Indian Ocean. However, hot spot tracks associated with the Conrad Rise are not clearly established and the origin of the Conrad Rise is not well demonstrated. Moreover, the breakup process in the Southern Indian Ocean still remains poor-defined because of the sparse observations in this area. Total intensity and vector geomagnetic anomaly data as well as swath bathymetry data obtained to understand the tectonic history of the Conrad Rise related to the Gondwana breakup in the Southern Indian Ocean. The dredge rock samplings were also conducted at the Ob and Lena Seamounts in the Conrad Rise.

Sediment wave structures influenced by the Antarctic Circumpolar Current are found in the southwestern slope of the Conrad rise. The Ob Seamount in the east of the Conrad Rise exhibits flat top bathymetric features with about 250m. The Lena Seamount also presents flat top bathymetric features with about 450m. Moreover, approximately one-third of the dredged rock samples at the Ob Seamount are of metamorphic origin, whereas half of recovered samples are volcanic rocks. The age of dredged basaltic samples at the Ob Seamount indicate 34-26 Ma.

Magnetic anomaly signals, most likely indicating Mesozoic magnetic anomaly sequence, are obtained almost parallel to the west of WNW-ESE trending lineaments just to the south of Conrad Rise inferred from satellite gravity anomalies. Most of the strikes of magnetic structures indicate NNE-SSW trends, and are almost perpendicular to the WNW-ESE trending lineaments. Mesozoic sequence magnetic anomalies with mostly WNW-ESE strikes are also observed along the NNE-SSW trending lineaments between the south of the Conrad Rise and Gunnerus Ridge. Magnetic anomalies originated from Cretaceous normal polarity superchron are found in these profiles, although magnetic anomaly C34 has been identified just to the north of the Conrad Rise. However Mesozoic sequence magnetic anomalies are only observed in the west side of the WNW-ESE trending lineaments just to the south of Conrad Rise and not detected to the east of Cretaceous normal superchron signals. These results show that counter part of Mesozoic sequence magnetic anomalies in the south of Conrad Rise would be found in the East Enderby Basin, off East Antarctica. NNE-SSW trending magnetic structures, which are similar to those obtained just to the south of Conrad Rise, are found off East Antarctica in the East Enderby Basin. However, some of the strikes show almost E-W orientations.

Moreover, the thickness of the crust estimated by gravity and bathymetric data increase just to the north of the Conrad Rise and clear magnetic anomaly signals considered to be magnetic anomaly C34 in this region may indicate continental-ocean boundaries while taking dredged continental origin rock samples at the Ob Seamount into account. Therefore, magnetic anomaly C34 identified in the Indian Ocean must be reconsidered. These suggest complicated ridge reorganization occurred during initial break up of Gondwana in the Indian Ocean.



## S06 – 366: Large Igneous Provinces in Gondwanaland

### *Cretaceous Volcanic Event in Peninsular India and Adjacent Oceanic Regions*

Misra K S<sup>1</sup>; Misra A<sup>2</sup>

University of Petroleum and Energy Studies, Dehradun, India<sup>1</sup>; Kumaun University, Nainital, India<sup>2</sup>

Cretaceous volcanism is the most significant geological event in the Phanerozoic history of peninsular India. Attempts have been made earlier, to understand volcanism, in localized areas by using different data sets. We investigated the causes for such an enormous outpouring of lava sequences, their stratigraphy, regional correlation both on land and oceans, pre- and post-tectonic events and sedimentation, magma generation and eruption, and transportation mechanism of lava flows.

Geological information obtained by extensive field mapping assisted by aerial photographs and high resolution satellite images; interpretation of aeromagnetic, gravity and seismic data sets and logs of approximately hundred drill holes is integrated. Field mapping and remote sensing images helped in establishing stratigraphy, regional disposition, identification of effusive centres and zones, remnants of lava channels and tubes and other physical volcanic features. Dyke swarms, dyke clusters and individual dykes are also mapped along with faults and their surface expressions in the form of lineaments. Aeromagnetic data was particularly useful in identification of basement faults and extent of sedimentary basins, while their vertical gradient derivative was extremely useful in mapping dykes and faults in areas covered by Tertiary rocks and Quaternary alluvium. High resolution satellite gravity data in oceanic region has been immensely helpful in establishing lateral continuity of several oceanic ridges. Seismic data from sedimentary basins has not only helped in extending volcanic units from land to oceanic regions but also cross section of oceanic features. Processing of seismic data by Pre-Stacking and Depth Migration (PSDM) and Pre-Stacking and Time Migration (PSTM) techniques have considerably improved the resolution of vertical profiles and provided geological details below the volcanic units. Drill hole logs have established the occurrence of lava sequences in subsurface, off-shore and oceanic regions. They have also confirmed the findings from other data sets; the thickness of volcanic units and their relative ages from interbedded fossil bearing sedimentary rocks.

Various geological evidences suggest that extensional tectonics prevailed since the beginning of Carboniferous period, during which rift and grabens have developed and accompanying normal faults have given rise to elongated basins. These basins formed locales for deposition of thick sedimentary sequences with coal seams in land areas. Continued extensional tectonics resulted in downward propagation of faults and commencement of decompression melting during the Cretaceous period. Several pulses of enormous volcanism are inter-layered with sediments and form volcano-sedimentary succession. This succession represents fossil record of approximately 90 million years, from the beginning to the end of Cretaceous. It is also logged in all the petroliferous basins in and around peninsular India and forms the re-laid floor over which complete sequence of Tertiary rocks has been deposited. Furthermore, this succession along with overlying Tertiary and underlying older Mesozoic successions continue laterally from land areas to oceanic regions and covers entire Bay of Bengal and the Arabian Sea. Although the entire succession is deformed by extensional tectonics, however, the Mesozoic rocks are more severely deformed than the Tertiary. The effect of these faults progressively diminishes in overlying younger rocks. Most of these faults show upward or downward convergence, intersecting each other in the Oligocene stratigraphic horizons, thus forming an hour-glass structure. The basal portions of these upward converging faults are occupied by several oceanic ridges. These ridges are characterized by gravity lows, being composed of felsic component of volcanism and represent remnants of effusive zones. Geological evidences suggest that these ridges are of tectonic origin and have cropped up all along their length during terminal part of Cretaceous period. They meander gradually in northern part and curve towards west in the southern part. Prolific growth of coral reef complexes is also observed on volcanic platform, which indicates gradual subsidence of certain blocks. The tectonic



grain of the ocean basins is thus defined by elongated basins and ridges which have also originated at Cretaceous-Tertiary boundary.

Volcanic cones, craters, calderas are identified by their characteristic shape. They are best exposed in areas where overlying flows or Tertiary Gaj beds are eroded off recently. Multiple centres and zones have thus emerged from the study. Remnants of lava channels and tubes are mapped from Deccan region of Maharashtra, Malwa in Madhya Pradesh, Saurashtra in Gujarat and Rajahmundry in Andhra Pradesh. Emanating pattern has helped in identifying, not only the effusive centers but also flow direction of lava. This has also established presence of multi-tier volcanic fields at different levels which are located at widely separated places.

Cretaceous period also experienced widespread emplacement of dyke swarms, dyke clusters and dykes in several parts of peninsular India. Parallel disposition of dyke swarms with the rifts and grabens exhibits mutual genetic relationship. Dyke clusters are located around major igneous complexes in both concentric and radial pattern, while dykes exhibit tectonic control. In early phase the volcanism was of felsic nature during which inter-layered rhyolite and obsidian flows with occasional alkaline trachyte have erupted. Tectonic deformation and explosive activity was also associated with this phase. This sequence shows moderate to steep dips and is best exposed in coastal belts of Saurashtra, Maharashtra and Karnataka. This unit is overlain by tholeiite flows which are separated by red tuffs, more common in western part of Deccan region, while inter-trappean sedimentary beds are more pronounced in eastern part. Furthermore, individual flows are having megacrystic flows, characteristic jointing and unique textural details, which have helped in establishing lava stratigraphy.

The study has led us to suggest that the Cretaceous volcanism was rampant in spatially wide spread areas, basins and oceanic regions. Continued extensional tectonics resulted in development of rift and grabens, decompression melting, magma generation and multi-central eruption. Large scale transportation has taken place by lava channels and tubes.

Several units inter-layered with complete Cretaceous sedimentary succession and disposition of oceanic ridges do not support the idea of hot spot volcanism and movement of Indian plate as has been proposed earlier.



**S06 – 392: Large Igneous Provinces in Gondwanaland**

***Petrological and Geochemical Significance of the Ultramafic Rocks of the Indo-Myanmar Ophiolite Belt, Northeastern India***

Nirupama Kh<sup>1</sup>; Maibam B<sup>1</sup>; Foley S.F<sup>2</sup>

Manipur University, Imphal, India<sup>1</sup>; Macquarie University, Australia<sup>2</sup>

**Background:**

The ophiolite belt of Indo-Myanmar Range which evolved as a result of obduction of the Indian and Burmese plates forms a belt extending about 200 km from Phokhpur (Nagaland state) in the north to Moreh (Manipur state) in the south. The rootless allochthonous ophiolitic belt consists of different igneous, metamorphic and sedimentary sequences. Ultramafic rocks forming the main component of the belt consists of mantle sequence of tectonised peridotites with mafic intrusives, volcanic rocks, pelagic sediments. In general, localized along the suture zones, ophiolites and associated ophiolitic melanges witness the closure of an oceanic domain during continent-continent convergence. The southern part of the belt falling in the Manipur state is dominated by mantle peridotites with minor basic rocks and extrusive volcanics. In contrast the northern part which falls in the Nagaland is represented by peridotite, cumulate mafic-ultramafic, mafic volcanics, eclogite, glaucophane schist, amphibolite and late felsic intrusives. The abundant mantle fragments and variable size provide an opportunity to study the mantle processes. Considering the difference in the nature of distribution and associated lithounits in the entire ophiolite belt, an understanding of the origin and nature of the ultramafite sequence is necessary. It is possible that variable degrees of melting may have preserved some compositional characteristics of the mantle prior to the subduction process. In general, as the ultramafic rocks are prone to serpentization, characterization of the relict mineral phases in these rocks would give a clear picture of the mantle processes.

**Objective:**

In this study we use whole rock geochemical and phase chemistry data of the mantle sequence ultramafic rocks of the Indo-Myanmar Ophiolite Belt (IMOB) to determine the petrogenesis and tectonic setting of the ophiolite. The aim of the proposed study is to carry out compositional characterization of the mineral phases and rocks, establish crystallisation environment and probable mantle processes of the rock and tectonic implication of the ultramafites.

**Analytical methods:**

Representative samples of ultramafic rocks were collected from the central (Ukhrul District, Manipur) and northern (Phek District, Nagaland) parts of the ophiolite belt. Thin sections were studied by petrological microscope. Major element composition of the mineral phases was determined by electron microprobe Jeol JXA 8900 RL with wavelength dispersive mode at the University of Mainz, Germany.

Olivine, orthopyroxene, clinopyroxene, and spinel were analyzed using an accelerating potential of 20 kV, a beam current of 12 nA, and a spot size of 2 micrometres. Counting times varied between 20 and 80 s on the peak and 10 and 40 s on the background. We used natural minerals and oxides (Si, Ti, Al, Fe, Mg, Mn, Cr and Zn) and pure element standards (V, Co) as standards. The oxide minerals were measured with five WDS spectrometers at 20 kV acceleration voltage, a probe current of 12 or 20 nA and either a focussed beam or a beam diameter of 2  $\mu\text{m}$ . The spinel stoichiometry was calculated assuming that all Ti is in the ulvöspinel component and that all V is present as  $\text{Fe}_7\text{V}_2\text{O}_{10}$ . Ferrous and ferric irons were then calculated assuming stoichiometry.

**Results and conclusion:**

Mineralogical study of peridotite samples reveal olivine, orthopyroxene, clinopyroxene and spinel as the primary mineral phases and serpentine as the most common secondary mineral, altered mainly from



olivine and orthopyroxene. Composition of olivine from EPMA analysis gives a consistent (Fo ~90) for Manipur samples and (Fo 84-94) for samples of Nagaland. Clinopyroxene composition for the two set of samples are ( $\text{En}_{47-49}\text{Fs}_{4-5}\text{Wo}_{47-49}$ ) and ( $\text{En}_{32-49}\text{Fs}_{7-23}\text{Wo}_{41-50}$ ) respectively. Orthopyroxene value ranges from ( $\text{En}_{88-90}\text{Fs}_{9-11}\text{Wo}_{0.8-2}$ ) in samples from Manipur and the range is ( $\text{En}_{88-90}\text{Fs}_{8.5-10}\text{Wo}_{0.8-5}$ ) in Nagaland samples. Equilibrium temperatures for the first set of samples were calculated between 1174-1206°C using two-pyroxene thermometry. For the samples from Nagaland, temperature was calculated between 1000-1383°C using spinel-olivine geothermometry. Oxygen fugacity ( $f\text{O}_2$ ) was calculated between -1.32 to -3.46 QFM. The studied ultramafic rocks were formed due to various degree of melting ranging between 0.5 to 11%. Various tectonic discrimination diagrams show that majority of the samples were found to be plotted within and in the margin of abyssal peridotite field. From our present study, we can conclude that peridotites from both sections of the IMOB were crystallized in upper mantle environment and had experienced multi stage melting history representing the heterogeneous character of the preserved oceanic lithosphere.



## S06 – 434: Large Igneous Provinces in Gondwanaland

### ***The Ferrar Large Igneous Province: Field, Geochemical, and Geochronological Constraints on Emplacement Order of Components of the Magmatic System***

David H. Elliot<sup>1</sup>; Thomas H. Fleming<sup>2</sup>

School of Earth Sciences and Byrd Polar Research Center, Ohio State University, Columbus, USA<sup>1</sup>;  
Department of Earth Sciences, Southern Connecticut State University, New Haven, CT 06515, USA<sup>2</sup>

Most large igneous provinces, particularly those associated with Gondwana break-up, include major sill complexes as well as flood basalt fields. In the Ferrar Province, which extends for 4000 km from the Theron Mountains to southeastern Australasia, geochronological data document a punctuated episode of magmatic activity (<0.4 M.y) but do not yield a clear temporal distinction between the lavas and sills; ongoing geochronological investigations may answer questions about lava eruption ages. Notwithstanding, within the resolution of existing geochronology, physical and chemical relationships play an important role in deciphering the pathways and order of emplacement of various components of the Ferrar magmatic system.

Chemically, Ferrar rocks are separated into two types. The first, designated the MFCT, comprises the bulk of the Ferrar province and the majority of all analyzed rocks, and shows a systematic range of geochemical compositions ( $Sr_i$  ~0.709-0.712; MgO ~9.3- 2.6 wt%; Zr ~60-175 ppm), which can be related by fractional crystallization accompanied by ~5% crustal assimilation. The remaining 1% (by volume), designated the SPCT, has a distinct, evolved, and restricted composition ( $Sr_i$  ~0.7095; MgO ~2.3 wt%; Zr ~230 ppm), which lies off the MFCT chemical trends. The SPCT, occurring as the stratigraphically youngest Ferrar lavas in the Transantarctic Mountains and as minor sills in the Theron Mountains and Whichaway Nunataks, extends over a distance of 3000 km. Intrusive equivalents of the SPCT lavas are absent through most of the TAM. The MFCT rocks are the principal focus of this investigation.

Throughout much of the Transantarctic Mountains, sills, with cumulative thickness of 1500 m or more, occur almost exclusively in the thick (2-2.5 km) Devonian-Triassic sedimentary sequence (Beacon Supergroup), which is capped locally by 500+ m of Ferrar lavas. It has been suggested that sill-fed dikes were the likely feeders for flood basalt eruptions. Further, for south Victoria Land (SVL), it has been proposed that the most chemically evolved Ferrar rocks were erupted first as lavas, and sills were emplaced at progressively greater depth as increasingly more magnesian magmas and crystal mushes were injected into supracrustal and finally basement rocks. This order of emplacement is locally supported in SVL where more magnesian dikes cross cut more chemically evolved sills. In north Victoria Land (NVL), however, field evidence suggests the MFCT lavas must have been erupted prior to the sills, in order to create the overburden needed for emplacement at shallow depths of thick sills (100+ m), lacking vesicles, into a thin (100 m) Upper Triassic-Lower Jurassic sedimentary sequence that overlies basement rocks. A similar situation, a thin sedimentary succession, is present in the Prince Albert Mountains (SVL).

In NVL most MFCT lavas have MgO between 6-8 wt% with a few as low as 4.5 wt%, whereas analyzed chilled margins of sills in the same region tend to be more evolved with MgO ranging from 3.7-5.6 wt%, plus a single sill with 7.2 wt%. In the Prince Albert Mountains, lava and sill compositions overlap (3.9-7.3 wt% MgO). In the greater Dry Valleys region (SVL), lavas at Carapace Nunatak range from 3.6-6.7 wt% MgO, whereas chilled margins of sills range from about 4.2 to 7.2 wt% MgO. In the Queen Alexandra Range, central Transantarctic Mountains (CTM), lavas are almost exclusively within the range 2.6-5.7 wt% MgO, and most are strongly evolved; sills in the region range from 4.5-9.2 wt% MgO. In the Otway Massif region (head of the Shackleton Glacier, CTM) most lavas are strongly evolved (2.7-3.4 wt% MgO); sills in the Shackleton Glacier region range from 4.3-7.3 wt% MgO and do not display a relationship with stratigraphy. Nowhere do lavas show unequivocal systematic temporal change in MgO, and notably in



CTM the initial thin flow is the most mafic (7.5-8.0 wt % MgO); one flow in the upper third is moderately mafic. Olivine-bearing dolerite sills (n=6), with chilled margins ~9 wt % MgO, are widely scattered in the province and occur either in basement granite or low in the stratigraphic section. Sills emplaced in basement rocks or Devonian and Permian strata are thicker (100-200 m) and more regular. Sills with orthopyroxene crystal-mush tongues are not known outside the Dry Valleys except possibly the Warren Range (SVL).

No province-wide systematic relationship is apparent between compositions of lavas and chilled margins of sills; furthermore NVL and CTM geochemical data do not conform well to either of the emplacement hypotheses noted above. Nevertheless, in CTM most lavas are significantly more evolved than the sills; within the sills there is no clear relationship between MgO and stratigraphic position, although some less evolved compositions occur at relatively high stratigraphic levels. In SVL compositional overlap is almost complete; locally, cross-cutting relations show that more mafic sills and sheets cut less mafic compositions. In NVL the geochemical relations between lavas and sills are the inverse of those advocated for SVL. Interpretation of sill relationships to stratigraphy is complicated by sills that exchange stratigraphic positions or climb stratigraphically. The SPCT lavas overlie sills that have only MFCT compositions, and demonstrate that magma pathways other than subjacent sills existed. Further, no CTM sill has cumulate bodies suggesting evolution to yield MFCT lavas with MgO as low as 2.6 wt%. Factors affecting magma emplacement include magma density, lithostatic pressure, overpressures required for lateral emplacement, and rock physical properties; when and where the evolving source was tapped may play an equal role in the emplacement order. Further, detailed work on the sills may show whether crystallization might have yielded lower density residual and evolved liquids that could have migrated and formed distal fingers of sills, or migrated to higher stratigraphic levels, or were erupted at the surface.



**S06 – 447: Large Igneous Provinces in Gondwanaland**

***Geodynamics of Malani Silicic Large Igneous Province (SLIP)***

Sharma Kamal Kant

Government Postgraduate College, Sirohi, Rajasthan, India

The Malani activity took place between ~750-770 Ma post-dating the Erinpura granite and closed prior to Marwar Supergroup sedimentation in the northwestern India. The Malani volcanism occurred on land. The Malani rocks are undeformed and do not show any type of regional metamorphism. The Malanis are bimodal in character with a dominant silicic volcanism with initial minor basaltic flows. The volcanism resulted in ignimbrite eruptions, rhyolite flows, hot avalanches and ash fall eruptions through multiple fissure/rift systems that developed in the intraplate tectonic setting. This was followed by granite plutonism and terminal felsic/silicic dykes. The Malani volcano-plutonic province is spread over approximately 50,000 km<sup>2</sup> in north-western Indian shield. Besides this, Malani activity is reported from Sind Province of Pakistan, Kutch, Madagascar and Seychelles. The entire region of Malani activity was more than 100,000 km<sup>2</sup> during Neoproterozoic time. Thus, The Malani represents an example of Silicic Large Igneous Province (SLIP) in the region.

The northwestern Indian shield evolved through orogenic, anorogenic, magmatic, granulite exhumation phases during the Precambrian time. The Aravalli, Delhi and Sirohi orogeny show the compressional tectonic regime in the shield. The western Indian shield was affected by the strong thermal event at around 1000 Ma, marking beginning of Rodinia amalgamation process in the region. The compressional tectonic regime continued up to 850 Ma, signifying completion of Rodinia Assembly in the northwestern Indian shield. The crust was thick and remained thermally insulated for a long time. This caused heat build up in silicic crust, which resulted extensional tectonics and intraplate anorogenic magmatism. The splitting of Rodinia supercontinent led to the development of intraplate anorogenic rift magmatism on the northwestern Indian shield, Madagascar, Seychelles and other landmasses.



**S06 – 459: Large Igneous Provinces in Gondwanaland**

***Mantle Melting Mechanisms and Mapping Shallow Magma Chambers in Deccan Volcanic Province and Other Large Igneous Provinces***

K. Vijaya Kumar

Swami Ramanand Teerth Marathwada University (SRTM) University, Nanded, Maharashtra, India

Continental Flood Basalts (CFBs) are the principal expressions of rapid basaltic magmatism on the Earth and constitute a significant member of Large Igneous Province (LIP) clan. Most erupted basaltic lavas in CFBs do not represent mantle-derived primary melt compositions, but are end products of complex magma chamber processes. Even the erupted primary basalt in these CFBs represents the average composition of aggregated partial melts derived from mantle. Experimental evidence suggests that the depth of melting in CFB provinces could be as deep as 70-100 km; for this pressure range, the primary liquids are picritic. Although minor picritic lavas occur in flood basalt provinces, most of the basalts are quartz tholeiites with fairly constant MgO contents (5-8 wt%). The geochemical hiatus between the predicted picritic composition and observed tholeiitic composition is interpreted mainly in terms of polybaric crystal fractionation.

Although crystal fractionation occurs chiefly at the crust-mantle boundary, which acts as a density and rheological barrier for high-Mg melts, gabbroic fractionation at shallower depths has equal importance in controlling the erupted bulk-rock compositions. High resolution sampling in semi-continuously exposed basalt column in the southeast DVP allowed us to model mantle-melting mechanisms and shallow magma chambers processes beneath Deccan Volcanic Province (DVP) in particular and LIPs in general. The Ajanta, Chikhli, Buldhana and Karanja formations crop out in the present study area with increasing elevation.

Modeling of geochemistry aided by field relations and petrography helped us to recognize dynamic melting of the mantle source, and magma chamber crystal fractionation, assimilation, addition of new magmas, and attainment of steady-state in the erupted basalts of the DVP. REE patterns in the erupted basalts in the DVP reflect dynamic partial fusion of the mantle. Further, a convex-upward REE pattern for the (calculated) mantle source also suggests a two-stage mantle melting. Low degrees of melting in the first stage resulted in alkaline magmas, and partial fusion of the residues in the second stage produced tholeiitic basalts. It is well established that during formation of the Deccan basalts, the earliest episode produced alkaline magmas whereas later ones gave rise to tholeiitic basalts. Our model predicts that the tholeiitic basalts were derived from the residual mantle left after the removal of small proportions of alkaline melt. Such a model indicates that the Deccan mantle might have undergone dynamic melting to generate both LREE-enriched and -depleted basalts, and explains the REE crossings measured in the Deccan basalts.

Further, the erupted basalts in these formations underwent differentiation either on the surface or in shallow magma chambers at ~ 2 kbar corresponding to 6 km depth. Many studies have shown that final pressures of equilibrium of basaltic liquids in the CFB provinces were attained around 3.8 kbar (12.2 km, considered to represent depth of brittle/ductile transition in the crust). The contrasting pressures of final equilibration in the DVP and other CFB provinces need to be assessed in order to understand continental crustal structure and basement composition. Highly heterogeneous crust beneath the Deccan basalts, causing density heterogeneities, could be one of the factors for the ponding of the magma at these shallower depths. The predicted bottom-to-top sequence within the shallow magma chambers is olivine gabbro (troctolite), leucogabbro (anorthosite), oxide-apatite gabbro. The present study suggests that anorthosites and oxide-apatite-rich gabbros are an integral part of the cumulate stratigraphy beneath the erupted mafic lavas. The Phenai Mata complex, a prominent shallow-level magma chamber exposed in the DVP, essentially contains the predicted layered sequence. We suggest that dynamic melting of the



## XII International Symposium on Antarctic Earth Sciences

13 - 17 July 2015, Goa, India



mantle may be relevant to a fuller understanding of LIPs in general and Deccan geochemistry in particular. Spatial and temporal variations in the geochemistry of a semi-continuous extrusive basaltic section of Deccan traps record progressive changes in mantle melting and crustal filtration and are relevant to understand magmatism in Large Igneous Provinces.



**S06 – 471: Large Igneous Provinces in Gondwanaland**

***Large Igneous Province Formation Offshore Antarctica and the Influence on Paleobathymetry***

Joanne Whittaker<sup>1</sup>; Maria Seton<sup>2</sup>; Ashby Cooper<sup>1</sup>

Institute for Marine and Antarctic Studies, University of Tasmania, Hobart, TAS, Australia<sup>1</sup>; School of Geoscience, University of Sydney, Sydney, NSW, Australia<sup>2</sup>

Global plate tectonic reconstructions of mid-ocean ridges, Large Igneous Provinces (LIPs), and plumes have demonstrated that the formation of LIPs repeatedly occur at specific ridge-plume interaction locations over periods of tens of millions of years. These associations indicate a strong feedback between the dynamics of slowly migrating ridges and deeply-sourced plumes, generated above Large Low Shear Velocity Provinces, at a global scale (Whittaker et al., 2015).

In the present-day southern Indian Ocean (offshore eastern Antarctica) lies a line of these ridge-plume interaction locations where the Bouvet, Marion and Kerguelen plumes interact with the Southwest Indian mid-ocean ridge, and the pre-43 Ma Southeast Indian mid-ocean ridge. Plate reconstructions of the southern Indian Ocean reveal that Antarctica (as part of West Gondwana), was located immediately over the absolute locations of these interaction locations in the Jurassic. As West Gondwana broke apart, continental Antarctica slowly moved away from this stationary line of ridge-plume interactions, with the newly formed oceanic crust of the southern Indian and Atlantic Oceans overlying these locations instead. Thus, since the Jurassic parts of East Antarctica and the adjacent Atlantic and Indian oceans have been repeatedly affected by the formation of LIPs at ridge-plume interactions. In order to assess the time-varying size, shape, location and depth of the LIPs in this region, we present maps of predicted paleobathymetry of the circum-Antarctic oceans. We focus on computing a more accurate estimation of the paleobathymetry of oceanic LIPs by taking into account the temporal plume swell that affects the wider region around each LIP, with a likely significant affect on the surface height of both onshore and offshore regions. Accurate reconstructions of paleobathymetry around Antarctica are important for understanding changing patterns of paleo-ocean circulation and climate.



## S06 – 507: Large Igneous Provinces in Gondwanaland

### *Depth Origin of Mantle Plumes: Inference from Seismology, Mineralogy and Isotopes*

Subrata Das Sharma<sup>1</sup>; Durbha Sai Ramesh<sup>2</sup>

CSIR-National Geophysical Research Institute, Hyderabad, India<sup>1</sup>; Indian Institute of Geomagnetism, Navi Mumbai, India<sup>2</sup>

#### **Background:**

The depth origin of mantle plumes has remained a controversial issue for more than three decades now. While some researchers have proposed their origin from the core–mantle boundary, others have suggested their origin from the upper mantle. There is some geochemical model as well, which proposes the origin from 660-km depth.

The region of the mantle that separates the upper and lower mantle is known as the mantle transition zone (MTZ), which is bounded by well-resolved seismic discontinuities at 410- and 660-km depths. While the 410-km discontinuity is mineralogically characterized by phase transition of olivine (from  $\alpha$ -olivine to  $\beta$ -olivine or wadsleyite) with positive Clapeyron slope ( $dP/dT$ ), the 660-km seismic discontinuity is a result of dissociation of  $\gamma$ -phase of olivine (ringwoodite) to bridgmanite and ferropericlase, which is characterized by negative  $dP/dT$ . Therefore if mantle plumes do originate at the lower mantle, then the thermal anomaly associated with them would alter the disposition of 410-km and 660-km seismic boundaries in such a way that the thickness of the mantle transition zone should shrink. The extent of shrinkage of MTZ obviously would depend on the thermal anomaly associated with the plume at a particular location. With this idea in mind, we planned our experiment at several oceanic hotspot locations in the globe that include Afar, Ascension, Azores, Canary, Cook islands, Easter, Eifel, Galapagos, Hawaii, Hoggar, Iceland, Kerguelen, Pitcairn, Samoa, St Helena, and Tahiti besides two continental hotspots such as Kenya Rift and Yellowstone.

#### **Objectives:**

In this work we estimate the MTZ thickness beneath each of the above-mentioned hotspots through use of  $P$ -to- $S$  converted seismic waves ( $P$  receiver functions) from the 410- and 660-km discontinuities. We also explore the relationship between our estimated MTZ thickness and strength of plume, measured as buoyancy flux. In the next step we integrate the data pertaining to yet another isotopic parameter known as the activity ratio,  $^{230}\text{Th}/^{238}\text{U}$ , which has been used as a geochemical indicator for excess plume temperatures. Finally the available  $^3\text{He}/^4\text{He}$  and  $^{21}\text{Ne}/^{22}\text{Ne}$  data pertaining to a number of hotspots are re-evaluated in the light of the results obtained in this study.

#### **Methods:**

Teleseismic earthquake records from the distance range 30–90° with high signal-to-noise ratio (SNR > 3.0) are used in this study.  $P$ -receiver function results from a total of 15 permanent seismic stations, for which sufficient data are available and analysed here, are presented. Of these, 13 are located on oceanic island hotspots, while two stations on plume-affected regions are located on the continents. In addition to our data, results from other researchers at three hotspot locations are also included in our analyses.

#### **Results and Conclusion:**

Exceptionally low MTZ thickness is documented (in the range 195–210 km) beneath Big Island of Hawaii, Kerguelen, Galapagos Islands and Pitcairn Island. Anomalous MTZ thicknesses centred on ~225-km are restricted to seismic stations beneath Samoa (AFI), Ascension Island, Iceland, Kenya Rift and Canary Island. Of the remaining hotspots, Cook Islands, Easter Island, St Helena and Eifel yield marginally lower MTZ thicknesses. The published literature data on three stations exhibit anomalously low MTZ thickness beneath Tahiti/Society and Yellowstone, whereas hotspot station Hoggar yields moderate thinning of



MTZ. The main qualitative inference from this analysis is that the MTZ beneath a significant number of the hotspot stations is indeed thinner, which means hotter than normal. Thus from the seismological information alone, we could already conclude that some of the hotspots have a direct relation to a hot MTZ underneath and therefore could qualify as mantle plumes.

In order to ascertain how the estimated MTZ thickness and strength of plume (measured as buoyancy flux,  $B$ ) are related, these two parameters are plotted where a logarithmic correlation of MTZ thinning as a function of increasing  $B$  is documented. Further, a possible upper limit of ~40 km to shrinkage of MTZ is observed indicating that the maximum mantle excess temperature is in the range 300–400 °C.

Analysis of global hotspots using  $B$  values and MTZ thickness as parameters enables us to demarcate regions underlain by clear hot and deep plumes, less hot and perhaps not as deeply seated plumes and those with no plume activity. Many hotspots in the Pacific seem to have their origin in the transition zone or deeper. Two continental hotspots (the Kenya Rift and Yellowstone) also seem to be deep plumes.

Integration of  $B$ –MTZ thickness– $^{230}\text{Th}/^{238}\text{U}$  data related to hotspots distributed around the globe leads to direct detection of mantle plumes with a majority of the Pacific plumes originating below MTZ depths. Our results when integrated with  $^3\text{He}/^4\text{He}$  and  $^{21}\text{Ne}/^{22}\text{Ne}$  values pertaining to the rocks sampled by the mid-ocean-ridge basalt (MORB) and ocean-island basalt (OIB) sources clearly differentiates the two, in conformity with other results presented in this study.

Finally, the observed MTZ behaviour has profound impact on our current understanding of plume–MTZ interaction and melt-generation.



**S07 – 59: Evolution of Antarctic Topography and Bathymetry: Understanding Links between Landscapes, Ice and Palaeoclimate**

***Bathymetry of Schirmar Lakes as an Input for Geomorphological Studies***

Swain A. K.<sup>1</sup>

Geological Survey of India, Faridabad, India<sup>1</sup>

The Schirmacher Oasis lying between latitude 70°44'33"S to 70°46'30"S and longitude 11°22'40"E to 11°54'00"E is an ice free area, bound by continental Polar ice sheet to its south and Nivlsenice-shelf to the north hosts more than hundred lakes. Some of these lakes are perennially frozen while others are periodically thawed during the austral summer periods when the temperature remains above 0°C. The origin of water and associated sediments, their transportation and deposition largely depend upon the amount of snow and various meteorological parameters. Being outside the range of direct glacial action, water plays an important role in landscape formation under periglacial conditions. The shape and size of the Polar lakes are influenced by the fluctuations of glacier and ice sheet as these forms the downward integrator of the sediment actions in their catchment areas. The spatial distributions of these lakes are also governed by the lithological and geological structures, which is modified by later fluctuations of the ice sheet/ glacier movement. Lakes In the Schirmacher Oasis are divided into three major groups on the basis of their geomorphological disposition and genesis viz., Pro-glacial, Land-locked and Epi-Shelf lakes. Bathymetric profiles of some lakes spread across the Schirmacher oasis were obtained during the austral winter period of 2008 using Ground Penetrating Radar (GPR) with different combinations of antennae to understand their genetic aspect vis-a-vis geomorphology. The spatially largest land locked lake L-49 appears to be formed by the fusion of three sub basins. Lake L-27 follows a lineament and L-75 is inferred to have their origin due to structural control. L-23 shows the presence of small elevated land mass at its bottom. Pro-glacial lake, P-9 follows a lineament and is in structural continuation with the lineament of L-27. The Pro-glacial lake of P-11 shows very shallow depth in the bathymetric profile. The Epi-Shelf lake E-14 show a faulted contact with the adjoining landmass towards south and E-15 is connected to water channel below the Ice shelf indicating its connection with the sea which ultimately show that though many melt-water channels from the Ice Shelf drain into these lakes, yet they maintain their levels. The amount and nature of sediments in these lakes differs widely and is dependent upon various factors including the cold-based/ warm-based nature of ice sheet/glaciers and climatic condition during deposition. All these indicate that the Schirmacher Oasis has undergone several episodes of ice sheet advancement and recession and re-shaping of the negative landform bears the testimony of geomorphological evolution this area has passed through in geological past.



**S07 – 65: Evolution of Antarctic Topography and Bathymetry: Understanding Links between Landscapes, Ice and Palaeoclimate**

***Landscapes Carved by Alpine Glaciers and Preserved in the Subglacial Topography of the Weddell Sea Sector of East Antarctica Reflect Restricted Ice Extent in The Past***

Stewart Jamieson<sup>1</sup>; Michael Bentley<sup>1</sup>; Neil Ross<sup>2</sup>; Marc Chang<sup>1</sup>; Fiona Hartland<sup>1</sup>; Andrew Jennings<sup>1</sup>; Charlotte Dorrington<sup>1</sup>; Rebekah Jacques<sup>1</sup>; Chris Stokes<sup>1</sup>

Durham University, UK<sup>1</sup>; University Of Newcastle, Australia<sup>2</sup>

Knowledge of the bed topography of Antarctica is improving all the time. However, although survey data pick out detail in some areas, others have only broad approximations of how the subglacial landscape varies. We present a geomorphological map of the subglacial landscape of the Weddell Sea sector of East Antarctica. The mapping is conducted by exploiting patterns visible at the ice surface in MODIS MOA and Radarsat AMM-1 data to identify the locations features including subglacial valleys and ridges, buried cirques and glacial breaches.

We link these features to their mode of evolution, and in particular, the scale of ice mass which cut the valleys. In some cases, valley distribution reflects the likely pattern of erosive ice both at present day, but we also identify many small buried valleys which may represent glacial erosion under alpine-style glaciation and which therefore reflect a time when the East Antarctic Ice Sheet (EAIS) was smaller. This may reflect either a past retreat of the EAIS, or simply a period prior to the establishment of the continental-scale EAIS.

By mapping features in this way, we can identify not only past and present patterns of erosion and ice flow, but also past and present basal thermal regime. For example, the numerous zones of alpine topography must have been eroded by relatively localised and warm-based ice masses. However, for such local-scale morphological landscapes to have survived under the modern ice sheet there must have been little subsequent erosion. One route to preserving these alpine landscapes is via significant incision in the large-scale troughs that bound alpine topographies. Rapid incision, for example at the onset of continental-scale ice sheet drainage, would drive uplift of these adjacent alpine systems, isolating them beneath a cover of relatively thin, cold-based ice.



**S07 – 113: Evolution of Antarctic Topography and Bathymetry: Understanding Links between Landscapes, Ice and Palaeoclimate**

***Characteristics and Origin of the Lakes and Ponds of Clearwater Mesa, James Ross Island, Antarctic Peninsula***

Lirio J.M.<sup>1</sup>; Coria S.H.<sup>1</sup>; Lopez S.N.B.<sup>1</sup>; Vignoni P.A.<sup>2</sup>; Kohler T.J.<sup>3</sup>; Kopalov K.<sup>4</sup>; Chaparro M.A.<sup>5</sup>; Lecomte K.L.<sup>6</sup>; Navlt D.<sup>7</sup>; Mac Cormac W.P.<sup>1</sup>

Instituto Antartico Argentino, Ciudad Autonoma De Buenos Aires, Argentina<sup>1</sup>; Escuela De Geologia – Facultad de Ciencias Exactas, Físicas y Naturales (FCEFyN), Universidad Nacional De Cordoba, Cordoba, Argentina<sup>2</sup>; Institute of Arctic and Alpine Research, University of Colorado, Boulder, USA<sup>3</sup>; Charles University, Prague, Czech Republic<sup>4</sup>; CIFICEN, CONICET-UNCPBA, Tandil, Argentina<sup>5</sup>; CICTERRA-CONICET-Universidad Nacional De Cordoba, Cordoba, Argentina<sup>6</sup>; Masaryk University, Brno, Czech Republic<sup>7</sup>

James Ross Island is located NE of the Antarctic Peninsula, and has important ice-free areas with numerous lakes and ponds. Clearwater Mesa is located at the SE side of Croft Bay, 250 m above sea level, is 8 km<sup>2</sup> in area, and represents a prominent volcanic mesa comprised of James Ross Island Volcanic Group rocks. This meseta has a very flat plateau, with vertical variability of no more than 30 m from the valley floors to the hilltops. The cliff-lined coasts of Clearwater Mesa prevent access to the area from the sea. As a result, more than 50 lakes and ponds unexplored by scientists are present on the mesa. In January 2015, travel by helicopters made a field campaign possible to study this pristine and poorly known area.

To document and better understand the physical processes and evolution of the Clearwater Mesa environment, we study the geology, chemistry, and associated flora and fauna of each waterbody in this important site. Each lake and pond was named, and area, perimeter and altitude were obtained using GPS. Additionally pH, conductivity and temperature were measured and depth estimated. Each basin was additionally sampled for biological and hydrochemical parameters. In the biggest lake, named Katerina, a bathymetric map was created, and a core was taken in order to reconstruct environmental history and evolution of the lake, and biological and microbiological content.

We found that the lakes and ponds are located within depressions formed by glacial erosion of the ice cap that previously occupied the meseta. A few lakes were found at lower altitude and close to the two glaciers surrounding Clearwater Mesa, located in depressions formed by glacial deposit. The water bodies are shallow and generally fed by snow melt. A NW-SE orientation of the lake's long axis prevails, similar to the elongated hills on the meseta. Stony rims are very common in the lower and humid surfaces of the depressions, especially in lake and pond coasts. Some ponds are actually inundated stony rim areas, and the biggest lakes used to be shallow open basins, and are no more than 2 m deep. Water bodies are connected by small streams with similar water chemistry, and visible fauna and flora. During the visit, no streams draining the lakes reached the cliffs, and instead disappear underground into a basement made by volcanic rocks. Waterbodies exhibited a gradient in conductivity, with closed basin lakes having the highest values and show white salt deposits on their coasts, evidencing a previous higher level. The observed pH of lakes was much less variable, and was neutral to slightly basic.

In the south sector of Clearwater Mesa, the hill altitudes are higher (282 m above sea level at Cerro Pablo), and the valley is U-shaped, with a NW-SE orientation. On the bottom of the valley it is possible to find rounded basalt clasts up to 70 cm in diameter, suggesting the presence of fluvial transport and the existence of previous streams, now absent, that drain the meseta as the ice cap that occupied the meseta melted. The lakes have few clastic inputs, and the bottoms are covered with high biomasses of cyanobacteria and green algae which support the fairy shrimp *Branchinecta gaini*, useful for



paleoenvironmental reconstruction. Previously found only in lake cores from James Ross Island by Björck et al. 1996, and supposed to be extirpated from James Ross Island, this species was present in the majority of lakes and ponds studied here, as well as in the Ulu Peninsula during the lake surveys of the last years.

At the top of the meseta, the presence of erratic striated boulders of igneous and metamorphic composition, provide evidence that glaciers from the Antarctic Peninsula had previously overrun the meseta. Physical weathering (congelifraction) has been important, and as a result the volcanic rock is split and broken in angular clasts of several cm in diameter. These angular volcanic rocks cover vast areas of the plateau and are material source for the formation of the stony rims very common in Clearwater Mesa. The prevailing SW wind contributes to rock erosion, snow drift accumulation, humidity and flora distribution: the luf-side of the rocks is generally dry and affected by wind abrasion. On the other hand, the lee sides allow snow drift accumulation, is more humid, and the arborescent lichens grow up protected from wind abrasion.

Clearwater Mesa has more than 50 lakes and ponds, each of them with a flora typical of the Antarctic Peninsula. Interestingly, *Branchinecta gaini*, a crustacean thought to be extirpated from James Ross Island, was found on the majority of the waterbodies. Better understanding the evolution of the lakes and associated biota here could help in disentangling the evolution of other areas in Antarctica now covered by ice and improve the environmental interpretation of lakes cores obtained in the area. Furthermore, Clearwater Mesa has been found an important area with high persistence under future climate changes based on the RACER analysis and supported by the expert opinion of our group.



**S07 – 144: Evolution of Antarctic Topography and Bathymetry: Understanding Links between Landscapes, Ice and Palaeoclimate**

***Palaeobathymetric Reconstruction of the Africa-Antarctic Conjugate Margins***

Castelino J. A.<sup>1</sup>; Jokat W.<sup>1</sup>

Alfred-Wegener-Institut Helmholtz-Zentrum für Polar- und Meeresforschung (AWI), Germany<sup>1</sup>

An extensive database of geophysical data in the Riiser-Larsen Sea and Mozambique Basin conjugate margins indicates a dynamic evolution that was actively influenced by different events. However, analyses of individual datasets are not sufficient to reconstruct the complete structural evolution of the rifted margins during Gondwana break-up and thereon. We use crustal age models and chronology of interpreted horizons from extensive seismic datasets in the Riiser-Larsen Sea and off Mozambique to create the palaeobathymetric reconstruction of the conjugate margins. We also incorporate the effects of different models for sediment decompaction, thermal subsidence and lithospheric flexure from sediment loading and sea level variation into our calculations. The geodynamics of the two passive margins is reconstructed on a  $0.5^\circ \times 0.5^\circ$  grid resolution. Plate kinematic model of Antarctic plate with respect to Africa controls palaeogeography of the break-up. The model shows the initial period of common phases of the geodynamic evolution of the two margins. The results provide new boundary conditions for palaeoenvironment settings, palaeoceanographic models and sediment deposition architecture in the Africa-Antarctic corridor.



**S07 – 159: Evolution of Antarctic Topography and Bathymetry: Understanding Links between Landscapes, Ice and Palaeoclimate**

***The Magia Mass - Wasting Complex. Morphology and Processes Affecting the Central Bransfield Basin (Antarctica)***

David Casas<sup>1</sup>; Margarita Garcia<sup>2</sup>; Fernando Bohoyo<sup>1</sup>; Andres Maldonado<sup>2</sup>; Gemma Ercilla<sup>3</sup>

Instituto Geologico y Minero De Espana (IGME) Madrid, Spain<sup>1</sup>; Instituto Andaluz De Ciencias De La Tierra (CSIC-UGR) Granada, Spain<sup>2</sup>; Institut De Ciencias Del Mar, CSIC, Barcelona, Spain<sup>3</sup>

Submarine mass-movement is a characteristic process on high latitude margins that results from the interplay of repeated advance and retreat of grounded ice, oceanographic, glaciogenic and tectonic processes. In the particular case of Antarctic continental margins, there are some important examples, some of them well-documented like the case of the GEBRA Debris Valley, located on the lower continental slope of the Antarctic Peninsula in the Central Bransfield Basin-CBB. It has been defined as a Quaternary Debris Valley formed as a result of repeated large-scale mass transport processes. This feature is included in the so-called GEBRA-MAGIA sedimentary instability complex formed by the GEBRA itself and a cluster of mass wasting features that makes up the MAGIA complex. New data from MAGIA are presented in this work with the aim to characterize its morphosedimentary features and the disintegrative dynamic affecting the area.

**Methods:**

This work is based on high-resolution bathymetry and seismic records. The main data were collected during the R/V Hesperides Cruise SCAN-2013. The seafloor bathymetry was mapped using a Simrad EM120 multibeam echosounder. The high-resolution seismic records were obtained with TOPAS (Topographic Parametric Sonar).

**Morphosedimentary characterization** The MAGIA mass-wasting complex covers an area of about 348 km<sup>2</sup>. The system displays a SW-NE trend, is about 27 km long and 18 km wide, and extends from 900 to 1915 m water depth, disappearing as it goes into the King George Basin. The MAGIA complex is composed of first order features such as scars, mass transport deposits, or a channel and second-order features (minor scars, channels, and escarpments). A set of individual seaward-concave scars, with a SW/W-NE/E trend, cut the lower continental slope of the Antarctic Peninsula from the shelf-break at about 900 mwd to 1700 mwd. These scars have lengths of 3-10 km, a relief of 37-150 m and slope gradients up to 24°. The seafloor area surrounding the major scars is irregular and is characterized by linear to slightly sinuous positive and negative relief features of hundreds of metres in scale that are interpreted as minor-scale scars and gullies. Downslope from the scars the seafloor is highly irregular and displays cross-section profiles that range from concave-upward to convex-upward, shaping terraced and mounded bulge geometries. In plain view, the area displays NE-SW lineations standing out two ridges up to 38 km long and an irregular to slightly sinuous negative relief feature (25 km long and 1-4 km wide) with oblique trend to the slope. This feature has an asymmetric cross section and is interpreted as a channel, named MAGIA channel. The channel is infilled by acoustically parallel deposits (7-11 ms thick) that can be interpreted as turbidite deposits. The near-surface sediments on the rest of the area comprise irregular/lenticular bodies that are 25-36 ms thick and 2-8 km long. They are internally defined by semi-transparent facies which can be associated with mass-transport deposits. These deposits are draped by irregular stratified deposits (up to 7 ms thick) that are also interpreted as turbidites. These turbidites are locally disrupted and contorted, and form seafloor irregularities that mimic the underlying irregular topography.

**Discussion and conclusions:**

Based on the identification of all instability features described, repeated failures are inferred to have affected the area along different periods of time.



The first-order scars affecting the lower continental slope configure the headwall or source area domain for all mass-movement deposits. Mounded geometries and sediment ridges below the headwall area are interpreted as failed sediments from further upslope. The trend of these major features suggests a preferential disintegrative direction toward N-NE.

The stratified facies overlying mounds and ridges may represent turbidity current deposits derived from mass-wasting processes affecting the headwall, but they may also represent primary deposition. These processes include turbidity flows of low and high density from glaciomarine proglacial processes and turbid glacial meltwater. Turbidity flows run basinward, going downslope as unchannelized or channelized flows, as suggested from the thickness of the deposits characterizing the MAGIA channel seafloor and their parallel acoustic facies. The presence of the stratified turbidites draping the near-surface sediments point to that the mass wasting activity has decreased in recent times.

The irregular to slightly sinuous trend of the MAGIA channel seems to result from the highly irregular/chaotic seafloor geometry. The deposition of different mass-transport deposits along the area, with different run-out distances, favoured the formation of a negative relief that has been subsequently used by flows as an evacuation pathway. The passage of turbidity flows help to erode the seafloor favouring the evolution to a channel structure.

Sedimentary processes involved in the origin and evolution of the MAGIA system may have been controlled by the interplay of several controlling factors. A local tectonic control similar to that proposed for the neighbour GEBRA Debris Valley should be considered, especially regarding the two main tectonic stages governing the main headwalls. A second major factor that should be regarded is the glacial cyclicality, since the entire MAGIA system develops on the lower slope of a margin characterized as a trough mouth fan that has been deposited by the accumulation of proglacial deposits since the opening of the Central Bransfield Basin. MAGIA is therefore classified as a mass-wasting complex that has contributed to the outbuilding and shaping the submarine landscape of Central Bransfield Basin.



**S07 – 174: Evolution of Antarctic Topography and Bathymetry: Understanding Links between Landscapes, Ice and Palaeoclimate**

***The Geomorphology of Rock Glaciers, near Trollstation in the Jutulsessen, Antarctica***

E.M. Rudolph<sup>1</sup>; K.I. Meiklejohn<sup>1</sup>; A. Bumby<sup>2</sup>

Rhodes University, Grahamstown, South Africa<sup>1</sup>; University of Pretoria, Pretoria, South Africa<sup>2</sup>

Rock glaciers are known to occur in a number of environments across the globe, yet they remain poorly understood geomorphic features and are not well documented in the Antarctic. The composition of ice and sediment found across these landforms has the potential to improve our understanding of past climates, their dynamics and morphology. Two rock glaciers in the vicinity of the Norwegian research station, Troll (72°01'S, 02°32'E), in the Jutulsessen of Dronning Maud Land, Antarctica were studied: Grjotøyra during the 2013/14 Austral summer season and Vassdalen in 2014/15, in order to characterise their structure and monitor slope movement. The study offers new research to this region of the Antarctic, and contributes to the existing knowledge of rock glaciers. Sediment samples were collected to determine moisture content, particle distribution and Sörting. Clast size and orientation were measured to determine slope movement. Near-surface temperature was recorded at 20 sites across the glacier and rock hardness measured at 30 sites using an Equotip 3. The geology of the region is predominantly gneiss and partially metamorphosed granites that have been weathered down into larger clasts of feldspar and quartz. The upper reaches of the rock glacier at Grjotøyra are characterised by random sediment Sörting with an absence of significant amounts of fines. The basal lobe is characterised by larger boulders with an increased portion of fines. Rock hardness is variable, as are ground temperatures. Liquid water accumulations found on the basal lobe indicate melt water as a moisture source, rather than precipitation. The presence of lichen and advanced weathering of rock surfaces on the basal lobe suggest an absence of movement. At Vassdalen the glacial processes, mass movements and active-layer related features such as contraction crack polygons have influenced the morphology of the rock glacier. A digital elevation model and stereographic projection of clasts were used to infer surface movement and morphology of both rock glaciers. Current observations suggest both to be relict, Vassdalen to be more influenced by present day processes than Grjotøyra. These could potentially be a resource of palaeoclimatic information and serve as a monitoring tool for climate change.



**S07 – 189: Evolution of Antarctic Topography and Bathymetry: Understanding Links between Landscapes, Ice and Palaeoclimate**

***Anatomy of a Submarine Channel - Fill Deposit in the Spurs Formation, the Mariner Group (Cambrian), Northern Victoria Land, Antarctica***

Kim, Y.-H.G<sup>1</sup>; Woo, J<sup>1</sup>; Park, T.-Y.S<sup>1</sup>; Choe, M.Y<sup>1</sup>

Korea Polar Research Institute, South Korea<sup>1</sup>

Early Paleozoic Ross Orogeny-related successions of northern Victoria Land, Antarctica are represented by an accretionary complex of sedimentary rocks in three tectonic terranes: Wilson, Bowers, and Robertson Bay terranes, from inboard to outboard. The Bowers Supergroup of the Bowers Terrane has been divided into the Sledgers, Mariner, and Leap Year groups in ascending order, which spans time period from the Cambrian Series 3 (middle Cambrian) to the Lower Ordovician. The Mariner Group is subdivided into three units: Edlin, Spurs, and Eureka formations. This study deals with the detailed sedimentology and stratal architecture of a submarine channel-fill deposit of the Spurs Formation.

The Spurs Formation is exposed on the east side of a glacier valley of the Mariner Glacier (Eureka Spur 3). This section is 1099 m (including gaps covered by snow) of the succession and the channel-fill deposit occurs in the lower part of the succession. This channel-fill deposit is ca. 190 m in width and ca. 20 m in thickness. Six sections (CU1 to CU6 from east to west) spaced about 10-45 m were measured and used to construct a two-dimensional correlation panel with line drawing of an outcrop photograph.

The channel-fill deposit is subdivided into the lower, laterally restricted unit (breccia, diamictite, and thin-bedded sandstone) and the upper, laterally extensive unit (fissile mudstone and very thick diamictite).

The breccia facies in the laterally restricted unit is composed mainly of clast-supported, unsorted, and disorganized polymictic clasts which are oolite (48%), sandstone (22%), mudstone (24%), and minor limestone (7%). Breccia beds range from 40 to 280 cm in thickness and are 130 cm in average. Most thick beds show lateral variability in thickness and some beds even pinch out. This breccia facies are interpreted to be formed by the downslope transport of shallow marine and slope sediments under the force of gravity. The medium to thick beds of diamictite facies in the laterally restricted unit is represented by matrix-supported, disorganized, poorly-sorted carbonates and siliciclasts in a muddy matrix. These beds are 10 to 140 cm in thickness. High-proportion of mud, ungraded sediments, and deformation structure in the matrix of this facies are suggestive of muddy debris-flow type deposition. Facies packages of the underlying breccia and the overlying diamictite form meter-scale fining-upward cycles. A total of 8 cycles are recognized. The lower boundary of each cycle is irregular, sharp, and erosional. The vertical transition from breccia to the overlying diamictite is abrupt with sharp undulated boundary. These cycle units are continuous in the channel but onlap or thin out toward the NW channel wall. It is interpreted as cycles of submarine debris avalanche deposits (breccia) and following debris flow deposits (diamictite) at the tail of debris avalanches. The laterally restricted unit shows channel-shape architecture with stepped margin.

In contrast, fissile mudstone and very thick diamictite overlying the channelized unit are laterally extensive. This laterally extensive unit of diamictite facies consists mainly of muddy matrix and large poorly-sorted carbonate and siliciclastic which are disorganized and matrix-supported. The clasts are comprised of limestone (38%), sandstone (32%), oolite (28%), and minor mudstone (2%). The meter-scale clasts (sandstone, limestone, and breccia blocks) are strongly deformed and the shape of clasts is very variable, which have angular to rounded corners. It possibly indicates that a deposition by sheet-like debris flow originated from the failure of channel bank or slopes flanking the channel system.



Further investigation on the clast composition of the laterally restricted unit and the laterally extensive unit may reveal unique submarine channel system sourced from both carbonate and siliciclastic shallow marine environments.



**S07 – 222: Evolution of Antarctic Topography and Bathymetry: Understanding Links between Landscapes, Ice and Palaeoclimate**

***Relative Sea-Level Changes and Sediments Deposition: A First Step towards a Fully Coupled System***

Paolo Stocchi<sup>1</sup>; Peter Bijl<sup>2</sup>; Simone Galeotti<sup>3</sup>; Ulf Nordlund<sup>4</sup>; Bert Vermeersen<sup>1</sup>; Henk Brinkhuis<sup>1</sup>

NIOZ Royal Netherlands Institute for Sea Research, Den Hoorn, The Netherlands<sup>1</sup>; Faculty Of Geosciences, Utrecht University, Urtecht, The Netherlands<sup>2</sup>; Earth, Life And Environmental Sciences Department, Universita Degli Studi Di Urbino “Carlo Bo”, Urbino, Italy<sup>3</sup>; Aze Interactive, Uppsala, Sweden<sup>4</sup>

Ice-proximal sedimentological evidences play a fundamental role in reconstructing past Antarctic ice-sheet (AIS) evolution because, upon correlation to the isotope record, they provide evidence of the direct response of the sedimentary systems to AIS fluctuations. These produce global ocean volume variations, which can be extracted from the isotope record, and sea-level changes. The latter result in bathymetric variations that drive the deposition of marine sediments as a consequence of the changes of the accommodation space and of the distance from shore. However, sea-level changes are not globally uniform, as described by the concept of eustasy, but strongly depend on the distance from the ice-sheets. In fact, an increase in the AIS thickness, which is compensated by a reduction of the ocean water mass and therefore would show up as a global sea-level drop according to eustasy, results in a large sea-level rise in the proximity of the ice-sheets margins as a consequence of the gravitational pull exerted by the added ice mass. As a consequence of mass conservation, the sea-level drop in the far-field sites is larger than in the eustatic case. Furthermore, the increase in ice-loading and the decrease in water loading on the ocean areas trigger a response of the solid Earth surface, which deforms to establish a new isostatic equilibrium and contributes to relative sea-level changes (RSL). Hence, the AIS expansion would ultimately show up, in the geological record, as a regressive phase in the northern hemisphere and in a transgressive phase characterized by an increase of accommodation space in the proximity of the AIS margins. In this work we investigate to what extent the regionally varying RSL changes that are driven by Glacial Isostatic Adjustment (GIA) affect the architecture of stratigraphic sections. For this purpose we model the deposition of sediments in space and time by means of fuzzy logic. Among the several variables under consideration that regulate the sedimentation, changes depth and distance from shore and ice margin stem from self-consistent GIA modeling. Furthermore, we also include the solid Earth and gravitational response to the evolving sedimentary loading in a synergistic manner and quantify the contribution to RSL changes. Hence, in the coupled algorithm we propose, the RSL changes follow from AIS fluctuations, and affect sediments deposition. The latter, therefore, affects RSL changes as well in a self-consistent manner. We propose this model as a tool for the geology community.



**S07 – 223: Evolution of Antarctic Topography and Bathymetry: Understanding Links between Landscapes, Ice and Palaeoclimate**

***Inversion of the Mesozoic Victoria Basin and uplift of the Terra Nova Bay segment of the Transantarctic Mountains***

Frank Lisker<sup>1</sup>; Jannis D. Prenzel<sup>1</sup>; Andreas Läufer<sup>2</sup>; Maria Laura Balestrieri<sup>3</sup>; Cornelia Spiegel<sup>1</sup>

University of Bremen, Germany<sup>1</sup>; Federal Institute for Geosciences and Natural Resources, Germany<sup>2</sup>; Institute of Earth Sciences and Earth Resources, Italy<sup>3</sup>

The Transantarctic Mountains (TAM) represent the main structural and morphological feature of Antarctica, and roughly divide the continent into the stable East Antarctic Craton and the mobile terrane assemblage of West Antarctica. Their high standing, dissected plateaus consist of variably metamorphosed basement rocks unconformably overlain by Devonian to Early Jurassic sedimentary rocks of the Beacon Supergroup. This terrestrial clastic and shallow marine sequence was then intruded or covered by Jurassic tholeiites of the Ferrar Group. The only rocks preserved above the Ferrar Group are some isolated Neogene volcanic rocks and shallow marine and glacial deposits. Due to the general lack of any Middle Jurassic to late Neogene sedimentary record, the morpho-tectonic evolution of the TAM chiefly relies on thermochronological data. Based on the qualitative interpretation of more than 500 apatite fission track (FT) data, the TAM were traditionally considered as a stable landform what was uplifted in three stages during Early Cretaceous, Late Cretaceous, and early Cenozoic times.

However, crossover age relationships between apatite FT ages from vertical sample profiles and the effusion age of Ferrar volcanic and volcanoclastic rocks throughout the TAM are in striking contrast to this established uplift/ exhumation concept. Instead, the regional compilation of thermochronological and stratigraphic data, the broad range of Late Jurassic to Cretaceous paleo temperatures derived from various methods, diachronous timing of thermal peaks, the presence of recycled Cretaceous fossils within Cenozoic strata in Ross Sea and Pennell Coast, and the stratigraphic record of the SE Australian shelf require the existence of a Mesozoic Victoria Basin along the western Ross Sea margin and continuing into the interior of SE Australia. Uplift of the TAM could not have commenced prior to early Cenozoic.

The Terra Nova Bay (TNB) forms a segment of the TAM between southern and northern Victoria Land in the central Ross Sea. Geological architecture and geomorphological pattern of the TNB are representative for the whole mountain chain and predestine the region as test case for uplift/ exhumation scenarios, and to study course, timing and mechanism of basin evolution, burial depth and heatflow development. New exhumation studies produced an extensive set of >100 thermochronological data from up to 2400 m high vertical profiles in several mountain ranges (Eisenhower Range, Deep Freeze Range, Prince Albert Mountains, Tourmaline Plateau). Both range of apatite FT data (ages 28-274 Ma; mean track lengths usually <14  $\mu\text{m}$ , with standard deviations >1.5  $\mu\text{m}$ ) and (U-Th-Sm)/He ages (37-173 Ma), and the tight correlation of these data with sample altitudes coincide with the general thermochronological data pattern throughout the TAM. Consistent thermal histories models of these data and complementary thermal indications detect heating of the Early Jurassic paleosurface across the TNB to temperatures ~80°C subsequent to Ferrar magmatism, and constrain Late Eocene rapid cooling. Regression of modelled paleotemperatures against sample altitudes refers to a high Jurassic (~45°C/km) and a moderate Cretaceous-Eocene (~28°C/km) geothermal gradient.

The texture of Beacon sandstones also supports strong mechanical compaction that requires a higher overburden than preserved in the stratigraphic record. Modelled paleotemperatures and pressures suggest basement burial that increases from Late Jurassic (0.6-2.4 km) to Eocene (up to ~3.4 km). Burial variation is apparently attributed to a higher thickness of Beacon and Ferrar rocks in the southern TNB and may represent the pre-Ferrar topography. The relative homogeneous post-Ferrar sediment thickness throughout the entire region indicates a continuous, uniform Mesozoic Victoria Basin. Mid-Jurassic basin



formation and subsequent sediment accumulation until the Late Eocene is explained by extension within a back arc basin along the active paleo-Pacific margin of Gondwana.

Rapid cooling of the TNB region between ~35 and 30 Ma implies fast erosion of the post-Ferrar sediments and (re-) exposure of underlying magmatic rocks. Subsequent differential cooling to present-day surface temperature infers ongoing exhumation by glacial incision enhanced by isostatic response to basin inversion. Decreasing amounts of exhumation from the coast (>3 km) towards the interior (1.5-2.2 km) point to backstepping incision along the fault controlled main glaciers. Substantial exhumation of the TNB region since the Late Eocene is hence triggered by both tectonic and climatic factors, superimposed by considerable lithological influence during the initial exhumation stage.



**S07 – 253: Evolution of Antarctic Topography and Bathymetry: Understanding Links between Landscapes, Ice and Palaeoclimate**

***Pre-30 Ma Glacial Erosion Beneath Western Ross Sea, Antarctica?***

Sørlien, C. C.<sup>1</sup>; Davis, S.M.<sup>2</sup>; De Santis, L.<sup>3</sup>; Luyendyk, B.P.<sup>1</sup>; Sauli, C.<sup>3</sup>; Bartek, L.R.<sup>4</sup>; Wardell, N.<sup>3</sup>; Cormier, M.-H.<sup>5</sup>; Bart, P. J.<sup>6</sup>; Böhm, G.<sup>3</sup>; Stocchi, P.<sup>7</sup>

University of California Santa Barbara<sup>1</sup>, Indiana University of Pennsylvania<sup>2</sup>; Istituto Nazionale Di Oceanografia E Di Geofisica Sperimentale, (OGS) Italy<sup>3</sup>; University of North Carolina, Chapel Hill<sup>4</sup>; Graduate, School of Oceanography University of Rhode Island<sup>5</sup>; Louisiana State University<sup>6</sup>; Royal Netherlands Institute for Sea Research, Netherlands<sup>7</sup>

Global isotopic records indicate an Antarctic ice sheet larger than today's at ~33 Ma. A recent publication utilizing a Global Climate Model (GCM), incorporating topography restored for rift-related subsidence and glacial erosion, produces an ice sheet over much of both East and West Antarctica for earliest Oligocene (~33 Ma) conditions. However, it is unclear how much of Ross Embayment this ice sheet covered. In particular, the GCM predicts almost no ice across the 900x500 km Ross Sea during that period. Here, we report possible evidence from seismic reflection data for pre-30 Ma glacial erosion that extended as far as 400 km north of the present Ross Ice Shelf edge and 300 km east of the present Trans-Antarctic Mountains coastline. If the erosion is due to ice and not water, this would call into question some aspects of the GCM.

Utilizing deep scientific core holes and all available seismic reflection profiles from the Antarctic Seismic Data Library System, we investigated subsidence, sedimentation, and erosion in the Ross Sea. As part of the international Rossmap project, a half dozen Oligocene through Miocene unconformities plus a deeper major unconformity were correlated through all the seismic reflection data across most of Ross Sea. In particular, the data clearly image two buried basement highs, Central High near the dateline in central Ross Sea, and Coulman High in western Ross Sea. Central High contains a smooth, tilted and laterally continuous (>200 km-wide) unconformity. We interpret that feature to have been eroded by waves and subaerial processes, into metamorphic and other rocks. Coulman High contains a similar acoustic basement unconformity. Aggradation of dated marine sedimentary rocks above this unconformity gives a minimum age for subsidence through wave base for each location. The end of subaerial and wave erosion is time-transgressive, older towards Central Trough. Almost all of the present location of Ross Sea was marine by 25 Ma. Ross Sea Unconformity 6 (RSU6), extrapolated to be ~30 Ma, was correlated from Eastern Ross Sea, where it was originally defined, to western Ross Sea. Subsidence patterns between ~30 and ~25 Ma were qualitatively projected back to ~33 Ma.

Based on our careful seismic stratigraphic work, we interpret the paleodepth and paleo-elevation of western and central Ross Sea to be much higher at ~33 Ma than proposed in published reconstructions for the slightly older Eocene-Oligocene boundary. This is inferred in part from the onlap of horizon RSU6 onto the acoustic basement major unconformity, assuming that sedimentation rates were high enough to keep the basins filled to near wave base. Central High was a large (200x500 km), mostly subaerial ridge or island within the future Ross Sea, and northern Coulman High was probably a 100x200 km island. Furthermore, at 33 Ma, much of the Victoria Land Basin between Coulman High and the Trans-Antarctic Mountains may have been just reaching sea level during subsidence associated with Eocene-Oligocene extreme extension.

The N-S Central Trough is located between Coulman High and Central High. It occupies a late Cretaceous-early Cenozoic rift basin that has continued subsiding after the cessation of rifting, due to a combination of sediment loading and thermal contraction. Our seismic stratigraphic interpretation reveals that the pre-~30 Ma part of Central Trough consists of two separate 200+ km-long by 50 km-wide U-shaped troughs each containing closed 6 km-deep basins, with 3 km-deep sills north of each one. A



published Bouguer gravity map shows two gravity highs that coincide with the two basins. These gravity highs have previously been interpreted as due to crustal thinning. Because both syn-extension and post-extension subsidence should be greatest over the most thinned crust, it is expected that initial relief of the two troughs has become further enhanced with time.

We interpret these two troughs to have eroded downward into acoustically reflective strata interpreted to be syn-rift sedimentary rocks cut by faults. The vertical relief of the major trough-base unconformity is as much as 2 km across a horizontal distance as short as 5 km. It is unclear how much of this relief was present before the latest erosion. The trough fill is nearly unfaulted; therefore, the latest erosion postdates the rifting. The upper tributaries of the northern trough are on Central High, while the upper reaches of the southern trough are beneath the Ross Ice Shelf.

We propose two possible explanations for the past-extension and erosion of the deepest parts of the Central Trough. The first possibility is two river and submarine canyon systems that continued eroding after major extension ceased ~55 Ma. The second possibility is a very large Piedmont glacier sourced from a Central High ice cap, down-cutting the northern U-shaped trough. The southern U-shaped trough could have been last eroded by an ice stream or glacier associated with the ~33 Ma Antarctic Ice Sheet. Depth conversion and quantitative elevation/depth restorations to 33 Ma are underway, and will help distinguish whether glacial erosion is a tenable model for the cause of the last erosion of the Central Trough.



**S07 – 256: Evolution of Antarctic Topography and Bathymetry: Understanding Links between Landscapes, Ice and Palaeoclimate**

***Did the Recent Geomorphic and Sedimentary Record off the Sabrina Coast, East Antarctica, Originate as Result of Past Subglacial Water Outbursts and Ice Sheet Collapse?***

Rodrigo Fernandez<sup>1</sup>; Eugene Domack<sup>2</sup>; Caroline Lavoie<sup>3</sup>; Sean Gulick<sup>1</sup>; Bruce Frederick<sup>1</sup>; Amy Leventer<sup>4</sup>; Alix Post<sup>5</sup>

University of Texas Institute for Geophysics, Austin, United States<sup>1</sup>; Indiana University of South Florida, Saint Petersburg, United States<sup>2</sup>; University of Aveiro, Aveiro, Portugal<sup>3</sup>; Colgate University, Hamilton, United States<sup>4</sup>; Geoscience Australia, Symonston, Australia<sup>5</sup>

Satellite observations in Antarctica indicate the presence of numerous subglacial water bodies that in some cases form large lakes. These water bodies maintain zero basal shear stress relative to the overlying ice and thus have the ability to initiate and maintain fast ice flow. There is observational evidence that subglacial lakes are connected to others and that there is transfer of water between them. Limited data from West Antarctica suggest that subglacial water outbursts occurred associated with the deglaciation of the continental shelf at the end of the last glacial cycle. It is theorized that a subglacial outburst would decrease the shear stress at the bottom of marine ice sheets near the margin, inducing ice acceleration, thinning and ultimately contributing to their collapse. However, little is known about the feedbacks between ice dynamics and subglacial water transfer to the ice margin, the role of subglacial sediments, influence of basal melting by ocean waters etc. We present results from the first geological and geophysical marine survey (NSF-USAP NBP1402) of the inner continental shelf off the Sabrina Coast in the Totten Glacier/Moscow University Ice Shelf area, East Antarctica. This area is located offshore of the Aurora Subglacial Basin, a deep subglacial trough that reaches more than 1 km below sea level where geophysical data suggest the existence of numerous water bodies.

Swath bathymetry mapping revealed part of an overdeepened trough, drumlins and mega-scale glacial lineations (MSGSL) indicating that grounded ice covered the inner shelf off Sabrina Coast and flowed northward from the Aurora basin towards the outer continental shelf. In the area dominated by MSGSL, we found a set of features we refer as 'feather moraines' that we interpret as representing the sedimentary and geomorphic record of past subglacial water outbursts. Additional evidence for subglacial water outburst is found on a sand plain with dunes and sand waves northwest from the feather moraines at water depths of about 500 mbsl (Meters below sea level). The feather moraines appear over-imposed an old set of well developed MSGSLs that originate from an area dominated by bedrock cored drumlins. The general orientation of the feather moraines is oblique to the old set of MSGSL suggesting that they were formed under different ice dynamics conditions. Each set of feather moraines is characterized on its surface by a corresponding set of glacial lineations and esker-like features that with different orientations and are elongated in the same direction.

High resolution multi-channel seismic show that the feather moraines consist of a stack of sedimentary units separated by erosional unconformities, which appear in the swath bathymetry as feather-like areas exhibiting cross and cut relationships between different sets, with distinct step-wise borders on the downstream side. The unconformities bounding each unit are roughly parallel to each other where they overlap but dip on a relatively high angle on the downstream end, with the top unconformity either converging onto the bottom one or overlapping an older set of unconformities. Internal structure reveals reflectors subparallel to the underlying. The seismic architecture of the feather moraines indicate a constructional origin growing in the upward and downstream directions, downstream progradational facies, and complex array of unconformable surfaces separating different development stages.

The upstream border of the feather moraines coincides with an area of drumlins near the limit of the glacial sediments and the outcropping of crystalline bedrock. The drumlins are in part eroded by a



network of channels that extent south into an area characterized by a network of channels that incise the crystalline bedrock up to depths near 1000 mbsl. The spatial association of incised bedrock, partially eroded drumlins, glacial lineations and feather moraines suggest a genetic link.

We will present results of an ongoing multi component study including geophysics (multi-channel seismic, sub-bottom profiler, and swath bathymetry), core analysis (petrography, grain size, shear stress, pore water etc.) and geochemistry of pore water (oxygen and carbon isotopes, chloride). This new dataset of a previously unexplored area of East Antarctica provides new insights on the role of subglacial water bodies and sediments for the stability of marine ice sheets.



**S07 – 266: Evolution of Antarctic Topography and Bathymetry: Understanding Links between Landscapes, Ice and Palaeoclimate**

***Weddell Sea Paleobathymetry Reconstruction from Pre-Glacial to Glacial Conditions and the Simulated Middle Miocene Weddell Gyre***

Huang, Xiaoxia<sup>1</sup>; Gohl, Karsten<sup>1</sup>; Jokat, Wilfried<sup>1</sup>; Lohmann, Gerrit<sup>1</sup>; Staerz, Michael<sup>1</sup>

Alfred-Wegener-Institut Helmholtz-Zentrum fuer Polar- und Meeresforschung, Germany<sup>1</sup>

The Weddell Sea basin is of particular significance for understanding climate processes, including the generation of ocean water masses and their influence on ocean circulation as well as the dynamics of the Antarctic ice sheets. The sedimentary record, preserved below the basin floor, serves as an archive of the pre-glacial to glacial development of these processes, which were accompanied by tectonic processes in its early glacial phase.

In this study, we analyze all existing seismic profiles of the Weddell Sea region and attempt to synthesize a unified stratigraphic model by integrating previously published local models with modifications in some cases. We calculate sediment depth, isopach and sedimentation rate grids for the entire basin from pre-glacial to full glacial times. Sediment thicknesses and volumes are estimated from basin-wide seismic horizon correlations using drill sites for stratigraphic control. The gridded maps are then used to discuss sediment transport and deposition processes corresponding to terrigenous sediment supply, as well as past ice sheet dynamics and ocean circulation of the Weddell Sea basin. We further calculate paleobathymetric grids at 15 Ma, 34 Ma, and 120 Ma by using a backstripping technique, which helped to constraint paleoclimate models. In order to test the paleobathymetry's impacts on paleo-ocean circulation and paleoclimate, we simulate ocean circulation in the Weddell Sea of Antarctica using coupled General Climate Model (GCM) runs forced with global warm climatic boundary conditions of the Mid-Miocene and high-resolution Weddell Sea paleobathymetry data. The advanced seafloor topography constraints effectively steer the wind stress, which results in the reduction of sea ice and relatively high SST as a consequence of the intensified clockwise Weddell Gyre circulation during the Middle Miocene Climate Optimum. In turn, the gyre circulation favours distinct vertical mixing via Ekman transport as shown by deepening of the mixed layer depth and Antarctic Bottom Water (AABW) formation. Increased AABW activity in the Mid-Miocene played a significant role in the evolution of the sea floor morphology in the western and southern Weddell Sea, where a number of large sediment drifts were built in this period. Our results provide constraints for an improved understanding of the paleo-ice sheet dynamics and paleoclimate conditions of the Weddell Sea.



**S07 – 268: Evolution of Antarctic Topography and Bathymetry: Understanding Links Between Landscapes, Ice and Palaeoclimate**

***Comparison of Cold-Based Glacial Geomorphology in Antarctica and NW Europe***

Atkins, C<sup>1</sup>; Bradwell, T<sup>2</sup>

Victoria University of Wellington, New Zealand<sup>1</sup>; University Of Stirling, Scotland<sup>2</sup>

Recent studies in Antarctica show that cold-based glaciers can cover and protect subglacial surfaces but can also modify landscapes in certain situations. A variety of geomorphological features documenting erosion, deformation and depositional processes has now been described from both contemporary and relict glacial landscapes in the Transantarctic Mountains.

Erosion features range from cm-scale grooves and gouges in bedrock to m-scale ice marginal meltwater channels. Deformation ranges from subtle features such as overturned ventifacts to large (100 m<sup>2</sup>) areas of brecciated bedrock and deformed permafrost. Deposition includes ice-cored mounds, boulder trains and also larger scale 'drop' moraines and 'boulder blanket' tills that can extend over several km. Recognising the often inconspicuous imprint of cold-based glaciers on the landscape has prompted some reinterpretations of the geomorphological record and cosmogenic exposure histories, thereby providing an improved understanding of the extent, style and timing of past glacial events in Antarctica.

Similar features have recently been recognised in peripheral locations along the Atlantic margin of the last European Ice Sheet. Field mapping of Pleistocene glacial landscapes in NW Scotland suggest that the region supported extensive cold-based glacial conditions during deglaciation following the Last Glacial Maximum (LGM). Mountain summits, previously thought to have been nunataks during ice-sheet maximum conditions, have been re-appraised using cosmogenic-nuclide analyses to indicate persistent cover by cold-based ice during the LGM. We extend the notion of cold-based glacier thermal regimes to low ground using morphological similarities between subtle geomorphological features in NW Scotland and those in contemporary settings in the Transantarctic Mountains. Brecciated bedrock, deeply weathered saprolite remnants and well-preserved periglacial features, as well as large-scale boulder trains, boulder 'blankets' (or 'matrix-free' tills) and small irregular mounds are found at low elevations (100-500 m asl) between the mountains of mainland NW Scotland and in the Outer Hebrides. The recognition of this landsystem in a landscape dominated by warm-based ice sheet evidence, may suggest a temporal and spatial co-association of cold- and warm-based glacial conditions, whilst also highlighting the palimpsest nature of the terrestrial geomorphological record.

This work offers a preliminary comparison of the geomorphology and sedimentology of cold-based glacial landforms in Antarctica with Pleistocene features in a presently temperate, maritime Northern Hemisphere setting (NW Scotland). Preliminary observations indicate that where these features survived deglaciation, they could provide a potentially powerful tool for reconstructing former glaciological conditions and glacial history in areas thought to have been dominated by warm-based ice sheets.



**S07 – 273: Evolution of Antarctic Topography and Bathymetry: Understanding Links between Landscapes, Ice and Palaeoclimate**

***Seismic Stratigraphy of the Sabrina Coast Shelf, East Antarctica: History of Late Paleogene to Early Neogene Glacial Evolution***

Aleksandr Montelli<sup>1</sup>; Sean Gulick<sup>1</sup>; Bruce Frederick<sup>1</sup>; Don Blankenship<sup>1</sup>; Amy Leventer<sup>2</sup>; Amelia Shevenell<sup>3</sup>; Eugene Domack<sup>3</sup>

University of Texas at Austin, Jackson School of Geoscience, Institute for Geophysics<sup>1</sup>; Colgate University, Department Of Geology<sup>2</sup>; University of South Florida, College of Marine Sciences, USA<sup>3</sup>

**Background:**

Studying shelf architecture of Antarctic margins can reveal major shifts and transitions in global climate imprinted within sedimentary record. Due to its remoteness, the Sabrina Coast (SC) (118°-121° E) inner and mid-shelf has lacked seismic data coverage. Here we report, for the first time, the results of examination of sedimentary architecture of the SC shelf using 2014 high-resolution seismic data acquired offshore Moscow University Ice Shelf (MUIS).

**Objectives:**

The objectives of this work were to constrain the number of major glaciations that have occurred since the onset of East Antarctic Ice Sheet (EAIS) expansion, examine the impact of these glaciations on the continental shelf, and resolve late Paleogene to early Neogene EAIS dynamics and their relation to global climate evolution.

**Methods:**

754 km of high (up to 3 m) vertical resolution multichannel seismic data were acquired on board of RV Palmer using 75 m long 24-channel streamer and paired 45 cubic inch Generator-Injector (GI) guns. The guns were towed at the depth of 2.5-3 m and fired every 5 s with a ~12.5 m spacing interval. The source frequency was within the range of 20-300 Hz. The seismic data set includes several dip- and strike-oriented profiles that extend across the shelf. Two-way travel time seismic profiles were used for the seismic stratigraphic interpretation. Data processing flow included trace regularization, bandpass and f/k filtering, spherical divergence correction, muting, automatic gain control, normal moveout correction, stacking, water-bottom muting, and finite-difference time domain migration. The seismic grid was used to create isopach maps and to analyze seismic facies. Cross-correlation between seismic profiles was performed in Decision Space Software.

In addition, grid of high-resolution multibeam seafloor bathymetry data was used to complement seismic stratigraphic interpretation and infer the most recent history of glaciation and sedimentation of the study area. Two cores were used in this study to provide chronological control of the strata identified from seismic data interpretation.

**Results:**

Overall, we identify at least nine erosional surfaces that indicate advances of the EAIS to the SC shelf. We interpret the sedimentary record of early glacial SC shelf stratigraphy based on analysis of seismic facies and morphological features. Of these, the most prominent features include two series of undulating, channelized erosional surfaces truncating strata below and showing highly irregular morphology with elevation amplitudes of up to ~120 m and widths of individual undulations of up to ~10 km. Two symmetric, incised channels with widths of up to 1500 m, depths of 120 m and flank gradients of ~15° are found downdip from the older undulating surface. Our observations show that this channel system forms anastomosing pattern, which together with the dimensions of separate features shows great resemblance to the subglacial tunnel valley systems reported from Northern Hemisphere high-latitude margins, such as of the North Sea and the Gulf of Alaska. These observations demonstrate the



presence of high-pressurized meltwater derived from wet-based glaciers, thus favoring for polythermal regime of early EAIS.

**Conclusions:**

Our major results show that: (1) Oligocene-early Miocene evolution of EAIS consists of low-frequency, high-amplitude glacial expansions followed by long periods of ice-distal to open marine conditions; (2) the presence of grounded EAIS expansions on the shelf is expressed in a series of deep, hummocky undulations and tunnel valleys suggestive of presence of subglacial meltwater and hence, a polythermal glacial regime; (3) at least nine erosional unconformities representing major ice advances have been found on the inner shelf; (4) the most intensive polythermal glaciations have occurred in late Eocene-early Oligocene followed by less aggressive erosion in early Miocene; (5) no evidence of focused ice stream(s) draining Aurora Basin Complex (ABC) through the Reynolds trough prior to the middle Miocene was found in the study area, and (6) transition to a polar glacial regime is marked by a regional angular unconformity overlain by largely non-reflective, chaotic units interpreted as till.



**S07 – 274: Evolution of Antarctic Topography and Bathymetry: Understanding Links between Landscapes, Ice and Palaeoclimate**

***A Submarine Landform Continuum across Marine Ice-Stream Margins***

Alastair G.C. Graham<sup>1</sup>; Johann P.Klages<sup>2</sup>; Robert D. Larter<sup>3</sup>; James A. Smith<sup>3</sup>; Claus-Dieter Hillenbrand<sup>3</sup>; Gerhard Kuhn<sup>2</sup>

College of Life and Environmental Sciences, University of Exeter<sup>1</sup>; Alfred-Wegener-Institut Helmholtz-Zentrum für Polar- und Meeresforschung, Bremerhaven, Germany<sup>2</sup>; British Antarctic Survey (Natural Environment Research Council), Cambridge, UK<sup>3</sup>

The interface between grounded ice and the open ocean is one of the most critical for resolving processes of change in Earth's ice sheets. However, this environment remains one of the least explored on the planet and is poorly understood as a result. While the sedimentological facies succession of the transition from grounded ice to (seasonal) open marine conditions is relatively well known from sediment cores recovered from the continental shelf around Antarctica, the corresponding geomorphological signature has been less well studied. Here we analyse high-resolution marine geophysical surveys from palaeo-ice stream troughs on Antarctica's continental shelf, including bathymetry from sub-ice shelf settings, that allow for the geological imprint of the transition between grounded and floating ice to be fully explored. We document six styles of landform assemblage from Antarctic palaeo-ice stream beds, which we further interpret as diagnostic of particular stages in the transition of a marine ice-stream margin from a fully grounded state to an open water setting. Descriptively, the six types comprise of

- (i) Mega-scale glacial lineations, evolving into
- (ii) Elongate lineations with corrugated ridges,
- (iii) Sub-parallel elongate keel-marks,
- (iv) Broadly-spaced elongate furrows,
- (v) Elongate furrows with sinuous or ridged termini, and
- (vi) Curvi-linear, randomly-oriented ploughmarks.

Whilst several of these landform types have been described in isolation in previous bathymetric studies, rarely have they been considered in the context of such assemblage groupings and have not been viewed together as a continuum. In drawing together observations, these landform types, exposed by past ice-margin fluctuations across the sea bed, demonstrate a close similarity to one another but significant differences in their extremes. We thus argue that they form a recognisable continuum (evolution) of forms within fully grounded, through ice-plain, sub-ice shelf, pro-marginal, distal marginal, and finally, polar open-marine zones. These observations, including recognition of a geological signature for 'lightly-grounded' ice plains, provide mechanistic explanations for the creation of some key landforms (e.g. corrugated ridges) on circum-Antarctic sea floors, and offer a more detailed framework for interpreting ice-sheet change from the buried and exposed sea-bed geomorphological records of glaciated marine basins worldwide.



**S07 – 297: Evolution of Antarctic Topography and Bathymetry: Understanding Links between Landscapes, Ice and Palaeoclimate**

***Impact of Topography and Bathymetry on Antarctic Ice Sheet Model Simulations [Invited]***

Edward Gasson<sup>1</sup>; Rob DeConto<sup>1</sup>; David Pollard<sup>2</sup>

Climate System Research Centre, University of Massachusetts, Amherst, USA<sup>1</sup>; Earth System Science Centre, Pennsylvania State University, State College, USA<sup>2</sup>

Bed elevation is an important boundary condition to ice sheet model simulations that can have a large impact on ice sheet stability. This is especially relevant for areas where the ice sheet bed is grounded below sea level. For example, run-away retreat can occur in marine-based ice sheets where the bed deepens upstream of the grounding line.

In addition to the marine ice sheet instability, another instability mechanism has recently been suggested, ice-cliff failure. Marine ice sheets may terminate as shear ice cliffs if their supporting ice shelves are removed, for example due to ocean melting or hydrofracturing from surface meltwater draining into crevasses. In regions with deep bed elevations these ice cliffs may become large enough to fail structurally, leading to rapid retreat into Antarctic subglacial basins.

Both of these instabilities are highly sensitive to the bed elevation. Therefore changes to the bed elevation through time, for example due to landscape evolution may have a large impact on past ice sheet stability. Here we explore how changes to bed elevation affect simulations of the Antarctic ice sheet with these new mechanisms included.

First, to determine how existing uncertainties on modern bed elevation datasets (Bedmap2) may affect ice sheet stability, we create bed elevation datasets with random topographic noise tuned to the bedmap2 uncertainty. We use a warm Pliocene climate forcing, a period when there is evidence for large scale retreat of the Antarctic ice sheet. The results from these experiments show large variability due to the addition of this topographic noise, showing the sensitivity of the model to bed elevation.

We next explore how the evolution of the Antarctic landscape since it was first fully glaciated across the Eocene-Oligocene transition (34 Myr ago) may also affect our understanding of past ice sheet stability. Using a reconstructed Antarctic topography for the Eocene-Oligocene, which features much reduced marine basins and a terrestrial West Antarctic, our results suggest an Antarctic ice sheet that is remarkably stable. We perform idealized experiments to show how the evolution of the Antarctic landscape may have affected ice sheet stability through time.



**S07 – 340: Evolution of Antarctic Topography and Bathymetry: Understanding Links Between Landscapes, Ice and Palaeoclimate**

***IBCSO - Discovering Antarctica's Present-Day Bathymetry***

Arndt J.E.<sup>1</sup>; Dorschel B.<sup>1</sup>

Alfred-Wegener-Institut Helmholtz-Zentrum für Polar- und Meeresforschung, Germany<sup>1</sup>

The International Bathymetric Chart of the Southern Ocean (IBCSO) project aims to create comprehensive and reliable digital bathymetric models (DBM) for the Circum-Antarctic waters. Due to the size, remoteness and inaccessibility of this area, the success of the project is depending on international efforts and collaboration. For this reason, IBCSO is well connected to internationally operating scientific and hydrographic organizations. IBCSO is an expert group of SCAR since 2004. Furthermore, it is a regional mapping project of the General Bathymetric Chart of the Ocean (GEBCO) under the joint auspice of the Intergovernmental Oceanographic Commission (IOC) (of UNESCO) and the International Hydrographic Organization (IHO).

In 2013, the first version of IBCSO has become available to the scientific community, accompanied by a publication in the Journal Geophysical Research Letters (Arndt et al., 2013). For this version, more than 30 institutions from 15 countries contributed data and knowledge. The DBM covers the area south of 60° with a resolution of 500 m. The data can be downloaded in various formats from the project website, as well as a chart and cartographic background data ([www.ibcso.org](http://www.ibcso.org)).

Even though all available data had been compiled for IBCSO V1.0, approximately 83% of the area remained not directly constraint by data and had been interpolated or determined by predicted bathymetry from satellite altimetry. Continuous acquisition of bathymetric data from an increasing fleet of research vessels equipped with multibeam sensors has increased the amount of available data and will do so in the future. In addition, due to the increased visibility of the project in the aftermath of the first version new collaborations with additional datasets have been established. Accordingly, the future of the project and a possible version 2.0 has been discussed during an IBCSO meeting at the 2014 SCAR conference in Auckland. We will present the results of IBCSO V1.0 and will give an outlook on the projects future.



**S07 – 365: Evolution of Antarctic Topography and Bathymetry: Understanding Links between Landscapes, Ice and Palaeoclimate**

***Seismic Imaging of Former Grounding Lines under Whillans Ice Stream, West Antarctica***

Tarun Luthra<sup>1</sup>; Sridhar Anandakrishnan<sup>1</sup>; Richard Alley<sup>1</sup>

Penn State University, USA<sup>1</sup>

We conducted an active source reflection seismic survey on Whillans Ice Stream, West Antarctica. We imaged a sequence of subglacial horizons that we interpret as layered lithified sedimentary beds. The topmost layer is an approximately 60 m thick sediment package directly beneath the ice-bed interface. This layer unconformably overlies deeper layers. All layers share similar dips in the downstream direction. The acoustic impedance of the sedimentary layer above the unconformity is lower than that of the deeper layers, we suggest that the uppermost layer is consistent with a glacial diamictite with deeper, more-lithified layers from prior glaciations. The deposition of sedimentary material in this fashion implies that these beds were formed as a grounding zone wedge and hence, signify the advance/retreat episode experienced by the ice sheet in the past. We further suggest that the glacier grounds and re-grounds preferentially in this area. The preference shown by the ice stream to reoccupy this site as a grounding line highlights the uniqueness of this area, possibly due it being a zone of local topographic high region. Thus, in the event of a future retreat of West Antarctic Ice Sheet (WAIS), it is possible that the current position could serve as a future grounding line zone.



**S07 – 380: Evolution of Antarctic Topography and Bathymetry: Understanding Links between Landscapes, Ice and Palaeoclimate**

***Landscape Evolution of the Marie Byrd Land Crustal Block from Aerogeophysics***

Young, Duncan A.

University of Texas Institute for Geophysics, USA

The elevated subglacial topography underlying the Marie Byrd Land dome likely has played a crucial role in the inception and evolution of the West Antarctic ice sheet through time. The Marie Byrd Land ice dome hosts a number of subaerial Miocene to recent propagating volcanic chains, but the crust underlying these volcanoes was poorly understood. The volcanic centers, a nearby abundance of high amplitude magnetic centers, and occasional exposures of a ~23 Ma elevated erosion surface have been used to argue for a distinct Cenozoic hotspot underlying this region and lifting topography over time. Other interpretations include that this region represents the collapsed remnant of an ancestral West Antarctic orogeny, or represents a broad region uplifted by subduction driven mantle flow. In 1998 the topography of the western edge was surveyed by the NSF SOAR aerogeophysics facility using incoherent ice penetrating radar, and in 2004 the eastern edge was surveyed at coarser resolution by the University of Texas Institute for Geophysics with an advanced ice sounding radar (HiCARS). Both used a short range Twin Otter. Surveying of the central core of the Marie Byrd Land dome required the use of a long range survey Basler. In January 2013 and late 2014, UTIG conducted 13 survey flights (and 25,000 line km of HiCARS, gravity and magnetics coverage) over central Marie Byrd Land, as part of the Geophysical Investigations of Marie Byrd Land Evolution (GIMBLE) project. A corridor of 5 km line spacing was achieved.

GIMBLE data show that the subglacial topography of the central domain of the Marie Byrd Land dome is truncated by a well developed alpine landscape, penetrated by overdeepened glacial troughs. The subaerial Marie Byrd Land volcanoes extend up to 2 km above this landscape, seemingly unaffected by the alpine erosional processes.

There is no evidence for an inboard tectonic scarp bounding the southern edge of the crustal block; instead, isolated plateaus in the basin to the south imply deep erosion of the southern edge of the dome. There is evidence for a non-alpine erosional surface on the northern and eastern margins of Marie Byrd Land, which has been tilted by coast parallel faulting.

We discuss these landscape elements in the context of the evolution of the Marie Byrd Land dome, and the West Antarctic Ice Sheet.



**S07 – 393: Evolution of Antarctic Topography and Bathymetry: Understanding Links between Landscapes, Ice and Palaeoclimate**

***Subglacial Conditions and Ice Flow across the Weddell Sea Sector of West Antarctica: Synthesis from Recent Aerogeophysical Surveys***

Robert G. Bingham<sup>1</sup>; Neil Ross<sup>1</sup>; Hugh F.J. Corr<sup>1</sup>; Fausto Ferraccioli<sup>2</sup>; Tom A. Jordan<sup>1</sup>; Anne M. Le Brocq<sup>1</sup>; David M. Rippin<sup>1</sup>; Kathryn C. Rose<sup>1</sup>; Andrew P. Wright<sup>1</sup>; David W. Ashmore<sup>1</sup>; Martin J. Siegert<sup>1</sup>

University of Edinburgh, United Kingdom<sup>1</sup>; NERC/British Antarctic Survey, Cambridge, United Kingdom<sup>2</sup>;

Institute and Möller Ice Streams (IMIS) together drain ~20% of the ice from West Antarctica, forming major contributors to the Weddell Sea Sector (WSS) of Antarctica. Before 2010, relative to the other major West Antarctic drainage basins feeding the Ross and Amundsen Seas, the WSS was rated as West Antarctica's 'pole of ignorance' concerning past and present glaciological conditions and sensitivity to change. Underpinned by the hypothesis that IMIS may be underlain by deformable marine sediments analogous to the Siple Coast ice streams, and may therefore be prone to similar ice-dynamical instabilities, a comprehensive aerogeophysical survey of IMIS was undertaken in the austral summer 2010/11 under the auspices of NERC's Antarctic Funding Initiative. Herein we present a synthesis of findings from the new data.

We now know that the lower portion of IMIS is underlain by a deep basin filled with marine sediments and sloping inland, rendering much of the region vulnerable to the marine ice-sheet instability. Inland of the marine basin, the subglacial terrain is composed of mixed roughness. This reflects, in part, a significant tectonic signature of faults, structural lineaments and Jurassic intrusions likely emplaced during opening of the Weddell Sea Rift. Superimposed is a geomorphological signature testifying to the basin's experience of waxing and waning ice cover over glacial cycles. An extensive plateau inland of the deep basin was likely created under ice-free conditions during the mid-Miocene (17-15 Ma), while large channels cut into the bedrock testify to the presence of thinner, temperate ice cover which allowed supraglacial-subglacial connections during the Pliocene (5.3-2.6 Ma). Today the regional ice cover is thinning steadily from the Last Glacial Maximum (20 ka). Patterns of englacial layering suggest that in the less topographically constrained western and southern parts of IMIS the spatial configuration of ice has changed considerably, likely in response to thinning and increased grounding of the Bungenstock Ice Rise and a proportional increase in drainage of IMIS via Institute Ice Stream. Multiple lines of evidence show that IMIS is today underlain by a highly dynamic subglacial hydrological system which may facilitate further changes to the ice flow. Modelling suggests that of all the WSS ice streams, IMIS may be particularly susceptible to considerable change after only a projected moderate increase in ice-shelf melt at its grounding zone.



**S07 – 397: Evolution of Antarctic Topography and Bathymetry: Understanding Links between Landscapes, Ice and Palaeoclimate**

***Thermotectonic and Geomorphic Evolution of Marie Byrd Land and the Pine Island Bay Area***

Frank Lisker<sup>1</sup>; Cornelia Spiegel<sup>1</sup>; Julia Lindow<sup>1</sup>; Peter Kamp<sup>2</sup>; Samuel Mukasa<sup>3</sup>; Gerhard Kuhn<sup>4</sup>; Karsten Gohl<sup>4</sup>

University of Bremen, Germany<sup>1</sup>; University of Waikato, New Zealand<sup>2</sup>; University of New Hampshire, USA<sup>3</sup>; Alfred-Wegener-Institut für Polar- und Meeresforschung, Germany<sup>4</sup>

Due to extensive glacial cover, the evolution of the West Antarctic Rift System (WARS) and the proto-Pacific margin of Gondwana are still poorly understood. Here we present the first low-temperature thermochronology data from eastern Marie Byrd Land and the Pine Island Bay area. The goal of our study is to decipher the long-term thermotectonic evolution of this area, infer its denudation history, and to provide estimates for paleotopography and potential links to the glaciation history. Our data show that during early and mid-Cretaceous subduction along the proto-Pacific margin, all of Marie Byrd Land and the Pine Island Bay area experienced rapid exhumation. This rapid exhumation continued for about 25 Myr after subduction stopped, presumably driven by tectonic denudation related to continental breakup between Zealandia and West Antarctica and rifting activity of the WARS. This late Cretaceous extension period was related to rapid topography reduction, as expressed by the formation of the West Antarctic erosion surface close to sea level, and was probably related to free-boundary gravitational collapse of the Gondwanide orogen. By ~60 Ma, rapid exhumation stopped, which we interpret as cessation of the first WARS rifting period. Cretaceous rapid exhumation was followed by very low exhumation rates throughout the Cenozoic, which we explain by tectonic quiescence and subdued topography.

After ~30 Ma, and restricted to the western Pine Island Bay area, rapid exhumation resumed, presumably coeval with large-scale crustal tilting of the eastern Pine Island Bay area towards the Pine Island trough. We interpret this as indicating renewed activity of the WARS, (i) suggesting that Cenozoic rifting activity was much more localized than Cretaceous rifting, and (ii) corroborating previous assumptions that the WARS branches from the continental interior into the Amundsen Sea. Our structural model, based on the thermochronology data, kinematically links the rift branches reaching into the Bellingshausen and Amundsen Seas with the Byrd Subglacial Basin and the Bentley Subglacial Trench, requiring dextral transtension for the Bellingshausen Sea area and sinistral transtension for the Amundsen Sea area.

Furthermore, our data suggest that enhanced denudation along the flanks of the Marie Byrd Land dome and thus presumably its uplift only started at ~20 Ma, that is, nearly 10 Ma later than previously assumed. The Marie Byrd Land dome is the only extensive part of continental West Antarctica elevated above sea level. Since the formation of a continental ice sheet requires a significant area of emergent land, our data imply that initiation of extensive glaciation of this part of West Antarctica may only have started since the early Miocene.



**S07 – 438: Evolution of Antarctic Topography and Bathymetry: Understanding Links Between Landscapes, Ice and Palaeoclimate**

**Preliminary Interpretations of Seafloor Geomorphology from a Near-Shore Multibeam Sonar Survey; Casey Station, East Antarctica**

Carson CJ<sup>1</sup>; Walker G<sup>2</sup>; Waring P<sup>2</sup>; Forrest D<sup>3</sup>; Bartley R<sup>4</sup>

Geoscience Australia GPO 378, Canberra, ACT, 2601, Australia<sup>1</sup>; Royal Australian Navy, Balls Head Rd, Waverton NSW, 2060, Australia<sup>2</sup>; IXSURVEY Australia Pty Ltd, PO Box 5536, Manly, QLD, 4179, Australia<sup>3</sup>; Australian Antarctic Division, 203 Channel Highway, Kingston, TAS, 7050, Australia<sup>4</sup>

The shallow-water (<160m) marine environment around the Australian research station, Casey station (east Antarctica) is a high use area, frequently visited by both large resupply vessels and smaller workboats conducting scientific research in the area. Yet high resolution modern bathymetric data in the area, as well as much of the east Antarctic continental margin, is limited. The Casey nearshore area hosts significant levels of biodiversity, but this knowledge is geographically restricted in scope (i.e. shallow depths, close to shore). This biodiversity faces pressures from human activities and effects of climate change, yet extensive knowledge gaps remain, limiting efforts to conserve and manage it effectively. Improved bathymetric surveying in this region will begin to fill these knowledge gaps by conducting representative mapping and sampling of both the physical environment and biological communities and, in addition, reduce the risk to maritime operations in the region.

During the period December 2014 to February 2015, a collaborative multibeam survey involving Australian Antarctic Division, Royal Australian Navy and Geoscience Australia was conducted in the shallow-water near-shore regions adjacent to Casey station and covered an area of ca. 28 km<sup>2</sup>. The survey employed Geoscience Australia's KONGSBERG EM3002 dual head sonar system mounted on an Australian Antarctic Division supplied science workboat, the RV *Howard Burton*.

In total, the surveyed region covered ca. 34 km<sup>2</sup>, to a maximum depth of ca. 170m (including a Royal Australian Navy survey conducted in 2013/14 covering an area of ca. 6 km<sup>2</sup>). The data was processed in CARIS v8 and a seafloor surface has been gridded at a resolution of 1m. Water column and backscatter data was collected and will be processed and presented at a later date.

**Results and preliminary interpretations:**

The results reveal the seafloor morphology in unprecedented detail (Fig. 1). Preliminary interpretation of the submarine geomorphology reveal several dominant features which can be simplified into 4 domains as follows: (1) NW and WSW trending fault and channel systems, (2) Glacio-fluvial seafloor features (possible terminal moraines) within channel features, (3) bedrock basement highs and (4) 'deep' isolated basins.

The most striking seafloor features evident in the multibeam data are the NW-SE trending channels and linear features that most likely represent brittle bedrock fault systems. These features are present on the north shore of Newcomb Bay, O'Brien Bay, in the bedrock highs along the Beall Reefs region and Robertson Channel. These sub-parallel basement bedrock faults or 'fractures' (or joints in geological terms) have been preferentially eroded and widened locally by glacial action (see below) to form narrow



channels, some 200-400 m wide and preserve typical 'U-shaped' profiles, characteristic of glacially eroded valleys seen in the terrestrial environment. A secondary set of SW to WSW trending linear features are characterised by broad eroded channels. These features are less distinct than the NW trending set of channels and are sub-parallel to the regional high-grade gneissic fabric exhibited by the basement rocks exposed onshore. The broad features are evident, for example, between Beall Island and Beall Reefs, the seaward end of Clark Peninsula. The general orientation of the coastline and channels in the Casey region suggest that these linear features fundamentally control the regional coastal and seafloor geomorphology.

Within the NW trending channels, particularly within O'Brien Bay and northern Newcomb Bay, distinct raised narrow curved (convex seaward) seafloor features can be seen. These seafloor features, presumably formed by glacial or glacio-fluvial processes, resemble 'terminal moraines' deposited at the terminus of channelized outlet glaciers that likely formed when the ice sheet locally extended seaward beyond its present day limits. Limited seafloor images show heterogeneous rocky detritus, consistent with diamictite typical of terrestrial moraines. The channels in which these submarine moraine features occur in Newcomb and O'Brien Bays trend NW initially then open out into the broader WSW trending channels and deeper basins further seaward. The 'moraines' are particularly well developed, for example in northern Newcomb Bay, and may be up to 25 m higher than the surrounding seafloor. Many smaller moraines, about 5-10 m high, are also easily discernible.

Bedrock highs are dominated by complex, rugged and variable topography, and dominated by steep knolls that can form small shoals and reefs (e.g. Gibney and Dahl reefs). Regions characteristic of this morphology are the areas seaward (west) of Clark Peninsula and Newcomb Bay and the E-W trending bedrock high of the Beall Reefs-Granholm Rock region near Beall Island. These regions are flanked by deep NW and WSW trending channels also containing terminal moraines. Bedrock highs do not appear (based on nil returns during sediment sampling) to be overlain by significant sediment coverage or basins. Finally, there are deep (80-100 m) sediment filled basins present in O'Brien Bay, Newcomb Bay and north of Shirley Island. These basins are either enclosed, in that there is no outlet for bottom drainage (north Shirley Island), or have limited drainage through a single channel (O'Brien and Newcomb Bay).

This information will enable a detailed appraisal of regional benthic biological community distribution and composition, facilitating the development of informed and appropriate environmental management for the Casey near-shore region. The bathymetric data will result in more accurate navigational charts and reduce risk to maritime operations in the Casey region. This work was conducted as part of Australian Antarctic Program (AAD3326; 'Hydrographic Surveying and Bathymetric Data Acquisition'), and is aligned with Geoscience Australia's strategic priority 'Managing Australia's Marine Jurisdictions'.



**S07 – 464: Evolution of Antarctic Topography and Bathymetry: Understanding Links Between Landscapes, Ice and Palaeoclimate**

***Isostatic Rebound Caused by Cenozoic Fluvial and Glacial Incision in the Gamburtsev Subglacial Mountains and their Pre-Incision Palaeotopography***

Fausto Ferraccioli<sup>1</sup>; Guy Paxman<sup>2</sup>; Tony Watts<sup>2</sup>; Tom A. Jordan<sup>1</sup>; Robin Bell<sup>3</sup>; Stewart Jamieson<sup>4</sup>; Carol Finn<sup>5</sup>; Detlef Damaske<sup>6</sup>

NERC-British Antarctic Survey, UK<sup>1</sup>; Oxford University, Dep. Earth Sciences, UK<sup>2</sup>; Lamont-Doherty Earth Observatory, USA<sup>3</sup>; Durham University, Dep. Geography, UK<sup>4</sup>; US Geological Survey, USA<sup>5</sup>; BGR, Germany<sup>6</sup>

The Gamburtsev Subglacial Mountains (GSM) are a paradoxical tectonic feature, as despite their modern Alpine-style geomorphology (Creys et al., 2014 GRL) they are located atop of stable Precambrian cratonic lithosphere, typical of interior East Antarctica. Unravelling the enigmatic topographic evolution of the GSM is particularly important, as this mountain range is thought to have provided a key nucleation site for the development of the East Antarctic Ice Sheet (EAIS) ca 34 Ma ago (DeConto and Pollard, 2003, Nature; Rose et al., 2013, EPSL).

New perspectives on possible mechanisms responsible for the uplift of the GSM have emerged from recent interpretations of AGAP aerogeophysical data (Bell et al., 2011, Science). Permian rifting and intraplate Cretaceous strike-slip faulting have been put forward as possible tectonic triggers for the uplift of the GSM (Ferraccioli et al., 2011, Nature). Although the hypothesis for a Cretaceous phase of denudation in the GSM is consistent with some geological and geophysical interpretations in the adjacent Lambert Rift (Lisker et al., 2007 OFR; Phillips & Läufer, 2009, Tectonophysics), more recent interpretations of detrital thermochronology from Oligocene-Quaternary sediments in Prydz Bay (Tochilin et al., 2012 G3) argue against major Cretaceous exhumation in interior East Antarctica (see also Thomson et al., 2013 Nature Geoscience). This raises the question of whether Cenozoic erosion and associated isostatic responses prior to and during the early stages of EAIS development may have been sufficient to drive a substantial part of the uplift of the GSM. To address this question, we (a) estimate the effective elastic thickness of the lithosphere ( $T_e$ ) in the GSM region; (b) calculate the amount of eroded material by using geophysical relief estimation; (c) estimate the resulting flexural isostatic uplift induced by valley incision for different  $T_e$  scenarios and finally (d) estimate the pre-incision elevation of the GSM.

To estimate  $T_e$  we used two standard approaches: (1) Free-air admittance and (2) Bouguer coherence methods. These results were also compared with previous estimates of  $T_e$  that also incorporated independent seismically-derived estimates of crustal thickness and the results of forward gravity modelling that revealed an anomalously thick high-density buried load in the lower crust beneath the northern GSM (Ferraccioli et al., 2011). We found that coherences between the topography of the GSM and gravity are among the highest ever reported in continental interiors. Both the admittance and coherence methods suggest anomalously low  $T_e$  values in the Gamburtsev province, in contrast with previous estimates that reported instead high  $T_e$  values of ca 70 km beneath the range and lower  $T_e$  of ca 30 km beneath the East Antarctic Rift System inferred to surround the GSM (Ferraccioli et al., 2011). The new admittance calculations also suggest that typical upper crustal densities for the GSM are anomalously high in the 2800-2900 kgm<sup>-3</sup> range.

The first step to estimate both the amount and the spatial distribution of eroded material is to construct a peak accordance surface. Peaks are identified using a circular moving window of fixed radius and an accordance surface (hereafter cap) is constructed by interpolating between the peaks. Different window sizes were tested to account for the variable width of the fluvial and glacial valley networks dissecting the GSM and adjacent LR region. The difference between the cap and the topography constitutes the eroded material, assuming the peaks have not been significantly eroded. We found that the two fundamentally



different styles of erosion Alpine-style dendritic fluvial and glacial incision in the GSM and major EAIS outlet glacier-type incision in the LR cause markedly different volumes and distributions of eroded material in these regions.

Using a variety of elastic plate models for different  $T_e$  scenarios [including our new results from admittance and coherence calculations and the variable  $T_e$  model of Ferraccioli et al. (2011)] we then quantified the spatial distribution and magnitude of flexural uplift in both the GSM and the adjacent LR region. We show that although the pattern of peak uplift is affected by the different  $T_e$  scenarios tested, the total amount of isostatic uplift is not as sensitive. Overall, we estimate that the total amount of flexural uplift is approximately 600 m in the GSM and up to 1.2 km in the LR. The latter is consistent with independent geological evidence in the Lambert Glacier area, such as estimates of the amount of glacial incision (Tochilin et al., 2012) and the present elevation of Oligocene-Miocene glacio-marine sediments up to 1,500m above sea level (Hambrey et al., 2000, *Geology*).



**S08 –57: Surficial Processes and Climate Change in Antarctic Terrestrial Environment: Changes and Impact on Permafrost, Erosion and Chemical Weathering**

***Late Quaternary Climatic Fluctuations and Holocene Warming of Schirmacher Oasis, East Antarctica***

Shrivastava P. K.<sup>1</sup>; Roy, S. K.<sup>1</sup>; Asthana, R.<sup>2</sup>; Swain, A.K.<sup>1</sup>; Mallik, R. K.<sup>1</sup>; Beg, M.J.<sup>3</sup>; Srivastava, H.B.<sup>4</sup>; Verma, K.<sup>1</sup>

Geological Survey of India, Faridabad, India<sup>1</sup>; Polar Geological Survey of India, Kolkata, India<sup>2</sup>; National Centre for Antarctic and Ocean Research, Goa, India<sup>3</sup>; Banaras Hindu University, Varanasi, India<sup>4</sup>

Schirmacher Range, located on the Princess Astrid Coast in Queen Maud Land, is one of the few periglacial climatic regions in East Antarctica that provides a valuable repository of various depositional features formed due to deglaciation process. The Schirmacher Oasis is dotted with more than 100 proglacial, land locked and epi-shelf lakes. The multi-proxy sedimentological data, generated from the sediment cores of proglacial lakes and land locked lakes, lying in the same drainage line in the central part of Schirmacher region provide better insight into the paleoclimatic evolution of the region. The lake sediments are immature, chemically unaltered in nature and have restricted drainage pattern. The patterns of fluctuations in different sedimentological parameters such as weight percentages of sand, silt, and clay and statistical parameters including mean grain size, S<sub>ø</sub>rting, S<sub>ø</sub>rting coefficient, skewness, kurtosis show warmer and cooler phases at different intervals. But in general, the overall trend shows evidences of gradual warming of this region since Late Quaternary. The warm period is not strong enough to alter the overall clay chemistry. The glacial signal is very clear and dominating in this region. The surface textures of quartz grains as studied by Scanning Electron Microscopy, show dominant glacial and glacio-fluvial actions. Exclusively physical weathering has controlled the overall sediments and composition of clay fraction. The clay minerals indicate a gradual shift in the weathering regime and therewith in climate from strongly glacial to fluvio-glacial during Holocene. Data from lake bottom sediment core from Priyadarshini (Zub) Lake, which is adjoining to the study area, shows warmer and cooler periods in Late Quaternary. The OSL dates of glacial sediments also indicate different stages of glaciation and de-glaciation during Late Quaternary. Proxy records of climatic variabilities from the sediment cores of different lakes and glacial terraces of Schirmacher Oasis, indicate short-period climatic oscillations during late Quaternary.



**S08 –58: Surficial Processes and Climate Change in Antarctic Terrestrial Environment: Changes and Impact on Permafrost, Erosion and Chemical Weathering**

***Snow Accumulation Pattern in the Larsemann Hills Area and in Schirmacher Oasis Region, East Antarctica***

Shah Md. Y<sup>1</sup>; Ayemi K. K.<sup>1</sup>; Shrivastava P. K.<sup>1</sup>

Geological Survey of India, Faridabad, India<sup>1</sup>

The periglacial environment of Schirmacher Oasis, central Dronning Maud Land and Bharati Promontory, Larsemann Hills of East Antarctica are currently ice-free coastal areas exposed in polar periglacial environment in two different physiographic settings. Schirmacher Oasis is bound by the presence of a vast stretch of ice shelf in the north and the polar ice sheet in the south. It exhibits well-developed glacial erosive and depositional features. In contrast, the occurrences of such features are sparse in Bharati Promontory region, where landmass and ice sheet is directly in contact with the ocean. The Bharati Promontory area represents a polar lowland periglacial climate with relatively lower amounts of precipitation than Schirmacher Oasis, restricted period of snow melting, and low rates of ice melt.

In Larsemann hills area, the average monthly snow accumulation/ablation pattern shows influence of persistent easterly winds, temperature fluctuations and ocean currents. The average monthly snow ablation is dominant over snow accumulation in the Larsemann Hills region, whereas in the Schirmacher region of central Dronning Maud Land, the snow accumulation is dominant over ablation. The accumulation has been recorded higher over ice shelf than on ice sheet. The snow accumulation shows some degree of positive correlation with average annual wind speed of this region indicating drift-snow as an important part of total snow accumulation. The progressive accumulation of snow on the ice shelf is shown by second order polynomial best fit curve with  $R^2=0.973$  (measure of reliability). The rate of snow accumulation over ice shelf is not uniform and is affected by local/regional factors.

The GPR survey using MLF and 200 MHz antennas on Polar Ice Sheet in Larsemann hills area has deciphered polythermal nature of ice containing many water filled fractures and melt water pockets. The maximum thickness of firn over blue ice varies from 04 to 05 meter. In Schirmacher region, the thickness of ice sheet increases rapidly from 0m to 380m within a distance of 12 km. The density of Antarctic ice is 0.65 at the surface and becomes nearly constant at 0.93 below 30 m.

During Austral winter, GPR survey with SIR-3000 control unit and 200 MHz antenna was used to obtain information on the thickness and internal structure of the fast ice between Bharati promontory, Fischer Island and Broknes Island in Quilty Bay/Clemence Fjord of Larsemann Hills. This study reflects that thickness of surface snow and fast ice gradually decreases from Grovnes (3 m) to Fischer Island (less than 2 m) which may be influenced by persistent easterly winds blowing the ice and snow from west to east, temperature fluctuations and ocean currents. Pack ice found in Clemence Fjord between Fischer Island and Broknes Island varies from 05 to 06 meter with surface snow less than one feet. GPR data also reflects few water filled fissures created by tensional forces on ice floes and melt water pockets within the fast ice. Rare polynyas areas occur towards north of Quilty Bay providing direct interaction between ocean and the atmosphere. In Schirmacher region, it has been observed that since April onwards, firn base has been developed which got connected with the shelf by gradual slope in May. The hinge line between ice shelf and fast ice do not show any tensional and compressional cracks till the end of austral winter. The thickness of fast ice varies between 0.61m to 3.17m. Average density of fast ice varies between 0.4 and 0.65 gm/cc.



**S08 –60: Surficial Processes and Climate Change in Antarctic Terrestrial Environment: Changes and Impact on Permafrost, Erosion and Chemical Weathering**

***Fluctuation of Snow Accumulation and Ablation Pattern near Schirmacher Oasis, East Antarctica***

Swain A. K.<sup>1</sup>; Shrivastava P. K.<sup>1</sup>; Asthana R.<sup>2</sup>; Roy S. K.<sup>1</sup>; Dharwadkar A.<sup>3</sup>; Raghuram<sup>1</sup>; Kumar P.<sup>1</sup>; Mallik R. K.<sup>1</sup>; Beg, M. J.<sup>4</sup>; Chaturvedi A.<sup>3</sup>

Geological Survey of India, Faridabad, India<sup>1</sup>; Geological Survey of India, Kolkata, India<sup>2</sup>; Geological Survey of India, Lucknow, India<sup>3</sup>; National Centre for Antarctic and Ocean Research, Goa, India<sup>4</sup>

Central Dronning Maud Land (cDML) region of East Antarctica encompasses a vast land of ice with only 3% of the area occupied by rocky outcrops in the form of mountains separating Polar plateau in the southern part and a vast ice shelf in northern part. Few nunataks and roughly E-W trending 19.5 km long Schirmacher Oasis situated between iceshelf to its north and Polar ice sheet to its south and is characterized by an ice-free zone in the coastal area of Antarctica with a distance of 80 km from the open sea. Spatial incoherence in the snow distributions from ice shelf to the polar plateau have been identified in this region which are manifested by two types of distribution patterns depending upon their increasing distance from open water and the elevation from mean sea level. Long term snow accumulation data taken from the edge of the ice shelf shows the influence of the direction and strength of atmospheric flow as well as the katabatic forcing from the high interior region. The later causing a superposed impression to different extent on the existing ESE-WSW trending snow trails. The surface mass balance remains always positive with more amount of snow fall measured every year compared to that in the Polar ice sheet. The snow fall in this region is also influenced by the seasonal freezing of sea ice. The snow accumulation and ablation studies carried out on Polar ice sheet by fixing stake networks indicate that the surface mass balance at 10 km south of Schirmacher Oasis is around 120 Kg/m<sup>2</sup> per annum and the equilibrium line altitude is around 515 m above mean sea level, below which a vast blue ice field is also observed. However the proximity to the ice-free landmass and a consistent wind direction contributes to the ablation rates in this region during austral summer period. This may be attributed to the exposure of rocks influencing the albedo due to their heat absorbing and reflective capacity during austral summer.



**S08 –61: Surficial Processes and Climate Change in Antarctic Terrestrial Environment: Changes and Impact on Permafrost, Erosion and Chemical Weathering**

***Depth Profiling and Recessional History of Hamtah Glacier and Parang Glacier in Lahaul & Spiti, Himachal Pradesh, India***

Swain A. K.<sup>1</sup>; Mukhtar, M. A.<sup>2</sup>; Majeed, Z.<sup>2</sup>; Kumar P.<sup>1</sup>; Shukla S. P.<sup>2</sup>

Geological Survey of India, Faridabad, India<sup>1</sup>; Geological Survey of India, Lucknow, India<sup>2</sup>

The Indian Himalaya is home to 9575 glaciers. These mountain and valley glaciers cover about 18054 sq. Km area. Together with the glaciers in the Himalaya of neighbouring countries (HKH Region), it is considered as the Third Pole, as the areal extent of the glacierised area in this region is highest outside the Polar Regions. The melt-water from these glaciers is one of the main sources of freshwater for the sizeable population living in the downstream, the amount of which depends on the amount of glacial melt; which again has a direct bearing on the health and volume of the glacier feeding it. Though the aerial extent of the glaciers has been assessed fairly by remote sensing methods and mapping of the glacier snout front, estimating the ice-volume of these glaciers is a serious challenge. Such data on ice thickness is very significant for estimating volume of locked up ice including for accurately compiling glacier inventory of the basin. For mass balance assessment, though estimation of ice thickness is not required; yet repeat surveys can help in change-detection studies, including assessing the third dimension of the glacier-recession as it is known that Himalayan glaciers are thinning.

For this objective, depth profiling of two north-facing glaciers, Hamtah and Parang, was carried out. These glaciers belong to Indus first order basin, which contains 83% of the total glaciers in Indian Himalaya. The accumulation zones of these glaciers lie at altitudes of 4600 mts and 5400 mts above mean sea level (msl), respectively. Hamtah is a valley glacier with 6 Km length, having an average width of 500 mts, is oriented mainly N 30°W - S 30° E and flows towards northwest whereas Parang glacier has a length of 2.5 Km, with an average width of 250 mts and is oriented N 20° E - S 20° W with a NNE flow direction. Both the glaciers have well-developed U-shaped valleys. The lateral moraines are developed parallel to the current orientation of the glaciers. However, the orientation of the recessional moraines of Hamtah glacier shows a complex nature with a variation in the orientation from the present snout along N 25°E - S 25° W to older ones along N 40° E - S 40° W and to N 75° E to S 75° W. Recessional moraines in Parang glacier are oriented mainly along N 20° W - S 20° E in a parallel series, indicating a less complex recessional pattern.

As Ground Penetrating Radar (GPR) profiling provides fast, non-destructive and accurate results compared to the time consuming and tedious conventional methods of geophysical surveys/ drilling the glacier ice for thickness estimation of glaciers, it was utilized on these two glaciers using the antennas of 100 and 200 MHz as well as multiple lowfrequencies of 16 to 80 MHz. The data was taken both in the point-mode as well as continuous-mode. On Hamtah glacier, the depth profiling was carried out in ablation zone as well as accumulation zone, by taking few spot readings using point-mode and continuous profiling was done with survey wheel mode. The depth of the ice-bed rock interface was measured to vary from 35 to 80 mts in the accumulation zone at an elevation of 4600 mts, with a snow cover of 8-10 mts at a few places. Very close to the bergschrund zone, where avalanche materials have covered the ice, the ice thickness is less than its immediate surroundings. Parang glacier is comparatively free from avalanche debris, so the bedrock reflection was distinctly observed in the radargrams; it indicates that the ice thickness varies from 60 mts in the ablation zone to 140 mts in the accumulation zone. The maximum thickness of 140 mts was found in the accumulation zone of Parang glacier at an elevation of 5400 m asl. The total volume of ice for Hamtah glacier is calculated to be approximately about 0.375 Km<sup>3</sup> and water equivalent about 0.30 Km<sup>3</sup>, whereas that in the Parang glacier is about 0.261 Km<sup>3</sup> with water equivalent about 0.208 Km<sup>3</sup>. The recessional history of these glaciers shows that the



Hamtah glacier has receded ~821 mts since 1963 at an average annual rate of 16.1 mts/yr; whereas Parang glacier has receded ~556 mts since 1962 at an average annual rate 11 mts/yr. The rate of glacier retreat is observed to have increased in the last decade. This increased ablation rate sometimes leads to the formation of supraglacial lakes, as is seen the accumulation area of Parang glacier, which has a supraglacial lake of approximately 190 mts width. Such lakes further enhance melting of the glacier. This type of ice thickness estimation using the GPR has helped in estimation of the ice volume of these glaciers; repeat-surveys in future can be helpful in estimating accurate loss of ice thickness and likely change in melt-water potential of these glaciers.



**S08 –63: Surficial Processes and Climate Change in Antarctic Terrestrial Environment: Changes and Impact on Permafrost, Erosion and Chemical Weathering**

***Comparison of Lake Water Hydrochemistry between Two Periglacial Zones of East Antarctica***

Asthana R.<sup>1</sup>; Swain A. K.<sup>2</sup>; Shrivastava P. K.<sup>2</sup>; Kumar P.<sup>2</sup>; Beg M. J.<sup>3</sup>

Geological Survey of India, Kolkata, India<sup>1</sup>; Geological Survey of India, Faridabad, India<sup>2</sup>; National Centre for Antarctic and Ocean Research, Goa, India<sup>3</sup>

Periglacial zones dominate the ice-free landmass in the peripheral parts of Antarctica. In the East Antarctica, the Schirmacher Oasis (70° 45' S; 11°45' E) represents a deglaciated region located between Polar ice sheet to its south and ice shelf to its north in the Princess Astrid coast while Fisher Island and Broknes Peninsula in Larsemann Hills (69° 23' S, 76° 53' E) exhibit polar lowland periglacial environment between the marine and glacial ecosystems. These landmasses are characterized by gently rolling hills and broad valleys interspersed with glacially scoured depressions now represented in the form of lakes, many of which are filled bywater during austral summer period. Physico-chemical parameters and ionic constituents of 30 water samples from 10 lakes each from these three locations are quite contrasting and have indicated influence of lithology and the processes including weathering, evaporation and atmospheric precipitation. All major cations and anions of lake waters show positive correlations indicating balanced ionic concentrations.

Analytical result shows that the lake water chemistry is mainly governed by the precipitation and drainage followed by lithological weathering. The main source of the water for all these lakes is snow precipitation and melting of the polar ice sheet. The relative high ratio of alkaline to the total cations, high alkaline/alkali ratio and low alkali to the total cations indicate the dominance of alkaline, specifically carbonate weathering as a major source for dissolved ions in the lakes connected by the surface channels. Though atmospheric precipitation has significantly obliterated the ionic distributions in the channels, carbonation is the main proton supplying geochemical reactions involved in the rock weathering of the study area. Rock weathering is the only geomorphological mechanism which controls the hydrochemistry, which is dominantly influenced by snow precipitation. In both the channels, the ionic strength of the lake water increases as its distance from the polar ice sheet increases due to its topographic effect as the gentle slopes of the channels allow the upper part of the melt water to go out of the concerned lake system with less affect on the weathering from incorporated geological materials and steep slope is accounted for more intermixing of melt water with the weathered products of the geological units, which in turn produce more ionic concentration in the downward direction. Unconsolidated sediments are sparsely distributed as patchy and scattered covering of glacial deposits, valley-fills and occasional moraine ridges influencing the hydrochemistry parameters of the interconnected surfacemelt water channels. All these indicate that the lake water hydrochemistry differs widely not only between two distant periglacial zones but also within a short distance of a single periglacial entity.



**S08 –69: Surficial Processes and Climate Change in Antarctic Terrestrial Environment: Changes and Impact on Permafrost, Erosion and Chemical Weathering**

***Intrinsic Redox Chemical Transformation of Metals in Icy Environment and its Impacts on Polar Regions***

Kitae Kim<sup>1</sup>

Korea Polar Research Institute (KOPRI), South Korea<sup>1</sup>

Most chemical processes are generally slowed down as temperature decreases. However, several chemical reactions can be accelerated in frozen environment. The bioavailability, mobility, toxicity, and environmental fate of metals or inorganic elements are controlled by their redox speciation. Although the chemical processes in ice play an important role on various Earth's system, they have rarely investigated. Firstly, we investigated the production of bioavailable trace elements (Fe(II)aq and Mn(II)aq) from the dissolution of iron and manganese oxide particles in water and ice. The dissolution of metal (iron and manganese) oxides particles in ice phase was significantly enhanced compared to those in aqueous solution both in the presence and absence of light although the dissolution rate was enhanced under UV irradiation. We also investigated both the reduction of Cr(VI) and the simultaneous transformation of Cr(VI) and As(III) in ice in comparison with those in aqueous solution. The reduction of Cr(VI) by various organic acids (electron donors) was negligible in ambient aqueous solution but was significantly accelerated in ice. The simultaneous reduction of Cr(VI) and oxidation of As(III) in ice phase proceeded stoichiometrically, whereas their mutual conversion was insignificant in aqueous solution. The enhanced redox transformation in ice phase is ascribed to the freeze concentration effect (when solution is solidified the existed organic and inorganic compounds are highly concentrated in unfrozen liquid-like regions) in ice crystal grain boundaries. These results imply that understanding the redox conversion of various inorganic/organic compounds in ice phase may provide newer views and insights on the environmental chemical processes in the icy environments (e.g., upper troposphere, permafrost, polar/high latitude environment and mid-latitudes during winter season) where the freeze-thaw cycles repeat.



**S08 –87: Surficial Processes and Climate Change in Antarctic Terrestrial Environment: Changes and Impact on Permafrost, Erosion and Chemical Weathering**

***Geochemical Characteristics of Volcanic Glasses from the Limnopolar Lake, Byers Peninsula, Livingston Island, Antarctica: Application as Age Indicator***

Min Kyung Lee<sup>1</sup>; Hyoun-Soo Lim<sup>2</sup>; Dermot Antoniades<sup>3</sup>; Manuel Toro<sup>4</sup>; Jae Il Lee<sup>1</sup>; Kyu-Cheul Yoo<sup>1</sup>; Ho Il Yoon<sup>1</sup>; Yong Il Lee<sup>5</sup>

Korea Polar Research Institute<sup>1</sup>; Pusan National University, South Korea<sup>2</sup>; Universite Laval, Canada<sup>3</sup>; National Centro De Estudios Hidrograficos<sup>4</sup>; Seoul National University, Seoul, South Korea<sup>5</sup>

Several primary and reworked tephra layers are present in core sediments collected from Limnopolar Lake on Livingston Island, maritime sub-Antarctica. Some of these tephra layers were used as a stratigraphic marker to construct the composite core (2.34 m long) by correlating overlapping two cores. This study intends to test the values of tephra for establishing regional tephrochronology for the lake in ice-covered landscape in the vicinity of volcano. This study uses volcanic glass samples from nine tephra layers of Limnopolar Lake. By visual observation using optical microscope, two distinct types of tephra are identified on the basis of color, vesicularity and morphology. Most common are brown, vesicular and bubble-wall fragments of andesitic clasts. Some microcrystals, mainly lath-shaped plagioclases as well as euhedral opaque minerals, are present and common in the brown glass shards. The second type consists of black blocky shards. Both types of glasses are isotropic under cross-polarized light. Major element analyses of glass shards reveal that the majority of glass fragments belong to basic glass (< 60 wt.% of SiO<sub>2</sub>), compositionally ranging from basalt to andesite, probably sourced from both Deception and King George islands. This result agrees with the previous studies that show Deception Island to be the major source of Quaternary tephra horizons in the northern Antarctic Peninsula region. However, it may suggest that they were the mixture of reworked tephtras from eruption events of Deception and King George Islands. Based on geochemical similarity results, most tephra samples in two overlapping cores of Limnopolar Lake are not similar enough to be correlated each other. Therefore, most tephra layers of Limnopolar Lake are interpreted not ashfall deposits but reworked and redeposited pyroclasts. They are probably derived from the catchment transported by surface runoff during snow pack melt and the permafrost thaw periods. In this case, reworked tephtras from the catchment and primary ash fall deposited on the lake ice cover would be trapped together in different ratios in the same horizon of lake sediments. The result of this study implies that geochemical study in addition to sedimentological information is necessary to study tephrochronology and regional correlation and to understand paleo-environmental changes using tephra in lacustrine environment in Antarctica.



**S08 –88: Surficial Processes and Climate Change in Antarctic Terrestrial Environment: Changes and Impact on Permafrost, Erosion and Chemical Weathering**

***Long Term Variation of Meteorological Parameters at Maitri***

M. Sateesh<sup>1</sup>; V.K.Soni<sup>1</sup>; S.K.Peshin<sup>1</sup>

India Meteorological Department, New Delhi, India<sup>1</sup>

The meteorological data collected at Maitri (70°45'7"S, 11°44'09"E) by India Meteorological Department have been used to determine long term trends in various meteorological parameters for the period 1990-2014. Due to low elevation of the sun (36° to 9°) and the geographically higher latitude, very low temperatures are observed at Maitri. The average annual temperature of Maitri is ~-0.2°C. The range of minimum temperatures is -30.6°C to 2.3°C and maximum temperature ranges from -26.2°C to 7°C. Maximum and minimum temperature showed decreasing trend of 0.004°C/year and 0.003°C/year respectively. At Maitri station, winds are mainly observed along the East-south-east direction with 10 to 25 knots throughout the year. These katabatic winds are dominant in May and June, because of the cooling of the air in the evening. The wind speed is showing a decreasing trend 0.013 knots/year. Maitri receives average 28 MJ/m<sup>2</sup> of global solar radiation on full sunshine day in December and almost zero in the no sunrise months of May and June. The annual mean global radiation showed a decreasing trend 0.0162 MJ/m<sup>2</sup>/year. Blizzards are stronger in winter season as compared to other seasons. Average wind speed recorded during the blizzard is about 50 knots but often exceed 100 knots. The highest wind speed recorded at Maitri is 110 knots (September, 1999 and July, 2009). The frequency of blizzards increases through the autumn (December-March) and in the winter season (April-September), thereafter the frequency decreases through the spring (October-November). On an average during the year, the frequency of blizzards varies from 10 to 35. The duration of blizzard may vary from few hours to several days. A maximum of 43 blizzards were reported during 1996 and longest duration of blizzard of 168 hours was observed in 1997. Long term analysis of data showed that frequency of occurrence of blizzards is decreasing at the rate of 0.214/year. From the Radiometer sonde data, it is noticed that the width of the tropopause is more in November (summer) and is less in June (winter) starting at 350hpa, 250hpa respectively. And the lapse-rate is -6.3°C/km in summer, -4.1°C/km in winter.

This paper presents the detailed long term analysis of meteorological parameters at Maitri, for the period of 1990-2014.



**S08 –226: Surficial Processes and Climate Change in Antarctic Terrestrial Environment: Changes and Impact on Permafrost, Erosion and Chemical Weathering**

***Analysis of Subsurface Heat Flux in High Density Snow near Maitri, Antarctica***

H.S. Gusain<sup>1</sup>; Prem Dutt<sup>1</sup>; Vinod Kumar<sup>1</sup>

Snow & Avalanche Study Estt (SASE), Chandigarh, India<sup>1</sup>

Subsurface heat flux is an important parameter of the surface energy balance of the snow cover, glaciers and ice sheet. It varies with density of the snow. In this paper we report on estimation of subsurface heat flux in high density snow using subsurface temperature observations and direct measurements of subsurface heat flux. The experiments were conducted on high density wind compacted snowpack in proximity to Indian Research Station Maitri (70°46'03.98" S and 11°41'40.72" E) in East Dronning Maud Land, Antarctica. The experiments were conducted during different seasons of the year 2014. Sub surface temperature was recorded using temperature profiler having thermistors at a distance of 5cm, 10 cm, 20 cm, 30 cm and 50 cm from the top. Two heat flux plates of 80 mm diameter and 5 mm thickness were used for the direct measurement of the net subsurface heat flux. These heat flux plates consist of thermopiles to measure the differential temperature across the thin layer of ceramics plastic composite of known thermal properties. The thermopiles of the heat flux plate generate a small voltage proportional to the local heat flux present and measure the combined effect of net conductive and radiative energy flux across a cross section in a horizontal plane. Conductive heat flux was estimated using sub surface temperature and density of snow. Conductive heat flux varied between -12 W m<sup>-2</sup> to + 6 W m<sup>-2</sup> during winter season, from -2 W m<sup>-2</sup> to + 6 W m<sup>-2</sup> during summer season, from 0 to + 12 W m<sup>-2</sup> during the transition period from summer to winter and from -3 W m<sup>-2</sup> to + 3 W m<sup>-2</sup> during the transition period from winter to summer, respectively. Radiative part in the sub surface heat flux was also analysed for each season. The results of the present study were also compared with the previous experiments on low density snow and blue ice in Antarctica. It has been observed that sub surface heat flux for high density wind compacted snow was comparatively lower.



**S08 –252: Surficial Processes and Climate Change in Antarctic Terrestrial Environment: Changes and Impact on Permafrost, Erosion and Chemical Weathering**

***Changes Climatically Induced on Maritime Antarctic Freshwater Ecosystems during the Last Decade (Uruguay Lake, King George Island)***

Eguren G.<sup>1</sup>; Silva G.<sup>1</sup>; Carrasco-Letelier L.<sup>2</sup>; Rivas N.<sup>1</sup>; Cabrera J.<sup>1</sup>

Environmental Sciences and Ecology Institute, Sciences Faculty, De La Republica University, Montevideo, Uruguay<sup>1</sup>; National Agricultural Research Institute, National Production and Environmental Sustainability Research Program, Uruguay<sup>2</sup>

The Global Climate Change and the fast global environmental change are scientific and public concerns. Over recent decades some authors reported a wide change in the temperature air trends across to Antarctica and particularly a considerable stronger warming in the northwest Antarctic Peninsula, with different seasonal and spatial influences on both side. In the northern part and in the South Shetland Islands an increasing air temperature trends and alternating cold and warm periods were recorded during 1950-2003. The extreme seasonal changes are observed in winter and spring, in August the warming is most marked and in October the surface air temperature show the greatest decrease. In this framework, Antarctic lakes and ponds are highly sensible to small physical, chemical or biological changes induced by climate and may provide insights on the controlling variables of aquatic productivity at other latitudes. In this way, Fildes Peninsula located at the southwest of King George Island (South Shetland Islands) is an important free-ice land and present several lake basins that might be a valuable long-term limnological reference site for monitoring environmental change. The main goal of this study was to assess the effects of multi-year condition weather variability on circulation patterns and nutrient fluxes of Uruguay Lake (King George Island). During the period of study (2006- 2014) air temperature, precipitation and snow fall frequency data were obtained from automatic Antarctic Uruguayan Meteorological station. Besides, in austral summers water samples were collected with Ruttner-type bottle across two horizontal transects at different depths (top, half depth and bottom) during break up and free water periods. In situ were determined water transparency, vertical temperature profile, acidity, conductivity, dissolved oxygen and alkalinity. Filtered and unfiltered water samples were shipped to Ecotoxicology and Environmental Chemical Laboratory (Sciences Faculty, Uruguay) for to determine suspended total solid, particulate organic matter, phosphate and nitrate.

According our results the lake present an ice layer around 1m during most of the year, but never freezes completely. The water column remained completely mixed and the vertically homogeneous temperature indicate that this lake is holomictic in summer, a typical pattern of cold monomictic lake. On the other hand, was observed a reduction of the free-ice period from 8 weeks in 2006-2009 to 4 or less weeks in 2010-2014. In this sense, the air temperature showed a inter-annual bimodal pattern in summer seasons with warm summers ( $1.5 \pm 0.8^{\circ}\text{C}$ ; mean 40.7 mm and ) in 2006-2009 and cold summers ( $0.4 \pm 1^{\circ}\text{C}$ ; mean 396.0 mm and ) in 2010-2014 period. Same pattern was observed in precipitations (annual mean 40.7 mm and 396.0 mm) and snow fall (141 and 176 days). The nutrients concentrations, mainly phosphorus, showed a decreasing pattern in the coldest summers may be due the changes on thaw pattern may be affecting the nutrient fluxes from catchment basin and, controlling the chemical water characteristics.



**S08 –254: Surficial Processes and Climate Change in Antarctic Terrestrial Environment: Changes and Impact on Permafrost, Erosion and Chemical Weathering**

***Initiation and Phases of Deglaciation in East Antarctica***

Yogesh Ray<sup>1</sup>; Mirza Javed Beg<sup>1</sup>

National Centre for Antarctic and Ocean Research, Vasco Da Gama, Goa, India<sup>1</sup>

Glaciation-deglaciation are physical phenomenon resulted by perturbing climatic conditions. These glacial-interglacial cycles are archived in many marine and terrestrial records. The glacial landforms are one of such terrestrial archives. The past geological record in the form of glacial sediments and landforms reveal much about the changes which the earth is witnessing. Schirmacher oasis is an ice free area of approx 35 Sq Km situated in the central Dronning Maud Land, East Antarctica. Three nearly parallel glacial valleys traverse the oasis. The Long lake valley originates from the snout of the Dakshin-Gangotri glacier and it is situated nearly in the centre of the oasis, it is about 4.6 km in length. The valley formed as the glacier retreated and the valley floor is occupied by paternoster lakes. The moraines and the lake deposits provide the archives to study the causative events in generation of such landforms. Earlier workers had focussed on the lake sediments and provided good insight. In study we are focussing on the moraines and the distinct surfaces in this valley. It is clear to visualise the retreat of glacier and the initiation/formation of lakes. The deglaciation pattern will shed light on the climatic changes and chronology of such events.



**S08 –259: Surficial Processes and Climate Change in Antarctic Terrestrial Environment: Changes and Impact on Permafrost, Erosion and Chemical Weathering**

***Spatio-Temporal Characteristics of Aerosol Optical Depths and Cloud Parameters over Antarctic Tropical Land Region using MODIS Satellite Retrieved Collection 5 Level 3 Data***

Adarsh Kumar<sup>1</sup>

Amity University, Noida, India<sup>1</sup>

The MODIS derived Aerosol Optical Depth (AOD) data is well suited for the seasonal and inter annual study of aerosols distribution and their effects over a long period. Daily averaged MODIS retrieved satellite (collection 5 level 3) AOD data has been used to investigate AOD distribution in spatio-temporal domain over Antarctic tropical land region during the three years period (2008-2010). During the three years period of 2008-2010, the cloud parameters such as cloud fraction (CF), water vapour (WV), cloud optical depth (COD), and cloud top temperature (CTT) were also spatially correlated with aerosol optical depth over Antarctic tropical land region. Results have been compared with some of the significant and important investigations made by other workers on AOD and cloud parameter values over different regions of India.

Keywords: Antarctica, Satellite data, TERRA, AOD, Cloud parameters



**S08 – 318: Surficial Processes and Climate Change in Antarctic Terrestrial Environment: Changes and Impact on Permafrost, Erosion and Chemical Weathering**

***Factors Controlling Enrichment of Minor and Trace Metals in Chandra Basin Meltwater Stream Draining through Sutri Dhaka Glacier, Western Himalayas***

Ajit Singh<sup>1</sup>; CM Laluraj<sup>1</sup>, Meloth Thamban<sup>1</sup>; Sharma Parmanand<sup>1</sup>; Patel Lavkush<sup>1</sup>; Ravindra Rasik<sup>2</sup>

Earth System Science Organisation - National Centre for Antarctic and Ocean Research, MoES, Vasco-DA-Gama, Goa, India<sup>1</sup>; Earth System Science Organization - Ministry Of Earth Sciences (MoES), Prithvi Bhavan, Lodhi Road, New Delhi, India<sup>2</sup>

Himalayan glaciers form an important fresh water reservoir regulating the water supply of all the major North Indian rivers. Since the river water quality depends on the input of trace metals into these reservoirs, it is important to monitor the melt water quality of Himalayan glaciers. Source region of the streams and rivers originating from the Himalayan glaciers have been less studied, although their downstream regions are increasingly polluted due to anthropogenic input. Chandra basin in the Lahaul-Spiti valley is one of the major glacier basin (~2380 Km<sup>2</sup>) in Western Himalayas and consist of nearly 200 glaciers covering ~ 30% of the total basin area. In order to understand the meltwater pattern and geochemical characteristics of the meltwaters of Sutri Dhaka glacier in Chandra basin, we measured the meltwater composition during different ablation period, on a daily basis from 1st July to 30th September, 2014. The main objectives were to study the variations in the minor and trace metal characteristic of the glacial melt during the different ablation periods and identify their possible sources using inductively coupled plasma mass spectrometry (ICP-MS). The study showed that Fe and Al are the most dominant elements followed Ti, Mn, Ba, Ni, Cr, Co, Cu, Pb, Ga and U. The melt water showed enrichment for some elements (Fe, Al, Ti, Mn, Ni, Cr, Co, Ga, U) compared to the world streams, while Cu and Pb showed depletion. The trace element concentration revealed the close relationship with melt discharge. The initial and final ablation periods were characterized by trace metal enrichment, whereas the peak ablation period was depleted in all the elements. The ablation rate is inversely proportional to the release of trace metal into the meltwater possibly because of the longer interaction between the subglacial rocks and hydrological systems. The depletion in concentration can be due the dilution of supraglacial melt water with concentrated subglacial melt. Glaciers are very sensitive and respond much faster to climate change than do ice sheets. Therefore, the present study provides a baseline data on trace elements during ablation in Himalayan glaciers.

Keywords: Meltwater, Glacier ablation, Chemical Composition, Chandra Basin and Environmental variation.



**S08 –324: Surficial Processes and Climate Change in Antarctic Terrestrial Environment: Changes and Impact on Permafrost, Erosion and Chemical Weathering**

***Scatterometr Based Spatio-Temporal Variations in Surface Melting over Fimbul (near Maitri) and Amery (near Bharati) Shelves in Antarctica during 2001-2014***

S Anoop<sup>1</sup>; PVN Rao<sup>1</sup>; CBS Dutt<sup>1</sup>; VK Dadhwal<sup>1</sup>

National Remote Sensing Centre, Hyderabad, India<sup>1</sup>

Ku band scatterometer data which is sensitive to presence of liquid water in the snow has made it possible to identify melt/freeze dynamics over different shelves in Antarctica which are affected by heat from atmosphere above and ocean below. Data from OSCAT onboard OCEANSAT-2 which is similar to QuikSCAT satellite was analysed to generate melt/freeze scenario in the Antarctic shelves for recent years. The present study is for Fimbul and Amery shelves near Bharati and Maitri stations of India in Antarctica. Amery ice shelf which is near Bharati station is the major embayed shelf in East Antarctica which is fed by massive inland Lambert Glacier basin. Amery has a coast line of 550 km and the area is around 60000 sq km. Fimbul shelf is located along coast in Queen Maud land with area similar to Amery but with more coast line length.

The study utilises enhanced resolution daily images at 2.25km resolution from Ku band scatterometer QuikSCAT(2001-2009) and OSCAT (2009-2014) which operate at 13.6 GHz. To understand the shelf response to variations in temperature, data from Davis automated weather station situated near Amery is used.

Backscatter response ( $\sigma^{\circ}$ ) from different locations over the shelf was studied by plotting time series of ( $\sigma^{\circ}$ ). It was observed that there is steep reduction in the  $\sigma^{\circ}$  of the order of 15dB or more during austral summer due to sensitivity of normalised radar backscatter to the water content of snow/ice. The analysis of winter data indicates that there are minor variations during winter months. Looking at the spatial and temporal variability in the  $\sigma^{\circ}$  in HH polarisation over the shelves, an adaptive classification system was used to differentiate between melt and freeze pixels. Melt duration was found out for each location over the years. Onset of melt was also found out. To compare the spatial and temporal variation over the years, Melt Index (MI) and Melt Area (MA) were calculated and compared. Based on the analysis it was found that there is lot of spatio-temporal variability in melt pattern over the shelves. During majority of the years melt is observed over entire shelf area of Amery and Fimbul. Amery has minimum shelf area under melt during 2007-08 (56%), 2010-11(74%) and 2011-12 (88%). Fimbul observed minimum melt area during 2006-07(59%), 2011-12(71%) and 2007-08(75%). The average melt duration was observed to be more for Amery in comparison to Fimbul shelf except for the years 2012-13 and 2013-14. The austral summer of 2005-06 produced different melt conditions over Amery and Fimbul with average melt duration of 44 and 8 days respectively. Spatially the melt over Amery shelf is initiated along coast and then spread inwards towards South-West. Fimbul has no observed spatial pattern during study period. Surface melting is a variable phenomenon and fluctuations are observed over year to year and place to place. It is important to monitor melt surface area for Amery and Fimbul shelves due to their proximity to Indian stations. The study provides insight to melt dynamics considering 13 austral summers and 12 austral winters.



**S08 –329: Surficial Processes and Climate Change in Antarctic Terrestrial Environment: Changes and Impact on Permafrost, Erosion and Chemical Weathering**

***Morphological and Limnochemical Description of Ponds around to Bellingshausen Dome (King George Island, Antarctica)***

Silva G<sup>1</sup>; Eguren G<sup>1</sup>; Cabrera J<sup>1</sup>

Environmental Sciences and Ecology Institute, Sciences Faculty, de la Republica Universtity. Montevi<sup>1</sup>

High latitude regions such as the Arctic and Antarctica are showing the effects of climate change at higher rates than other regions. In this vein the global circulation models evidenced a rapid and pronounced increase of air temperature over time. Several authors attribute this phenomenon to feedback processes that amplify warming mostly toward the poles and could be altered ecosystem structure and functions. Some observed effects have been the reducing of thickness and extent of glaciers, reducing of ice sheets and sea ice, changes in the balance of the relationship precipitation vs. evaporation with respect changes in the regional distribution of rainfalls. In spite of Antarctica is a region under strict environmental protection protocols in order to preserve natural resources, the effects caused by climate change have already begun to be observed. For example, changes in the physical, chemical and biological conditions of freshwater ecosystems are being amplified and are leading to significant changes in the limnological characteristics. Therefore, freshwater Antarctic ecosystems provides comparative advantages for the development of studies to understand mechanisms, processes and establish future scenarios linked to climate change. Some lakes and ponds have already begun to show significant impacts, such as loss of perennial ice cover with consequences for the mixing regime and complete disruption of the limnological gradients, increased temporal window open water condition (free of ice), increased water temperature, strong stratification of the water column along with changes in the balance, which in some cases leads to complete or partial drainage drying and even total system. In some islands, belonging maritime Antarctica, the accelerated melting of permafrost in recent years has created new basins, where recently developed ponds and shallow lakes. Maritime Antarctic is a region with a wet and relatively warm climate regime compared to the mainland. For example, some islands of the South Shetland archipelago are considered excellent concerning environmental change, as well as a reference site for surveillance and monitoring studies. In this sense, the study aims to perform analysis of variables, through the incorporation of physical and chemical indicators to determine the characterization of 8 freshwater ponds present in King George Island, more exactly at Fildes Peninsula near Bellingshausen Dome, these ponds have unknown origin and poorly been studied or no information is available. Through the characterization of these water bodies we can make an approach to the dynamics of the basin in relation to the dome, or hydrological cycles and climate phenomenon's that's occurs in region, besides generating a baseline for future research studies or long-term limnological reference site for monitoring environmental change. Some Morphometric and limnological characteristics were recorded in situ and through analysis of satellite images and maps. Water samples were collected with Ruttner-type bottle and in situ were determined water transparency, vertical temperature profile, acidity, conductivity, dissolved oxygen and alkalinity. Filtered and unfiltered water samples were shipped to Ecotoxicology and Environmental Chemical Laboratory (Faculty of Sciences, Uruguay) for determine suspended total solid, particulate organic matter, phosphate and nitrate. According our results all ponds showed vertically homogeneous temperature (which never exceeded 4° C), indicated that these freshwaters ponds are holomictic in summer; which is a typical pattern of cold monomictic lakes. During the most year, surfaces of ponds are covered by ice, and the ice- free period consists only of few months during the austral summer, during these period the action of winds induce the mixing of water column. Only one pond showed a small portion of surface covered by ice during the time of sampling. The morphology results showed differences between ponds, with depths ranging between 0.9 – 10.5 meters and surfaces between 1400 - 20000 m<sup>2</sup>. We classified ponds according to literature into two geographical types based on their altitude, freshwater marine ponds (formed as isolated pockets of water on the sea floor) and, non marine freshwater ponds (formed via the inflowing of melt water from surrounding glaciers and snow into



the basin). In the present study, 7 ponds are classified as non marine ponds, while one pond is classified as marine, because this is found at low altitude above sea level. Ponds were also classified according in and outflow water in open and closed basin types. In the first type, 4 ponds the inflows come from snow and glacial melt water and are interconnected between them. While 2 ponds only receive snow melt water and flow to the sea. The interconnected ponds are located near Bellingshausen Dome edge and some factors like water transparency, alkalinity and conductivity showed similar values. The rest of psychochemical parameters such temperature, dissolved oxygen and pH for all ponds showed no significant differences between them. The nutrients concentrations (phosphates and nitrates) showed values between (2- 70  $\mu\text{gL}^{-1}$ ) & (13- 60  $\mu\text{gL}^{-1}$ ) respectively. These values allow us to classify ponds in 2 trophic states: Ponds with low primary productivity classified as oligotrophic, and ponds more productive classified as mesotrophic. Trophic status is important to understand the dynamic of allochthonous inputs and will improve our overall knowledge of the basin.



**S08 –336: Surficial Processes and Climate Change in Antarctic Terrestrial Environment: Changes and Impact on Permafrost, Erosion and Chemical Weathering**

***Calcium Isotopic Geochemistry of an Antarctic Aquatic System***

Lyons W.B.<sup>1</sup>; Bullen T.<sup>2</sup>; Welch K.A.<sup>3</sup>

The Ohio State University, School of Earth Sciences, Columbus, OH, USA<sup>1</sup>, Water Resources Division U.S. Geological Survey, USA<sup>2</sup>, The Ohio State University, Byrd Polar and Climate Research Centre, Columbus, OH, USA<sup>3</sup>

Calcium is an important element in both geological and biogeochemical systems. A number of processes can cause variations in its stable isotopic signature and thus provide important information regarding how these processes have affected calcium dynamics. We present here the first calcium isotopic measurements from the aquatic systems within the McMurdo Dry Valleys, Antarctica. The streams and surface waters of the lakes yield  $\delta^{44}\text{Ca}$  values of  $\sim 1$ , suggesting that chemical weathering, not marine aerosols or ancient seawater, is the primary source of dissolved Ca to these waters. Waters from deeper portions of the lakes have heavier  $\delta^{44}\text{Ca}$  values, strongly suggesting either the removal of  $^{40}\text{Ca}$  has occurred through calcium carbonate mineral precipitation or the mixing with ancient seawater being introduced sub-aerially. These data along with previous work provide insight into the processes controlling the calcium biogeochemistry in these environments.



**S08 –355: Surficial Processes and Climate Change in Antarctic Terrestrial Environment: Changes and Impact on Permafrost, Erosion and Chemical Weathering**

***Estimating Glacier Meltwater Fluxes in the Palmer Station Region, Antarctica***

W. B. Lyons<sup>1</sup>; Dailey K.R.<sup>1</sup>; Saelens E.<sup>1</sup>; Welch S.A.<sup>1</sup>; Corbett D.R.<sup>2</sup>; Null K.<sup>2</sup>; Crenshaw J.<sup>2</sup>

The Ohio State University, School of Earth Sciences, Columbus, OH, USA<sup>1</sup>; East Carolina University, Department of Geological Sciences, Greenville, NC, USA<sup>2</sup>

Glacier melt water from Antarctica is a major source of freshwater into the Southern Ocean. Yet the quantification of the input is difficult to assess. In addition, the actual source of the melt, surface versus sub-glacial, is even more difficult to determine. Both the quantity and the chemical composition of this glacier melt may play an important role in nutrient and micro-nutrient addition to the near shore and coastal regions of Antarctica. We have collected samples in the vicinity of Palmer Station and analyzed the salinity and the  $\delta^{18}\text{O}$  of the water. We have used the  $\delta^{18}\text{O}$  and salinity relationship of these waters to estimate the amount of glacier melt that was introduced into the surface ocean. In addition, we discuss the potential significance of these waters in the introduction of filterable iron into the coastal ocean.



**S08 –360: Surficial Processes and Climate Change in Antarctic Terrestrial Environment: Changes and Impact on Permafrost, Erosion and Chemical Weathering**

***Thermokarstic Erosion of Buried Ice in Garwood Valley, Mcmurdo Dry Valleys: Rates of Gully Erosion***

Jaclyn Watters<sup>1</sup>; Joseph Levy<sup>1</sup>

University of Texas at Austin<sup>1</sup>

**Background:**

Previous work has shown that thermokarst formation in the Garwood Valley, McMurdo Dry Valleys (MDV), Antarctica, has accelerated to ~10 times the average Holocene rate. A large retrogressive thaw feature known as the Garwood ice cliff is among the thermokarst features representative of this rapid landscape evolution. Landscape change in the MDV appears fastest where buried ice deposits become exposed to insolation as overlying debris covers thin, or where active layers thicken. The thermokarstic backwasting along the Garwood ice cliff measured by a continuous monitoring station was shown to be approximately 2cm a day between November 12th and December 30th of 2011. Between 2002-2012, linear retreat of the ice cliff by melting and mass-wasting spanned 10-55 m along the ~500 m length of the exposure, based on repeat LIDAR scans of the area.

Gullies are a slope feature which transport sediment on steep slopes. Their characteristic features are an alcove, the sediment source, a channel, the means of transport, and a fan-shaped apron where the sediment is redeposited and accumulates. Along the Garwood ice cliff, gullies are eroding alcoves into the buried ice and overlying sedimentary cap, incising channels in the ice-cored talus cones at the base of the cliff, and are depositing new fans along the Garwood River banks.

**Objectives:**

The goal of this study is to map the changing area and volume of gully features in the Garwood Valley ice cliff and vicinity through time (2001-2015) and to relate changes in erosion and deposition to local microclimate conditions. This work will help to determine the causal relationship between thermokarst erosion, ice-loss and sediment transport in a rapidly evolving, ice-dominated landscape.

**Methods:**

Repeat terrestrial LiDAR scans were collected twice yearly in Garwood Valley, once before austral summer (melting season) and once at the end of summer (typically early November and late January). LiDAR scans produce a 3D point cloud which is interpolated into a 10 cm/pixel digital elevation model of the ice cliff and surrounding landscape features. We measure gully cross-section through time and track the evolution of gully slopes from alcove to channel to apron as the ice cliff recedes. We difference LiDAR DEMs to determine where sediment erosion and redeposition and/or ice subsidence occur across the landscape as a result of gully processes. At a particular point of the hillslope any additional volume added can be interpreted as deposited sediment and as such only occurs in the downslope apron. A combination of ice loss and sediment erosion can account for any point with a loss in volume. Any volume unaccounted for by sediment transport, therefore, is interpreted as ice loss. Sediment removal from the aprons by the Garwood River cannot be directly measured through this method as such all sediment volume deposited downslope should be considered a minimum bound in areas where the apron is cut by the river. The gullies' presence as a perennial feature in this rapidly evolving system suggest that increasing erosion rates do not affect their stability, and they continue to be a geomorphic expression of sediment transport in the Garwood valley.

Annual erosion and ice loss rates will be compared to radiative balance measurements made at a weather station at the base of the ice cliff in order to constrain the thermodynamics of melting and landscape change.



#### Results:

Data analysis is ongoing; however, preliminary results show that ice cliff erosion is strongly influenced by radiative balance at the ice cliff. Both melting (in gullies) and dry mass wasting occur overwhelmingly during periods where incoming longwave and shortwave radiation exceed outgoing radiation, even under conditions of sub-freezing air temperatures. This suggests that both mass wasting and fluvial (gully) erosion of the buried ice deposits is a thermally activated process.

In addition, preliminary mapping shows that gully erosion has migrated along the ice cliff over the 2001-2015 period. This suggests that changes to local microtopography and/or buried ice content may strongly influence surface change in MDV permafrost environments.

Finally, time-lapse observations that coincide with LiDAR scans show that gully erosion can occur rapidly. Fluvial downcutting through ice-cemented talus can erode a new gully channel in the space of a day. However, fan deposits from gullies are largely resistant to erosion, and can persist even after the ice-hosted alcove and channel have been obliterated by melting. This suggests that reworking of tills and paleolake deposits in the MDV by small-scale melting may be an important sediment Sörting process in the cold desert.

#### Conclusions:

Understanding gully evolution in Garwood Valley helps connect drivers of landscape change in the MDV to their effect on the landscape. Understanding how gullies evolve contributes to the study of buried ice ablation in the Antarctic as climate change begins to influence old landscapes to evolve in new ways.



**S08 –412: Surficial Processes and Climate Change in Antarctic Terrestrial Environment: Changes and Impact on Permafrost, Erosion and Chemical Weathering**

***Chemical Weathering in Antarctic Streams: More Evidence***

W.B.Lyons<sup>1</sup>; C.B.Gardner<sup>1</sup>; P.H.Cable<sup>2</sup>; B.McKee<sup>3</sup>; K.A.Welch<sup>4</sup>; D.M.McKnight<sup>5</sup>

School of Earth Sciences and Byrd Polar and Climate Research Center, The Ohio State University, Columbus, USA<sup>1</sup>; Department of Environmental Sciences & Engineering, University of North Carolina, Chapel Hill, USA<sup>2</sup>; Department of Marine Sciences, University of North Carolina, Chapel Hill, USA<sup>3</sup>; Byrd Polar and Climate Research Center, The Ohio State University, Columbus, USA<sup>4</sup>; Institute for the Study of Arctic and Alpine Research, University of Colorado, Boulder, USA<sup>5</sup>

Over the past 15 years, the nature and rate of chemical weathering in Antarctic streams such as those in the McMurdo Dry Valleys region (~78°S) have been documented. This previous work has clearly demonstrated that chemical weathering rates are high, and the primary loci of weathering are in the hyporheic zones of these streams. In this work we present the Ge/Si ratio of stream water and the <sup>234</sup>U/<sup>238</sup>U ratios of the hyporheic zone waters from streams in the Taylor and Wright Valleys to further illustrate the role of chemical weathering versus physical weathering in these environments. Both of these geochemical tools have provided important insights into weathering regimes in temperate watersheds. Ge/Si ratios range from 0.34-1.3 umol/mol, with a mean of 0.7 umol/mol, while hyporheic zone waters from Von Guerard Stream in Taylor Valley have <sup>234</sup>U/<sup>238</sup>U activity values between 1.27-1.37. The Ge/Si data suggest that these Antarctic streams are similar to transport-limited streams in both temperate and tropical climates, while the U isotope data reflect the dissolution of pore water sediments with <sup>234</sup>U/<sup>238</sup>U >1 and minimal physical weathering and erosion in these systems. Both data sets support the notion that chemical weathering, as opposed to physical weathering, is the more important of the two processes.



**S08 –428: Surficial Processes and Climate Change in Antarctic Terrestrial Environment: Changes and Impact on Permafrost, Erosion and Chemical Weathering**

***Topography and Velocity Field from GPS around Dome Argus, Antarctica***

Zemin Wang<sup>1</sup>; YuandeYang<sup>1</sup>; Songtao Ai<sup>1</sup>; Fei Li<sup>1</sup>; Hong Geng<sup>1</sup>

Chinese Antarctic Center of Surveying and Mapping, Wuhan University<sup>1</sup>

Knowledge of the surface topography, velocity field and strain field at an ice-core site is critical to the accurate interpretation of ice-core records. At Dome Argus (Dome A), where a Chinese deep ice-core drilling project is being carried out, we have produced an accurate surface digital elevation model from GPS measurements in January 2013 at 47 sites. We identify two peaks at Dome A, with the northern peak about 7 cm higher than the southern peak. Repeat GPS measurements at 12 sites in 2008 and 2013 provide a surface velocity field around the dome. The surface velocity ranges from  $3.1 \pm 2.6$  to  $29.4 \pm 1.2$  cm/a, with a mean of  $11.1 \pm 2.4$  cm/a. The surface flow directions are near perpendicular to the surface elevation contours. With these GPS velocities, we evaluate the accuracy of velocity from satellite radar interferometry (InSAR). It shows that velocities from GPS are lower than that derived from InSAR. From GPS velocities, the accuracy of velocity from the existing InSAR velocity field is determined, resulting in a standard deviation of 0.570m/a in speed and 117.58 in direction. This result is consistent with the reported accuracy of InSAR, showing the value of in situ GPS measurements for assessing and correcting remote-sensing results.



**S08 –446: Surficial Processes and Climate Change in Antarctic Terrestrial Environment: Changes and Impact on Permafrost, Erosion and Chemical Weathering**

***The Preliminary Results of Iron Concretions from Mckinnon Member of Bainmedart Coal Measures of Amery Group in Northern Prince Charles Mountains, East Antarctica***

Yingchun Cui<sup>1</sup>; Chenguang Liu<sup>1</sup>; Xuefa Shi<sup>1</sup>

First Institute of Oceanography, SOA<sup>1</sup>

The Northern Prince Charles Mountains locate at the Southeast Antarctica, and the Permo-Triassic sedimentary succession known as the Amery Group deposited in this region. The first field work for china in here has been carried out during the 2014-2015 Antarctic Expedition season supported by State Oceanic Administration, P. R. China (Project CHINARE-02-05) through the cooperation with Australia. During this season, the McKinnon member of Bainmedart Coal Measures of Amery Group which contains more coal seams was surveyed. The section of this member contains several sedimentary cycles from coarse sandstone to fine grained sandstone with a gentle dipping (average 15°). The interesting finding is that more iron concretions occur in the coarse sandstone of this member. These nodules have the spherical shapes and nucleated around the pebbles or others. Some of them show the different zones from the core to rim, while others do not. The diffusion aureoles around the small cores commonly occur, and this could give us a key clue about the growth process of these nodules. The McKinnon member reasonably has a latest Permian age. At the end-Permian, as we all know, the mass extinction took place. Previously work on the nodules from Radok Conglomerate in this area has tested that the nodules could be used as the environmental index. Thus the nodules in this member probably help us insight into this event. Here we will report our latest results.



**S08 –499: Surficial Processes and Climate Change in Antarctic Terrestrial Environment: Changes and Impact on Permafrost, Erosion and Chemical Weathering**

***Investigations on Atmospheric Boundary Layer Characteristics and Vertical Flux of Energy and Momentum Flux over Indian Antarctic Station, Bharati***

Kiran Kumar N.V.P.<sup>1</sup>; Subrahmanyam K.V.<sup>1</sup>; Siva Kumar Reddy N<sup>2</sup>, Shreedevi, P.R<sup>1</sup>, Varma A.K.<sup>3</sup>, More R. S.<sup>4</sup>

Space Physics Laboratory, Trivandrum, India<sup>1</sup>, Research Fellow, Department of Physics, Sri Krishna Devaraya University, Ananthapur, Andhra Pradesh.<sup>2</sup>; Scientist, India Meteorology Division, Vadodara<sup>3</sup>, Scientist, India Meteorology Division, Pune<sup>4</sup>

Continuous observations of three-dimensional winds and virtual temperature observed using sonic anemometer (25 Hz) mounted at 3 m level above the ground is used to investigate the atmospheric boundary layer over the Indian Antarctic station, Bharati (-69.41S, 76.18E) during the 05-13 February, 2015. In addition to the fast response sensors, slow response meteorological data obtained from co-located automatic weather station from India Meteorology Department (IMD) were also used for the present study. In general, the wind speed is found to be maximum during the post-midnight to early morning period (with an average wind speed of  $8 \text{ ms}^{-1}$ ) and minimum during 14-18 LT (average wind speed of  $5 \text{ ms}^{-1}$ ). However, the wind speed often exceeds  $12 \text{ ms}^{-1}$  several nights. The mean wind direction remained rather steady and nearly easterly during the period. The generally trend of TKE and MF are in phase with wind speed. The temperature generally peaks at around 12-13 LT ( $2^{\circ}\text{C}$ ) and minimum value ( $-7^{\circ}\text{C}$ ) at 3 LT. Unlike in the tropics (dominated by diurnal cycle of ABL evolution), temporal variations of ABL characteristics caused by the diurnal cycle of surface energetics and due to the effect of air mass movement (advection) are comparable. Further, the presence of sea ice, open water, snow covered regions and orographic features create a highly heterogeneous environment over the Antarctic region, which makes the Antarctic ABL processes complex.



**S09 – 106: ANTPAS - Antarctic Permafrost, Soils and Periglacial Environments**

***Characterizing Active-Layer Dynamics, Teleconnections and Landform Morphology on Selected Nunataks in Western Dronning Maud Land, Antarctica***

Kotze C<sup>1</sup>; Meiklejohn I<sup>1</sup>

Rhodes University, Grahamstown, South Africa<sup>1</sup>

Permafrost plays an important role within terrestrial landscapes/ecosystems and as a climate change indicator, however permafrost research in the Antarctic has been less systematic than its Northern Hemispheric counterpart. Despite advancements on the permafrost and active-layer monitoring network made by ANTPAS, observational gaps still exist in most of Antarctica with Western Dronning Maud Land (WDML) being one of them. Therefore, further research on Antarctic permafrost dynamics and the influence of teleconnections thereon is required. Such elucidation is critical to both the cryospheric and life sciences. Variations in the surface climate of Antarctica can be seen as a result of inter-annual variations in atmospheric circulation; particularly temperature, precipitation and wind stress. This in turn impacts landscape and geomorphic processes, principally through permafrost degradation and active layer thickening which directly affects soil processes such as Sörting and cryoturbation. Ground temperatures down to ca. 60 cm depth from WDML are analysed from 2006 to 2014. The study sites exhibit altitudinal variation, ranging between ca. 450m asl to ca. 1300m asl, seasonal freezing, as well as periglacial landforms. Using ground thermal regime and regional climate data, we characterize the spatial and temporal variability of the active-layer in the Ahlmannryggen area of WDML. Current analysis suggests a correlation between the SAO (Semi-Annual Oscillation) and measured ground temperatures, particularly during the transitional season of the SAO in May and September. Defining the relationship between climate and ground surface temperatures will aid in a better understanding of permafrost dynamics and landform morphology in continental Antarctica.



**S09 – 109: ANTPAS - Antarctic Permafrost, Soils and Periglacial Environments**

***HPLC Analysis of Chromophoric Dissolved Organic Matter in Antarctic Soil Core: Comparison with Microbiology Data***

Enn Kaup<sup>1</sup>; Lepane, V.<sup>2</sup>; Künnis-Beres, K.<sup>3</sup>; Gorohhova, J.<sup>2</sup>; Sharma, B.<sup>4</sup>

Institute of Geology, Tallinn University of Technology, Tallinn, Estonia<sup>1</sup>; Institute of Chemistry, Tallinn University of Technology, Tallinn, Estonia<sup>2</sup>; Marine Systems Institute, Tallinn University of Technology, Tallinn, Estonia<sup>3</sup>; Antarctica Laboratory, R & D Division, Shriram Institute for Industrial Research, India<sup>4</sup>

Chromatographic method based on HPLC has been used to investigate changes in dissolved organic matter (DOM) from soil core collected from Schirmacher Oasis, Antarctica. High-performance size exclusion chromatography was coupled with diode-array detection and separated fractions of DOM were subject to qualitative and semi-quantitative analysis. The chromophoric DOM pool was comprised of a very small low molecular mass fraction which increased down the core in permafrost soil layers. The down-core changes in macronutrients (total N and P), the ratios C:N and C:P, followed total organic carbon profile. Microbiological analyses resulted in decreasing vertical concentrations of 26 active heterotrophic bacteria. Statistical data treatment methods enabled clustering of soil core into 3 periods according to depth. The upper 0-20 cm had statistically relevant differences in comparison to other periods as revealed by the absence of DOM in soil water and high number of heterotrophic bacteria. Samples from 133-193 cm depth differed from others by relatively high DOM content and the lack of heterotrophic bacteria. The statistical analyses revealed that some chromatographic, spectrometric and microbiological parameters can be used to differentiate between soil layers.



**S09 – 110: ANTPAS - Antarctic Permafrost, Soils and Periglacial Environments**

***An Evaluation of Diurnal Temperature Regimes for Three Sites in Dronning Maud Land, Antarctica: Nonshøgda, Vesleskarvet and Robertskollen***

Christel Dorothee Hansen<sup>1</sup>, Keith Ian Meiklejohn<sup>1</sup>, Werner Nel<sup>1</sup>

Rhodes University, South Africa<sup>1</sup>

Diurnal frost environments in the Antarctic are less understood than in Northern polar and sub-polar environments. However, the conditions within which frost cycles occur in these areas may be vastly different. To better understand the diurnal frost environments in the Southern Hemisphere, frost cycles at three sites with different altitudes in Western Dronning Maud Land, Antarctica were evaluated. At each site, ground temperature, processes and resultant landforms were recorded. In particular, the role of altitude, ambient air temperatures and water availability on these short-term cycles are examined. The Nonshøgda logging site, located on a talus slope and lateral moraine near Troll Station in the Jutulsessen, is the highest study site at 1290m.a.s.l. and is characterised by low ground moisture content (<1%). The active layer for this site is app. 36cm deep. A second study site at Vesleskarvet, is located on a flat and level area on the Northern Buttress of the nunatak, at an altitude of 850 m.a.s.l., where the active layer is app. 23cm deep. The third site studied, Robertskollen, with an altitude of 360 m.a.s.l., exhibits an active layer of app. 55cm depth and is characterised by melt water ponds during the Austral summer months. It was established that ground freezing most took place at approximately -2.5 °C. The number of freeze-thaw events and the number of frozen hours at the 0 °C, as well as -2.5 °C isotherm were, thus, determined. Ground ice, storm events, and snowfall were shown to impact on diurnal temperature cycles.

Diurnal frost cycles were observed to increase in prominence in summer and were entirely absent in winter when the ground was frozen. Snow during summer had an insulating effect, minimising or even preventing the occurrence of diurnal frost cycles. The three sites exhibited different ambient air temperature regimes, which were reflected in their respective diurnal ground temperature regimes. The Vesleskarvet site was shown to be warmest for both ground and ambient air temperatures, with the Nonshøgda site recording the coldest temperatures. The greatest variance and highest maximum near-surface temperatures of the three sites were recorded at Robertskollen. Altitude alone was, therefore, not the only control on ground temperature regimes, and specifically diurnal frost cycles. It is argued that additional factors, such as moisture availability, geology and sediment composition, must also be considered when evaluating ground surface temperature regimes.



**S09 – 164: ANTPAS - Antarctic Permafrost, Soils and Periglacial Environments**

***Ice-Wedge Temperature Trends in East Antarctica: A Thermal Puzzle?***

Raffi R.<sup>1</sup>; Bramati M.C.<sup>1</sup>; Baldassarre M.A.<sup>2</sup>

Department of Earth Sciences, Sapienza University, Roma, Italy<sup>1</sup>; Department of Methods and Models for Economy, Territory and Finance, Sapienza University, Roma, Italy<sup>2</sup>

A monitoring programme on ice-wedge thermal regime has been undertaken from 2004 to 2014 at three sites in northern Victoria Land: Baker Rocks (74°12'27" S; 164°50'01" E; 11 m a.s.l.), Boomerang Glacier (74°30'13" S; 163°50'09" E; 874 m a.s.l.) and Mount Jackman (72°23'07" S; 163°10'49" E; 1326 m a.s.l.). Four sensors took hourly temperature of the air, the ground surface, the ice-wedge top and bottom.

In the recording period the mean monthly ground surface temperature (recorded at 2 cm) (GST) ranged between -37.7°C (July 2004) and 9°C (January 2015) at Baker Rocks, -34.4°C (July 2004) and -8.9°C (January 2015) at Boomerang Glacier and -38°C (July 2010) and -0.7°C (December 2012) at Mount Jackman respectively. In the same period the mean monthly air temperature ranged between -34.4°C (July 2004) and 1.3°C (January 2007) at Baker Rocks, -33.5°C (July 2004) and -3.1°C (January 2013) at Boomerang Glacier and -34.7 (July 2010)°C and -7.7°C (January 2014) at Mount Jackman, respectively. Air temperature is always higher than GST in winter, indicating the absence of a significant snow cover. On the other hand, during summer the air temperature is lower than the GST. As for the mean monthly temperature of the ice-wedge top (recorded at -50 cm) ranges between -27.6°C and 0°C at Baker Rocks, between -29.9°C and -4.1°C at Boomerang Glacier and between -36.1°C and -1.5°C at Mount Jackman, respectively. At the ice-wedge bottom (at -80cm), the monthly average temperature is between -26.4°C and -2.6°C at Baker Rocks, between -30°C and -4.6°C at Boomerang Glacier and between -35.1°C and -3.2°C at Mount Jackman, respectively. The thermal offset measured at the top of ice wedges is small, ranging between -2.0 °C and -0.5 °C at Baker Rocks, -0.5 °C and -0.1 °C at Boomerang Glacier and -0.6 °C and -0.1 °C at Mount Jackman, respectively. The active layer has been computed daily for each of the three sites, according to Gold and Lachenbruch (1973). The monthly average thickness of the active layer ranges between 0.17 m and 0.61 m at Baker Rocks, between 0.10 m and 0.71 m at Boomerang Glacier and between 0.01 m and 0.42 m at Mount Jackman.

In general, the active layer decreases in thickness with increasing altitude. This is confirmed when the active layer computed at Baker Rocks is compared to the one at Mount Jackman. However, this is not the case for the Boomerang Glacier site, where the active layer seems generally thicker than Baker Rocks, despite the higher altitude. Interestingly, the active layer shows a stochastic trend in all sites, indicating a clear non stationary pattern. As for the temperatures, they have strong seasonal unit roots at the daily, weekly and monthly, and quarterly frequencies. Yet, they do not show a significant stochastic trend. To better investigate and understand the reasons for the different pattern of active layer, which has a significant trend, and the stationary GST and air temperature, we compute the thermal diffusivity of the ground at the daily level, using the Carslaw and Jaeger (1959) formula related to the amplitude attenuation with depth. Monthly mean thermal diffusivity values range between  $1.68 \times 10^{-7} \text{ m}^2/\text{sec}$  and  $3.44 \times 10^{-7} \text{ m}^2/\text{sec}$  at Baker Rocks, between  $0.85 \times 10^{-7} \text{ m}^2/\text{sec}$  and  $18.03 \times 10^{-7} \text{ m}^2/\text{sec}$  at Mount Jackman and between  $2.07 \times 10^{-7} \text{ m}^2/\text{sec}$  and  $8.60 \times 10^{-7} \text{ m}^2/\text{sec}$  at Boomerang Glacier. They clearly show a seasonal pattern, being in general higher in winter and lower in summer time. This could indicate the presence of higher moisture in summer than in winter, which is less conductive and therefore decreases also the thermal diffusivity. In this work we use a time series approach to model the variability of the observed temperature and active layer series, which is quite new in this field and it represents therefore the main contribution to the existing literature.



**S09 – 220: ANTPAS - Antarctic Permafrost, Soils and Periglacial Environments**

***Mountain Permafrost Mass Movement in Hurd Peninsula (South Shetland Islands, Antarctic Peninsula) from Visible Band Imagery (1950-2010)***

Gonçalo Vieira<sup>1</sup>; Cláudio Sousa<sup>1</sup>; João Catalão<sup>1</sup>; Gonçalo Prates<sup>1</sup>

Universidade de Lisboa, Lisboa, Portugal<sup>1</sup>

Aerial photography and satellite images are widely recognized as a source of data for the production of maps of large areas of extension. The use of appropriate photogrammetric techniques can provide representative maps of the geomorphology of a place and through them the quantification of mass movement. In mountain permafrost the active layer deformation visible in rock glaciers are induced by climate, revealing thus a geo-indicator of environmental modification. Changes in these glaciers can reach surface velocities from a few centimeters to a few meters per year, depending on soil properties and thermal conditions. In Antarctica, mass movement velocities are still little studied, especially in the Antarctic Peninsula region, where particularly in the ice free areas of the South Shetland Islands several rock glaciers can be identified. Today's capability to measure mass movement previous to satellite based remote sensing and global navigation satellite systems geodetic measurements are possible by re-analyzing available photogrammetric frames. This study's objective is to measure the active layer of permafrost mass movement in the South Shetland Islands, made with the use of high-resolution images (frames and satellite images - visible band) and applying photogrammetry and digital image processing. Frames from the 1950's of the Hurd Peninsula (Livingston Island) were analyzed and compared to 2010's satellite images. From both data sets, orthorectified images were produced from which horizontal mass movement of the rock glacier was inferred to a few decimeters per year, varying with the rock glacier steepness. Contrasting these inferred velocities with recently measured velocities by phase-differential global navigation satellite systems geodesy at staves deployed throughout the rock glacier provide an outlook to this region environmental evolution.



**S09 – 248: ANTPAS - Antarctic Permafrost, Soils and Periglacial Environments**

***Surface / Subsurface Interaction in Lake Bonney in the McMurdo Dry Valleys.***

Doran, P.T.<sup>1</sup>; Obryk, M.K.<sup>1</sup>; Spigel, R.H.<sup>2</sup>; Priscu, J.C.<sup>3</sup>; Mikucki, J.A.<sup>4</sup>; Tulaczyk, S.<sup>5</sup>; Dugan, H.A.<sup>6</sup>; Virginia, R.A.<sup>7</sup>; Wislow, L.<sup>8</sup>; Auken, E.<sup>9</sup>; Chiuchiolo, A.<sup>3</sup>

Louisiana State University, Baton Rouge, United States<sup>1</sup>; National Institute of Water and Atmospheric Research, New Zealand<sup>2</sup>; Montana State University, Bozeman, United States<sup>3</sup>; University of Tennessee, Knoxville, United States<sup>4</sup>; University of California, Santa Cruz, United States<sup>5</sup>; University of Wisconsin, Madison, United States<sup>6</sup>; Dartmouth College, Hanover, United States<sup>7</sup>; United States Geological Survey<sup>8</sup>; Aarhus University, Nordre Ringgade 1, Denmark<sup>9</sup>

The perennially ice-covered lakes of the McMurdo Dry Valleys have been studied since the early 1960s. Most of this research has considered the lakes to be isolated basins perched above thick regional permafrost. Lake inflow has been assumed restricted to surface streams, and outflow restricted to evaporation or sublimation from the lake surface. Several lines of evidence have recently called this model into question.

Lake Bonney in Taylor Valley is dammed at one end by the Taylor Glacier which is a large outlet glacier from Taylor Dome. It is a chemically stratified, permanently ice-covered Antarctic lake. This lake is unique in that it is divided into two lobes (east and west), each with unique temperature and salinity profiles. Most data presented here was collected from the west lobe of the lake to determine the role of the Taylor Glacier in the vertical stability of the lake.

Since the first expeditions to the region in the early 1900's a curious iron brine discharge coming from the snout of Taylor Glacier suggested that subglacial water was flowing to the surface. In late 2008 and 2009, we deployed an Autonomous Underwater Vehicle (AUV) to make high resolution measurements of several parameters including the physical structure (temperature and conductivity) in the west lobe of Lake Bonney. Results suggested that a cold discharge of subglacial water flows into West Lobe Bonney at the same temperature as Blood Falls discharge. The extent of the discharge indicated the flow is coming into Lake Bonney all across the glacier front and the discharge is variable from year-to-year. Blood Falls seems to be a very small manifestation of the much larger system.

The presence of subglacial brine connected to Lake Bonney was further substantiated by an airborne electromagnetic survey which showed a large area of low resistivity similar to the bottom waters of Lake Bonney extending for several km upglacier.

This talk will review the results from the AUV and resistivity surveys and how they tie together. We will also present and discuss new data from continuous lake level measurements, CTD casts and an autonomous profiler to further constrain the nature of this inflow.



## S09 – 288: ANTPAS - Antarctic Permafrost, Soils and Periglacial Environments

### Hydrogeological Research in the Machu Picchu Peruvian Antarctic Scientific Station: Preliminary Results

Ng, W.<sup>1</sup>; Masías, P.<sup>1</sup>; Ramos, D.<sup>1</sup>; Cerpa, L.<sup>1</sup>; Peña, F.<sup>1</sup>; Morales-Reyna, M.<sup>1</sup>; Torres, D.<sup>1</sup>

Instituto Geológico Minero y Metalúrgico – INGEMMET Av. Canadá 1470. San Borja. Lima – Perú<sup>1</sup>

Machu Picchu Peruvian Antarctic scientific station is a research installation on King George Island, South Shetland Islands (Antarctic Peninsula), was founded in 1988, as temporal scientific base, and it's open in austral summer.

In January and February 2014, INGEMMET hydrogeological preliminary studies conducted around the Peruvian base to identify an aquifer. Our work was focused to perform a hydrogeological classification of materials by surface mapping, make subsurface explorations (through four piezometers) and take underground and surface water samples, for identify a potential aquifer body.

This year during the ANTAR XXIII expedition, we start the Project: "Hydrogeology of Machu Picchu aquifer, hydroclimatic implications". These studies pretend know the characteristics of the aquifer, hydrochemical and isotopic characteristics of groundwater and new prospects for improvement and implementation of the project for the next two years. With the certainty that there is groundwater, we perform the following activities: clean and deeper the old piezometers, install temperature sensors within these piezometers, and collect water samples.

Machu Picchu aquifer is a detrital aquifer. Superficially, it is composed of glacial, alluvial, marine, fluvial, alluvial fluvial and alluvial glacial deposits. Preliminary studies show three horizons. The Horizon 1 (more superficial) consists of cover material with sandy gravel with blocks of different sizes, from 0.05 m in alluvial-fluvial deposits to 1 m in glacial deposits. The Horizon 2 (intermediate) presents silty sandy gravel, silty gravel and sandy silty gravel with thickness of 0.16 m to 0.95 m. The Horizon 3 consists in sandy gravel interbedded with fine levels up to coarse sand lenses, this horizon is wet, saturated and stores groundwater. Our wells have not reached the base level of 3<sup>th</sup> horizon.

In the last expedition groundwater was confirmed in 6 installed piezometers. These level is not static, along the ANTAR XXII expedition level fell between 0.01 and 0.10 m per day, because there extraction of groundwater by rustic well for use in the Peruvian station. Also the data shows the direction of groundwater flow, which is generally from south to north (Ng, 2014). The chemical characteristics of groundwater, show that these Na-Ca-SO<sub>4</sub>, Ca-SO<sub>4</sub> and Na-Cl, with smaller conductivities than 550.0 µS/cm.

Machu Picchu aquifer consists of a permeable material, is semi-confined aquifer and stores groundwater, and that by a controlled appropriate exploitation can supply to the Machu Picchu Peruvian station.



**S09 – 353: ANTPAS - Antarctic Permafrost, Soils and Periglacial Environments**

***Permafrost Monitoring of the Mt. Dolence, Dry Valley, Ellsworth Mountains, Continental Antarctica***

Eduardo Senra<sup>1</sup>; Carlos Ernesto Schaefer<sup>1</sup>; Roberto Michel<sup>2</sup>; Karoline Delpupo<sup>2</sup>; Ulisses Bremer<sup>3</sup>

Universidade Federal de Viçosa, Brazil<sup>1</sup>; Universidade Estadual de Santa Cruz (UESC), Brazil<sup>2</sup>; Universidade Federal do Rio Grande do Sul (UFRGS), Brazil<sup>3</sup>

The Ellsworth Mountains occur along the southern edge of the Ronne-Filchner Ice Shelf and are subdivided by the Minnesota Glacier into the Heritage Range to the east and the Sentinel Range to the West. The climate of the Ellsworth Mountains is strongly controlled by proximity to the Ronne-Filchner Ice Shelf and elevation. The mean annual air temperature at the 1,000 m level is estimated to be  $-25^{\circ}\text{C}$ , and the average annual accumulation of water-equivalent precipitation likely ranges from 150 to 175 mm yr<sup>-1</sup> (Weyant, 1966). The entire area is underlain by continuous permafrost of unknown thickness. Based on data collected from 22 pits, 41% of the sites contained dry permafrost below 70 cm, 27% had ice-cemented permafrost within 70 cm of the surface, 27% had bedrock within 70 cm, and 5% contained an ice-core (Bockheim, unpublished; Schaefer et al., 2015). Dry-frozen permafrost, which may be unique to Antarctica, appears to form from sublimation of moisture in ice-cemented permafrost over time. Active-layer depths in drift sheets of the Ellsworth Mountains range from 15 to 50 cm (Bockheim, unpublished); our understanding of Antarctic permafrost is poor, especially at the continent. The permafrost monitoring sites were installed at Mt Dolence Hills, Ellsworth Mountains, in the summer of 2012, and consist of thermistors (accuracy  $\pm 0.2^{\circ}\text{C}$ ) installed at 1 m above ground for air temperature measurements at two soil profiles on quartzite drift deposits, arranged in a vertical array (Lithic Haplorthel 886 m asl, 5 cm, 10 cm, 30 cm and Lithic Anyorthel 850 m asl, 5 cm, 10 cm, 30 cm). All probes were connected to a Campbell Scientific CR 1000 data logger recording data at hourly intervals from January 2nd 2012 until December 29th 2013. We calculated the thawing days (TD), freezing days (FD); isothermal days (ID), freeze thaw days (FTD), thawing degree days (TDD) and freezing degree days (FDD); all according to Guglielmin et al. (2008). The active layer thickness was calculated as the  $0^{\circ}\text{C}$  depth by extrapolating the thermal gradient from the deepest positive temperature measurement (Guglielmin, 2006). Temperature at 5 cm reaches a maximum daily average in late December 2012, reaching a minimum in mid July 2013 ( $10.9^{\circ}\text{C}$ ,  $-37.9^{\circ}\text{C}$ ,  $\pm 11.1$ ) on P1. P2 recorded maximum daily average in early January, reaching a minimum between late July and early August. Mean daily air temperature reached a maximum of  $0.2^{\circ}\text{C}$  and a minimum of  $-38.9^{\circ}\text{C}$ . The active layer thickness reaches a maximum of 48.4 cm at P1 on January 17th 2013 and 47.8 cm at P2 on January 7th 2012. No ID were recorded for the studied period, one TD was recorded at 5 cm on P2, 143 FTD were recorded at 5cm, 81 at 10 cm and 46 days at 30 cm on P1, on P2 118 FTD were recorded at 5 cm, 80 at 10 cm and 42 days at 30 cm. The majority of the days were classified as FD for both sites; 585 at 5 cm, 647 at 10 cm and 684 days at 30 cm on P1, on P2 611 FD were recorded at 5 cm, 650 at 10 cm and 688 days at 30 cm. Only 17 FTD were recorded for the air temperature and 713 FD. Over the 728 days of the studied period the sum of all positive daily average temperatures was 166.3 TDD at 5cm and 23.8 TDD at 10 cm on P1, 45.0 TDD at 5 cm and 5.2 TDD at 10 cm on P2. No positive daily average was recorded at 30 cm for both sites. The sum of all negative daily average temperatures was -13504.5 FDD at 5 cm, -13389.9 FDD at 10 cm and -13381.0 FDD at 30 cm on P1, -13508.0 FDD at 5 cm, -13486.6 FDD at 10 cm and -13398.9 FDD at 30 cm on P2. Only 0.28 TDD were summed for the air temperature and -14430.7 FDD.

The soil thermal regime at the dry valley of Edson Hill, Ellsworth - Mountains is characteristic of polar desert affected by Dry-frozen permafrost, although air temperature does not reach high positive values. Variations in soil temperature are more intense during the year, showing the soil's response to solar radiation.



**S09 – 374: ANTPAS - Antarctic Permafrost, Soils and Periglacial Environments**

***Wind Regimes and Nivo-Eolian Corrosion in Maritime Antarctic (Hurd Peninsula, Livingston Island)***

Carla Mora<sup>1</sup>; Gonçalo Vieira<sup>1</sup>; António Lopes<sup>1</sup>; Alexandre Nieuwendam<sup>1</sup>; Alice Ferreira<sup>1</sup>; Ana David<sup>1</sup>

CEG/IGOT - Universidade Lisboa, Portugal<sup>1</sup>

The South Shetland islands are an archipelago with Polar maritime climate, mean air temperatures at sea-level of 2 °C, strong winds all year-round and annual precipitation of 400-700 mm, most of it in the form of snowfall. The terrain is rugged in most islands, with prevailing glaciated areas, but with frequent ice-free peninsulas and nunataks. The ice-free peninsulas frequently show rock outcrops and boulders, which are wind-exposed above the snow surface, even during winter. Nivo-eolian corrosion features associated to the impact of wind-blown snow are commonly found in wind-exposed rock surfaces in many areas of the South Shetlands (e.g. Hurd Peninsula, Deception Island, Fildes Peninsula and Barton Peninsula). The geomorphic effect of saltating snow is therefore ubiquitous but has been poorly studied and almost nothing is known about the current rate of corrosion.

Hurd Peninsula in Livingston Island is mountainous and shows several ice-free areas with exposed and convex rock outcrops, which enable for nivo-eolian corrosion to develop. In order to characterize the meteorological and snow conditions, we have installed a meteorological station near the Bulgarian Antarctic Station, including an anemometer and wind-vane, time-lapse cameras for snow monitoring, as well as several snow thickness measuring poles (based on temperature). Wood poles have been installed at different sites and repainted annually, allowing assessing of prevailing corrosive wind directions. At key sites we have conducted high resolution mapping (1:500) of polished rock outcrops due to nivo-eolian corrosion. Rock varnish has been also described and sampled (currently samples from Fildes Peninsula are being chemically analysed).

Bioindicators of scarce snow cover during the cold season (*Usnea* spp.) have been mapped in situ and using high resolution remote sensing (QuickBird). The wind data from the meteorological station was used to force wind fields over a digital elevation model and the velocity and direction data were compared to the mapped features and wood pole data. The results show that the climate of Livingston Island favours the action of nivo-aeolian corrosion on exposed surfaces. Observations of abraded surfaces of boulders, fast corrosion of painted poles, as well as wind data coincide and show that erosional winds are mainly from NE to SE. The erosive action of wind-blown snow is clear on the mitigation of lichen growth in exposed rock surfaces, but also leads to the development of erosive features, such as polishment and pitting. Rare ventifacts have been observed in Hurd Peninsula, but are more frequent in nearby Deception Island. Despite the wet character of the Maritime Antarctic climate, with relatively mild temperatures in the Antarctic framework, wind erosion is an important geomorphic process, which may even show a significant impact on existing infrastructure. The application of wind modelling forced by climate data over digital elevation models, shows that areas with strongest corrosion can be identified and measures for mitigating its impact on infrastructure can be implemented. This research has been conducted in the framework of project PERMANTAR-3 (PTDC/AAG-GLO/3908/2012 - FCT) PERMANTAR-3



**S09 – 376: ANTPAS - Antarctic Permafrost, Soils And Periglacial Environments**

***Rates and Significance of Rockglacier Deformation in Hurd Peninsula (Livingston Island, Antarctic)***

Vieira G<sup>1</sup>; Catalão J<sup>2</sup>; Prates G<sup>1</sup>; Ferreira A<sup>1</sup>; David A<sup>1</sup>; Correia A<sup>3</sup>; Reis A R<sup>2</sup>; Sousa C<sup>4</sup>

CEG/IGOT-Universidade de Lisboa, Portugal<sup>1</sup>; IDL-Universidade de Lisboa, Portugal<sup>2</sup>; Universidade de Évora, Portugal<sup>3</sup>; Universidade do Algarve, Faro, Portugal<sup>4</sup>

**Introduction:**

Rock glaciers have been described by various authors in the South Shetlands archipelago (Antarctic Peninsula region), with the main contribution being that of Serrano and Lopez-Martínez (2000), who have described 9 rockglaciers and 11 protalus lobes. However, little is known about the deformation rates of rockglaciers neither in the region nor about possible changes associated with climate warming. The Hurd rockglacier is located in the south part of Hurd Peninsula (Livingston Island), in a small valley with a ridge at 227-301 m asl. The valley opens to False Bay through a series of raised beach terraces. The bedrock is composed of sandstones, shales and greywackes of the Myers Bluff formation. Valley rockwalls are steep with extensive scree slopes and a small retreating glacier with a prominent frontal moraine between 90 and 170 m asl, from where the rockglacier develops. The rock glacier body is 630 m long and 290 m wide, ending at a fluvio-glacial plain at 30 m asl. The rockglacier surface shows pressure ridges and furrows, especially towards the frontal zone, which is 15-20 m high with a slope of 45°.

The climate is cold oceanic with mean annual temperatures at sea-level of ca. -2 °C and precipitation of 400-700mm. During the short summer rainfall events are frequent and mean monthly temperatures are ca. +2 °C, snow cover over the rock glacier can melt completely during warm summers, but in recent years, snow still prevailed extensively in furrows and sheltered areas.

Permafrost in Hurd Peninsula is continuous above 150 m and absent in the raised beach terraces, but occurs in relict bodies. The sporadic-discontinuous permafrost belt occurs from 30 to 150 m asl. Permafrost temperature at 275 m is -1.8 °C.

**Methods and results:**

Rockglaciers in mid-latitude mountains have shown to react to climate changes by changing deformation rates. Generally, warmer summers induce faster movement. Hurd rockglacier is being monitored since 2011 with objective of assessing the effects of climate change on rockglacier dynamics. The following methods have been used: i) geomorphological mapping, ii) orthophoto generation from old aerial photos, iii) vertical electrical soundings for assessing the presence of permafrost, iv) Persistent Scatterer analysis using interferometry (TerraSAR-X), and v) annual DGPS surveying of stakes. The model resulting from a vertical electrical sounding shows 3 units with different resistivities: i) 0-1 m =  $3.8 \times 10^3$  ohm.m - Unfrozen boulders and gravels, ii) 1-14.5m =  $1.44 \times 10^5$  ohm.m - Ice body, iii) below=  $2.8 \times 10^4$  ohm.m - possibly frozen but low ice-content material. The results agree with electrical resistivity soundings conducted by Serrano et al (2004). A set of 15 images from TerraSAR-X was obtained from the DLR (Project LAN1276). The images were acquired along ascending (8) and descending (7) passes and cover from January to March 2014. The coherence of interferograms is considerably low and the Persistent Scatterers approach seems to be the only reliable technique to extract useful information from interferograms. STAMPS software (Hooper et al., 2007) was used to determine the Permanent Scatterers using the stack of interferograms already processed for the ascending and descending passes. We were able to identify and process pixels that are phase-stable in this short period of time that allow us to estimate the DTM error and the displacement rate. The results seem to be reliable and are on the same order of magnitude of D-GPS surveys.



Surface deformation was monitored with differential GPS once per year from 2011 to 2015. Measurements are made in stakes inserted *ci* 30 cm in the ground and the movement is the sum of permafrost creep and active layer deformation. The measurements have been conducted in late January and as early as February depending on logistical possibilities. The GPS base station is installed at a fix point in bedrock within the catchment. Measurements have been made in Real Time Kinematics mode by staying for 30s at each point with the rover antenna. Accuracy is below 1 cm. Recorded downslope movement values ranged from 3 to 35 cm/year, with average values over the rockglacier from 11 to 15 cm/year. Interannual variability was small, but spatial differences within the rockglacier body are clear. The eastern part of the rockglacier shows the fastest displacement rates (>15 cm/year) and the western part, the slowest (generally <8 cm/year). The 3 stakes located in the northeast part of the rock glacier also show consistently slow rates during the whole period.

#### Conclusions:

The preliminary results from monitoring of 4 years of surface deformation in Hurd rockglacier with DGPS show rates from 3 to 35 cm/year with average values of 11 to 15 cm/year. The interannual variability of the measured values was very small, with two zones of movement having been found in the rockglacier. DINSAR interferograms of the summer 2013-14 showed poor results but a preliminary assessment using a Persistent Scatterers (PS) approach shows values of deformation in the order of 8-10 cm, which is in accordance with the deformation rates monitored in the field. Moreover, the spatial distribution of the deformation rates found with PS is similar to that measured in the field. The results suggest that the Persistent Scatterers approach using TerraSAR-X imagery can be used to accurately map surface deformation in the Maritime Antarctic. The main limitation is the short snow free period and the irregularity of snow fall events that occur also during the summer. At the moment of the abstract submission the deformation data series, which includes data from 2015, is still being compared to climate data and we plan to present the first results at the conference,

This research has been conducted in the framework of project PERMANTAR-3 (PTDC/AAG-GLO/3908/2012 - FCT).



**S09 – 395: ANTPAS - Antarctic Permafrost, Soils and Periglacial Environments**

***Permafrost Degradation in a Recently Deglaciaded Environment in Elephant Point (Livingston, Antarctica)***

Marc Oliva<sup>1</sup>; Jesus Ruiz-Fernández<sup>2</sup>

Institute of Geography and Spatial Planning, Universidade de Lisboa, Portugal<sup>1</sup>; University of Oviedo, Oviedo, Spain<sup>2</sup>

The western half of Livingston Island (South Shetland Islands) presents several small ice-free environments surrounding the Rotch Dome glacier. One of these areas is Elephant Point, encompassing an area of 1.16 km<sup>2</sup> in the SW corner of Livingston Island. The retreat of the Rotch Dome glacier during the Holocene has exposed this peninsula. The ice-free area has increased during the last decades in response to the warming trend recorded in the Antarctic Peninsula: 17.3% of the present-day land surface in Elephant Point appeared after 1956.

During the field work season in January 2014 we carried out an accurate geomorphological mapping of the landforms and processes existing in Elephant Point. Four main geomorphological units were observed: proglacial area, moraine system, bedrock plateaus and marine terraces. Two of these environments are located in this new ice-free area: a polygenic moraine extending from the W to the E edges of the peninsula and a relatively flat proglacial environment. The glacier sat next to the northern slope of the moraine in 1956, but the retreat of the glacier during the last decades has left these environments free of glacier ice. Following the deglaciation, the postglacial environmental dynamics in these areas showed the characteristic response of paraglacial systems.

Geomorphological processes occurring today in the northern and southern slopes of the moraine are very different. This is due to the different stage of paraglacial adjustment in both slopes. The southern slope shows a low to moderate activity of slope processes operating on coarser sediments that have built pronival ramparts, debris flows and alluvial fans. By contrast, mass wasting processes are very active in the northern slope, which is composed of fine-grained unconsolidated sediments. Here, ice-rich permafrost has been observed in slumps degrading the moraine. The sediments of the moraine are being mobilized down-slope in large amounts by landslides and slumps. Up to 9.6% of the surface of the moraine is affected by retrogressive-thaw slumps. Other features indicative of the degradation of the ground ice were found in Elephant Point, such as the kettle lakes distributed in the hummocky terrain between the moraine ridges and in the proglacial environment.

It is expected that paraglacial processes and permafrost degradation will continue in this maritime permafrost environment in the near future, though their intensity and extension will depend on the future climate conditions prevailing in the northern Antarctic Peninsula.

**Acknowledgements:**

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**S09 – 454: ANTPAS - Antarctic Permafrost, Soils and Periglacial Environments**

***Three Years of Permafrost Monitoring In a Calm Site in Livingston Island (Maritime Antarctica) Using Electrical Resistivity Tomography***

Correia A.<sup>1</sup>; Vieira G.<sup>2</sup>

University of Evora, Evora, Portugal<sup>1</sup>; University of Lisbon, Lisbon, Portugal<sup>2</sup>

Under the framework of projects PERMANTAR and PERMANTAR-2 electrical resistivity tomography (ERT) profiles were done in a Circumpolar Active Layer Monitoring (CALM) site in the Hurd Peninsula of Livingston Island, near the Bulgarian Antarctic Station St. Kliment Ohridski, in 2009, 2012, and 2013 with the objective of studying the spatial and time distribution of permafrost in the area. Electrical resistivity tomographies were made along different directions in the CALM site. However, only two profiles are considered in this study. One of the profiles done in 2009 was never repeated because of the snow accumulated in the years 2012 and 2013.

For each electrical resistivity tomography 40 electrodes were used in a Wenner configuration; adjacent electrodes were 2 m apart. The software RES2DINV was used for inverting the apparent electrical resistivity values into two-dimensional models of electrical resistivity of the ground. The models are a representation of the distribution of the electrical resistivity of the ground to depths of about 13 m along profiles 78 m long.

In general, the models show high electrical resistivity values in some zones (values as high as  $10^4$  ohm.m were obtained). As a preliminary interpretation, in some zones traversed by the two profiles there are patches of frozen ground or sporadic permafrost. Most of those patches persist from year to year. At the surface of the ground, some of those areas also coincide with patches of snow that were not yet melted when the geoelectrical profiles were made; those snow patches are, therefore, acting as an insulating cover to the ground maintaining the temperature below the values it would reach if there were no snow; to a certain extent, this could explain the existence of some of the frozen ground patches.



**S09 – 455: ANTPAS - Antarctic Permafrost, Soils and Periglacial Environments**

***Permafrost Distribution in Marine Terraces in Byers Peninsula (Livingston Island, Maritime Antarctica) Using Electrical Resistivity and Geomorphological Data***

Correia A.<sup>1</sup>; Oliva M.<sup>2</sup>; Ruiz-Fernández J.<sup>3</sup>

University of Evora, Evora, Portugal<sup>1</sup>; Universidade de Lisboa, Lisbon, Portugal<sup>2</sup>; University of Oviedo, Oviedo, Spain<sup>3</sup>

Geophysical surveying and geoelectrical methods have been proven to be an effective method to unveil permafrost distribution and permafrost conditions in polar environments; as a matter of fact, geoelectrical methods are particularly well adapted to study time and spatial distribution of permafrost because of its high electrical resistivity in comparison with electrical resistivities of soil and rocks with water above 0°C; in particular, electrical resistivity tomography has been used with a high degree of success in the study of permafrost detection and space and time evolution.

In the South Shetland Islands permafrost is considered to be marginal to discontinuous up to elevations of 20 - 40 m a.s.l., changing to continuous at higher altitudes. However, there are no specific data about the distribution of permafrost in the recently deglaciated areas in the Byers Peninsula of Livingston Island, in Maritime Antarctica, which is the largest ice-free area in the South Shetland Islands.

With the purpose of better understanding the existence (or inexistence) of permanent frozen conditions in this area, a geophysical survey using an electrical resistivity tomography methodology has been conducted during the field season of 2015. Three electrical resistivity tomographies of 78 m each were done along the same profile which ran from the coast to the highest marine terraces. Another profile from the glacier to the central plateau was also planned but the weather conditions did not allow to do it.

For each tomography 40 electrodes were used in a Wenner configuration; adjacent electrodes were 2 m apart. The software RES2DINV was used for inverting the apparent electrical resistivity values (apparent electrical resistivity pseudo-sections) into two-dimensional models of electrical resistivity of the ground. The models are a representation of the distribution of the electrical resistivity of the ground to depths of about 13 m along the 78 m long profiles. The snowy conditions during the cold season in 2014 in Byers Peninsula have conditioned a late melting of snow in 2015, which must be taken into account when interpreting the data related to frozen conditions inferred from the geoelectrical survey.

Several patches of high electrical resistivity are found along the three profiles done from the coast to the highest marine terraces, which are interpreted to be patches of sporadic permafrost. This may suggest the lower limits of sporadic permafrost in the area. In addition, an attempt to correlate the insulation effect of moss patches with the existence of permafrost is being done.



**S09 – 498: ANTPAS - Antarctic Permafrost, Soils and Periglacial Environments**

***Identification and Distribution of Active Periglacial Processes and Landforms on Deception Island Using Satellite-Borne Synthetic Aperture Radar Data***

Jerónimo López-Martínez<sup>1</sup>; Thomas Schmid<sup>2</sup>; Enrique Serrano<sup>3</sup>; Stéphane Guillaso<sup>4</sup>; Olivier D'Hondt<sup>4</sup>; Ana Nieto<sup>5</sup>; Sandra Mink<sup>6</sup>; Magaly Koch<sup>7</sup>; Adolfo Maestro<sup>6</sup>

Ciemat Centro De Investigaciones Energéticas Medioambientales Y Tecnológicas (CIEMAT), Madrid, Spain<sup>1</sup>; Facultad de Ciencias, Universidad Autónoma de Madrid, Spain<sup>2</sup>; Depto. Geografía, Universidad de Valladolid, Spain<sup>3</sup>; Technische Universität Berlin, Germany<sup>4</sup>; Autonomous University of Madrid (UAM), Madrid, Spain<sup>5</sup>; IGME, UAM, Madrid, Spain<sup>6</sup>; Boston University, Boston, USA<sup>7</sup>

Nowadays, active periglacial processes and landforms are commonly found within the South Shetlands archipelago. These islands are under the influence of maritime climate, and lie within a region which is known to be the fastest warming area of Antarctica. Due to a mean annual temperature range between -1 °C to -5 °C and an annual precipitation higher than 800 mm in some areas, the effects of freeze-thaw cycles influence the form and spatial distribution of surface features in ice-free areas and results in a mosaicked cover of different landforms. In this case, satellite-borne synthetic aperture radar (SAR) data are ideal for characterizing and mapping these areas with persistent harsh weather conditions and limited access. The objective of this work is to determine the distribution of different landforms on Deception Island using polarimetric SAR C-band RADARSAT-2 data. This active volcanic island is under the influence of different geomorphological processes, contains different types of surface covers and there is a high mobility of pyroclasts that contribute to a very dynamic landscape. The island contains interesting soils and vegetation covers and includes several Antarctic Specially Protected Areas (ASPAs). The SAR data used in this work were acquired by the Canadian Space Agency and included dual polarized data from the 7th March 2009 and quad polarized images from the 16th February and 15th March 2014. A pre-processing of the data included speckle filtering, terrain correction with a digital elevation model and geocoding. Polarimetric decomposition followed by an extraction of polarimetric parameters and texture analyses algorithms were applied to differentiate surface cover types identified with the remotely sensed data. Field work carried out over several field campaigns consisted in identifying the abiotic and biotic properties of different surfaces encountered on the island. Selected field sites were used as references to characterize the surface covers identified with the radar imagery. A supervised classification based on the Support Vector Machine (SVM) classifier was carried out to determine the main landforms related to periglacial processes as well as surface covers that represent particular volcanic features, soils and formation with possible vegetation areas. Therefore training sites where based on a series of selected field sites which represent homogeneous specific surface cover types of 30 m by 30 m. The data set for the classifier consisted of rescaled polarimetric decomposition data and terrain properties such as slope, aspect and curvature. Further field information was used for validating the distribution for the different surface covers. The results show that a number of surface features were well identified according to backscattering properties and were related to polarimetric parameters that have been extracted using different polarimetric decomposition schemes. These features are mainly related to their physical properties such as particle size and ruggedness. They include alluvial deposits of coarse sand, pavement and patterned ground, stone fields, fine sediments, rock outcrops, gravel and scoria deposits, lakes and flooded areas, and ice and snow cover. The results obtained with the SVM classification present a complex spatial distribution of these main surface features. In the case of pavement and patterned ground, the cover is influenced by a more developed soil structure and often with some types of sparse vegetation. This is contrary to the alluvial, gravel and scoria deposits which have an unsteady surface cover and the soil structure is absent or very slightly developed. The distribution of the surface covers could form an important aspect for comparing changes occurring within areas of interest, such as ASPAs, with existing mapping results as well as the future monitoring of periglacial landforms and surface covers on Deception Island where active geomorphological processes are ongoing. Furthermore, the advantage of using RADARSAT-2 data and future satellite-borne SAR systems with a corresponding methodology



such as presented in this work could allow a possible extrapolation of the results and this type of technique to other areas.



**S10 – 18: The structure and evolution of the Antarctic continent in light of recent geophysical and geological investigations**

***Deciphering the Tectonic Structure of the Northern Transantarctic Mountains***

Hansen S.E.<sup>1</sup>; Graw J.H.<sup>1</sup>; Brenn G.R.<sup>1</sup>; Kenyon L.M.<sup>1</sup>; Park Y.<sup>2</sup>; DuBay B.<sup>3</sup>

The University of Alabama, Tuscaloosa, United States<sup>1</sup>; Korea Polar Research Institute, South Korea<sup>2</sup>; Grissom Middle School, United States<sup>3</sup>

The Transantarctic Mountains (TAMs) are the largest non-compressional mountain range in the world, and their structure plays a key role in the climatic and tectonic development of Antarctica. To further assess the structure beneath the northern TAMs, the Transantarctic Mountains Northern Network (TAMNNET), a 15-station seismic array, was deployed in a previously unexplored portion of the mountain range in November-December 2012. Using data collected by this network over the past several years, numerous studies are currently underway to assess the crustal and lithospheric structure and to interpret the TAMs geologic history. Receiver functions indicate crustal thickening inland from the Ross Sea coast but comparable crustal thickness beneath the TAMs and the East Antarctic plateau. Body and surface wave analyses show a pronounced low-velocity anomaly beneath the Terror Rift, extending beneath Victoria Land. Shallow structure is being investigated with ambient noise tomography and joint seismic-gravity techniques. This presentation will highlight the most recent TAMNNET findings and their importance in understanding the complex tectonic structure of the TAMs.



**S10 – 68: The structure and evolution of the Antarctic continent in light of recent geophysical and geological investigations**

***The Extent of the West Antarctic Rift System in the Amundsen Sea and Bellingshausen Sea Sectors***

Gohl, K.<sup>1</sup>; Kalberg, T.<sup>1</sup>; Eagles, G.<sup>1</sup>; Dziadek, R.<sup>1</sup>; Kaul, N.<sup>2</sup>; Spiegel, C.<sup>2</sup>; Lindow, J.<sup>2</sup>

Alfred Wegener Institute, Helmholtz-Center for Polar and Marine Research, Germany<sup>1</sup>; University of Bremen, Department of Geosciences<sup>2</sup>

The West Antarctic Rift System (WARS) is one of the largest continental rifts globally, but its lateral extent, distribution of local rifts, timing of rifting phases, and mantle processes are still largely enigmatic. It has been presumed that the rift and its crustal extensional processes have widely controlled the history and development of West Antarctic glaciation with an ice sheet of which most is presently based at submarine level and which is, therefore, likely to be highly sensitive to ocean warming. While the western domain of the WARS in the Ross Sea has been studied in some detail, only recently have various geophysical and geochemical/thermochronological analyses revealed indications for its eastern extent in the Amundsen Sea and Bellingshausen Sea sectors of the South Pacific realm and in the eastern Marie Byrd Land, Ellsworth Land, Thurston Island and Antarctic Peninsula crustal blocks. One of the current models, based on these studies and additional data, suggests that the WARS activity included tectonic translateral, transtensional and extensional processes from the Amundsen Sea Embayment to the Bellingshausen Sea region of the southern Antarctic Peninsula, basically following the eastward migrating collision of the Phoenix Plate with the Antarctic Plate. We present the range of existing and novel hypotheses regarding the extent of the eastern WARS as well as published and yet unpublished data that support a conceptual WARS model for West Antarctica with implications for glacial onset and developments.



**S10 – 73: The structure and evolution of the Antarctic continent in light of recent geophysical and geological investigations**

***Crustal Shear Velocity Structure beneath the Maitri Station, East Antarctica***

Akilan Athiswamy.<sup>1</sup>; Sandeep Gupta.<sup>1</sup>; Nagaraju.<sup>1</sup>

CSIR-National Geophysical Research Institute, Hyderabad<sup>1</sup>

We investigate the crust and uppermost mantle velocity structure beneath the Maitri station, East Antarctica through the inversion of tele-seismic receiver functions following the neighbourhood algorithm. The receiver functions are computed using iterative time domain deconvolution approach from 41 earthquakes of good S/N ratio and magnitude  $>5.5$  in the epicentral distance range 30 to 95. The modelling result and grid search approach shows the average crustal thickness is  $\sim 38$  km with average  $V_p/V_s$  ratio  $\sim 1.8$ . We observe a thick ( $\sim 7$  km) low velocity layer ( $V_s \sim 1.5-2.0$  km/s) on the top followed by gradual velocity increase. The upper mantle velocity is  $\sim 4.2$  km/s.



**S10 – 89: The structure and evolution of the Antarctic continent in light of recent geophysical and geological investigations**

***Gravity Gradients at GOCE Satellite Altitude for Lithospheric Modelling in Antarctica***

Jörg Ebbing<sup>1</sup>; Johannes Bouman<sup>2</sup>; Martin Fuchs<sup>2</sup>; Theresa Schaller<sup>1</sup>; Wolfgang Szwillus<sup>1</sup>

Kiel University, Kiel, Germany<sup>1</sup>; DGFI-TU Munich, Germany<sup>2</sup>

We explore how GOCE gravity gradient data can improve modelling of the Earth's lithosphere and thereby contribute to a better understanding of the Earth's dynamic processes. For example, in recent years, it has become evident that the thermal structure and composition of the upper mantle have a large influence on topography. For Antarctica, we present gravity gradient grids at GOCE satellite altitude computed from combining GOCE with GRACE gravity information. The combination allows providing data in the polar gap of GOCE coverage, and we show that such a regional solution based on a tesseroid approach may contain more signal content than global gravity field models. The gravity gradients data have a depth sensitivity that makes them a useful tool to study the density distribution in the uppermost mantle and crust. The characteristic of the gradients is that they are less sensitive to possible sub-lithospheric regional trends (unlike terrestrial gravity and the geoid), but especially sensitive to the uppermost 150 km of the lithosphere. But gradients in a geographic reference system are not well suited for studying Polar Regions and could transform to an adequate local oriented reference frame. An alternative is to calculate rotational invariants of the gradients and to use these in combination with the vertical gravity gradient. With this approach, the satellite gradients help to validate models of ice and crustal thickness by testing the model against the representation of the full gravity tensor. In addition, seismic tomography can be considered to define upper mantle composition and temperature and consequently base lithosphere, defined as the 1315°C isotherm. Hence, the lithospheric model can be used to estimate the regional heat-flow component. This combined approach provides more realistic lithospheric models than by just using conventional gravity data sets and can complement seismological methods in defining the lithospheric architecture of Antarctica.



## **S10 – 91: The Structure and Evolution of the Antarctic Continent In Light of Recent Geophysical and Geological Investigations**

### ***Geology and tectonics of the Lake Vostok Region***

Leitchenkov German<sup>1</sup>; Luneov Pavel.<sup>2</sup>; Belyatsky Boris.<sup>3</sup>

Institute for Geology and Mineral Resources of the World Ocean, Russia<sup>1</sup>; Polar Marine Geosurvey Expedition, Russia<sup>2</sup>; All-Russia Geological Institute<sup>3</sup>

Lake Vostok is located beneath a thick (3500-4000 m) ice sheet covering the East Antarctic interior more than 1000 km inland from the coast. Available geophysical data suggest that Lake Vostok occupies an extensive generally north-south-trending bedrock depression about 250 km long and 50 to 80 km wide. The bottom of the lake averages about 1000 m below sea level and about 1500 m relative to its flanks. The Lake Vostok depression is surrounded by the bedrock upland (200- 500m high) from the east and by the highland (known as Vostok Subglacial Highlands; 500-1000 m high) from the west.

The first tectonic models of the Lake Vostok region were suggested after acquisition of regular geophysical data at the turn of the century (Leitchenkov et al., 1999, Studinger et al., 2003). Based on radio-echo sounding profiling and reflection seismics, Leitchenkov et al. (1999) interpreted the lake depression as an extensionally-induced graben which was a part of the spacious Late Mesozoic rift system extended from Prydz Bay toward the Antarctic interior. Using airborne magnetic and gravity data, Studinger et al. (2003) inferred that Lake Vostok was a result of minor extensional reactivation of the thrust fault within an ancient (Precambrian) continental collision zone. Recently collected geophysical data over the Gambutsev Mts. region gave additional valuable information about tectonics of central Antarctica and supported idea about existence of the vast rift system including Lake Vostok (Ferraccioli et al., 2011).

The unique opportunity to obtain direct information about the bedrock geology of the Lake Vostok region arose when the deep borehole at the Vostok station recovered the basal layer of the ice sheet. This layer contains rare sediment inclusions of up to few millimeters in size which have been derived from the lake bottom. Inclusions are represented by soft aggregates consisting mainly of clay-mica minerals and micron-sized quartz grains. Some of inclusions contain subangular to semi-rounded rock clasts ranging from 0.3 to 8 mm in size. Most of them are identified as quartzose siltstones with equigranular hydromicaceous cement. 31 grains of zircon and 5 grains of monazite have been identified in 2 siltstones and dated by SIMS SHRIMP-II. The ages of the studied zircons range between 0.6 and 2.0 Ga with two distinct clusters between 0.8 and 1.2 Ga and 1.6 and 1.8 Ga. Rock clasts were obviously come from the Vostok Subglacial Highlands (western lake shore) which are thus composed of terrigenous strata with an age of not older than Late Neoproterozoic. Sedimentary nature of the Vostok Subglacial Highlands is also confirmed by magnetic and gravity modelling (Studinger et al., 2003) as well as by recently collected refraction seismic data which show seismic velocities of 5.4-5.5 km/s at the bedrock surface. Gondwanaland and Antarctica itself are characterized with broad development of rift- and basin-related rocks of different ages but high values of seismic velocities correspond better to older (rather Late Precambrian- Early Palaeozoic) strata for the Vostok Sub-glacial Highlands. The age data on the detrital zircons and monazites suggest that their provenances are mainly represented by ancient Ruker and/or Mawson Cratons and Mesoproterozoic-Neoproterozoic Mobile Belt.

Reflection and refraction seismic experiments conducted in the southern part of Lake Vostok show very thin (200-300 meters) stratified sedimentary cover overlying crystalline basement with velocity of 6.0-6.2 km/s. At present, deposition in southern Lake Vostok is absent and similar conditions occurred likely at least last 3 m.y. It can be also inferred that from the Late Miocene the rate of deposition in Lake Vostok was extremely low and so the most of sedimentary cover formed during the Oligocene to middle Miocene



when the Antarctic ice sheet was worm-based and deposition was more vigorous. Small thickness of sedimentary cover calls into question existence of the lake (rift) depression during pre-glacial time.



**S10 – 102: The Structure and Evolution of the Antarctic Continent in Light of Recent Geophysical and Geological Investigations**

***Determining the Upper Mantle Seismic Structure beneath the Northern Transantarctic Mountains from Regional P- And S-Wave Tomography***

Gregory R. Brenn<sup>1</sup>; Samantha E. Hansen<sup>1</sup>; Y. Park<sup>2</sup>

The University of Alabama, Tuscaloosa, United States<sup>1</sup>; Korea Polar Research<sup>2</sup>

The Transantarctic Mountains (TAMs) are the longest non-collisional mountain belt in the world and represent a tectonic boundary between the East Antarctic (EA) craton and the West Antarctic Rift System. Multiple geologic models have been proposed to explain the uplift and high elevations in the TAMs, and the geodynamic origin of these mountains has important implications for understanding the tectonic and climatic evolution of Antarctica. While regional body wave tomography studies can help constrain the upper mantle velocity structure, and therefore the TAMs uplift mechanism, such studies have only been performed along the central portion of the mountain range. In this study, P- and S-wave travel-times from tele-seismic events recorded by the Transantarctic Mountain Northern Network (TAMNNET) are being used to tomographically image the upper mantle structure beneath the northern TAMs. TAMNNET includes 15 seismic stations, which are deployed across the northern TAMs and the adjacent EA craton, providing coverage of a previously unexplored portion of the mountain range. Using >500 earthquakes recorded by TAMNNET, as well as >300 events recorded by the previously deployed Transantarctic Mountain Seismic Experiment (TAMSEIS), P- and S-wave travel-time residuals are being computed and inverted to determine the upper mantle velocity structure beneath this area. The generated tomographic models will be used to assess the TAMs uplift mechanism. Preliminary results will be shown.



**S10 – 132: The Structure and Evolution of the Antarctic Continent in Light of Recent Geophysical and Geological Investigations**

***Coexisting Mylonite and Pseudotachylyte from the Veteheia Nunatak, Central Dronning Maud Land, East Antarctica: An Evidence of Paleo-Seismicity***

Mandal A

Geological Survey of India, Publication & Information Division, Central Head Quarter

Mylonites and pseudotachylytes are two different types of fault rocks representing two contrasting modes of deformation. While mylonites are the products of crystal plastic deformation, pseudotachylytes are formed by brittle failure thus representing products of two contrasting and incompatible modes of deformation. Complex deformation mechanisms have been proposed by several workers to explain this paradox. The spatial association of pseudotachylytes with mylonites, though apparently incompatible, is reported from some ductile shear zones. In some cases it is interpreted that the pseudotachylytes are formed at a late stage where mylonites are brought at a higher crustal level by erosion or upliftment that facilitates brittle deformation. Pseudotachylytes are also reported to have developed simultaneously along with mylonites during progressive ductile deformation.

Currently, pseudotachylytes are the only recognized indicator of ancient seismic activity in exposures containing exhumed faults and as such, they provide a unique tool for investigating seismic processes from the rock record. The recording, description and interpretation of the structures within plastically deformed, mylonite hosted pseudotachylyte layers, and their spatial and temporal relationship with cataclasis of host rock, have therefore gained importance in the geological and geophysical literature. In recent years, research work on pseudotachylytes has mostly attempted to unravel the dynamics of seismic fracturing and slip.

The enderbitic gneisses on the western flank of Veteheia nunatak (in close proximity to Schirmacher Oasis) exhibit shear deformation. A 3-4 meter wide sub-vertical discrete shear zone (N20°W-S20°E trending) is located within the enderbitic gneisses. This shear zone cuts across the dominant D2 Schirmacher shear plane (N60°E-S60°W) which may attribute to the retrogressive event represented by amphibolite facies (M2) condition. The kinematic indicators indicate a predominant sinistral sense of strike-slip movement along this discrete shear zone. The enderbitic gneisses are affected by the shear with varying intensity resulting in different textures, micro-structures and grain size refinement. Enderbitic gneisses are converted to mylonites as a result of crystal-plastic deformation in the shear zone. In contrast, there are localized zones of brittle failure with frictional heat generation exemplified by the development of thin but conspicuous bands and veins of pseudotachylytes, which are emplaced mostly sub-parallel with or at times transgressing the C-planes of the mylonites. Synchronous development of mylonite-pseudotachylyte during progressive ductile deformation or a two stage model for their development is a subject of discussion. The geometry and kinematics of this discrete shear zone indicate that this could be the last major deformational event in this area. This is significant in the quest for the cause of formation of the mylonite and pseudotachylyte. The clasts in pseudotachylytes are made up of coarse rock fragments and folded mylonitic fabric, whereas the matrix is composed of microlites and opaque glass together with fine grained crushed components formed by repeated mechanical granulation/brecciation of the host mylonitic rock. The presence of an isotropic glassy matrix, injection features, corroded grains and dendritic microlites can be the evidences for the existing melt phase. The composition of pseudotachylyte matrix (by EPMA) indicates silica deficiency with higher normative hypersthene, plagioclase and lower quartz compared with average whole rock composition of the host. This chemical variation is corroborated to the effects of partial melting, mechanical fractionation of melt. The pseudotachylyte melts are more mafic in composition due to the preferential melting of mafic minerals like biotite. This is a strong evidence for disequilibrium melting. Pseudotachylytes have not



suffered further deformation and no overprinting of mylonitic fabric on pseudotachylyte is observed in any scale.

Some authors suggested gradual tectonic upliftment along the shear zone to be the cause of simultaneous development of mylonite and pseudotachylytes in certain areas. But, the dominantly strike slip nature of movement in this discrete shear zone of Veteheia nunatak rules out such a possibility. It can be concluded that near synchronous development of these two deformational features occurred more or less at the same crustal depth and perhaps at the same P-T condition. Whereas, the cataclasis of the host mylonitic rock could have been take place after reactivation indicate reactivation of the shear zone during a later tectonic event or shock induced melting related to seismic events at depth. The prominent influencing factor appears to be the variation in strain rate along the movement planes (Cplanes) as a result of increasing differential stress. The occurrence of pseudotachylytes mostly along the Cplanes also corroborates the idea of localized higher strain rates. Thus, in the discreet shear zone in Veteheia nunatak in comparison to Schirmacher shear plane, pulsating change in the rate of strain in this dominant ductile deformation regime can be the cause for the development of two otherwise mutually exclusive phenomena i.e. mylonites and pseudotachylytes. Such presence of pseudotachylyte is first time reported from the Schirmacher Oasis area of central Dronning Maud Land, East Antarctica. Hence, an evidence of paleo-seismic event cannot be ruled out.

The Antarctic continent has been believed to be one of the aseismic regions of the Earth for many decades. However, according to the development of Global Seismic Networks and local seismic arrays, the number of tectonic earthquakes detected in and around the Antarctic continent has been increased. In the light of such pseudotachylyte occurrences in the polydeformed and polymetamorphosed terrain of central Dronning Maud Land, interdisciplinary geological and geophysical research initiatives can be taken up to find a unique tool for investigating seismic processes from the rock record in these part of East Antarctica.



**S10 – 137: The Structure and Evolution of the Antarctic Continent in Light of Recent Geophysical and Geological Investigations**

***Combining Field Geology and Geophysics to Decipher Continental Arcs: Crustal Development on the Lassiter Coast, Antarctic Peninsula***

Alex Burton-Johnson<sup>1</sup>; Teal Riley<sup>1</sup>; Fausto Ferraccioli<sup>1</sup>

British Antarctic Survey, Cambridge, UK<sup>1</sup>

With large swathes of geology concealed by ice and extensive unmapped outcrops, Antarctica is a prime example of a region where combining geological and geophysical data is invaluable to understand the crustal structure and tectonic history. Here we present initial results from new research initiated during the 2014-15 Antarctic field season to the Lassiter Coast Intrusive Suite (LCIS) of the SE Antarctic Peninsula, a region of significant mid-Cretaceous magmatism and crustal growth.

The LCIS covers an area of ~13600 km<sup>2</sup> and is dominated by calc-alkaline plutons (diorite-tonalite-granodiorite) which intrude a sequence of back-arc Mesozoic sediments and record the largest Phanerozoic intrusive magmatic event on the Antarctic Peninsula. It was emplaced between 119-95 Ma, but with most magmatism occurring in the interval 110-105 Ma, a period of major global plate reorganisation with extensive oceanic and continental magmatism. This project aims to determine through field geology, geophysics and geochemistry the causes and processes involved in the suite genesis and its broader relevance for understanding linkages between arc magmatism and tectonics. Presented here are preliminary results from the combined field geology and magnetic investigations. Through this combined approach, large scale features have been identified in regional aeromagnetic images and their source determined from field investigations. Results include: identifying the extent of individual plutons; identifying both high and low susceptibility plutons (the comparative age and origins of which are being determined); distinguishing individual plutons from large composite batholiths and investigating their internal structure; identifying major structures including faults beneath large valley glaciers, and investigating their kinematics; and determining the inland extent and structure of the suite, beneath the ice sheet. Through modelling of magnetic data the scale and depth of some prominent magnetic structures can also be estimated (including zoned plutons and unexposed mafic bodies) providing further insight into the deeper crustal structure of this significant intrusive suite.



## S10 – 140: The Structure and Evolution of the Antarctic Continent in Light of Recent Geophysical and Geological Investigations

### *Paleostress Field in Tierra Del Fuego and Their Relationship with The Scotia Arc Based on Brittle Mesostructure Population Analysis*

Maestro, A.<sup>1</sup>; Ruano, P.<sup>2</sup>; Torres-Carbonell, P.<sup>3</sup>; Bohoyo, F.<sup>1</sup>; Galindo-Zaldivar, J.<sup>2</sup>; Pedrera, A.<sup>1</sup>; Ruz-Costn, A.<sup>1</sup>; Gonzalez-Castillo, L.<sup>2</sup>; Ibarra, P.<sup>1</sup>; Lopez-Martinez, J.<sup>4</sup>

Instituto Geológico y Minero de España, Madrid, Spain<sup>1</sup>; Departamento De Geodinmica, Universidad De Granada, Spain<sup>2</sup>; Centro Austral De Investigaciones Cientificas (CADIC-CONICET), Argentina<sup>3</sup>; Facultad De Ciencias, Universidad Autonoma De Madrid, Spain<sup>4</sup>

Tierra del Fuego represents the largest emerged part at the northwestern end of the Scotia Arc and is considered the continuity of the Antarctic Peninsula. It also comprises the southernmost segment of the Andean Cordillera known as Fuegian Andes with a very complex tectonic history. Its recent history is linked to the Scotia Arc evolution, which promoted the development of geological features that are significantly different from the rest of the southern Andes.

The main objectives of this research were: (i) characterize the late Jurassic to Quaternary tectonic palaeostress fields in the Fuegian Andes region and (ii) to establish the relationship between the evolution of major tectonic structures and the orientation of the stress fields.

To contribute to the knowledge of the tectonic evolution of the Fuegian Andes region, 1523 brittle mesostructures (1263 faults, 129 joints, 67 tension gashes and 64 clastic dikes) were measured at 86 sites in Late Jurassic to Quaternary Metamorphic, igneous and sedimentary rocks. A total of 125 palaeostress tensors were obtained. Fault data were analyzed using the Right Dihedra, y-R diagram, Etchecopar's and Search Grid Inversion Palaeo-stress determination methods. Although the tectonic analysis was primarily based on palaeo-stress reconstructions using fault-slip data, the orientations of tensional joints and gashes and clastic dikes have also been used to establish maximum and minimum horizontal stress trends, although no quantitative estimation of stress ratios can be made.

The whole faults are represented by 619 normal faults, 336 reverse faults and 308 strike-slip faults. All them show dips between 10° and vertical. Faults offset range between centimetres and a few metres. The population of normal faults presents a main N-S direction and two relative maxima striking ENE-WSW and ESE-WNW. The reverse faults show NNW-SSE and EW directions meanwhile the strike-slip faults have preferentially N-S, NE-SW and NW-SE directions. Joints present a main NE-SW direction and three relative maxima striking ESE-WNW, NWSE and N-S. Tension gashes data show N-S to NNE-SSW main directions and several relative maxima striking NE-SW and NW-SE. Finally, clastic dikes show NNE-SSW to NE-SW directions. From the stress axes directions, a dominant NESW horizontal (maximum compression) direction and NW-SE and N-S secondary horizontal stress directions are observed. The (minimum compression) orientation shows two main modes trending ENE-WSW and NW-SE, and three secondary horizontal stress directions (NE-SW, E-W and NNW-SSE). The obtained (horizontal maximum compression) orientation have a main mode trending NE-SW and two secondary modes with NW-SE and N-S directions. The R relationship of the NE-SW stress direction mode mainly indicates an axial compression to wrench regime. The NW-SE and N-S horizontal main stress directions have an R relationship ranging from axial compression to tensional regime.

These stress tensors are consistent with, and characterize: i) a N directed contraction that developed during the late Cretaceous-early Paleogene oroclinal bending of the southernmost South America-Antarctic Peninsula continental bridge, and further movement of the Fuegian backstop toward South America until the Miocene; and ii) the major strikeslip faulting in Tierra del Fuego, consistent with evolution of the North Scotia Ridge since ~10 Ma.



**S10 – 157: The Structure and Evolution of the Antarctic Continent in Light of Recent Geophysical and Geological Investigations**

***Constraining the Evolution of the Deception Island Volcano (South Shetlands Archipelago) by Paleomagnetic Studies***

Lopez-Martinez, J.<sup>1</sup>; Oliva- Urcia, B.<sup>1</sup>; Gil-Pena I<sup>2</sup>; Maestro, A.<sup>2</sup>; Soto, R.<sup>3</sup>; Gil Imaz, A.<sup>4</sup>; Rey, J.<sup>5</sup>; Galindo-Zaldivar, J.<sup>6</sup>

Universidad Autonoma de Madrid, Spain<sup>1</sup>; Instituto Geologico Y Minero De Espana, Madrid, Spain<sup>2</sup>; Instituto Geologico Y Minero De Espana, Zaragoza, Spain<sup>3</sup>; Universidad De Zaragoza, Spain<sup>4</sup>; ESGEMAR, Malaga, Spain<sup>5</sup>; Instituto Andaluz De Ciencias De La Tierra, CSIC, Universidad De Granada, Spain<sup>6</sup>

Deception Island is an active volcano located in the Bransfield Basin, between the South Shetland Block and the Antarctic Peninsula. It shows a well-known sequence of episodes, which are broadly separated in two main sequences in the island, pre- and post-caldera collapse.

Dating volcanic episodes by radiometric methods in Deception Island is relatively difficult probably due to post depositional alteration, unsuitable mineral content (low K-content as in basalts from intra-oceanic volcanoes) or because rocks are too young to provide an accurate date (especially when using Ar/Ar and K/Ar methods). Therefore, the use of the variation of the magnetic field as dating tool could provide new insights into the age of the evolution of the volcano. Dating with this method depends on the availability of a reliable geomagnetic model and the accuracy of the paleomagnetic data. Paleomagnetic studies in volcanic materials have been widely used for correlating purposes since the 1960's, given the good results due to the usually high content of Fe-Ti oxides, which are main carriers of natural remanent magnetization (NRM). The stepwise demagnetization technique applied in the laboratory allows obtaining a characteristic component (ChC) of the NRM. Providing that there are not rotations after the acquisition of the ChC, a combination of the paleomagnetic results with a geomagnetic model will provide a probable date for the studied materials. In this work, results from a new paleomagnetic investigation carried out in 157 samples grouped in 20 sites in the volcanic deposits are presented, together with previous paleomagnetic results (17 sites) and the occurrence of tephra layers in the region from earlier studies.

The new sites are distributed in a wide variety of volcanic materials: volcanic breccia, pillow lavas, lava flows, scoriaceous lava flows and dikes cutting pre- and the lowermost post-caldera collapse units.

The information revealed by paleomagnetism provides new data about the evolution of the multi-episodic volcanic edifice of this Quaternary volcano, suggesting that the present day position of the volcanic materials is close to their original emplacement position since no large tilting in the paleomagnetic data is found. The new and previous paleomagnetic data provide a probable age for each studied volcanic unit when comparing with a global geomagnetic model. Despite the uncertainties in the use of averaged paleomagnetic data per volcanic units, the new data in combination with tephra occurrences suggest that the caldera collapse in Deception Island took place in Holocene times.



**S10 – 163: The Structure and Evolution of the Antarctic Continent in Light of Recent Geophysical and Geological Investigations**

***Keweenawan and Grenvillian (?) Magmatism Followed by Pan African Collision in the Recovery Frontier of East Antarctica***

Fausto Ferraccioli<sup>1</sup>; Rene Forsberg<sup>2</sup>; Joachim Jacobs<sup>3</sup>; Tom Jordan<sup>1</sup>; Kenichi Matsuoka<sup>4</sup>; Ian Daziel<sup>5</sup>; Owen King<sup>6</sup>; Arne Olsen<sup>2</sup>; Marta Ghidella<sup>7</sup>

NERC\British Antarctic Survey, Cambridge, UK<sup>1</sup>; DTU Space, Denmark<sup>2</sup>; Univeristy of Bergen, Bergen, Norway<sup>3</sup>; Norwegian Polar Institute, Tromsø, Norway<sup>4</sup>; The Univeristy of Texas at Austin, United States<sup>5</sup>; University of Leeds, UK<sup>6</sup>; Istituto Antartico Argentino, Argentina<sup>7</sup>

East Antarctica is often regarded as a keystone within the Gondwana and Rodinia supercontinents. The processes that were responsible for the final amalgamation of Gondwana and that led to the development of Pan-African age orogenic belts in East Antarctica remain, however, hotly debated. Particularly poorly constrained are the location, extent and architecture of the inferred sutures in East Antarctica where the collision of parts of East and West Gondwana is thought to have occurred. The paucity of knowledge on the location of Pan-African sutures and the effects of collisional tectonics also hampers our ability to reconstruct the evolution of East Antarctica within the Rodinia supercontinent.

Coats Land is of particular importance when investigating potential links between East Antarctica and Laurentia within Rodinia. Small outcrops of 1112 ± 4 Ma (Keweenawan-age) undeformed rhyolites and granophyres in Coats Land may be relicts of ~1.1 Ga old magmatism associated with the continental-scale Mid-Century Rift System in North America (Loewy et al., 2011 Geology).

Further south, in the adjacent Shackleton Range, a late Pan-African age collisional suture may separate the Coats Land block from a mosaic of other distinct East Antarctic crustal provinces (Ferraccioli et al., 2011 Nature), based on the occurrence of ~500 Ma ophiolites (Talarico et al., 1999, Terra Antarctica), high-P metamorphism including eclogite facies metamorphism (Schmadicke and Will, 2006 Geology), and the identification of major thrust faults and nappes (Buggish and Kleinschmidt, 2007 USGS OFR). The inferred collisional suture lies at 90 degrees to the ca coeval subduction related Ross Orogen that formed along the paleo-Pacific margin of Gondwana.

Aeromagnetic and airborne gravity data collected in 2013 and 2011 over the previously unexplored Recovery Frontier (named here after the Recovery ice stream) provide new geophysical views of the Coats Land block and the inferred Shackleton Range suture zone. To investigate the larger-scale crustal architecture and its linkages with Pan-African and older tectonic and magmatic events, we also combine these new data with previous aeromagnetic datasets and continental-scale satellite magnetic and gravity imaging.

The new magnetic images reveal a significantly more extensive rift-related(?) Keweenawan-age granitic magmatic province in the Coats Land block than apparent in outcrop. Residual gravity anomalies suggest that mafic intrusions may also be present at depth. A major paired gravity anomaly straddles the boundary between the Coast Land block and the Recovery Glacier region. The gravity anomaly signature is comparable to the one observed over several major Precambrian and Phanerozoic collisional suture zones. The geophysical data appear therefore to support the hypothesis that a major suture zone extends from the Shackleton Range at least 500 km into the interior of East Antarctica but indicate that it is unlikely to extend ~E-W or NE-SW across the whole of East Antarctica, in contrast to several geological reconstructions. Instead, aero-geophysical and satellite data suggests that it bends sharply to the south, on the eastern side of the Recovery Lakes.



Prominent magnetic highs fringe parts of the inferred suture zone and are interpreted as caused by several-km thick blocks of Precambrian felsic gneiss, similar to the magnetite-rich gneisses exposed at Fuchs Dome (Sergeyev et al., 1999 Terra Antarctica). Although these rocks are, to our knowledge undated, the magnetic anomalies closely resemble those over Grenvillian-age arc-related rocks, in both Dronning Maud Land and the Haag Nunataks.

Irrespective of the current lack of control over the age of the magnetic anomaly sources, it is clear that the magnetic anomalies of the Shackleton Range/ Recovery ice stream region lie at high angle with respect to those previously imaged over the Paleoproterozoic to Mesoproterozoic Nimrod Igneous Province of the Mawson Craton (Goodge and Finn, 2010 JGR). Satellite magnetic data hint to the existence of two major intervening lithospheric blocks, the South Pole and the Recovery provinces.

Speculatively the Recovery/Shackleton Range region may form part of a composite terrane/block that may contain a greater proportion of Grenvillian age arc-related crust than previously known. This inference agrees with findings from the Eastern Terrane of the Shackleton Range, where ca 1060 Ma meta-granitoids that formed in a continental volcanic arc have been recognised (Will et al., 2010 Precambrian Res.). A combination of new geochronological and geochemical studies of the Fuchs Dome, sediment provenance studies, and the acquisition of aero-geophysical data over the largely un-surveyed South Pole area could help test this interpretation further.



**S10 – 167: The Structure and Evolution of the Antarctic Continent in Light of Recent Geophysical and Geological Investigations**

***Crustal Architecture and Evolution of the Ross Orogen in Northern Victoria Land: New Aeromagnetic and Gravity Perspectives***

Fausto Ferraccioli<sup>1</sup>; Egidio Armadillo<sup>2</sup>; Laura Crispini<sup>2</sup>; Giovanni Capponi<sup>1-2</sup>

NERC\British Antarctic Survey, Cambridge, UK<sup>1</sup>; DISTAV- University of Genova, Italy<sup>2</sup>

The Cambro-Ordovician Ross Orogen in East Antarctica is linked to the evolution of the paleo-Pacific active margin of Gondwana. Northern Victoria Land (NVL) contains several key geological records of these active margin processes. Most models depict NVL as a collage of three terranes, the Wilson, Bowers and Robertson Bay terranes. However, whether these are exotic terranes or merely different components of an evolving and migrating backarc-arc-trench system (or both) is still uncertain. The linkages between tectonic and magmatic processes within the proposed terranes and the larger scale geodynamic processes are in many aspects still cryptic.

Here we interpret new aeromagnetic, aero-gravity and land-gravity compilations derived from over 2 decades of geophysical exploration that enable us to trace the sub-glacial extent of several major terrane-bounding and intra-terrane faults in NVL, investigate crustal architecture, and propose a new evolutionary model for the active margin of the craton.

Prominent aeromagnetic anomalies lie along the eastern edge of the Wilkes Sub-glacial Basin. Zircon U/Pb dating over small exposures of gabbro-diorites within the Prince Albert Mountains further south suggest that these anomalies may be delineating the buried extent of an early-Ross magmatic arc (ca 530 Ma?). This arc may speculatively have accreted as an exotic element onto the former Neoproterozoic rifted margin of East Antarctica, or may have developed in situ perhaps upon a pre-existing (Mesoproterozoic?) suture zone. The latter hypothesis would provide a good match with some geophysical interpretations for the eastern edge of the Curnamona Craton in southern Australia.

Magnetic segments of the arc are also identified ca 150 km further to the east within the eastern parts of the Wilson Terrane. We infer that these may have originally been adjacent or at least closer to each other and that extension/transension triggered arc boudinage separating the western and eastern arc segments in the Wilson Terrane. Such a configuration might be expected in an overall retreating Early Cambrian subduction setting.

Extension/transension in the overriding East Antarctic plate may also have created the accommodation space for the development of thick mid-Cambrian(?) sedimentary basins within the central Wilson Terrane, which are imaged by prominent magnetic lows with an overall en-echelon geometry. Less clear is the linkage with the Wilkes Subglacial Basin region that has recently been interpreted as a possible Ross-age back-arc region (Ferraccioli et al., 2009 Tectonophysics). However, given that provenance studies suggest that older arc magmatism may also have existed in this region, a long-lived and predominantly retreating active margin setting linked to subduction rollback is a plausible geodynamic scenario for this region too.

Basin inversion is proposed here for the central Wilson Terrane during a later predominantly transpressional stage of the Ross Orogen (ca 490-460 Ma) that triggered the development of a major pop-up structure within the Wilson Terrane. Several buried thrusts of the pop-up can now be traced in enhanced aeromagnetic images linking previous geological studies in Oates Land and along the Ross Sea coast. Relatively thin sheets of mylonitic sheared granitoids and potentially sheets of ultramafic rocks (such as those found as lenses in the Matusевич Glacier region) are modelled as the sources of the magnetic anomalies along some of the thrust faults. Notably, comparable magnetic anomalies are not



observed over the Wilkes Subglacial Basin, suggesting that a major late-Ross fold and thrust belt did not develop there. A prominent residual gravity high delineates the high-grade metamorphic core of the pop-up forming the central part of the Wilson Terrane.

Intriguingly, our new magnetic images and 3D magnetic inversions also reveal previously unrecognised linkages between the Exiles Thrust region within the western Wilson Terrane and the Lanterman Fault, which in turn is a major boundary between the Wilson and Bowers terranes. A seemingly simple explanation would be that these two terranes were originally adjacent arc and forearc segments of the active margin (e.g. Finn et al., 1999 *Geology*) and that later strike-slip motion separated them. Notably strike-slip motion focussed along the boundary between arc and the forearc has been identified in many modern and paleosubduction systems.

Regardless of the uncertainties associated with the original position of the two terranes, high amplitude magnetic and gravity anomalies suggest that oceanic basement floors the northern Bowers Terrane, which has previously been interpreted as representing either uplifted Early Cambrian(?) forearc crust or (in Australia) remnants of even older late Neoproterozoic oceanic (or transitional) crust formed during Rodinia break-up. Previous geophysical interpretations (Ferraccioli et al., 2002 *GRL*) suggested that oceanic basement may have subsequently been uplifted and obducted onto to the margin because of a phase of renewed but more oblique Cambrian subduction (further to the south beneath the Wilson Terrane). An alternative explanation that we put forward here is that docking of a microcontinent inferred to underlie the northernmost part of the Robertson Bay Terrane occurred, and this facilitated obduction. The latter scenario is particularly intriguing, as it bears similarities with recently proposed geodynamic models for the Tasmanian sector of the Gondwana active margin (Moore et al., 2014 *Aus. J Earth Sci*).

Overall, this new geophysical interpretation of NVL lends support to the notion of a long-lived, composite and evolving backarc-arc-forearc-system for this part of the Ross Orogen, which likely migrated in response to changes in the geometry and dynamics of the subduction system and also involved microcontinents, much like several modern systems.



## **S10 – 169: The structure and evolution of the Antarctic continent in light of recent geophysical and geological investigations**

### ***Bits and Pieces of the Gamburtsev Province Puzzle in East Antarctica***

Fausto Ferraccioli<sup>1</sup>; Carol Finn<sup>2</sup>, Robin Bell<sup>3</sup>; Tom Jordan<sup>1</sup>; Detlef Damaske<sup>4</sup>

NERC\British Antarctic Survey; Cambridge, UK<sup>1</sup>; U.S. Geological Survey<sup>2</sup>; Lamont Doherty Earth Observatory, USA<sup>3</sup>; BGR<sup>4</sup>

The Gamburtsev Subglacial Mountains (GSM) are the most enigmatic intraplate mountain range on Earth, despite their importance as one of the major nucleation sites for the development of the East Antarctic Ice Sheet. Prior to the International Polar Year (IPY), the GSM region was largely a terra incognita. Little was known about the form of these sub-glacial mountains, let alone about their underlying crustal and lithospheric structure or their origin and evolution. Extensive international aerogeophysical investigations and a passive seismic experiment were performed during the IPY in the GSM region, as part of the AGAP (Bell et al., 2011, *Science*; Ferraccioli et al., 2011 *Nature*) and the GAMSEIS projects (e.g. Hansen et al., 2010 *EPSL*) respectively. The results of these investigations are transforming our knowledge of this frontier. They are also stimulating new controversies and raising new questions regarding the mechanisms responsible for the uplift of the GSM and, more broadly speaking, the geological processes that shaped the interior of East Antarctica in relation to supercontinental evolution. Here we review several of these results and discuss some of the emerging controversies and open questions, with a view of also identifying future geophysical and geological research strands.

Recent passive seismic and gravity-derived models broadly agree in identifying anomalously thick crust in the interior of East Antarctica beneath the GSM (50-60 km thick). Ferraccioli et al., (2011) showed that a good agreement between receiver function estimates of crustal thickness and gravity-derived inversions of Moho depth can be reached, if a dense lower crustal root is modelled beneath the GSM. They suggested that the anomalously dense (Precambrian?) root is similar to roots imaged beneath stalled orogens (i.e. orogens where orogenic collapse and root delamination was not widespread), such as the Phanerozoic Urals, and segments of the Proterozoic Grenville Orogen and Trans Hudson Orogen. However, more recent analyses of lower crustal seismic velocities support only a moderately dense lower crust beneath the GSM (Heeszel et al., 2013 *JGR*). New joint inversions of gravity and seismic velocity data are required to reduce ambiguities in defining crustal density structure. Alternative models may e.g. include higher densities at upper to mid-crustal level due either to erosion of the upper crust and/or to the original crustal composition of the Gamburtsev Province (see e.g. models for parts of the Urals where high upper to mid crustal densities relate to mafic island arc crust). An improved estimation of crustal density structure is important to better constrain both crustal formation processes in interior East Antarctica and to estimate how much of the uplift of the GSM can be explained by the buoyancy of the root.

The origin of the thick GSM crust remains controversial. Crustal thickening may have resulted from the collision of a mosaic of Precambrian crustal provinces in East Antarctica, potentially as part of accretionary and collisional events responsible for Rodinia supercontinental assembly (Ferraccioli et al., 2011). However, An et al., (2015 *JGR*) compared an Swave seismic velocity model for the GSM with one for the Grenville Orogen in North America and noted that, although the models are broadly similar down to 30 km, they differ significantly in the 30-170 km depth range. They proposed that the thick crust that extends from Dome A to the interior of Dronning Maud Land is linked instead to the collision between Greater India and East Antarctica ~550 Ma, during the assembly of Gondwana. However, high seismic velocities in the thick lithospheric root beneath the GSM are more typical of Precambrian regions where the lithosphere has not been substantially altered by Phanerozoic subduction or collision (Heeszel et al., 2013). The hypothesis for Pan-African suturing is nevertheless appealing, particularly in light of recent geophysical interpretations, suggesting that the Indo-Antarctic-Australian suture may extend from the



Denman region to the Lake 90°E/Sovetskaya region and may also link to the previously identified Gamburtsev Suture (Aitken et al., 2014 GRL). New aero-geophysical surveying over Princess Elizabeth Land is a priority to help connect these regions and enable ground-truthing of geophysical interpretations of Pan- African vs Grenvillian-age collision in East Antarctica.

Particularly contentious is the role of the recently proposed East Antarctic Rift System (EARS) in triggering the uplift of the modern GSM. The Permian to Cretaceous rift-flank uplift model for the GSM (Ferraccioli et al., 2011) is appealing because it links enigmatic intraplate mountain-building to the geodynamic processes that led to the separation of India from East Antarctica during Gondwana break-up. However, while Permian rifting is generally accepted in the Lambert Rift (LR) and in the Mahanadi and Pranhita Godavari rifts in India, recent detrital thermochronology results from Oligocene-Quaternary sediments in Prydz Bay, suggest that Cretaceous exhumation may not have been significant in neither the LR nor further in the interior of East Antarctica (Tochlin et al., 2013 G3). Additionally, there is currently no seismic evidence in support of lithospheric thinning beneath the EARS outside the Lambert Rift segment, suggesting that if rifting did occur it was accommodated within the crust (Llyod et al., 2013 G3). Models invoking the existence of a diffuse plate boundary in interior East Antarctica that allowed for compressional uplift in the GSM and extension in the LR, could provide a viable alternative (Heeszel et al., 2013), but need further development and testing.

Other significant areas of current geophysical research centre on estimating the isostatic responses to Cenozoic fluvial and glacial erosion and their effects on peak-uplift in the GSM. Although preliminary 2D models suggest that only ca 25% of their relief can be accounted for via incision (Ferraccioli et al., 2011) the far-field 3D effects of glacial incision in e.g. the LR (Thomson et al., 2013 Nature Geoscience) and the other subglacial basins surrounding the GSM remain poorly understood. The role of Cenozoic dynamic topography in supporting the regional elevation of the GSM and the broader East Antarctic Plateau is also an important future research area (e.g. O'Donnell & Nyblade, 2014 EPSL). Ultimately targeted future drilling to bedrock will be key to link geophysical and geological investigations of the Gamburtsev Province.



**S10 – 172: The structure and evolution of the Antarctic continent in light of recent geophysical and geological investigations**

***Preliminary Observations from the WEGAS / GEA IV Survey in Eastern and Southern Dronning Maud Land***

Graeme Eagles<sup>1</sup>; Antonia Ruppel<sup>2</sup>; Daniel Steinhage<sup>1</sup>; Wilfried Jokat<sup>1</sup>; Andreas Laufer<sup>2</sup>; Joachim Jacobs<sup>3</sup>

Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research<sup>1</sup>; Federal Institute for Geosciences and Natural Resources (BGR)<sup>2</sup>; Norwegian Polar Institute<sup>3</sup>

Over the course of the 2014 and 2015 seasons, the Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research (AWI) and the Federal Institute for Geosciences and Natural Resources (BGR) collected around 150 hours of new airborne gravity, magnetic and ice-penetrating radar data in the area of Dronning Maud Land to the east and south of Princess Elisabeth station. Survey was completed at 10 km line spacing. The 2014 survey used a LaCoste and Romberg Air-Sea gravimeter (LCR) at constant barometric altitude. The 2015 survey was completed at constant ground separation with a Gravimetric Technologies GT2A gravimeter. Both surveys used a Scintrex Cs-3 caesium vapour magnetometer mounted in a tail boom and a fuselagemounted three-component fluxgate magnetometer. The GT2A gravity data can be shown to reliably reflect the effects of the density contrast between basement rocks and the ice sheet at much shorter wavelengths than the LCR data. Results of the cross-over analysis are consistent with the advertised sub-milliGal repeatability of data collected with the GT2A. Gravity data reveal a prominent sub-glacial channel separating eastern Sr Rondane from the Yamato Belgica Mountains to the east. The area to the south of eastern Sr Rondane is characterised by a dendritic pattern of valleys that converges away from the prominent channel in the east. At longer wavelength, the data suggest the presence of a compensating root beneath eastern Sr Rondane and thinner crust towards the extended continental margin north of the mountains.

The magnetic data reveal strong NS-trending magnetic anomalies coincident with the Yamato-Belgica Mountains, and a more subdued set of ESE trending anomalies that confirm the eastwards continuation of the SE Dronning Maud Land province into the region. Instead, a new and unexpected feature is a strong NNW-trending anomaly, also present in the gravity data, at which the SE Dronning Maud Land province, which had been suggested to continue much further towards Prydz Bay, appears to terminate. In contrast, the deep sub-glacial valley between Sr Rondane and the Yamato-Belgica Mountains has little or no magnetic signature of its own.



**S10 – 177: The Structure and Evolution of the Antarctic Continent in Light of Recent Geophysical and Geological Investigations**

***Continental Rifting in the Western Ross Sea***

Fred Davey

GNS Science, New Zealand

The Ross Sea forms the north western end of the West Antarctic Rift system, a major continental rift that lies across the western part of Antarctica, and results from rifting during the break-up of Gondwana starting some 180 m.y. ago. In the Ross Sea region, extension comprised a regional thinning associated with the break-up of New Zealand and Australia from Antarctica, and a more focussed extension during the Cenozoic. The last episode of extension, largely from 46 Ma-25 Ma, formed the Victoria Land Basin (VLB) in the southwest, the Northern Basin (offset from the VLB) in north western Ross Sea and the Adare Basin in the deep ocean to the north. Marine magnetic anomalies associated with the seafloor spreading that formed the Adare Basin, extend continuously onto the continental shelf of the Northern Basin, suggesting that the basin is underlain by oceanic crust, consistent with high gravity anomalies across the continental shelf edge. No seismic data exist for the deeper crust of Northern Basin. The amplitude and gradient of gravity anomalies across the basin limit the depth, density contrast and thickness of the dense body underlying it and are consistent with oceanic crust with steep margins at a depth of about 8-10 km. The VLB in contrast shows an extensional thinning of the continental crust. The three basins thus show seafloor spreading in the north, continental rifting at the continental margin, and continental thinning in the south. The pole of rotation for the extension lies to the south of the VLB so the rate of extension increases to the north. In addition, the azimuth of the axis of spreading changes relative to the extension direction, presumably as it followed pre-existing zones of weakness in the Antarctic lithosphere. This has resulted in a much larger degree of strike slip motion in the Northern Basin rifting that may be a significant factor in the development of narrow rifting of the continental lithosphere. The extension forming Northern Basin may have also caused the reactivation of the major NW trending faults of Northern Victoria.



**S10 – 192: The Structure and Evolution of the Antarctic Continent in Light of Recent Geophysical and Geological Investigations**

***Magnetotelluric Study across the Schirmacher Oasis of Central Dronning Maud Land, East Antarctica: Electrical Characteristics of the East African-Antarctic Orogen as a Possible Aid to Link Gondwana Fragments***

Abdul Azeez K. K.<sup>1</sup>; Prabhakar E Rao, S.<sup>1</sup>; Gupta, A. K.<sup>1</sup>; Basava, S.<sup>1</sup>; Harinarayana, T.<sup>1</sup>

CSIR-National Geophysical Research Institute, Hyderabad, India<sup>1</sup>

Antarctica has been a vital continental piece of the Gondwana supercontinent assembly existed at ca. 500 Ma, and shared common boundary with other present-day continents (e.g., Africa, India, Australia, and South America) prior to the breakup of Gondwana in the Late Mesozoic. The East Antarctica encompasses older crustal blocks of Achaean to early Palaeozoic. It is widely accepted that, during the Gondwana supercontinent formation, the northern region of East Antarctica (mostly represented by the Dronning Maud Land) was stitched to the African continent through the Pan-African Orogeny, and later dispersed along the present-day eastern continental margin of Africa during the Gondwana breakup. The Central Dronning Maud Land [CDML] have had boarder with the Mozambique belt in East Africa, a part of the East African orogenic belt, and several studies inferred the extension of East African Orogen into Antarctica.

Geophysical exploration is extremely useful, and perhaps it is the only means, to know the geology and tectonics underlying the thick ice cover present over almost every part of East Antarctica. In the absence of any significant tectonic deformation occurring beneath East Antarctica, it can be presumed that the lithosphere of Antarctica may be still preserving the crustal and upper mantle characteristics inherited during the amalgamation and evolution of the Gondwanaland. Imaging the subsurface resistivity structure and studying the variations in electrical resistivity of the subsurface formations in a given geological setting have been proved to be an effective approach to investigate the active tectonics and geologic evolution of the region. The magnetotelluric [MT] method, the only electromagnetic tool capable of imaging both crustal and mantle resistivity structures, is employed to derive the crustal resistivity section across the Schirmacher Oasis, a coastal nunatak in the CDML.

Broad-band MT measurements were made at ten locations along a profile of about 18 km length and approximately perpendicular to the trend of Schirmacher Oasis and the coast. TenSør decomposition of the MT impedance tenSør was carried out using different approaches to determine the dimensionality and geo-electric strike direction needed for a valid two dimensional [2D] interpretation. The results showed a consistent +90o rotation to derive the regional (2D) MT impedances parallel (TE) and perpendicular (TM) to the electric strike. The 2D MT data were inverted independently and jointly using non-linear conjugate gradient inversion algorithm. The presence of ocean in the northern part of the study area was incorporated in the initial model to avoid the artifacts of ocean effect in the generated resistivity models. Final models were obtained using an inversion smoothing parameter value of 1 determined using the L-curve. The resistivity model derived from the simultaneous inversion of TE and TM responses, by down weighting the apparent resistivity with respect to the phase data, is considered to characterize the subsurface resistivity structure and for geological interpretation.

The MT model delineate a high resistive (103 to ~104 Ohm.m) upper layer underlain by a moderately resistive (100-300 Ohm.m) layer. The moderately resistive (relatively conductive) layer occurs at quite deep (~25 km) in the southern part of our profile and gradually become shallow underneath Schirmacher Oasis. The bottom of the above layer approximately coincides with the Moho estimated from seismic and magnetic data, which range between 32 and 38 km in the region. Further down, the upper mantle shows elevated resistivity. The resistivity structure is largely consistent with the resistivity models obtained for many Achaean/Proterozoic geologic terrains. The implications of the observed resistivity structure and its



## *XII International Symposium on Antarctic Earth Sciences*

*13 - 17 July 2015, Goa, India*



correlation to electrical structures observed in Proterozoic mobile belts within other Gondwana fragments will be discussed.



**S10 – 243: The Structure and Evolution of the Antarctic Continent in Light of Recent Geophysical and Geological Investigations**

***Distribution of Jurassic High Heat Production Granites in the Weddell Rift, Antarctica, from Geophysical and Geochemical Data***

Leat PT<sup>1</sup>, Jordan TA.<sup>1</sup>; Flowerdew MJ<sup>2</sup>; Riley TR<sup>1</sup>; Ferraccioli F<sup>1</sup>; Vaughan APM<sup>3</sup>; Rose K<sup>4</sup>; Whitehouse MJ<sup>5</sup>  
British Antarctic Survey<sup>1</sup>; CASP, Cambridge<sup>2</sup>; Trinity College Dublin<sup>3</sup>; University of Bristol<sup>4</sup>; Swedish Museum of Natural History<sup>5</sup>

The distribution of heat flow in Antarctic continental crust is critical to understanding ice sheet nucleation, growth and basal rheology and hydrology. We identify a group of High Heat Production granites, intruded into Palaeozoic sedimentary sequences, which may contribute to locally high heat flow beneath the West Antarctic Ice Sheet. Four of the granite plutons are exposed above ice sheet level at Pagano Nunatak, Pirrit Hills, Nash Hills and Whitmore Mountains. A new U-Pb zircon age from Pirrit Hills of  $177.9 \pm 2.3$  Ma confirms earlier Rb-Sr and U-Pb dating that suggested an Early-Middle Jurassic age for the granites, coincident with the Karoo-Ferrar large igneous province and the first stage of Gondwana break-up. Our recently acquired aero-geophysical data indicate that the plutons are distributed unevenly over  $1000 \text{ km}^2$  and were intruded into the actively extending, locally transcurrent, Jurassic Weddell rift. In the NW part of the rift, the Pirrit Hills, Nash Hills and Whitmore Mountains granites form small isolated intrusions within relatively weakly deformed upper crust. In the SE part of the rift, where granite intrusion was strongly structurally controlled within transtensional structures, the Pagano Nunatak granite is the only outcrop of a probably multiphase, ca. 180 km long sub-ice granite intrusion. The granites are weakly peraluminous, S-type and have Th and U abundances up to 60.7 and 28.6 ppm respectively (new and published information). Measured heat production of the Weddell rift granite samples is  $2.96\text{-}9.06 \text{ W/m}^3$  (mean  $5.35 \text{ W/m}^3$ ), significantly higher than most Antarctic granites, and toward the upper limit of values for High Heat Production granites globally. The granites are imaged by aero-geophysical data suggesting that the granites are ca. 8 km thick. This implies local heat flow of ca.  $62\text{-}98 \text{ mW/m}^2$ . The granites are thought to have been generated during mafic underplating of the Weddell rift during eruption of the contemporaneous Karoo-Ferrar magmatism. The high Th and U abundances may be related to fractionation of the high Th-U Ferrar basaltic magmas combined with assimilation of pelitic sedimentary rocks. The granites correspond to an area of West Antarctica that may have heat flow significantly above the Antarctic average, as predicted from satellite magnetic data.



**S10 – 285: The Structure and Evolution of the Antarctic Continent in Light of Recent Geophysical and Geological Investigations**

***An Antarctic Gravity Anomaly Grid for Applications in Geophysics and Geodesy***

Mirko Scheinert<sup>1</sup>; Fausto Ferraccioli<sup>2</sup>; Joachim Schwabe<sup>1</sup>; AntGG Group<sup>3</sup>

TU Dresden, Germany<sup>1</sup>; BAS, Cambridge, UK<sup>2</sup>; SCAR GIANT and IAG SC 2.4f<sup>3</sup>

It is a major goal to close the gaps in Antarctic gravity data. For this purpose, within the SCAR Expert Group on Geodetic Infrastructure in Antarctica (GIANT) the working group on Gravity Field was initiated, closely coordinated with the International Association of Geodesy (IAG) Sub commission 2.4f Gravity and Geoid in Antarctica (AntGG). Members of both groups are actively involved in all kinds of gravity measurements in Antarctica and are fostering new observation campaigns. A variety of different surveys has been accomplished in recent years. Especially airborne gravimetry has proven to be the state-of-the-art technique to cover huge areas and to reliably operate in the hostile environment of Antarctica. Recent surveys will be discussed with respect to accuracy and resolution, but also concerning further issues like gravimetric datum and systematic effects. A new gravity anomaly grid will be presented comprising all gravity data available at the AntGG data base at TU Dresden. We will discuss the principal methods to infer this grid. The Antarctic gravity anomaly grid is in the process of publication such that the access for the scientific community will be ensured.

There are many applications of Antarctic gravity data. In geophysics, these are being used to enhance our knowledge about the internal structure of the earth and the geological evolution in Antarctica. For this, further functional like the Bouguer anomaly are inferred and will be discussed. In geodesy, it is crucial to combine ground-based and airborne data with satellite gravimetry in order to come up with high-resolution global gravity field models. Thus, the new gravity anomaly grid will help to close the Antarctic data gap. This is of great importance since the GOCE mission (2009 2013) delivered high quality data enabling the highest resolution of satellite-only gravity field models but left, due to the orbit inclination of 96.5 degree, a data gap with a diameter of about 1,400 km at the pole. On a continental and regional scale, improved regional geoid solutions can be inferred. An improved geoid is also of great interest for neighbouring disciplines, e.g. in oceanography to determine the (mean) sea-surface topography or in glaciology to determine free-board heights of floating sea ice or ice shelves.

Finally, an outlook will be given on future plans to realize further gravimetry surveys in Antarctica and to work towards the above mentioned goals.



**S10 – 301: The Structure and Evolution of the Antarctic Continent in Light of Recent Geophysical and Geological Investigations**

***Seismic Stratigraphic Mapping and Evolution of the Ross Island Flexural Basin in Western Antarctica over the Past ~5 Ma.***

Sumant Jha<sup>1</sup>; Christopher P. Wenman<sup>1</sup>; Dennis L. Harry<sup>1</sup>

Department of Geosciences, Colorado State University, Fort Collins, Colorado, USA<sup>1</sup>

Ross Island is located at the southern end of the Terror Rift, which lies within the broader Victoria Land Basin in the western Ross Sea of West Antarctica. The Victoria Land Basin and the Terror Rift were formed by crustal thinning during formation of the West Antarctic Rift System (WARS). The evolution of the WARS progressed in two stages. Extension began during the Cretaceous Period, and was initially broadly distributed throughout the Ross Sea region. Extension became more focused in the Victoria Land basin, located near the boundary with East Antarctica, during the Paleogene Period. This second phase of extension ultimately led to development of the Terror Rift. Extension continued at least into the Pleistocene Epoch, and may be slowly ongoing today.

Volcanic eruptions at the southern end of the Terror Rift began 5.2 Ma ago, which created the first surface expression of Ross Island. The volcanic centers on Ross Island – Mt. Bird, Mt. Terror and Mt. Erebus - were a result of eruptive phases that occurred between 5.2 – 2.9 Ma, 1.78 – 0.68 Ma and 1.33 – 0 Ma, respectively. As the island was built, volcanic loading of the crust resulted in subsidence of the seafloor and formation of several sub-basins, which collectively form the present flexural moat around Ross Island.

In this study, we use marine seismic reflection data to map the locations and shapes of the flexural sub-basins that comprise the Ross Island flexural moat. The goals are to constrain the spatial and temporal evolution of the flexural moat in order to identify variations in the shape and location of the flexural depocenters and their associations with the different Ross Island volcanic loading events, and to estimate the flexural rigidity of the lithosphere surrounding Ross Island and its possible variation over the past ca. 5 Ma.

Three flexural sub-basins that combine to form the larger flexural moat around Ross Island were identified on the basis of stratal relationships. Specifically, sub-basins are recognized as distinct wedge-shaped packages of reflections that dip and diverge toward Ross Island and thin and on lap toward the distal edges of the basin. These sub-basins are interpreted to result from loading of the crust during different eruptive phases on Ross Island. The dipping reflection packages filling the sub-basins are separated by packages of relatively planar reflections that are interpreted to indicate periods of quiescence between eruptive events. Correlation of the basin bounding reflections to published regional seismic markers shows that the three sub-basins formed during the periods 7.6 Ma - 5.2 Ma (Pre-Ross Island), 5.2 Ma - 1.76 Ma (Mt. Bird) and ~1.3 Ma to present (Mt. Terror and Mt. Erebus). Sediment compaction curves from the AND-1 drillhole were used to create decompacted isopach maps for each sub-basin. The decompacted isopach maps record the amount of flexural subsidence that occurred during the period of time in which each sub-basin was subsiding.

The seismic data reveal a well-developed flexural moat on the west side of the island, visible on seismic line NBPO401-126 m, where the moat is approximately 45 km wide with a sediment fill thickness of ~1.8 km. The eastern side of the island has a poorly developed flexural basin, as indicated by gently dipping sub-parallel reflections visible on seismic line PD90-018.

To understand the spatio-temporal evolution of the Ross Island flexural basin, we used an elastic plate model to fit the decompacted sediment thickness of strata filling each of the three flexural sub-basins.



These models examined two tectonic scenarios: i) an infinite plate subjected to a point load representing the volcanic center, and ii) a semi-infinite (broken) plate geometry under a line load. The semi-infinite plate models suggest that the flexural rigidity of the lithosphere between 7.6 Ma to 5.2 Ma was approximately  $3.85 \pm 1.65 \times 10^{21}$  N-m. The flexural rigidity between 5.2 Ma - 1.76 Ma and 1.3 Ma to present is estimated to be  $1.25 \pm 0.25 \times 10^{20}$  N-m in both instances. The infinite plate models suggest that the flexural rigidity of the lithosphere between 7.6 Ma and 5.2 Ma was  $1.65 \pm 0.45 \times 10^{22}$  N-m. As was the case with semi-infinite plate geometry, a lower flexural rigidity of  $8.90 \pm 0.30 \times 10^{19}$  N-m was estimated for the sub-basins between 5.2 Ma - 1.76 Ma and between 1.3 to present.

The absence of a flexural moat to the east of Ross Island and its presence to the west suggests an abrupt change in the mechanical properties of the lithosphere beneath Ross Island. This could be due to a mechanical rupture or weak zone in lithosphere under Ross Island, or it could indicate a rapid change in lithospheric strength, with the eastern side of Ross Island being underlain by much stronger lithosphere. An abrupt, large variation in flexural rigidity seems improbable over such short distances. Consequently, we consider it more likely that the lithosphere beneath Ross Island is ruptured or weakened, either by reactivation of a pre-existing tectonic fabric, by faulting associated with extension in the Victoria Land Basin, or as a consequence of Ross Island magmatic activity. This scenario favours the broken plate model and suggests the presence of two half-plates under Ross Island, with the load on Ross Island being supported by the western half-plate and the eastern half-plate bearing little or no load.



**S10 – 322: The Structure and Evolution of the Antarctic Continent in Light of Recent Geophysical and Geological Investigations**

***Tectonic Inheritance in Northern Victoria Land (Antarctica) and the Role of the Palaeozoic Lineaments in the Recent Geodynamics: New Insight from Fracture Analysis.***

Crispini Laura<sup>1</sup>; Cianfarra P.<sup>2</sup>; Salvini F.<sup>2</sup>; Capponi G.<sup>1</sup>

DISTAV - University of Genova<sup>1</sup>; Dipartimento Di Scienze Geologiche - University of Roma Tre<sup>2</sup>

The Mesozoic geodynamic evolution is responsible for the separation of Antarctica from Australia, Tasmania, New Zealand and the other fragments of the Gondwana puzzle. This phase of separation was achieved by tectonic activity along first rank lithospheric discontinuities, with several reworking phases. Along some lineaments the activity continues until present, as proved by GPS determinations in NVL (e.g. Dubbini et al., 2010).

The activity of such regional faults during the Ross Orogeny is fairly known (Capponi et al., 1999; Capponi et al., 2002), as far as their re-activation during the Cenozoic (Salvini et al. 1997; Salvini & Storti, 1999; Rossetti et al., 2003); whereas a late/post-Ross activity has been reported only in the recent literature.

The aim of this study is to improve the knowledge of the geodynamic evolution of northern Victoria Land, with emphasis on the fragmentation stage and separation from the other elements of Gondwana, which deeply influenced the climatic variations and the set-up of the antarctic glaciation. Here we focus on the Rennick fault damage area, trying to unveil the phases of re-activation of the major Palaeozoic lithospheric discontinuities and identify the main factors that control the reworking of the existing tectonic lineaments.

For this aim, during fieldwork in 2010-2012-2104 Italian Antarctic Expeditions, we collected more than 1000 structural data in over 50 structural stations.

We performed a multi-scale analysis of the damage zones of the fracture systems along major tectonic discontinuities, with emphasis on the reconstruction of the kinematic history and identification of kinematic indicators, evidence for reactivation and fluid circulation.

We present the preliminary results from our analysis of the mechanical features and the spatial distribution of deformation and its homogeneity along the major discontinuities. We integrate and compare our data with the GPS data (Dubbini et al 2010) and with the fault patterns linked to the present day tectonics proposed in the past literature.

Results allow the preparation of a more constrained structural model for the fault pattern along the Rennick Fault that shows a regional right-lateral trans-tensional kinematics in Cenozoic time.

We propose a more reliable scenario for the tectonic evolution of the major lithospheric discontinuities, active during the Cambrian and later re-activated in the Late Palaeozoic and in the Cenozoic; along some lineaments the activity continues until present, in agreement with GPS data.



**S10 – 323: The Structure and Evolution of the Antarctic Continent in Light of Recent Geophysical and Geological Investigations**

***Tectonic Evolution of the Gondwana Paleo-Pacific Margin: Hints from the Millen Range Structures (Northern Victoria Land)***

Crispini Laura<sup>1</sup>, Federico L.<sup>1</sup>, Capponi G.<sup>1</sup>

DISTAV - University of Genova<sup>1</sup>

Northern Victoria Land (Antarctica) was part of the active proto-Pacific margin of Gondwana, which has been site of protracted convergence during the Palaeozoic.

In northern Victoria Land, the Transantarctic Mountains are characterised by a main phase of amalgamation and docking of the three terranes (Wilson, Bowers and Robertson Bay terranes), usually interpreted as the result of the Ross-Delamerian Orogeny, with an arc/back-arc/trench system that developed during south westward-directed subduction.

This study deals with the structural architecture of the Transantarctic Mountains in northern Victoria Land, with emphasis on the high strain zones at the terranes boundaries and in particular at the boundary between the Bowers and the Robertson Bay Terranes, i.e. the Millen Schist belt. Our aim is to frame such structural features in a geodynamic model of the northern Victoria Land segment of the Ross-Delamerian Orogeny.

We show and discuss the structural data we collected during fieldwork in the 2014/15 Italia Antartide Expedition (PNRA), together with our data from other 7 Italian expeditions, over the years 1988-2006. We performed also structural and kinematic analysis, integrated with petrographic investigations and lithologic observations; the data are discussed in the framework of the geodynamics of the area.

We interpret the Millen Schist belt as a high strain zone presently delimited by two main tectonic lineaments. The structural setting of the area is the result of a complex structural history, deriving from a long-lasting southwest northeast contractional regime, during the Cambrian Ross-Delamerian Orogeny and still active afterwards, at least up to the Ordovician; a Cenozoic tectonic phase reworked the main tectonic lineaments and added complexity.

New unveiled geologic features (structural architecture, type of mineralization, lithology and age of deformation) integrated with well known geological characteristics of the study area supports the correlation of the Bowers and the Robertson Bay terranes with the Stawell Zone of the Lachlan Fold Belt and corroborates the hypothesis of a prolongation into Antarctica of the Lachlan Orogeny of south eastern Australia.



**S10 – 325: The Structure and Evolution of the Antarctic Continent in Light of Recent Geophysical and Geological Investigations**

***VLNDEF: An Integrated Geodetic Project and its Latest Results***

Alessandro Capra<sup>1</sup>; A. Zanutta<sup>2</sup>; M. Negusini<sup>3</sup>; S. Gandolfi<sup>2</sup>; F. Salvini<sup>4</sup>; P. Sterzai<sup>5</sup>; L. Vittuari<sup>2</sup>; P. Cianfarra<sup>4</sup>; M. Dubbini<sup>6</sup>; A. Galeandro<sup>7</sup>

DIEF-University of Modena and Reggio Emilia, Italy<sup>1</sup>; DICAM-UNIBO-Italy<sup>2</sup>; INAF-Italy<sup>3</sup>; DSG-UNIROMA3-Italy<sup>4</sup>; OGS-Italy<sup>5</sup>; DSCC-UNIBO-Italy<sup>6</sup>; DICATEC-POLIBA-Italy<sup>7</sup>

GPS measurements are the core of the Italian geodetic activity in Antarctica. A large network devoted to the detection and monitoring of crustal deformations in the Northern Victoria Land (NVL) was established during 1999-2000 expedition. Nowadays, 28 markers are monumented on rocky outcrops and form the VLNDEF (Victoria Land Network for DEFormation Control) network. VLNDEF extends over 500 km North-South and 300 km East-West, and its markers can be accessed by means of helicopter from MZS or, more conveniently, planning remote camps in the North and or South of NVL.

During 2014/2015 expedition a full repetition of the whole network have been performed, together with a new monumentation of VL27. Three markers were semi-permanent stations, namely VL01, VL05 and VL18. Since the last campaign VL10, together with 2 more VLNDEF markers (VL12 and VL10) host 3 POLENET permanent stations. Since its establishment, VLNDEF has been surveyed more than ten times, of which four are surveys of the whole network.

A permanent GPS station (TNB1) is working since 1998 at the Italian Base, Mario Zucchelli Station, supported by an additional permanent GPS station TNB2 installed in 2008.

The remarkable amount of GPS data collected so far can be used to shed some light on the ongoing crustal deformations, their pattern and the presence of any neo-tectonic activity. We present the results, included the latest measurement campaign, of the network obtained using the Bernese V.5.0 and the GIPSY-OASIS software, adopting a common analysis strategy, models and parameters.

The solutions, expressed into ITRF2008, of the Victoria Land appear to be rather consistent with a general motion toward South-West with mean velocity of 16 mm/a.

Subtracting the estimated absolute plate rotation Pole, we found very small residual horizontal velocities. The tectonic model of active faulting proposed in Dubbini et al (2010) is mostly confirmed by the new results for the period (1998-2012). Although a general decrease of the residual velocities, the relative motions along most of the monitored regional faults can be confirmed.

The vertical velocities of the network, except few VLNDEF sites experiencing subsidence, show a general uplift of few mm/a. These news results, vertical and horizontal velocities, will be used to refine the neo-tectonic model and will be compared with the most up-to-date GIA models.

Other geodetic are performed in MZS and NVL. In 2002 a new activity started, acquiring more than 100 gravity data with the aim to evaluate an high accuracy local geoid for all Northern Victoria Land, in an area located around Mario Zucchelli Station. In 2012 the activity continued including the regions in the northern part of MZS, extending the measurements until the Rennick glacier. In 2014/2015 gravimetric measurements have be performed in order to complete the geoid definition of the whole NVL. The new model will be presented.

In 2006 a tide gauge Aandaraa WRL7 has been installed at a depth of 27 meters under the sea surface overlooking MZS. Local measurements have been performed for the co-location with GPS systems, by



means of GNSS observations. The data are stored into an internal memory module and downloaded every year. Tsoft (Van Camp et al., 2005) and T\_Tide (Pawlowicz et al., 2002) have been used to perform the data analysis and to compute the main tide components.



**S10 – 333: The Structure and Evolution of the Antarctic Continent in Light of Recent Geophysical and Geological Investigations**

***A Paleozoic Intra-Arc / Back Arc Deformation Zone: Structural and Petrographic Evidence from the Lanterman-Mariner Suture, Northern Victoria Land***

Giorgetti Giovanna<sup>1</sup>; Crispini L.<sup>2</sup>; Palmeri R.<sup>3</sup>; Sandroni S.<sup>3</sup>; Capponi G.<sup>2</sup>

DSFTA - University of Siena<sup>1</sup>; DISTAV - University Of Genova<sup>2</sup>; MNA - University Of Siena<sup>3</sup>

In Antarctica, northern Victoria Land is a very suitable area for the study of the Ross Orogeny, as rocks and structures of this belt are well exposed.

In northern Victoria Land, the boundary between the Wilson and the Bowers Terrane is known as the Lanterman-Mariner Suture zone. Such suture is characterised by a complex structural architecture: discontinuous slices of rocks of varied provenance are accreted and amalgamated. They display different metamorphic evolution, from medium-P amphibolite facies to ultrahigh-P eclogite facies, with a late retrograde imprint at the transition amphibolite-greenschist facies. Therefore, the Lanterman-Mariner Suture zone can be considered as a high T tectonic melange, resulting from the accretion of an arc/back-arc system to the palaeo-Pacific continental margin of Gondwana during the Ross Orogeny.

In this work we focus on the Black Spider Greenschist and the Sledger Group (Molar and Glasgow formations), that outcrop along the southern sector of the Lanterman-Mariner Suture zone. We supply new structural data collected during the XIX (2003-04), XXI (2005-06) and XXX (2014-15) Italian Antarctic Expeditions and results from microstructural and petrographic investigations of the sampled rocks.

The metavolcanites and the metasediments sampled along a transect between the medium-P amphibolite facies rocks of the Dessent unit and the very-low grade rocks of the Molar Formation are analysed; the Black Spider Greenschist interposed in between is also studied. From the structural point of view, the Black

Spider Greenschist can be considered as a high strain equivalent of the adjacent Sledger Group, with a more complex polyphase deformation history. Deformation is non-homogeneously distributed throughout the area, and slices of undeformed gabbro and basalt are surrounded by mylonitic zones. Similarly, the metamorphism is heterogeneously distributed with metavolcanics showing both syntectonic albite-chlorite-actinolite-epidote assemblage (greenschist facies) and oligoclase-hornblende assemblage, which are typical of the transition from greenschist to amphibolite facies. The metasediments show the quartz-chlorite-muscovite-Mg-biotite (+ graphite) assemblage, indicating greenschist facies metamorphism with T > 350° C.

Our data contribute to the comprehension of the structural and metamorphic setting of this part of the Palaeo-pacific margin of Gondwana which will lead to a better understanding of the tectonics of the intra-arc/back-arc suture zone.



**S10 – 335: The Structure and Evolution of the Antarctic Continent in Light of Recent Geophysical and Geological Investigations**

***Geodynamic Evolution of Eastern Dronning Maud Land Based on Research Highlights from an International Geological-Geophysical Approach***

Laufer A.<sup>1</sup>; Jacobs J.<sup>2</sup>; Elburg M.<sup>3</sup>; Ruppel A.<sup>1</sup>; Kleinhanns I.<sup>4</sup>; Mieth M.<sup>5</sup>; Jokat W.<sup>5</sup>; Estrada S.<sup>1</sup>; Henjes-Kunst F.<sup>1</sup>; Eagles G.<sup>5</sup>

Federal Institute for Geosciences and Natural Resources (BGR)<sup>1</sup>; Department Of Earth Science, University Of Bergen, Norway<sup>2</sup>; University Of Johannesburg, Department Of Geology, Johannesburg, South Africa<sup>3</sup>; FB Geowissenschaften, University Of Tübingen, Germany<sup>4</sup>; Alfred-Wegener-Institute, Helmholtz Centre For Polar And Marine Research (AWI), Bremerhaven, Germany<sup>5</sup>,

East Antarctica formed by amalgamation of a number of cratons along distinct late Neoproterozoic to early Palaeozoic mobile belts. These include the c. 640-500 Ma old East African-Antarctic Orogen (EAAO) and the Kuunga Orogen, which appear to converge in the region of Dronning Maud Land. In central Dronning Maud Land, the prominent Forster Magnetic Anomaly separates rocks with Grenville-age protolith ages (ca. 1130-1000 Ma) to the West, from rocks with early Neoproterozoic protolith ages (ca. 1000-900 Ma) to the East. The Forster Magnetic Anomaly is therefore interpreted as a suture between these two provinces. New combined geological and geophysical data were obtained from four joint AWI-BGR international expeditions GEA I to IV between 2010 and 2015, which reveal a complex tectonic architecture between central Dronning Maud Land and the Latzow-Holm Bay in eastern Dronning Maud Land. East of the Forster Magnetic Anomaly, the magnetic anomaly pattern changes significantly and typical Maud-type crust is apparently lacking. Particularly, the GEA II campaign targeted a range of previously unvisited nunataks in the largely icecovered region between central Dronning Maud Land and Sr Rondane from Urna and Srsteinen in the West to Blettane and Bergekongen in the East. This region is characterized by a distinct linear magnetic anomaly pattern of general NW-SE trend referred to as the SE Dronning Maud Land Province, which was previously interpreted to represent a potentially older cratonic fragment south of an Ediacaran-Cambrian mobile belt that crops out in Sr Rondane. SHRIMP/SIMS U-Pb zircon ages and geochemical analyses of rock from this region show that it consists of Rayner-age (c. 1000-900 Ma) juvenile arc and metasedimentary cover rocks with intense medium- to high-grade reworking of Pan-African (c. 630-520 Ma) age and abundant felsic melt injections. These juvenile rocks show close similarities to a gabbro-tonalite-trondhjemite-granodiorite (GTTG) complex that forms the southern part of the SW Terrane in Sr Rondane. U-Pb zircon dating indicates crystallization between c. 1000 to 920 Ma of these rocks, and the juvenile character may point to a long-lived accretionary history in the early Neoproterozoic. In contrast to the rocks in the Borchgrevinkisen region, the GTTG complex in Sr Rondane shows evidence of Pan-African up to lower amphibolite-facies thermal overprint but large domains with apparently only weak tectonic overprint except for its northern margin that is affected by dextral high-strain shear of the Main Shear Zone. The age of the Main Shear Zone is estimated to be latest Ediacaran-earliest Cambrian (c. 560-530 Ma). It separates the Rayner-age GTTG complex from a variety of greenschist- to granulite-facies meta-supracrustal rocks of mostly volcano-sedimentary origin, which in turn are separated from the amphibolite- to granulite-facies NE Terrane in the north to north-east by the Main Tectonic Boundary introduced by the Japanese National Antarctic Program. Existing literature and new geochronology data indicate that peak and retrograde metamorphism in the NE and northern SW terrane was between c. 640 and 530 Ma and that all units were affected by different pulses of granitoid magmatism between c. 650 and 500 Ma. These units thus appear to have East African rather than Indo-Antarctica affinities as the GTTG complex south of the Main Shear Zone and the similar rocks of the nunataks cropping out in the SE Dronning Maud Land Province to the west. Furthermore, grey heterogeneous gneisses and augen-gneisses of the aforementioned meta-volcanosedimentary rocks of the SW Terrane close to the Main Shear Zone gave zircon crystallization ages of c. 750 Ma. Such ages are unknown from the EAAO in central and western Dronning Maud Land west of the Forster Magnetic Anomaly. Taking all evidence together, we propose that the Forster Magnetic Anomaly separates distinctly different parts of the EAAO. These are (i) a reworked, mainly Grenville-age crust to the west



representing the overprinted margin of the Kalahari Craton, and (ii) a part of the orogen dominated by Neoproterozoic accretionary tectonics to the east. This difference is also reflected in the geochemistry of voluminous late-tectonics granitoids across the whole belt.



**S10 – 350: The Structure and Evolution of the Antarctic Continent in Light of Recent Geophysical and Geological Investigations**

***New Russian Aerogeophysical Data Revealed Further Evidences of Riftogenic Crust in Eastern Princess Elizabeth Land, East Antarctica***

Alexander Golynsky<sup>1</sup>; Dmitry Golynsky<sup>1</sup>; Alexander Kiselev<sup>2</sup>

VNIIOkeangeologia, St. Petersburg, Russia<sup>1</sup>; PMGE<sup>2</sup>

Analysis of radio-echosounding and RADARSAT mosaic data (Golynsky & Golynsky, 2007) reveals at least 500 km long structure called the Gaussberg rift over the eastern part of Princess Elizabeth Land, East Antarctica. This previously unknown curvilinear structure consists of two sub-parallel depressions separated by segmented horst-like escarpments that are largely hidden under the East Antarctic Ice Sheet. One of these segments is Mount Brown escarpment, which reaches a height of 1982 m above sea level. It was suggested that this rift was probably initiated at the same time as the Lambert graben, marked by the deposition of coal-bearing Permian sediments and probably inherited the tectonically weak zone of the Proterozoic igneous belt along its boundary with the Vestfold-Rauer Archean cratonic block. Apparently, the Gaussberg rift may be considered as a hypothetical accommodation zone of the Carboniferous-Permian intracontinental rift along 4000 km of the West Australian and East Indian margins, which filled with thick Permian-Triassic sediment including alluvial coals (Harrowfield et al., 2005). It was inferred that the Gaussberg rift corresponds to the Mahanadi Valley of East India and the Lambert rift system has across-rift alignment with Godavari Valley.

New Russian ice penetrating radar data collected by the Polar Marine Geosurvey Expedition during 2012-14 field seasons in eastern Princess Elizabeth Land over the south-western part of the suggested rift shows that in places the floor of the central depression placed more than 1000 m below sea level. Horsts and grabens are heavily dissected by N-S and NW-SE running transverse lineaments that in addition were clearly discernible by analysis of ice surface satellite imagery. There is profound correlation between lineaments or faults determined by two independent methods.

New high-quality aeromagnetic anomaly data show that outstanding changes of the magnetic anomaly fabric observed in vicinity, along strike and over shoulders of the inferred Gaussberg rift are thought to have the tectonic origin. Abrupt disappearance of the longwavelength high-intensity magnetic anomaly belt with a number of shortwavelength anomalies associated with eastern boundary of the Vestfold-Rauer cratonic block in vicinity of western depression can't be explained by subglacial erosion. In our interpretation, these changes of magnetic anomaly pattern apparently associated with development of regional fault zones during initial stages of rifting.

The Mount Brown horst is clearly evident in magnetic anomaly data as an area of concentration of high-intensity anomalies with amplitude up to 1575 nT and with N-S and NW-SE trends. The observed trends are in agreement with the strike of the metamorphic rocks in Mount Brown, which experienced c. 980-920 Ma high-grade metamorphism (Mikhalsky et al., 2015). This suggests that this area experienced the Rayner Orogeny, distinguished in Kemp Land and the northern Prince Charles Mountains and area may represent suspect suture of the Mesoproterozoic age, as evidenced by new date for Mount Brown mafic rocks at c. 1480 Ma.

Linear short-wavelength anomalies (5-7 km) of low amplitude developed over horsts and grabens are interpreted to be responsible for the Pan-African megascale shear zone system of Princess Elizabeth Land (Golynsky et al., 2015, this volume). The distinguished length of this curvilinear feature exceeds 900 km, while it might be extended up to the Leopold and Astrid Coast, where similar linear anomaly with NE-SW trend was determined by historical aeromagnetic data collected by Russian researches in 1956 (Golynsky et al., 2001). The discovered early Paleozoic shear zone with NE-SW trend is collinear with



orientation of the Gaussberg rift thereby contradicts to the idea that ca 500 Ma event is concentrated along coastal regions and attenuated inland (Mikhalsky et al., 2015). This idea based on extensive indications of a ca 500 Ma event in coastal areas (granitoid intrusions in Mirny Oasis and inherited zircons found in Gaussberg volcano), together with the lack of indications of this age in Mount Brown.

The mega-scale Princess Elizabeth Land shear zone has fundamental implications in terms of tectonic inheritance and intraplate strain localization for later reactivation linked to development of the Lambert and Gaussberg rifts and rifting and intraplate strike-slip motion in interior of East Antarctica (EARS, Ferraccioli et al., 2011) before and during Gondwana break-up. Depth-estimates of magnetic anomaly sources indicate that the central depression of the rift is likely underlain by a 3-5 km thick sedimentary basin, thereby supporting our idea of existence of riftogenic structure in the eastern part of Princess Elizabeth Land. Crustal two-dimensional modelling by using gravity profile collected within the IceBridge Project (Blankenship et al., 2014) also shows over 4 km deep sedimentary basins beneath central depression of the rift. Future geophysical investigations allow to better understand the crustal architecture of the East Antarctic shield, geology and geodynamics of rifting in an ice-covered environment.



## S10 – 351: The Structure and Evolution of the Antarctic Continent in Light of Recent Geophysical and Geological Investigations

### *Mega-Scale Princess Elizabeth Land Shear Zone Linked to Gondwana Supercontinent Assembly*

Alexander Golynsky<sup>1</sup>, Dmitry Golynsky<sup>1</sup>, Alexander Kiselev<sup>2</sup>, Fausto Ferraccioli<sup>3</sup>

VNIIOkeangeologia, St. Petersburg, Russia<sup>1</sup>; PMGE<sup>2</sup>; British Antarctic Survey, United Kingdom<sup>3</sup>

Evidence of the early Palaeozoic tectonism along the Prydz Bay coast is highly variable in scale and is preserved as discrete east-west trending zones of high-strain at the Brattstrand Bluffs, Larsemann Hills and in the Bolingen Islands and pegmatite emplacement, or as a pervasive early Palaeozoic granulite facies tectonism (~550-465 Ma). SHRIMP U-Pb zircon isotopic data indicate an emplacement age of c. 514.3±6.7 Ma for the Progress Granite that occupies a high-strain zone with dextral movement sense and is located in the Larsemann Hills. Emplacement of this granite was synchronous with a transpressional event and pre-dates an extensional collapse event, confirming the presence of a major high-grade tectonothermal episode in this region during the Early Palaeozoic. Other granitic plutons (Dalkoy, Munro Kerr and Amanda Bay granites) from the Prydz Bay coast were dated at 519±2 Ma, 497±2 Ma and 498±7 Ma, respectively (Li et al., 2007). All granitoids are in accord with A-type granites. This suggests that magmatism in Prydz Bay is probably related to the post-collisional orogeny, including lithospheric thinning, magmatic underplating and crustal relaxation. In the Rauer Group the extent and nature of the early Palaeozoic tectonism is controversial; it contains reworked Archaean- Proterozoic crust in high strain zones that formed during a pervasive high-temperature ductile deformation event related to intracratonic mechanisms (Dirks & Wilson, 1995). The effects of this event extend southwards from Prydz Bay into the southern Prince Charles Mountains. The associated structural evolution involved development of brittle and ductile structures that formed during transpressional deformation event that is confined to high-grade shear zones in the Rauer Group. Thermal histories derived from hornblende, biotite and feldspar suggest that the onset of rapid cooling began prior to 510 Ma with cooling rates of c. 42 to 33°C myr<sup>-1</sup> from c. 510 Ma to c. 500 Ma. 40Ar/39Ar data obtained from plagioclase and K feldspar suggest a slower cooling from c. 500 Ma to c. 460 Ma with cooling rates from 5 to 2°C myr<sup>-1</sup>. Episodic reactivation of the shear system continued in response to the evolving proto-Pacific margin from 530-420 Ma (Wilson et al., 2007). These results demonstrate that the early Palaeozoic cooling history and comparable palaeostress regimes are regionally extensive, although was not focused along specific linear structures but deformed the crust pervasively over large areas and produced multiple fold generations (Boger & Wilson, 2005). Aeromagnetic data should provide the best constraints on the location of Antarctic orogenic belts and fault systems under the ice-cover. For instance, Wilson et al. (2007) assumed that the Prydz Bay shear system correlates with the Amery Lineament (Golynsky et al., 2002), an east-west trending linear magnetic anomaly that running southward of the Prydz Bay coast, then continuation of the overall shear zone system can be implied over a distance of c. 1000 km on an east-west trajectory. However, recent Russian aeromagnetic data together with previous survey data allowed determining a spectacular curvilinear system of low amplitude short-wavelength magnetic anomalies (5-7 km) that interpreted to be responsible for the overall shear zone system of Princess Elizabeth Land. It displays two NE-SW trending constituents that correspond to the eastern shoulder of the Amery Ice Shelf and a territory located westward of Mount Brown and joining them system running W-S over a distance c. 450 km. The observed structural pattern of magnetic anomalies shows a typical expression of mega-scale shear zones with dextral movement sense. The mapped length of this feature exceeds 900 km, while it might be continued up to the coast.

The tectonic relationships between the Princess Elizabeth Land shear zone and the recently proposed Indo-Australo-Antarctic Suture (Aiken et al., 2014) and the Gamburtsev Suture (Ferraccioli et al., 2011) are unclear but there may well be tectonic linkages. Although we currently lack the aeromagnetic data coverage required to demonstrate such tectonic linkages with either features this remains a viable hypothesis. It has some mileage based on analysis of ice surface satellite imagery, particularly over the



GSM region but could be tested in the future by new aeromagnetic surveys over the interior. Traditionally the Prydz Bay region is considered as a complex transpression zone, involving a significant component of transcurrent flow where recorded pressures (6-11 kbar, Kelsey et al., 2003) suggest that overly thickened continental crust during high temperature metamorphism is not required. The following cooling event implies that post-orogenic collapse was a significant component during the late stage movement on the discovered megascale shear zone of Prince Elizabeth Land. This major fault system holds tantalizing new clues towards understanding the early Palaeozoic cooling history and comparable palaeostress regimes, which has important implications for the tectonothermal and stress-field variability across Gondwana. The elevated thermal conditions would induce lithospheric weakening and promote the early Palaeozoic intraplate orogeny with the development of a large intracratonic shear system, which are a response to distal plate boundary forces and plate reorientation on the proto-Pacific margin (Wilson et al., 2007).

Undoubtedly, it has fundamental implications for understanding the setting for some of the reworking segments of Grenvillian and older crust and in terms of tectonic inheritance and intraplate strain localization for later reactivation linked to the Lambert rift system and the proposed Gaussberg rift (Golynsky & Golynsky, 2007) and rifting and intraplate strike-slip motion in interior of East Antarctica (EARS, Ferraccioli et al., 2011) before and perhaps even during and after Gondwana break-up. It effectively may have affected how this part of East Antarctica heralded and subsequently responded to Gondwana break-up. In a broader sense, this newly inferred megascale shear zone shows remarkable similarities with those formed in complex modern collisional systems.

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**S10 – 402: The Structure and Evolution of the Antarctic Continent in Light of Recent Geophysical and Geological Investigations**

**ADMAP-2: A New International Magnetic Anomaly Compilation Project to Aid Antarctic Geosciences**

Alexander Golynsky<sup>1</sup>; Fausto Ferraccioli<sup>2</sup>; T.A. Jordan<sup>2</sup>; Detlef Damaske<sup>3</sup>; Don Blankenship<sup>4</sup>; J. Holt<sup>4</sup>; D.A. Young<sup>4</sup>; Sergey Ivanov<sup>5</sup>; A.V. Kiselev<sup>5</sup>; V.N. Masolov<sup>5</sup>; Jokat Wilfried<sup>6</sup>; M. Mieth<sup>6</sup>; K. Gohl<sup>6</sup>; G. Eagles<sup>6</sup>; Robin Bell<sup>7</sup>; Dmitry Golynsky<sup>1</sup>; Egidio Armadillo<sup>8</sup>; E. Bozzo<sup>8</sup>; G. Caneva<sup>8</sup>; Rene Forsberg<sup>9</sup>; Alan Aitken<sup>10</sup>; Carol Finn<sup>11</sup>; Yoshifumi Nogi<sup>12</sup>; Marta Ghidella<sup>13</sup>; Ralph von Frese<sup>14</sup>; Hyung Rae Kim<sup>15</sup>; Jongkuk Hong<sup>16</sup>

VNIIOkeangeologia, St.-Petersburg, Russia<sup>1</sup>; British Antarctic Survey, Cambridge, UK<sup>2</sup>; Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover, Germany<sup>3</sup>; University of Texas Institute For Geophysics, Austin, TX, USA<sup>4</sup>; Polar Marine Geosurvey Expedition, Lomonosov, Russia<sup>5</sup>; Alfred Wegener Institute, Bremerhaven, Germany<sup>6</sup>; LDEO, Columbia University, Palisades, New York, USA<sup>7</sup>; Università di Genova, Genova, Italy<sup>8</sup>; Technical University of Denmark, Copenhagen, Denmark<sup>9</sup>; University of Western Australia, Perth, Australia<sup>10</sup>; USGS, Denver Federal Center, Denver, USA<sup>11</sup>; National Institute of Polar Research, Tokyo, Japan<sup>12</sup>; Instituto Antártico Argentino, Buenos Aires, Argentina<sup>13</sup>; Ohio State University, Columbus, USA<sup>14</sup>; Kongju National University, Gongju, South Korea<sup>15</sup>; Korea Polar Research Institute, Incheon, South Korea<sup>16</sup>

The Antarctic Digital Magnetic Anomaly Project completed the first international magnetic anomaly compilation of the Antarctic region south of 60°S (ADMAP-1) some six years after its launch (Golynsky et al., 2001). This magnetic anomaly compilation provided tantalizing new insights into the structure and evolution of Antarctica, including its Proterozoic-Archaean cratons, Proterozoic-Palaeozoic orogens, Palaeozoic-Cenozoic magmatic arc systems, continental rift systems and rifted margins, large igneous provinces and the surrounding oceanic gateways. The ADMAP-1 database was produced from air, ship borne and satellite magnetic observations by the international ADMAP working group. More than 1.5 million line-kilometres of near surface magnetic recordings were used in the construction of the map. The compilation merged available magnetic survey data collected by the international community from the IGY 1957-58 to 1999.

Since the production of this first Antarctic magnetic anomaly map, the international geomagnetic community has been extremely active, and acquired more than 1.9 million line-km of new air- and shipborne data. This implies that the amount of magnetic anomaly data over the Antarctic continent has more than doubled. In particular, the increased international dimension of magnetic surveying has enabled several major largely unexplored Antarctic frontiers to be investigated, such as the enigmatic Gamburtsev Sub-glacial Mountains (Ferraccioli et al., 2011), Wilkes Land (Aitken et al., 2014), which is one of the least understood geological regions on Earth, largely unexplored sectors of the Wilkes Sub-glacial Basin (Ferraccioli et al., 2009) and Dronning Maud Land (Mieth & Jokat, 2014) and many others. The more than 350,000 line-km of new airborne and marine magnetic observations for the East Antarctic continental margin lead to essential improvements in definition of magnetic anomaly patterns compared to the first ADMAP compilation (Golynsky et al., 2013).

To initiate the production of the next generation magnetic anomaly map and database for the Antarctic south of 60°S, an international ADMAP-2 steering committee was formed, which met at the Korean Polar Research Institute (KOPRI) in August 2013. Here, we review the status of the new ADMAP-2 project compilation with the broader community involved in Antarctic geomagnetic studies. Specific issues that will be considered include: identifying high-priority regional compilations for which datasets are currently available; engaging with international stakeholders and data owners who have yet to release their data; re-assessing the roadmap, milestones, timelines and products to be delivered by ADMAP-2; reviewing planned data processing techniques; expanding the geological utility of Antarctic magnetic



surveys; interfacing with the next generation World Digital Magnetic Anomaly Map; promoting new international magnetic anomaly surveys; and strengthening interdisciplinary links with other Antarctic geosciences communities.

In general, the creditability of any magnetic anomaly compilation depends on characterizing the input data and procedures used for their processing. The processing of recently acquired data was achieved in several consistent steps and all new surveys data were re-examined and their quality assessed by careful statistical analysis of the crossover errors. Most magnetic data used in the present compilation were delivered as profiles, although several of them in raw form, even though the data holders had already cleaned, corrected and leveled the data for other uses. Some datasets come decimated or upward continued form to altitudes of 4 km or higher, thus smoothing out high frequency signals that are however important for subsequent geological interpretation. Accordingly, sets of line data used for ADMAP-1 compilation must be reprocessed for a number of obviously erroneous values and residual corrugations. The new near-surface magnetic data were corrected for the international geomagnetic reference field and diurnal effects, edited for high-frequency errors and leveled to minimize line-correlated noise.

It was obvious that magnetic anomaly data collected mainly in the 21-st century cannot be simply stitched together with previous surveys. Overlapping surveys required mutual levelling adjustments and these procedures were treated individually. The final compilation merged all the available aeromagnetic and marine grids to create the new composite grid of Antarctica with minimal mismatch between the datasets along their boundaries. The adjusted magnetic data were interpolated onto a 5 km grid using a minimum curvature algorithm. Regional coverage gaps in the composite grid will be filled with anomaly estimates constrained by both the near-surface data and satellite magnetic observations taken mainly from the CHAMP and Swarm missions.

The preliminary version of the ADMAP-2 map provides a new geophysical foundation to develop a better understanding of the geological structure and tectonic history of the Antarctic continent. In particular, it will enable improved interpretation and modeling efforts of the geodynamic evolution of the Antarctic lithosphere that was a key component in the assembly and break-up of both the Rodinia and Gondwana supercontinents. Improved views of the nature of the transition from the Antarctic continental lithosphere to its oceanic basins will also derive from the ADMAP-2 compilation. Our current aim is to release the final version of this map and digital databases by the SCAR meeting in 2016.

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**S10 – 407: The Structure and Evolution of the Antarctic Continent in Light of Recent Geophysical and Geological Investigations**

***Terrane Spotting in East Antarctica: Where is the Kuunga Suture?***

Ian Fitzsimons<sup>1</sup>; Reichelt, L.S.<sup>1</sup>; Kirkland, C.L.<sup>1</sup>; Taylor, R.J.M.<sup>1</sup>

Curtin University, Perth, Australia<sup>1</sup>

The Prince Charles Mountains are the only significant rock outcrop in the interior of East Antarctica, making them critical in attempts to ground-truth geophysical data and infer sub-glacial geology. Reconnaissance geochronology has identified three terranes in the Prince Charles Mountains: the Beaver Terrane in the north with dominant magmatism and metamorphism at 1000-900 Ma, the Ruker Terrane in the south with major periods of magmatism and metamorphism at c. 3100 and 2700 Ma, and the Lambert Terrane sandwiched between them with dominant magmatism and metamorphism at c. 2400 and 2100 Ma. Detailed studies of these rocks have been focused on the Mawson Escarpment at the eastern edge of the mountains, where more than 100 km of semi-continuous outcrop provides a north-south cross section through all three terranes allowing the relationships between them to be tightly constrained. Importantly the Lambert Terrane in this area records metamorphism at 1000-900 Ma indicating a link with the Beaver Terrane to the north, while there is no evidence of this metamorphic event in the southernmost Ruker Terrane. The boundary between the Ruker and Lambert terranes is well exposed in the Mawson Escarpment as a high-strain zone recording metamorphism at deformation at c. 500 Ma. This structure has been interpreted as a continent scale Cambrian collision zone that extends east-west across Antarctica for more than 3000 km from the Mawson Escarpment to a similar aged terrane boundary in the Shackleton Range of Coats Land. It is widely referred to as the Kuunga Suture and appears on many recent reconstructions of Antarctica, but despite its adoption by the broader geological community no conclusive geological or geophysical evidence for this suture has ever been reported other than in the Mawson Escarpment and Shackleton Range. There are, however, a number of small outcrops immediately west of the Mawson Escarpment that lie in the path of this inferred suture zone, and we have undertaken a SHRIMP U/Pb zircon study of key samples from these outcrops to test this model. Two samples of garnet-biotite-quartz gneiss contain detrital zircon grains with identical age populations at c. 3100, 2700, 2500, 2300, and 2100 Ma. These ages correlate closely with basement rocks in the Ruker and Lambert terranes, suggesting the protolith was eroded from both these terranes sometime after they had amalgamated. Garnet amphibolite interleaved with the felsic gneiss contains un-zoned, low-uranium zircon grains with a concordia age of  $962 \pm 8$  Ma. This age is interpreted as the age of amphibolite metamorphism in the region, and is consistent with a concordia age of  $969 \pm 5$  Ma for high uranium magmatic zircon from an undeformed pegmatite. Our data suggest that these rocks are part of the 1000-900 Ma Beaver Terrane. None of the samples record any event younger than 960 Ma, challenging the widely held view that a Cambrian suture passes east-west through the Prince Charles Mountains. While there is good palaeomagnetic evidence for a Cambrian plate boundary extending into the Indian Ocean sector of East Antarctica and several suggestions have been made for where this suture might be located, these suggestions will remain speculative until they are corroborated by conclusive geological evidence from multiple outcrops that can be linked by geophysical data.



**S10 – 414: The Structure and Evolution of the Antarctic Continent in Light of Recent Geophysical and Geological Investigations**

***Distribution of Sediments within the Wilkes Subglacial Sedimentary Basin, East Antarctica***

Bruce Frederick<sup>1</sup>; Duncan Young<sup>1</sup>; Jamin Greenbaum<sup>1</sup>; Tom Richter<sup>1</sup>; Fausto Ferraccioli<sup>2</sup>; Don Blankenship<sup>1</sup>

UTIG<sup>1</sup>; British Antarctic Survey, United Kingdom<sup>2</sup>

Topography, sediment distribution and heat flux are all key boundary conditions governing the dynamics of the East Antarctic ice sheet (EAIS). EAIS stability is most at risk in Wilkes Land across the 1400 km x 600 km marine-based catchment of the Wilkes Subglacial Basin (WSB). Numerical models of ice sheet evolution over the WSB will require accurate deformable sediment distribution and lithologic character constraints to estimate overall flow velocities and evaluate potential instabilities.

To facilitate this goal, we provide the first detailed subglacial sedimentary basin model for the WSB representing a composite of aerogeophysical datasets compiled from contemporary and historical surveys including the University of Texas Institute for Geophysics (UTIG) ICECAP (Investigating the Cryospheric Evolution of the Central Antarctic Plate) and WLK (Wilkes Land Transect) campaigns from field seasons spanning 1999-2013 as well as the WISEISODYN (Wilkes basin/transantarctic mountains System Exploration-Ice-house Earth: Stability or DYNamism?) campaign undertaken by the British Antarctic Survey. Leveraging airborne ice penetrating radar, magnetics, and gravity data, a 3D structural model of the entire WSB basin was constructed to enable implementation of forward and inverse gravity data processing methods along 2D flight transects to evaluate sedimentary basin thickness. Vertical basin constraints were established with resultant 2D magnetic depth to basement (DTB) and free-air gravity spectral analyses with horizontal basin constraints being provided by magnetic and gravitational response. Subglacial sedimentary basin detection and characterization was also complimented through an assessment of topographic roughness defined by root mean squared (RMS) height deviation over correlation length.

The new WSB composite bedrock topographic map identifies a series of sub-basins, including the eastern, central and western sub-basins in the Northern WSB first identified by Ferraccioli et al (2009), which appear to coalesce and extend deep into the interior reaches of the Southern WSB maintaining bed elevations between -1700 m to -1100 m below mean sea level (msl). Evaluation of gravitational isostatic residual anomalies, with adjustments for glacial and subglacial topography and depression of the Moho due to ice sheet and crustal loads, suggest mass deficiencies in the interior Southern WSB model on the order of > -150 mGals. Power spectrum analyses confirmed no apparent mid-crust discontinuity with Moho depths shoaling from approximately 1 km to 20 km South to North, respectively. These results provide further confirmation of Bouguer gravity anomalies identifying thinning lithosphere toward the George V Coast and the western bounding Mertz Shear Zone (MSZ) fault. Werner deconvolution of magnetic line data leveraged the consistent sampling and high data density characteristic of the 2D flight lines, to confirm estimated sedimentary basin thicknesses generally ranging from 1.1 km to 5.4 km across the Northern and Southern WSB. Subglacial bed surface roughness quantifiably constrained horizontal sediment distribution with RMS height deviations below 10 m over an 800 m correlation length. Subsequent iterative 2D forward modeling of freeair gravity data using a coincident Airy 3D lithospheric structure model revealed sedimentary basin isopachs for the WSB largely confined to isolated basins ranging from 1 km to as much as 6 km thick deposits.

In summary, based on the first comprehensive subglacial sedimentary basin models for the WSB, we hypothesize that the most significant sedimentary deposits are confined to finite subbasins within the Northern and Southern WSB that are characterized by low topographic bed elevations, low bed roughness, and characteristically negative isostatic residual anomalies. These sedimentary basin findings



are supported by prior, historical aerogeophysical transects made across portions of the WSB including Drewry (1976), Steed and Drewry (1982), and Ferraccioli et al (2001). We further suggest that the character and distribution of these interior WSB sediments are potentially the result of a combination of polythermal alpine regime configurations in the early Miocene followed by a more dynamic Pliocene/Pleistocene EAIS than historically proposed. These WSB sediment distribution models support more recent climate simulations and marine geologic data implying a Wilkes Land Pliocene ice cap more vulnerable to climate forcing than historically suggested (Pollard et al., 2015; Mengel and Levermann, 2014; Cook et al, 2013).



**S10 – 422: The Structure and Evolution of the Antarctic Continent in Light of Recent Geophysical and Geological Investigations**

***Lithospheric Structures and Deformation of Antarctica based on Satellite Geodesy***

Ravikumar Muppidi<sup>1</sup>; C.D.Reddy<sup>1</sup>

Indian Institute of Geomagnetism, Navi Mumbai, India<sup>1</sup>

Geological and tectonic fabric of Antarctica have a large attraction and challenge due to ice cover and its geodynamic importance in the Gondwana break up. Numerous expeditions are taken up to understand the geology of underlying the ice sheet of Antarctica. Geophysical studies gave a clear picture about the tectonic features and the geodynamic evolution of Antarctica continent. Nevertheless, many intricacies pertaining to structural variations and glacial isostatic adjustments (GIA) remain enigmatic. Gravity, magnetic and GPS studies have been useful to find out the structural features, plate motions and crustal deformation of the continent.

Investing the crust and lithosphere - Asthenosphere boundary of Antarctica and the adjacent regions is essential in delineation of geological structures and unravelling the intriguing nature of geodynamical processes taking place in this region. In present effort, we mainly focus on understanding the subsurface structure and isostatic behaviour over the Antarctica. A large volume of new data has been analyzed mostly from seismic experiments, as well as receiver functions and geophysical studies. In general, the oldest Achaean and Proterozoic crust of East Antarctica has a thickness of 45 km (i.e. thick crustal root beneath the Trans Antarctic Mountains), where as the youngest rifted continental crust of the West Antarctic Rift System has a thickness of 25 km. Structural variability is reflected both in thickness and physical properties of the crust. In this paper, on one hand, we attempt addressing the crustal and Lithospheric structure over Antarctica using recent satellite global gravity models, on the other hand investigate the geodynamics processes from GPS derived velocity and GRACE models.



**S10 – 424: The Structure and Evolution of the Antarctic Continent in Light of Recent Geophysical and Geological Investigations**

***Near-Surface Magnetic Anomaly Estimates in Coverage Gaps of the Admap-2 Compilation***

Hyung Rae Kim<sup>1</sup>; Golynsky, D.<sup>2</sup>; Hong, J. K.<sup>3</sup>; Golynsky, A.<sup>2</sup>; Von Frese, R.<sup>4</sup>

Kongju National Univ, Gongju, South Korea<sup>1</sup>; VNIIOkeangeologia<sup>2</sup>; KOPRI<sup>3</sup>; The OSU<sup>4</sup>

Roughly 2 million line-km of new near surface (i.e., airborne and marine) magnetic survey data, as well as enhanced satellite magnetic gradient observations from the Swarm mission, are being incorporated with about 1.5 million line-km of previously compiled near-surface survey data for the Antarctic region south of 60°S. This next generation magnetic anomaly map, ADMAP-2, will permit quantitative high-resolution modelling of crustal magnetic anomalies and their related components anywhere from the earth's surface to satellite altitudes, and thus greatly enhance the utility of ADMAP's database for Antarctic crustal studies. To help fill in near-surface survey coverage gaps of the previous ADMAP-1 compilation, crustal magnetic models were developed that honoured available near-surface and Orsted and Champ satellite magnetic observations. As some of these older coverage gaps in marine areas and East Antarctica persist in the new compilation, this study tests the geological utility of the initial gap predictions in the context of the new near-surface surveys and the Swarm data. Ultimately, however, there is no substitute to mapping for filling in the coverage gaps because magnetic anomaly predictions are not unique.



**S10 – 445: The Structure and Evolution of the Antarctic Continent in Light of Recent Geophysical and Geological Investigations**

***The Characteristics of Gravity Anomalies and Structural Analysis of Prydz Bay, East Antarctica***

Chenguang Liu<sup>1</sup>; Pei Yanliang<sup>1</sup>; Zheng Yanpeng<sup>1</sup>; Kan Guangming<sup>1</sup>; Han Guozhong<sup>1</sup>

First Institute of Oceanography, SOA, Qingdao, P.R. China<sup>1</sup>

From 2011 to 2015, over 20000 km gravity data have been collected by R/V Xuelong around Prydz Bay, East Antarctica, and also 5 sites of ocean bottom seismometer (OBS) have been recovered successfully. This work was funded by State Oceanic Administration, P.R. China (project CHINARE-01-03, CHINARE-04-01 and CHINARE-04-02). The primary free air gravity anomaly and Bouguer gravity anomaly maps, as well as some geophysical comprehensive interpreting maps are compiled, and the geological significances are discussed, based on the OBS data which recorded more than 2500 earthquake events.



**S10 – 458: The Structure and Evolution of the Antarctic Continent in Light of Recent Geophysical and Geological Investigations**

***Uplift Patterns, Crustal Structure and Ice Mass Variations in the Weddell Embayment, Antarctica***

Saddler, D.M.<sup>1</sup>; Wilson, T.J.<sup>1</sup>; Bevis, M.<sup>1</sup>; Dalziel, I.<sup>2</sup>; Ferraccioli, F.<sup>3</sup>; Jordan, T.<sup>3</sup>; Von Frese, R.<sup>1</sup>; Aster, R.<sup>4</sup>; Chaput J.<sup>5</sup>; Wiens, D.<sup>6</sup>

Ohio State University, OH, USA<sup>1</sup>; Institute for Geophysics, University of Texas, TX, USA<sup>2</sup>; British Antarctic Survey, Cambridge, UK<sup>3</sup>; Colorado State, University, CO, USA<sup>4</sup>; Joseph Fourier University, Grenoble, FR<sup>5</sup>; Washington University, MO, USA<sup>6</sup>

Airborne geophysical data have better defined the crustal structure of the Weddell Embayment region, allowing interpretation of the inland extent of the Weddell Sea Rift associated with early Gondwana breakup and a previously unknown left-lateral shear zone, the Pagano Shear Zone, between the East Antarctic craton and the Ellsworth-Whitmore Mountains block of West Antarctica. Seismology results document changes in crustal thickness and a transition from relatively stiff East Antarctic to weak West Antarctic mantle properties. Superposed on this solid earth template is a complex set of modern ice streams that provide an outlet for roughly one fifth of Antarctica continental ice volume, draining the East Antarctic Ice Sheet, the West Antarctic Ice Sheet and the Antarctic Peninsula Ice Sheet. Recent work has demonstrated that the ice sheet in the Weddell Embayment region was thinner than previously suggested at the Last Glacial Maximum and that deglaciation history may have been complex in the Holocene. A relatively dense network of GPS stations is providing vertical and horizontal crustal motion data across the Weddell region. Crustal motion patterns diverge significantly from predictions from GIA modeling. Here we compare the GPS-derived crustal motions with the geophysically-defined structure to better understand how GIA may be influenced by lateral variations in earth properties.



**S10 – 461: The Structure and Evolution of the Antarctic Continent in Light of Recent Geophysical and Geological Investigations**

***Micro-Continents Offshore Western Australia: Insights into the Make-Up and Break-Up of East Gondwana***

Jacqueline A Halpin<sup>1</sup>; Daczko, Nathan R.<sup>2</sup>; Whittaker, Joanne M.<sup>3</sup>; Williams, Simon E.<sup>4</sup>; Gardner, Robyn L.<sup>2</sup>; Kobler, Madeline E.<sup>2</sup>; Quilty, Patrick G<sup>5</sup>

University of Tasmania, Australia<sup>1</sup>; Department of Earth and Planetary Sciences, Macquarie University, Sydney NSW, Australia<sup>2</sup>; Institute for Marine and Antarctic Studies, University of Tasmania, Hobart TAS, Australia<sup>3</sup>; Earthbyte Group, School of Geosciences, University of Sydney, Sydney NSW, Australia<sup>4</sup>; CODES/Earth Sciences, School Of Physical Sciences, University Of Tasmania, Hobart TAS, Australia<sup>5</sup>

The seafloor offshore Western Australia records the spreading history between Greater India and Australia Antarctica during the Cretaceous breakup of East Gondwana. During 2011, we retrieved the first dredge samples from prominent bathymetric highs, Gulden Draak and Batavia knolls two submarine plateaux that lie > 1000 km west of the Perth Basin, at the boundary between the Perth Abyssal Plain and Wharton Basin, Indian Ocean. We recovered continental rocks from the steep western slopes that rise more than 3000m above the surrounding seafloor including granite, gneiss, schist and sandstone. Isotopic analysis of zircon and palaeontology has constrained the age and affinity of basement and sedimentary rocks, confirming that these knolls are micro-continents rifted from the Indian plate during the Mesozoic breakup of East Gondwana.

Gulden Draak Knoll comprises a high-grade basement complex, including pelitic paragneiss (deposited < 1.1 Ga) and mafic orthogneiss (emplaced > 600 Ma) intruded by Cambrian granite (~540 Ma). Boulders and cobbles of felsic orthogneiss with Archean (~2.85 Ga), Mesoproterozoic (~1.3-1.2 Ga) and Cambrian (~530-510 Ma) zircon ages were likely locally sourced. Sampled basement from Batavia Knoll comprises granite and felsic orthogneiss emplaced at ~540-530 Ma. Dating of metamorphic zircon constrains the timing of granulite facies metamorphism to ~530-510 Ma. Fossil assemblages and detrital zircon ages constrain sampled sandstones to the late Early Cretaceous (Albian). The newly discovered micro-continents represent the Indian conjugate to both the Antarctic Wilkes-Queen Mary Land margin, and the Australian Naturaliste Plateau.

Our new data provide important constraints on the pre-rift configuration of East Gondwana. Incorporation of the newly discovered micro-continents in a Leeuwin full-fit model satisfies key geological and geophysical constraints. Onshore in East Antarctica, rare geological outcrops recording latest Neoproterozoic to Cambrian-aged magmatism and metamorphism in this sector have been interpreted to represent part of a Pan-African-aged orogenic belt. The path of this belt into the Antarctic interior as well as the tectonic context is controversial, but the prevailing model is that a Gondwana-forming collision zone between blocks of broadly Indo-Antarctic and Australo-Antarctic affinity. There is strong evidence for Cambrian metamorphism and magmatism in the dredge samples from the knolls. However, our isotopic data do not easily fit within a convergent plate boundary model, as clear evidence of Cambrian subduction and arc magmatism during ocean closure is lacking. Instead we explore alternative models whereby the Gulden Draak and Batavia basement rocks were located at a transpressive plate margin or major shear zone at ~540-510 Ma. Exhumation some 350-400 Myrs later occurred near the nexus of East Gondwanan Mesozoic breakup, with final rifting from India at ~102 Ma.



**S10 – 486: The Structure and Evolution of the Antarctic Continent in Light of Recent Geophysical and Geological Investigations**

***Recent and Active Deformation in Elephant Island Area Related to the Scotia-Antarctic-South Shetlands Block Triple Junction: Onshore-Offshore Data Integration***

Galindo-Zaldivar, J.<sup>1</sup>, Bohoyo, F.<sup>2</sup>, Maestro, A.<sup>2</sup>, Lopez-Martinez, J.<sup>3</sup>, Mink, S.<sup>2</sup>, Trouw, R.<sup>4</sup>, Gamboa, L.<sup>5</sup>

IACT, CSIC - Universidad de Granada, Granada, Spain<sup>1</sup>, Instituto Geologico Y Minero De Espana, Madrid, Spain.<sup>2</sup>, Universidad Autonoma De Madrid, Madrid, Spain<sup>3</sup>, Universidade Federal Do Rio De Janeiro. Rio De Janeiro, Brasil<sup>4</sup>, Universidade Federal Fluminense, Niteroi, Brasil<sup>5</sup>

Elephant Island is located in the northeastern end of the South Shetland archipelago, nearby the triple junction between the Antarctic-Scotia plates and the South Shetlands Block. The Shackleton Fracture Zone (SFZ) constitutes a prominent NW-SE oriented relief with related thick oceanic crust formed by sinistral transpressional convergence of the Antarctic and Scotia plates in the western Scotia Sea. The oceanic crust of the Former Phoenix Plate (at present a part of the Antarctic Plate) and the SFZ are subducted below the South Shetland continental block along the South Shetlands Trench. Elephant Island constitutes a prominent elevation of the South Shetlands Block, located above the southeastwards prolongation of the subducted SFZ. The Scotia Plate, formed by oceanic and thinned continental crusts, is thrust and affected by transcurrent sinistral faults along the contact with the South Shetlands Block, eastwards of Elephant Island. This block is bounded to the south by the Antarctic Plate along a sinistral transtensional fault zone that is located in the South Scotia Ridge (SSR), which extends towards the Bransfield Basin. Elephant Island is composed by metamorphic rocks, including blueschists, that evidence high pressure/low temperature metamorphism related to Cretaceous subduction processes. The area has undergone a very fast recent exhumation process that may be related to the SFZ subduction, crustal thickening and uplift.

The integration of geological inland and marine observations together available seismicity allow to characterize the present-day and recent variability of stresses in this triple junction area. Plate motion and seismicity indicate that the present day regional setting is determined by NE-SW compression and orthogonal extension. However, the NW-SE oriented Shackleton Fracture Zone evidences sinistral transpressional tectonic activity related to a local perturbation of the stress field with E-W compression and orthogonal extension since at least 8 M.a. In the northwestern part of Elephant Island, a shallow reverse earthquake focal mechanism is in agreement with field observation of reverse faults. Paleostress analysis from small scale faults supports the presence of NE-SW regional compression which is in agreement with the results of lineaments studies. Marine multichannel seismic reflection profiles located west of the island show the presence of large open folds in recent sediments that agree with recent NE-SW to E-W compressional stresses. Deformation has been progressive, since these folds partially developed previously to a regional unconformity. Moreover, NW-SE compressional stresses, probably related to the subduction of the SFZ below the South Shetlands Block, have been determined.

There is a sharp change in the stresses, paleostresses and deformational style southward of Elephant Island that become extensional with radial to NW-SE oriented minimum stresses. The area is characterized by the development of NE-SW normal faults, half-graben structures and extensional earthquake fault mechanisms that are related to the sinistral transtensional boundary between the South Shetlands Block and the Antarctic Plate. Seismic profiles located southwestwards of Elephant Island and several seismic profiles of the SSR reveals that this region has undergone both overprinted extensional and compressional deformations. Extensional faults are related to half-graben development, but in some areas the sedimentary infill shows large open folds typical of compressional deformation. These overprinted deformations suggest stages of tectonics inversion. In this context, the recent compressional deformation to the north of Elephant Island and extensional deformation to the south could have



## *XII International Symposium on Antarctic Earth Sciences*

*13 - 17 July 2015, Goa, India*



facilitated the islands fast recent uplift above the subducted SFZ, which represents a main heterogeneity along the South Shetlands Block margin.



**S10 – 489: The Structure and Evolution of the Antarctic Continent in Light of Recent Geophysical and Geological Investigations**

***Oceanic Spreading of the Drake Passage: New Evidence of the Early Stages of Opening***

Jesus Galindo-Zaldívar<sup>1</sup>; Bohoyo, F.<sup>2</sup>; Martos, Y.M.<sup>3</sup>; Ruano, P.<sup>1</sup>; Schreider, A.A.<sup>4</sup>; Suriach, E.<sup>5</sup>; Hernandez-Molina, J.<sup>6</sup>; Maldonado, A.<sup>1</sup>; Lobo, F.J.<sup>1</sup>; Rodr - Guez-Fernndez, J.<sup>1</sup>

Instituto Andaluz de Ciencias de la Tierra (CSIC-Universidad de Granada), Armilla, Granada, Spain<sup>1</sup>; Instituto Geologico y Minero de Espana, Madrid, Spain<sup>2</sup>; British Antarctic Survey (NERC), Cambridge, United Kingdom<sup>3</sup>; P.P. Shirshov Institute of Oceanology, RAS, Moscow, Russia<sup>4</sup>; Universitat de Barcelona, Barcelona, Spain<sup>5</sup>; Royal Holloway University of London, Egham, United Kingdom<sup>6</sup>

The opening of the Drake Passage had global significance, as it gave rise to both the in stauration of the Antarctic Circumpolar Current and the climatic isolation of Antarctica. Magnetic data acquired by the R/V Hesprides yield evidence to constrain the age of the initial stages of oceanic spreading. The oldest continental break-up phase, recognized in a small basin located at the northern border of the South Scotia Ridge, suggests that initial continental stretching probably allowed basic rock intrusions responsible for magnetic anomalies at least chron C12r (31.116-33.266 Ma) or even older. Subsequently, the extensional axis jumped northwards and a slightly asymmetric oceanic spreading with faster rates in the north began at chron C11r (30.217-30.627 Ma). The youngest well recognized chron in the western Scotia Sea is 3n.1r (4.300-4.493 Ma), before spreading ceased. Early opening gateways in the Drake Passage are essential for deep-bottom circulation related to sharp climatic cooling of the earliest Oligocene.



**S10 – 490: The Structure and Evolution of the Antarctic Continent in Light of Recent Geophysical and Geological Investigations**

***Variability of Oceanic Spreading in Scan Basin from Magnetic Anomalies Standpoint (Southwestern Scotia Sea, Antarctica)***

Jesus Galindo-Zaldivar<sup>1</sup>; Martos, Y.M.<sup>2</sup>; Perez, L.F.<sup>3</sup>; Schreider, A.A.<sup>4</sup>; Bohoyo, F.<sup>5</sup>; Ruano, P.<sup>1</sup>; Cataln, M.<sup>7</sup>; Hernandez-Molina, J.<sup>8</sup>; Maldonado, A.<sup>1</sup>

Instituto Andaluz de Ciencias de la Tierra (CSIC-Universidad de Granada), Spain<sup>1</sup>; British Antarctic Survey (NERC), Cambridge, United Kingdom<sup>2</sup>; Geological Survey of Denmark and Greenland, Copenhagen, Denmark<sup>3</sup>; P.P. Shirshov Institute Of Oceanology, RAS, Moscow, Russia<sup>4</sup>; Instituto Geologico Y Minero De Espana, Madrid, Spain<sup>5</sup>; Real Instituto Y Observatorio De La Armada. San Fernando, Cadiz, Spain<sup>6</sup>; Royal Holloway University Of London, Egham, United Kingdom.<sup>7</sup>

The Scotia Arc is formed by the fragmentation and widespread of the continental connection between South America and Antarctica since the Oligocene, favored by the eastward asthenospheric flows from the Pacific. Several small sized oceanic basins are developed in the southern Scotia Sea, from W to E: Ona, Protector, Dove and Scan basins surrounded by continental fragments. Scan basin is an elongated roughly triangular basin, narrower toward the South and wider northwards, located between the westwards Bruce Bank and the eastward Discovery Bank. This basin was formed by rifting processes and subsequent spreading accretion from the Oligocene to the Miocene, based on morpho-structural and seismo-stratigraphic analyses of the available multichannel seismic reflection profiles. The magnetic anomaly profiles orthogonal to the continental margins obtained during several cruises on board of the R/V Hesperides contribute to constrain the oceanic spreading. Scan basin is divided in three main regions: the southern characterized by NE-SW linear magnetic anomalies, a central disturbed area with wide intense magnetic anomaly minima in the western side and a northern region with N-S linear magnetic anomalies. The anomalies may be interpreted at least comprised between anomaly C8n (25.5 Ma) and C7n.1r (24 Ma), with faster spreading rates in the northern part (up to 11 cm/yr) than in the southern (5.8 mm/yr). Oceanic spreading was asymmetrical with faster western than eastern rates. Although magnetic anomalies have a clear linear character typical of oceanic spreading, due to the short length of the profiles, other alternative older ages models may fit the data. A tectonic model with an aborted triple junction and late rotation is proposed. for the opening of the SCAN basin.



**S10 – 491: The Structure and Evolution of the Antarctic Continent in Light of Recent Geophysical and Geological Investigations**

***Geophysical Study of a Volcanic Structure and Flexure of the Lithosphere. in the West Scotia Sea (Antarctica)***

Martos, Y.M.<sup>1</sup>; Martín-Jiménez, D.<sup>2</sup>; Galindo-Zaldívar, J.<sup>3</sup>

British Antarctic Survey (NERC), Cambridge, United Kingdom<sup>1</sup>; Universidad De Granada, Granada, Spain<sup>2</sup>; Instituto Andaluz de Ciencias de la Tierra (CSIC-Universidad de Granada), Spain<sup>3</sup>

The seafloor is characterized by a large number of seamounts, most of them are volcanic. These structures are useful for studying the flexure of the lithosphere and help to describe the regional oceanic evolution. This work focus on the study of a volcanic structure (VS) located in the West Scotia Sea, between South America and Antarctica, providing new insights into the geodynamic of the area. The main objectives of this research are to characterize the upper structure of the lithosphere, the flexure based on elastic plate model and to calculate the elastic thickness of the lithosphere ( $T_e$ ). For that, we have mainly used free air gravity anomalies analyses. These are combined with other geophysical data, such as multibeam bathymetry, magnetic anomalies and multichannel seismic profiles. The gravity models show that the lithosphere is deformed by the VS following a pattern of continuous plate flexural model. The maximum deflection of the base of the lithosphere is 14 km beneath the VS and the seafloor elevation (bulge) is 605 m in adjacent areas to subsidence at a distance of 20 km from the center of the VS.  $T_e$  values, obtained from the different models, are low (between 1 and 4 km) for the age of the oceanic crust (around 22 Ma) at the time of loading according to equation  $(2.7 \pm 0.15) \sqrt{t_1}$  or 450 °C isotherm, but consistent with the size of the load and the flexural parameter. Additionally we found that the VS were formed at least in two different polarities of the Earth's magnetic field. Finally, the results of elastic thickness and magnetic anomaly studies allowed us to estimate the origin of VS associated with the eastward Pacific upper mantle outflow in the Scotia Sea. Also, the VS behave as a barrier for the deep water masses of the Antarctic Circumpolar Current, which control the sedimentary processes of the region.



**S10 – 493: The Structure and Evolution of the Antarctic Continent in Light of Recent Geophysical and Geological Investigations**

***Geophysical Study of a Volcanic Structure and Flexure of the Lithosphere. In the West Scotia Sea (Antarctica)***

Martos, Y.M.<sup>1</sup>; Galindo-Zaldívar, J.<sup>2</sup>; Catalán, M.<sup>3</sup>; Maldonado, A.<sup>2</sup>

British Antarctic Survey (NERC), Cambridge, United Kingdom<sup>1</sup>; Instituto Andaluz de Ciencias de la Tierra (CSIC-Universidad de Granada), Spain<sup>2</sup>; Real Instituto Y Observatorio De La Armada, San Fernando, Cdiz, Spain<sup>3</sup>

The opening of the Drake Passage marked the final break-up of Gondwana Supercontinent, with the creation of the Scotia Arc. The Scotia Sea, located between South America and Antarctica, is constituted at present by the Scotia and Sandwich plates. To the west of the Scotia Plate, the Shackleton Fracture Zone accommodates the Phoenix Plate and Scotia Plate movements. The development of the Scotia Sea is considered a key gateway for both asthenospheric and oceanic currents. The opening of the Drake Passage is evoked as the last Southern Ocean gateway, which led to the instauration of the Antarctic Circumpolar Current, isolating the Antarctic Continent and bearing a major influence on climatic and global changes. In this recent study we show that the opening of the Drake Passage meant a gateway for Pacific mantle outflow because of the absence of deep lithospheric roots in the passage. The mantle material fed the West Scotia Ridge until the uplift of the Shackleton Fracture Zone in the middle Miocene. The Shackleton Fracture Zone relief formed a lithospheric root in the Drake Passage, serving as a barrier for the asthenospheric flows, avoiding the mantle material fed the West Scotia Ridge properly. Simultaneous to this asthenospheric setting, the uplift of the Shackleton Fracture Zone together with the initial incursions of the Weddell Sea Deep Water in the Scotia Sea forced the Circumpolar Deep Water and the Polar Front to move even farther from Antarctica. This had profound climatic implications, favoring the thermal isolation of Antarctica and the growing and permanent ice-sheets.

As the Scotia Sea is considered a small ocean formed as a back-arc, and fed mostly by the Pacific mantle, the small convection cells responsible for oceanic spreading lend the West Scotia Sea a very different thermal behavior than large oceans. The mantle dynamics also control the tectonic distribution of the Scotia Arc and surrounding areas. The subduction of the Phoenix Plate in the western margin of the Antarctic Peninsula formed the batholithic body known as the Pacific Margin Anomaly, which is used to propose an initial distribution of the continental blocks in the Antarctic Peninsula and in the Scotia Arc, and an opening model of the Scotia Sea.

In summary, an interdisciplinary analysis of the Scotia Arc and surrounding areas is accomplished in this study in order to improve in knowledge and understanding of the Scotia Arc evolution and the implications in global scale.



**S10 – 494: The Structure and Evolution of the Antarctic Continent in Light of Recent Geophysical and Geological Investigations**

***Anomalous Thermal Behaviour and Subsidence of the West Scotia Sea in Comparison with Large Oceans: Evidences of Mantle Cell Evolution***

Martos, Y.M.<sup>1</sup>; Galindo-Zaldívar, J.<sup>2</sup>; Catalán, M.<sup>3</sup>; Bohoyo, F.<sup>4</sup>; Maldonado, A.<sup>2</sup>

British Antarctic Survey (NERC), Cambridge, United Kingdom<sup>1</sup>; Instituto Andaluz de Ciencias de la Tierra (CSIC-Universidad de Granada), Spain<sup>2</sup>; Real Instituto y Observatorio de la Armada, San Fernando, Cádiz, Spain<sup>3</sup>; Instituto Geológico y Minero de España, Madrid, Spain<sup>4</sup>

The progressive sinking of the ocean seafloor is a consequence of lithospheric cooling. This process is controlled by lithospheric thermal behaviour, influenced, in turn, by the activity of mantle cells. Here we show that the West Scotia Sea, a good example of an isolated small ocean basin, reach thermal equilibrium more quickly than larger oceans do, following a different subsidence relationship ( $d(t) = 4480 - 19380\exp(-t/4)$ , where  $d$  and  $t$  are the depth in metres and time in millions of years, respectively). Heat flow data are often used to date oceanic crust. However, we found that, for oceanic crust of the same age, the lower heat flow in small oceans, like the West Scotia Sea, implies older apparent ages than if plate model empirical relationships for large oceans are considered. In addition, the asymptotic heat flow values for oceanic crust older than 15 Ma in this setting impedes their use as a suitable dating method. This circumstance may be a consequence of the small size of the mantle cells, with low heat and energy transport. Based on our results in the West Scotia Sea, we propose that small oceans have faster thermal evolution and behave like old oceanic crust in large oceans. The West Scotia Sea is a good example of a small ocean affected by this process, which controlled global climate change and the thermal isolation of Antarctica because it constituted the last gateway during the inception of the Antarctic Circumpolar Current.



**S10 – 495: The Structure and Evolution of the Antarctic Continent in Light of Recent Geophysical and Geological Investigations**

***Curie Isotherm Map of Scotia Arc from Magnetic Anomaly Data.***

Martos, Y.M.<sup>1</sup>; Catalán, M.<sup>2</sup>; Hemant Singh, K.<sup>3</sup>; Galindo-Zaldívar, J.<sup>4</sup>

British Antarctic Survey (NERC), Cambridge, United Kingdom<sup>1</sup>; Real Instituto y Observatorio de la Armada, San Fernando, Cádiz, Spain<sup>2</sup>; Dept. Of Earth Sciences, Indian Institute Of Technology, Bombay, India<sup>3</sup>; Instituto Andaluz de Ciencias de la Tierra (CSIC-UGR), Armilla, Granada, Spain<sup>4</sup>

The opening of the Drake Passage, situated between South America and Antarctica, represents the final stage of the fragmentation of Gondwana supercontinent. It led to the Scotia Arc formation, bordering the Scotia Sea, which is surrounded by fragments of the former continental connection. It is currently composed of Scotia and Sandwich Plates.

Shackleton Fracture Zone constitutes its sinistral transpressive western boundary and it is a key structure that accommodates former Phoenix and Scotia Plates' differential movement. The formation of the Drake Passage and the Scotia Sea is considered of great importance to ocean circulation, as it allows the establishment of the Antarctic Circumpolar Current that isolated the Antarctic continent, with strong implications for climate and global changes.

Thermal structure of the Earth's crust is one of the main parameters controlling geodynamic processes. There is few information regarding heat flow values on Scotia arc. These values are mainly located in its westernmost, southern and easternmost part, which are not enough to extract conclusions regarding lithospheric thickness variations and asthenospheric flow. Taking advantage of the World Digital Magnetic Anomaly Map Project's compilation we have extracted magnetic anomaly data, which fall inside the Scotia Arc and surrounding areas. This magnetic anomaly picture provides the best representation of magnetic properties to date. We have used spectral methods on this regional magnetic compilation to obtain depth to the bottom of magnetic sources (DTBMS) as a proxy to infer Curie depth and heat flow distribution in the Scotia Sea.

Results show a complex DTBMS picture, where Curie's depth varies less than 10 km from deepest to shallowest values. Although scarce information regarding heat flow values is available in the area, they are in good agreement with our results. Besides we compare DBTMS wherever possible with Moho depth values. Our DTBMS are always deeper. As a by-product we present a 2D heat flow map of this remote area which complements the scarce heat flow information available.



**S10 – 497: The Structure and Evolution of the Antarctic Continent in Light of Recent Geophysical and Geological Investigations**

***Stratigraphy and Tectonics of Indian Ocean: Implications on Movement of Plates in the Region.***

K. S. Misra

University of Petroleum and Energy Studies, Dehradun, Uttarakhand India

It is generally believed that the Antarctic continent is surrounded by the divergent plate boundaries. Further complications are added by fitting the entire continent along eastern margin of peninsular India, within the present position of the Bay of Bengal. Rapid northerly movement of Indian plate and consequent rise of Himalayan ranges has also been envisaged. The present study elucidates the stratigraphy and tectonic history of peninsular India and surrounding oceans to suggest that conflicting plate tectonic views need modifications. Exploration for hydrocarbons in land, off-shore and oceanic regions, has provided enormous amount of seismic, gravity and drill hole data sets in recent years. Obtained geological details from these data sets are incorporated for the refinement of existing models. The stratigraphic succession in Indian Ocean region can be classified in to three sequences. The oldest sequence comprises Pre-Cretaceous sedimentary rocks, which exhibit maximum deformation. Broad regional folds and normal faults have developed, mainly due to vertical tectonics. On land this sequence is exposed in Kutch region and is logged in off-shore regions of Kutch, Saurashtra, Kaveri and Krishna-Godavari basins. Fairly good reservoirs of hydrocarbons are located within this sequence and many have started production. The middle sequence is rather most interesting and comprises several inter layered units of volcanic and sedimentary rocks. This sequence is logged in Barmer, Cambay, Bombay offshore, Kerala, Kaveri, Krishna-Godavari, Mahanadi and Bengal basins. Both sedimentary and volcanic units are reservoir rocks and produce hydrocarbons. Furthermore, this sequence is characterized by unique seismic attributes and continues laterally to oceanic regions to cover entire Bay of Bengal and western half of Arabian Sea. On this Cretaceous sequence, uninterrupted Tertiary sequence is deposited.

The tectonic trend in the Bay of Bengal is largely defined by the oceanic ridges and other parallel corrugations. We found that the oceanic ridges represent the effusive zones and gravity lows associated with them, are remnants of initial felsic volcanism. Ridges, such as 82° E, 85° E and a couple of minor ones, have formed by exactly similar tectonic processes and at the same time, all along their length. The 85° East Ridge is a very significant geological feature. It meanders along the 85° East longitude in the northern part and gently curves towards west the southern part. This ridge is completely buried under the uninterrupted Tertiary succession and Quaternary Ganga-Brahmaputra submarine fan deposits. Earlier views suggested that this ridge represents a trail left by a hot spot on the northerly moving Indian Plate. The present study based on interpretation of seismic profiles generated by Pre-Stacking and Depth Migration (PSDM) techniques and high resolution gravity data, has suggested that this ridge has originated due to a combination of tectonic and related igneous phases. The upward reverse movement along nearly vertical faults is believed to have taken place during Cretaceous igneous activity. The central axis of the ridge is incised indicating continuing extensional tectonics. Extrusive phase corresponds with colossal and spasmodic Cretaceous volcanic flows in land areas of peninsular India. In oceanic regions, this sequence is overlain by an uninterrupted Tertiary sedimentary succession. The intrusive relationship with this succession indicates a Cretaceous-Tertiary event, where Paleocene succession is affected and its wedge-outs are conspicuously seen. The faults located on top of this ridge, form an hour-glass structure, with upward continuing inter sectional region.

It is emerged that the extensional tectonics and related vertical movements prevailed since the beginning of Carboniferous period. No evidences to suggest large scale horizontal movement are recorded. Rift and grabens have developed and accompanying normal faults have given rise to elongated basins. These basins formed locales for deposition of thick sedimentary sequences with coal seams in land areas and petroliferous basins in areas where they meet the ocean. Continued extensional tectonics resulted in



downward propagation of faults and commencement of decompression melting, outpouring of enormous volcanism, several units of which are inter layered with sediments and form volcanosedimentary succession. This succession represents nearly 90 million years, from the beginning to the end of Cretaceous. This finding does not support the idea of hot spot origin of volcanism, as it is very difficult to explain stationary hot spot for such a long time, below sedimentary basins located on fast moving Indian plate.

Geological evidences suggest that the tectonic history started since the beginning of Mesozoic Era and was dominated by extensional forces. However, a few pulses of compression have contributed to the development of final configuration of ocean floor. During initial extensional phase nearly vertical faults have developed, subsidence along them has given rise to huge sedimentary basin comprising innumerable horst and grabens. Mainly graben portions have been filled by Triassic and Jurassic sediments. The stratigraphy and tectonic history suggests extensional tectonics and vertical faulting. No evidences to support large scale horizontal movement are found during Mesozoic and Tertiary Era.



**S11 – 49: Cryosphere - Solid Earth Interactions**

***Horizontal Crustal Motion due to Postglacial Rebound above a Viscosity Contrast***

Paolo Stocchi<sup>1</sup>; Pippa Whitehouse<sup>2</sup>

Durham University, UK<sup>1</sup>; Netherlands Institute for Sea Research, Horntje, Netherland<sup>2</sup>

There is a large contrast between the seismic velocities found beneath West and East Antarctica, which likely corresponds to a large contrast in viscosity. Such a strong contrast likely influences the flow of the mantle in response to glacial loading.

During the Last Glacial Maximum, the expansion of the West Antarctic Ice Sheet meant that an additional surface load was applied across the Ross Sea region, close to the viscosity contrast beneath the Transantarctic Mountains. Following deglaciation, rebound is expected to produce radially outwards horizontal motion. However, observed horizontal motion along the Transantarctic Mountains is directed towards the former load centre. The viscosity contrast beneath the Transantarctic Mountains could play a role in explaining this pattern. Here we use a finite-element model to see if a viscosity contrast can explain the reversed horizontal motion.

The model is a 2D axisymmetric spherical model with an ice cap located from colatitude 0 degs to 15 degs. With this simple geometry computation time is short and we can investigate several parameters, such as the influence of the location and magnitude of the viscosity contrast. Based on mantle temperature maps inferred from seismic models, the viscosity contrast can be as large as 6 orders of magnitude.



## S11 – 356: Cryosphere - Solid Earth Interactions

### *Ice Shelf Seismology: Recent Broadband Seismological Observations and Future Prospects*

Richard Aster<sup>1</sup>; Peter Bromirski<sup>2</sup>; Peter Gerstoft<sup>2</sup>; Andrew Nyblade<sup>3</sup>; Ralph Stephen<sup>4</sup>; Douglas Wiens<sup>5</sup>

Colorado State University, USA<sup>1</sup>; Scripps Institution of Oceanography, USA<sup>2</sup>; Penn State University, USA<sup>3</sup>; Woods Hole Oceanographic Institution, USA<sup>4</sup>; Washington University, USA<sup>5</sup>

Recent developments in polar broadband seismographic instrumentation (spanning the band from 100s of s to 100s of Hz at micron scale amplitudes) have facilitated increasingly extensive deployments of instruments across Antarctica during the past decade. These investigations have included a number of experiments atop icebergs and ice shelves that have produced an extensive variety of oceanic and seismic observations, illuminating cryospheric processes while showing the broad applicability of seismology to such studies. Oceanic signals of interest include the translational and strain fields of floating icebodies excited by tides and gravity waves from the short periods well to infra gravity wave band, including tsunamis. Seismologically detected motions reveal deepwater dispersion curves that enable us to range/locate gravity wave source regions and processes, including both storm and calving generated waves. Seismic (elastic wave) signals of interest include teleseismic and local earthquakes, with cryospheric signals ranging from tidally modulated long period events to ultra-repetitive tremor generating subevent transients that create oscillating iceberg phenomena via stick slip processes arising from ice/ice and/or ice/seabed interactions. The rapid and ongoing development of ambient noise methodologies in seismology suggests that application of correlation based methods for extracting elastic response characteristics may be particularly valuable for in situ identification and tracking of temporal changes in the thickness, strength, and other properties of ice shelves. During November-December 2014, the most extensive and multi scale ice shelf seismological deployment to date was deployed across the Ross Ice Shelf to study its vibrational excitation and properties, as well as to facilitate tomographic imaging of the Antarctic crust, and mantle. Following a brief summary of prior results from floating seismographic deployments, we will summarize the goals of the just initiated Ross Ice Shelf Vibrations/Solid Earth deployment and present some results from early data collected at the end of 2014. We will also suggest future prospects for utilizing such data on ice shelves to advance understanding of ocean cryosphere coupling, ice shelf evolution, and to address associated challenges related to ice shelf processes and integrity.



## S11 – 369: Cryosphere - Solid Earth Interactions

### ***Development of the Next Generation of Seismological Instrumentation for Icy Places: The Geophysical Earth Observatory for Ice Covered Environs (GEOICE)***

Audrey D Huerta<sup>1</sup>; Jeremy Paul Winberry<sup>1</sup>; Steven P Bernsen<sup>2</sup>; Susan L Bilek<sup>2</sup>; Tim Parker<sup>3</sup>; Paul Carpenter<sup>3</sup>; Bruce C Beaudoin<sup>3</sup>; Kent Randall Anderson<sup>4</sup>

Central Washington University, Ellensburg, WA, United States<sup>1</sup>; New Mexico Tech., Socorro, NM, United States<sup>2</sup>; IRIS PASSCAL Instrument Centre, Socorro, NM, United States<sup>3</sup>; IRIS ConSørtium, Washington, DC, United States<sup>4</sup>

We report on the developments of a new NSF MRI-community supported seismic observatory designed for studies in ice-covered regions the Geophysical Earth Observatory for Ice Covered Environs (GEOICE). This project is motivated by the need to densify and optimize the collection of high-quality seismic data relevant to key solid Earth and cryosphere science questions.

The GEOICE instrument, and its power and other ancillary systems, are being designed to require minimal installation time and logistical load (i.e., size and weight), while maximizing ease-of-use in the field, data handling, and telemetry compatibility while being able to withstand conditions associated with icy environments (including cold/wet conditions and high-latitude solar limitations).

The instrument capability will include a hybrid seismograph pool of broadband and intermediate elements, for observation of both long-period (e.g, long-period surface waves and slow sources), and intermediate-to-short-period (e.g., teleseismic body waves, local seismicity, and impulsive or extended glaciogenic signals) signals.

Key features will include a design that integrates the seismometer and data logger into an single, environmentally and mechanically robust housing; very low power requirements (<~1 watt) for the intermediate-band systems, and advanced power/battery systems that optimize battery capacity and operational limits. The envisioned ~100 element GEOICE instruments will nearly double the current polar inventory of stations and will be maintained and supported at the IRIS PASSCAL Instrument Centre to ensure full and flexible peer-reviewed community use.



## **S11 –417: Cryosphere - Solid Earth Interactions**

### ***A Statistically Derived Model for Basal Sliding***

Evan Cummings<sup>1</sup>; Jesse Johnson<sup>1</sup>

University of Montana, United States<sup>1</sup>

Basal sliding, is, and has always been a source of great uncertainty in glacier dynamics. Yet it is the primary control on the fast flow of ice, responsible for more than 90% of the flux of ice into the Earth's oceans. Mathematical models of basal sliding typically relate the speed of sliding to the shear stress as well as basal water pressure, topography, and composition. To date, a general 'sliding law' has eluded investigators at least in part due to a lack of observational data.

In recent years, Interferometric Synthetic Aperture Radar (InSAR) surface velocity observations have grown from a few outlet glaciers to nearly complete coverage of both Antarctica and Greenland. Reported errors in these data sets are typically less than 1% of the observed speed. These data, in turn, can be inverted using a thermo-mechanically coupled higher-order ice sheet model. The result of this inversion is a continuous basal friction field. While the inverse process for determining basal friction, and hence basal sliding rates, is dependent on model assumptions regarding the mathematical formulation of ice dynamics, these inversion results nonetheless represent the scientific community's best estimate of basal sliding rates.

In this work, we will focus on basal friction fields determined through inverse modelling of the observed surface speed. We will treat these modelled basal friction fields as observations, effectively removing the primary obstacle of formulating a general sliding law. Our approach utilizes dual general and generalized linear models, utilizing possibly transformed independent and dependent variables of the control model as explanatory variables, complete with all 2nd order interactions. The resulting statistically generated basal friction fields produce a surface velocity similar to the observations, while the linear-model coefficients offer some physical insight into the corresponding variable's effect on basal sliding.



**S11 –435: Cryosphere - Solid Earth Interactions**

***Ice Mass Loading and Deformation Structures under Grounded Ice Sheets: Examples from the And-1b and And-2a Cores***

Cristina Millan<sup>1</sup>; Terry Wilson<sup>1</sup>; Timothy Paulsen<sup>2</sup>; Richard Jarrard<sup>3</sup>; Andreas Laufer<sup>4</sup>; Simona Pierdominici<sup>5</sup>; Thomas Wonick<sup>6</sup>; Scott Aleshire<sup>1</sup>

Ohio State University, Columbus, United States<sup>1</sup>; University of Wisconsin-Oshkosh, United States<sup>2</sup>; University of Utah, United States<sup>3</sup>; Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), Denmark<sup>4</sup>; Helmholtz-Zentrum Potsdam, Deutsches Geo Forschungszentrum GFZ Wissenschaftliches Bohren Telegrafenberg, Germany<sup>5</sup>; Leibniz-Institut für Angewandte Geophysik, Germany<sup>6</sup>

Deformation of substrate beneath flowing, grounded ice sheets is a common manifestation of cryosphere-solid earth interactions. Here we investigate whether abundant mineralized fractures and clastic intrusions in two sedimentary rock cores recovered from the Victoria Land Basin of Antarctica by the ANDRILL project formed due to subglacial deformation. Horizons interpreted to represent glacial surfaces of erosion marking grounded ice over the drillsite locations are commonly recognized based on internal fabrics within diamictites and features such as boxwork veining and clastic intrusions. If mineralized fractures and clastic intrusions formed during subglacial deformation, the expectation is that they (1) would be present and abundant in strata immediately above and below the interpreted glacial surfaces of erosion; (2) would be most abundant where the most numerous grounded ice intervals have been interpreted from the stratigraphic record; (3) could show high abundance in stratigraphic intervals coeval with glacial thermal regimes associated with abundant meltwater; (4) would conform to the Riedel fracture model for horizontal shear at the base of the ice and (5) would have a geometry consistent with the sense of shearing associated with the direction of ice flow.

The abundance and distribution of mineralized fractures and clastic intrusions from the AND-1A and AND-2B cores show inconsistent spatial relations with respect to inferred depths of glacial surfaces of erosion; increased abundance does not correlate with stratigraphic intervals in which grounded ice is interpreted to have repeatedly been present. The geometry and orientation of mineralized fractures in the sedimentary cores does not conform to a geometric fracture pattern defined by the Riedel shear model expected of brittle subglacial deformation or the shear direction imparted by the direction of ice flow over the substrate. Vein abundance and volume has been compared to the inferred glacial thermal regime (i.e., polar, polythermal, and wet-based glaciers) and the prediction of a larger abundance and overall volume of mineralized fractures within intervals where large volumes of subglacial meltwater are present is not supported. Origin of the mineralized fractures and clastic intrusions by the direct influence of shear deformation beneath flowing grounded ice appears to be precluded. However, overcompaction, dewatering and changing stress regimes due to mass loading by grounded ice sheets are all considered important factors in developing fracture sets in Victoria Land Basin strata.



**S11 –457: Cryosphere - Solid Earth Interactions**

***Geological Controls on the Behavior of an East Antarctic Outlet Glacier***

J. Paul Winberry<sup>1</sup>; Howard Conway<sup>2</sup>; Michelle Koutnik<sup>2</sup>

Central Washington University<sup>1</sup>; University Of Washington<sup>2</sup>

Discharge of East Antarctic Ice Sheet through the Transantarctic Mountains is routed through a few relatively few large outlet glaciers. The behavior of these glaciers is fundamental to understanding the response of the East Antarctic Ice Sheet to changing climates. However, to date only minimal geophysical surveys have targeted these glaciers. To illuminate the role of geological controls on fast flow, we conducted an integrated geophysical survey on the Beardmore Glacier that included ice penetrating radar, GPS, passive seismic, and active seismic observations. Our study sampled an area where the fast flowing main trunk of the glacier is directed around a slow moving "sticky spot". These results reveal that the main trunk of the glacier resides in a deep basin (> 2 km below sea level), while the slow moving sticky spot is underlain by bedrock bump (nearly at sea level). The large topographic offset is consistent with previous geologic studies that suggested a large fault in the middle of the Beardmore Glacier. Additionally, the fast moving region is underlain by a thick sedimentary-deposit, while the sticky spot is hard bedded. Thus, similar to ice streams draining both of Antarctica's ice sheets, the geologic structure and presence of a soft bed appears to exert significant influence on the behavior of outlet glaciers flowing through the Transantarctic Mountains.



**S11 –466: Cryosphere - Solid Earth Interactions**

***Understanding Antarctic Ice Mass Change using GPS Measurements of Horizontal Crustal Motion***

Stephanie Konfal<sup>1</sup>; Terry Wilson<sup>1</sup>; Michael Bevis<sup>1</sup>; Eric Kendrick<sup>1</sup>; Pippa Whitehouse<sup>2</sup>; Ian Dalziel<sup>3</sup>; Robert Smalley<sup>4</sup>; David Heeszel<sup>5</sup>; Douglas Wiens<sup>6</sup>

Ohio State University, Columbus, OH, United States<sup>1</sup>; Durham University, Durham, United Kingdom<sup>2</sup>; University Of Texas at Austin, Austin, TX, United States<sup>3</sup>; University Of Memphis, Memphis, TN, United States<sup>4</sup>; Nuclear Regulatory Commission, Washington, DC, United States<sup>5</sup>; Washington University In St. Louis, St. Louis, MO, United States<sup>6</sup>

Essential constraints for models of glacial isostatic adjustment come from GPS observations of crustal motion driven by changes in ice mass. In Antarctica, where a strong boundary in earth properties and mantle viscosity separates East and West Antarctica, horizontal motions are of particular interest. Modelling studies assessing the sensitivity of present-day motions to laterally heterogeneous earth structure show that horizontal crustal displacements are strongly influenced by the flow from rheologically stronger to weaker mantle, in some cases resulting in a reversal of the original radial rebound signal. Here we present GPS-derived horizontal crustal motion data from Antarctica acquired by the Antarctic Network (ANET) component of the Polar Earth Observing Network (POLENET) validating predictions that GIA-induced horizontal motions across an extreme earth properties boundary can be reversed, resulting in motion toward, rather than away from former ice mass centers. In unloading scenarios, horizontal motions are expected in a radial pattern away from the center of mass loss. We instead observe motion towards West Antarctica and modelled former ice mass centers, with horizontal displacements consistently near-perpendicular to the strong gradient in mantle viscosity mapped by seismology. Additionally, a gradient in crustal motion is observed, with smaller magnitude motions originating from within the stronger, East Antarctic side, and larger magnitude motions originating from within the weaker, West Antarctic side. The agreement between observed horizontal rates of crustal displacement and modelled viscosity values in the region is strong, and suggests a causal relationship. However, an alternative explanation for the mismatch between GIA models and observed motions may relate to the ice history model input. To assess the feasibility of East Antarctic ice mass loss as a source for observed horizontal crustal motions, an alternative ice history of unloading in the Wilkes Subglacial Basin region is explored.



## S11 –511: Cryosphere - Solid Earth Interactions

### ***GPS and Grace Constrains on Present Day Antarctic Glacial Isostatic Adjustment (GIA)***

Sunil P, Sukumaran<sup>1</sup>; Ajish P, Saji<sup>1</sup>; Ajay Dhar<sup>1</sup>

Indian Institute of Geomagnetism, Navi Mumbai, India<sup>1</sup>

The advancement of space geodesy enabled very precise and accurate space based observations in Polar regions, especially in Antarctica facilitating the study of crustal dynamics, post glacial rebound, ice sheet mass balance, total electron content, water vapor studies etc. One of the important tasks in the study of present day crustal deformation of Antarctica remain, constraining the Glacial Isostatic Adjustment (GIA), i.e. the ongoing response of the viscoelastic Earth to changes in surface ice and water loads. Because, the effect of GIA is global as it modifies Earth's shapes, motion of its rotational pole, its gravitational field and gravity based ice dynamics etc. Today, several continuously observing GPS stations are available mostly along the coast of Antarctica to measure the elastic crustal deformation of the Earth in response to ongoing ice mass changes, the viscoelastic response due to GIA and possibly tectonic motion. Further satellite missions like GRACE, which measures temporal changes in the Earth's gravity field, which can infer near surface mass changes with unprecedented precision. It is therefore important to model the present day elastic response with high resolution and precision, when GPS and GRACE observations are available in tandem.

In the present study we investigate the temporal changes in the present day elastic response caused by mass changes of the Antarctic continent. We used 28 continuous observing GPS stations distributed across the Antarctic continent established by different countries, including the 2 continuous observing GPS stations by India at Maitri (Schirmacher Oasis) and Bharati (Larsemann Hills), and 12 International GNSS Service (IGS) stations. We analyzed GPS data using GAMIT/GLOBK software developed by Massachusetts Institute of Technology (MIT) and estimated the viscoelastic response from GRACE harmonic fields of the French Groupe de Recherche en Geodesie Spatiale (GRGS), at all 28 GPS locations, which provide abutting estimates of the gravity field. Compared the GPS vertical deformation time series with temporal changes found in the modeled viscoelastic response from GRACE. As the crustal displacement is a combination of the elastic response from present day mass changes and the viscoelastic effect from ice changes, the viscoelastic signal from GRACE is subtracted from the GPS observations to constrain GIA signal, and compared the sum of the modeled elastic uplift and present day GIA rates, with the observed uplift rates at all 28 GPS sites. The spatial variation of correlation between GPS and GRACE over the Antarctic continent due to GIA effect and its contribution in terms of crustal deformation pattern are explained.



**S12 – 98: Antarctic Geothermal Heat Flux, Subglacial Geology and Ice Dynamics**

***Temperature Gradient and Geothermal Flux in the Deep Boreholes Drilled Through Antarctic Ice Sheet***

Zhang Nan<sup>1</sup>; Pavel Talalay<sup>1</sup>; Markov Alexey<sup>1</sup>

Polar Research Center, Jilin University, China<sup>1</sup>

The temperature distribution in Antarctic ice sheet forms an important research topic in view of the temperature dependence of ice-flow properties, information about past variations of surface temperature, in-situ estimations of geothermal flux. Some properties such as the velocity of seismic waves and the absorption of radio waves, on which depend methods of measuring ice thickness, also vary with temperature.

In spite of the extensive use of various thermodynamics modelling methods, only direct temperature observations can give the reliable temperature distribution data. During last five decades, seven deep ice-drilling projects (Byrd, Dome C, South Pole, Kohnen, Dome F, Vostok, and WAIS Divide) were succeeded to drill to, or nearly to, the bedrock at inland of Antarctica. Two of the holes (Byrd and Kohnen) met the water layer under the ice sheet and water had welled up into the hole. The borehole at Vostok contacted with the subglacial Lake Vostok water at a drilling depth of 3769.3 m and the subglacial water rose from the lake to a height of more than 340 m.

The measured temperature profiles in most of the boreholes on the Antarctic ice sheet (Vostok, Dome C, Kohnen, Dome F, and South Pole) are monotonously increasing with depth as expected at dry locations with small vertical velocities. Vertical advection is much greater in West Antarctica (Byrd and WAIS Divide) and temperature distribution displays nearly isothermal upper layers, but in the lower parts temperature increases almost with the same gradient as at the other sites. Temperature gradients at the bed are 2.2-2.5°C/100 m at Dome C, Dome F and Vostok, and much more i.e. 3.04°C/100 m at Kohnen. Direct transforming of temperature gradient into geothermal flux indicate that the geothermal flux on ice sheet bed at Dome C, Kohnen, and Dome F sites varies in between 51.1-62.7 mW m<sup>-2</sup>. The geothermal heat flux at Vostok on the boundary ice sub glacial water is lower and equal to 46.1 mW m<sup>-2</sup>. The temperature at the ice sheet bed in drilled deep boreholes is estimated in the range of 1.85 -2.55°C accounting pressure melting point and Clapeyron temperature-pressure slope. However, measurements of basal temperature gradients do not give exact values of geothermal flux without extensive analysis. Even in the deep boreholes, the history of climate change can affect the basal temperature gradient. What is more important, frictional heat must be accounted for reasonable estimates of Earth's geothermal flux at drill site.



**S12 – 107: Antarctic Geothermal Heat Flux, Subglacial Geology and Ice Dynamics**

***The Extent of the West Antarctic Rift System into the Amundsen Sea Embayment: New Indications, by Curie Depth Estimates and Geothermal Gradients***

Ricarda Dziadek<sup>1</sup>; Karsten Gohl<sup>1</sup>; Nobert Kaul<sup>2</sup>

Alfred Wegener Institute Helmholtz-Centre for Polar and Marine Research, Germany<sup>1</sup>; University of Bremen, Department of Geosciences, Germany<sup>2</sup>

The West Antarctic Rift System (WARS) provides a key component to Antarctica's tectonic evolution. The system's expansion is thought to progress from the Ross Sea to the Bellingshausen Sea and Amundsen Sea, where smaller rift arms seem to spread more diffusely. The rift troughs provide pathways for major ice streams, thus, their dynamics might directly be coupled to tectonic-morphological constraints. Together with regional crustal uplift (e.g. Marie Byrd Land), a common process in continental rift systems, this has widely shaped the West Antarctic landscape during the Neogene. In the Amundsen Sea Embayment (ASE), a key sector of the West Antarctic Ice Sheet (WAIS), rapid changes have occurred over recent decades. The adjacent Pine Island Glacier and Thwaites Glacier, two outlets from a large drainage basin in the centre of the WAIS, exhibit highest increase in flow velocity in all of Antarctica. A large fraction of the WAIS is discharged into the embayment here. However, various models have been developed on the crustal architecture and tectonic history of this region, based on recent geophysical surveys, but any possible WARS activity remains uncertain.

To investigate the possible effects of rifting history from the WARS on the ASE ice sheet dynamics, we use Curie Point Depth (CPD) estimates. They are based on airborne-magnetic anomaly data and provide an additional insight into the deeper crustal properties. The CPD estimates image the depth of the deepest magnetic layer, hence the bottom depth of the igneous crust. For our estimates we assume a Curie temperature of 580°C at this depth. The well-established centroid method is used to calculate 30 CPDs in area windows of 200 x 200 km each with 50% overlapping the magnetic anomaly grid. We find that shallow CPDs and, therefore, higher geothermal gradients coincide with the location of previously postulated rift arms on the ASE shelf. Our in-situ temperature measurements and derived geothermal heat flow provide a further geophysical data-set to investigate the extent of any crustal thinning and possible rift arms into the Amundsen Sea Embayment. The crustal thickness is an important contributor to the observed regional-scale geothermal heat flux variations and provides a geophysical proxy for thermal status of crust and upper mantle.



**S12 – 165: Antarctic Geothermal Heat Flux, Subglacial Geology and Ice Dynamics**

***Geological Boundary Conditions for the East Antarctic Ice Sheet in the Northern Wilkes Subglacial Basin***

Fausto Ferraccioli<sup>1</sup>; Egidio Armadillo<sup>2</sup>; Duncan Young<sup>3</sup>; Tom Jordan<sup>1</sup>; Donald Blankenship<sup>3</sup>; Martin Siegert<sup>4</sup>

Natural Environment Research Council (NERC)-British Antarctic Survey, UK<sup>1</sup>; DISTAV- University of Genova, Italy<sup>2</sup>; The University Of Texas At Austin, United States<sup>3</sup>; Grantham Institute, Imperial College, UK<sup>4</sup>

The Wilkes Subglacial Basin (WSB) extends for 1,400 km from George V Land into the interior of East Antarctica and hosts the catchments of several major glaciers (Cook, Ninnis, Mertz and David) in its northern part that drain a large sector of the East Antarctic Ice Sheet (EAIS), which may already be experiencing modest mass loss, which could however potentially increase in the future in response to ocean and climate warming. This region is of particular significance for the longer-term stability of the EAIS, as it lies well below sea level and its bedrock deepens inland, making it potentially prone to marine ice sheet instability like more dynamic areas of the West Antarctic Ice Sheet (WAIS) that are currently experiencing significant thinning.

Notably, major debate has centred on the longer term stability of this marine-based part of the EAIS during former warmer paleoclimatic conditions in the Neogene that may be akin to those expected for the end of the 21<sup>st</sup> century. Major drilling efforts conducted as part of IODP leg 318 have provided tantalising new geological glimpses into the possibly more dynamic behaviour of this sector of the EAIS as recently as the warm mid-Pliocene. It is therefore important to better comprehend subglacial geological boundary conditions and their potential influence on ice sheet behaviour in this key sector of the EAIS. Understanding subglacial geology is also important in order to provide a regional context that can further assist when interpreting sedimentary records from the margin of the EAIS.

Here we present new potential field imaging of the WSB combined with radar data to investigate geological controls on bedrock topography and ice flow regimes in this key sector of the EAIS. Our images reveal major Precambrian and Paleozoic basement faults that exert tectonic controls both on the margins of the basin and its sub-basins, including the Eastern Basins, the Central Basins and the Western Basins in the interior, at the onset of enhanced glacial flow. Using recent ICECAP aerogeophysical data we demonstrate that some of these interior basins connect to newly imaged coastal basins underlying the Cook Ice Shelf region. This connection implies that ocean-induced changes at the margin of the EAIS could potentially propagate into the interior with potentially de-stabilizing effects.

Our interpretations and models predict that the WSB is unlikely to presently include extensive and thick post Jurassic sedimentary infill. If thicker Cretaceous to Cenozoic sediments were originally deposited here, then they appear to have been mostly eroded away, possibly because of widespread glacial erosion. We infer highly variable bedrock geology, including Proterozoic basement, Neoproterozoic(?) and Cambrian sediments, intruded by Cambrian arc-related rocks, and cover rocks formed primarily by Beacon sediments extensively intruded by Jurassic Ferrar tholeiitic sills, and in parts overlain by Kirkpatrick Basalt. Thinner drapes of sediments cannot however be detected from potential field data and the existence of flat plateau-like surfaces in parts of the WSB could speculatively be interpreted as evidence for widespread marine erosion, similar to what has been suggested for the Siple Coast region of WAIS. However, age constraints are lacking for these surfaces in the WSB and they could potentially even be pre-glacial features.

Overall, present-day enhanced ice flow in the WSB is both topographically and structurally controlled, and occurs in an area of mixed and spatially variable bedrock geology with thin (and patchy) Beacon



sedimentary cover. This is in marked contrast with some parts of the WAIS where younger Cretaceous to Cenozoic sedimentary basins are inferred and widespread rift-related magmatism occurs, and both of which are thought to represent important geological templates facilitating fast glacial flow.

The role of geothermal heat flux variations in influencing subglacial hydrology and ice dynamics in this key part of the EAIS remains an outstanding question. However, given that this part of East Antarctica was adjacent to southern Australia prior to Gondwana break-up, where the South Australian Heat Flow Anomaly is characterized by surface heat flows as high as  $126 \text{ mWm}^{-2}$  (i.e. some 2-3 times that of typical continental values) this is potentially an important factor in the WSB, especially where basement highs occur and the overlying Neoproterozoic, Cambrian and Devonian (?) to Jurassic sedimentary basins we imaged are thinner.



**S12 – 166: Antarctic Geothermal Heat Flux, Subglacial Geology and Ice Dynamics**

***Aerogeophysical views of Subglacial Geology hidden beneath the Ice Streams flowing Into the Weddell Sea***

Fausto Ferraccioli<sup>1</sup>; Owen King<sup>2</sup>; Tom Jordan<sup>1</sup>; Neil Ross<sup>3</sup>; Robert Bingham<sup>4</sup>; Andrew Smith<sup>1</sup>; Richard Hindmarsh<sup>1</sup>; Anne Le Brocq<sup>5</sup>; David Rippin<sup>6</sup>

Natural Environment Research Council (NERC)-British Antarctic Survey, UK<sup>1</sup>; University of Leeds, UK<sup>2</sup>; University of Newcastle, Australia<sup>3</sup>; University of Edinburgh, UK<sup>4</sup>; University of Exeter, UK<sup>5</sup>; University of York, UK<sup>6</sup>

Sub glacial geology provides important controls on the onset and maintenance of fast glacial flow for the West Antarctic Ice Sheet (WAIS). Widespread sub glacial sediments deposited within deep rift basins, thinner drapes of marine sediments within the West Antarctic Rift System (WARS) and high geothermal heat flux associated with widespread Cenozoic magmatism have been previously identified as key geological controls that can also modulate ice sheet dynamics.

Here, we compile a suite of new and vintage aeromagnetic and airborne gravity observations to examine the large-scale geological setting of several major ice streams flowing into the Weddell Sea Embayment and assess the role of geological controls on sub glacial topography and WAIS flow regimes. We focus on the sub glacial geology beneath the glacial catchments of the Institute and Moeller ice streams, and the Rutford ice stream and the Evans ice stream.

We show that the Moeller ice stream is underlain by a major strike-slip fault system, dubbed the Pagano Shear Zone (Jordan et al., 2013, Tectonophysics), which is part of the tectonic boundary between East and West Antarctica. The fault system has recently been interpreted as a major Jurassic fault that also controlled the emplacement of Jurassic granitic intrusions. Intraplate reactivations of the fault system in post-Jurassic times may well have occurred but geological evidence is currently lacking. A set of en-echelon subglacial basins formed along the strike-slip fault system and these topographic basins appear to be a major control steering enhanced flow far inland. Deep sedimentary basins are not present along this fault system, however, suggesting that subglacial sediments are not necessarily a geological template for the onset of fast glacial flow in the interior of this part of WAIS. This fault system may potentially also connect to the previously identified offset rift basins (Studinger et al., 2001 GRL) that have instead been modelled as containing sedimentary infill and that appear to exert controls on the onset of fast flow for one of the ice streams flowing into the Ross Sea Embayment.

The recently identified Robin Subglacial Basin (Ross et al., 2012 Nature Geoscience) that underlies the fast flowing coastal region of the Institute ice stream contains ca 1-3 km of sedimentary infill and smooth bedrock topography. The basins here appear to connect to the Weddell Sea Rift System where thick sedimentary infill has been estimated from previous and new depth to magnetic source calculations. Rift basins onshore may connect with glacially overdeepened rift basins offshore in the continental shelf region hidden beneath the Ronne/Filchner ice shelf, and may provide important controls on ice sheet/ocean interactions, as recently proposed in the Bellingshausen sector of WAIS (Bingham et al., 2012 Nature).

Enhanced flow in the tributaries of the Institute ice stream cuts across the Ellsworth Mountains and is controlled by basement faults displacing metasedimentary and metavolcanic rocks of Cambrian to Permian age. It is likely that these faults provided major structural controls for the development of the fjords that dissect the Ellsworth Mountains (Ross et al., 2014 Geol. Soc of America).

Prominent magnetic anomalies overlie outcrops of Jurassic granitic intrusions and enable us to trace their subglacial extent beneath the catchments of Institute, Moeller and also Rutford ice streams. These large



granitoid plutons form topographic highs that appear mainly to divert fast flow around them. Notably just upstream of two of these highs a prominent plateau-like feature is preserved (Rose et al., 2015 ESD), suggesting that the occurrence of granitoids has played a significant role in modulating long-term ice dynamics even further upstream. Whether some of these granitoids are also highly radiogenic and hence may represent sources of enhanced geothermal heat flux, which could affect sub-ice hydrology is a topic currently under investigation.

Magnetic anomalies also delineate the extent of Precambrian basement of the Haag block that underlies a significant part of the Evans ice stream catchment. Narrow rifts developed along the edges of this uplifted Precambrian block and at the base of a separate crustal block, the Antarctic Peninsula. These rifts appear to exert significant controls on fast flow for the Evans and Rutford ice streams. The rifts may be tectonically related to both the Weddell Sea rift system and potentially also a branch of the West Antarctic Rift System that has recently been inferred to underlie the Siple Basin (Bingham et al., 2012). There is however no evidence for voluminous Cenozoic rift-related magmatism in these basins in contrast for example to the basins that underlie the catchment of Pine Island Glacier.



**S12 – 291: Antarctic Geothermal Heat Flux, Subglacial Geology and Ice Dynamics**

***An Evaluation of Active Subglacial Volcanism as a Source of Thwaites Glacier Heterogeneous Geothermal Flux***

Quartini Enrica<sup>1</sup>; Blankenship D.D<sup>1</sup>; Young D.A.<sup>1</sup>; Schroeder D.M.<sup>2</sup>

University of Texas Institute for Geophysics, Jackson School of Geosciences, University of Texas at Austin, Austin, TX, United States<sup>1</sup>; Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA<sup>2</sup>

Geothermal flux is one of the most critical but least constrained basal conditions that can affect the stability and evolution of the marine based West Antarctic ice sheet (WAIS). The impact of geothermal flux is especially significant for the stability of WAIS as this flows within the volcanically active West Antarctic Rift System (WARS).

Until recently, existing estimates of geothermal flux in Antarctica were greatly limited in spatial resolution and offered little or contradictory information on its spatial heterogeneity and distribution. As a result, models of ice sheet flow often adopted constant values of geothermal flux over large regions, using values from either one of the two indirect measurements available (from satellite magnetic or seismic shear velocity models) or from average crustal geothermal fluxes based on sparse outcrop sample of the bedrock.

We have recently published a new approach to airborne radar sounding data analysis that, combined with a sub glacial water routing model, provides the first catchment-size evaluation of geothermal flux distribution in a subglacial environment at a kilometer- based resolution. The study showed that Thwaites Glacier, one of West Antarctica's most rapidly changing and potentially unstable glaciers, is affected by heterogeneous and anomalously high geothermal flux with an average value of  $\sim 114 \pm 10$  mW/m<sup>2</sup> (almost twice continental average).

Here we present a detailed characterization of Thwaites Glacier's geothermal flux at locations of interest. We evaluate the nature of each heat flux anomaly using analysis of magnetic anomalies and basal topography and englacial layers from radar sounding data. Both datasets were collected during the AGASEA (2004-2005) airborne geophysical survey. We use the gathered information to test our hypothesis that the nature of the heterogeneous geothermal flux measured over Thwaites Glacier is volcanic, consistently with previous aerogeophysical and seismic observations have indicated the presence of active subglacial volcanism in the WARS.



### S13 – 26: Past Antarctic Ice Sheet Behaviour and Response to External Forcing

#### ***Seismic Stratigraphy of Prydz Bay (East Antarctica) with Focus on Glacial Deposition and Environments***

Leitchenkov G.L.<sup>1</sup>; Guseva Yu.B.<sup>2</sup>; Gandyukhin V.V.<sup>2</sup>

Institute for Geology and Mineral Resources of the World Ocean, Russia<sup>1</sup>; Polar Marine Geosurvey Expedition, St.-Petersburg, Russia<sup>2</sup>

Prydz Bay is a large shelf embayment and the only shelf of East Antarctica studied with MCS surveys. This region is dominated by SW-NE trending intracontinental rift zone which on the outer shelf connects to the marginal rift (Leitchenkov et al., 1991). First seismic investigations in the Prydz Bay were carried out by BMR (Australia) in 1981 and afterwards great amount of data was obtained by Japanese and Russian Expeditions. Two ODP Legs (119 and 188) provided valuable information on geology, deposition and paleoenvironments of this region.

Previous seismic stratigraphy models were suggested by Stagg (1985) and slightly modified by Cooper with coauthors (1991). Stagg (1985) identified five seismic units (PS.1 to PS.5) and acoustic basement beneath the Prydz Bay shelf. Units from PS.5 to PS.3 were referred to as Late Paleozoic to Mesozoic rift infill while the overlying units PS.2 and PS.1 - as post-rift strata including post-mid-Miocene tillites (PS.1). Cooper et al. (1991) have revised acoustic stratigraphy of Stagg (1985) based on reprocessing of Australian MCS lines, sonobuoy data and drilling results. They redefined PS.5 as a metamorphic basement and subdivided PS.2 on PS.2B and PS.2A interpreting them as preglacial and glacial units, respectively.

We use about 2000 km of new high-quality 352-channel seismic data collected in Prydz Bay by Russian Antarctic Expedition in 2012 for development of seismic stratigraphy and depositional models of this region suggested earlier by Stagg (1985) and Cooper et al. (1991). Moreover, all other seismic data available from SDLS were utilized to map areal distribution of acoustic units, facies and depositional features.

New data showed that unit PS.5 corresponds to the sedimentary layer (not to a basement as Cooper et al. suggested) because demonstrates stratification, medium velocity (4,8-5.3 m/s) from refraction experiments data) and irregular bottom (true crystalline basement). It is mapped at the main rift graben (with a maximum thickness of 2.5-3.0 km) and within extensional half-grabens locally developed on the western rift flank. The top of PS.5 is highly reflective and flat boundary which dips toward the rift depocenter at an angle of 6-7 degrees.

Unit PS.5 is interpreted as a rift infill which deposited at the early stage of intracontinental rifting in the Late Paleozoic to Early Mesozoic. Thickness and physical properties of unit PS5 are close to Permian-Triassic Amery Group outcropped 200 km landward of the Prydz Bay coast. Similar (2-3 km thick) deposits are also mapped in the Perth and Mentelle rift basins in Western Australia. Unit PS5 is traced from the shelf to the outer continental rise marking the position of the intracontinental rift zone modified by later pre-breakup stretching.

Unit PS.4 fills the main rift graben and half-grabens on the western rift flank. It is outcropped (or overlain by a veneer of quaternary sediments) along the eastern part of the inner shelf. In the axial part of main graben, PS.4 is up to 5 km thick and slightly disturbed by normal faults. The top of this unit is well-defined boundary representing an angular unconformity which dips oceanward at an angle of 2-3 degrees. PS.4 was sampled by ODP drilling (Barron et al., 1991) but its age was not defined. We correlate its deposition with a second (Late Jurassic-Neocomian) phase of rifting which preceded Gondwana break-up. Post-rift preglacial unit PS2B is developed in most of Prydz Bay outcropping at the sea floor within the inner shelf.



According to drilling data its middle and upper parts contain fluvial deposits of Late to Early Cretaceous and Late Eocene age. PS2B varies in thickness from a few hundred meters beneath the inner shelf to about 1.5 km beneath the outer shelf.

The top of PS2B (glacial onset unconformity) is better identified on the outer shelf due to change in seismic pattern of overlying strata and can be traced from there toward the middle shelf. Glacial unit PS2A extends from the middle shelf toward the ocean. Where sampled (3 ODP holes), unit PS.2A is mostly composed of massive to stratified diamictites (Barron et al., 1991). This unit consists of two principal sequences showing different styles of sedimentation. The lower sequence is characterized by the development of cross-shelf interchanging and laterally distributed mounded seismic facies beneath the outer shelf (within the zone of 25-50 km wide). Such depositional patterns resemble grounding line fans which are formed at the front of warm-based glaciers by the outflow of meltwater during the stages of ice advance, still-stand, retreat and readvance (Powell, 2003). Lateral distribution of fans along the outer shelf suggests that meltwater portals changed position or were multiple. The lower sequence was deposited at the early stage of large-scale Antarctic glaciation near the Eocene/Oligocene boundary. The upper sequence of unit PS2A is distinguished by the occurrence of the flat-laying (topset) and steeply dipping (foreset) reflections beneath the middle and outer shelf, respectively. The topset beds are interpreted as lodgement till while the foreset (prograding) beds - as till deltas. Several separate forest packages (till deltas) can be identified based on their stratal geometries and bounding unconformities (Boulton, 1990). The oldest till delta has been deposited 50-100 km landward of the present-day shelf break and according to drilling data at Site 739 it is of Early Oligocene age. Younger till deltas formed during subsequent glaciations and ice advances. Most of them were not sampled but outermost is of late Miocene - Early Pliocene age based on tracing nearly flat reflections seaward from Site 739. During the Late Pliocene, the Lambert Glacier-Amery Ice Shelf drainage system flowed across Prydz Bay in an ice stream that reached the shelf edge and built a trough-mouth fan (O'Brien et al., 2004), the feature genetically similar to a till delta. Trough-mouth fan has prograded the shelf edge about 40 km seaward. Thickness of glacial strata ranges from almost 0 km beneath the inner shelf to 1-1.5 km beneath the outer shelf and to 1.8 km beneath the upper continental slope. Syn-glacial (post-Eocene) strata on the continental rise off Prydz Bay vary in thickness from 1.0 to 2.8 km.



**S13 – 75: Past Antarctic Ice Sheet Behaviour and Response to External Forcing**

***Does Indian Ocean Dipole Influence Antarctic Sea - Ice?***

Xiaojun Yuan

Lamont Doherty Earth Observatory, Columbia University, USA

The role of Indian Ocean Dipole on Antarctic sea - ice is explored in this study. Singular value decomposition of sea - ice and SST during Austral spring reveals the Indian Ocean dipole in the Indian Ocean and El Nino in the equatorial Pacific. The sea - ice of the southern hemisphere reveals a co variability with the Indian Ocean Dipole largely by means of the warm/cold advections generated by the high and low pressure cells. These centres of pressure anomalies are formed by the propagation of the Rossby wave trains generated in the east Indian Ocean. Significant anomalies in sea - ice associated with the Indian Ocean Dipole was found west of the Ross sea. In the Pacific sector and in the Weddell Sea this relationship is difficult to assess because ENSO generates larger anomalies there. Also many of the positive (negative) IODs co-occur with El Nino (La Nina). When ENSO is removed, sea-ice in the Indian Ocean (near 60 °E) increases because of cold outflows west of low pressure centres while sea-ice near 90 °E decreases due to the warm advection west of a high pressure centre located south of Australia.



**S13 – 123: Past Antarctic Ice Sheet Behaviour and Response to External Forcing**

***Variability in Antarctic Precipitation and Future Projections Based on the CMIP5 Models***

Malcolm Tang<sup>1</sup>; Sheeba Nettukandy Chenoli<sup>1</sup>; John Turner<sup>1</sup>; Azizan Abu Samah<sup>1</sup>; Ooi See Hai<sup>1</sup>

National Antarctic Research Centre, University of Malaya, Malaysia<sup>1</sup>

The projections from 39 global climate models of the Coupled Model Intercomparison Project phase 5, the Era-Interim Reanalysis, and Global Precipitation Climatology Project satellite data were used to estimate the variability of Antarctic precipitation. Two main periods, 1979-2013 and 2014-2100, of data were analyzed. The historical climatology (1979-2013) shows a slight increase in precipitation since the year 1979, indicating that Antarctic precipitation is mitigating global sea level rise as expected. We also compared the historical climatology in terms of continental precipitation and the precipitation that falls in the entire Antarctic Circle by using the land-sea mask. We investigated further the role of the Southern Annular Mode (SAM), the El Nino Southern Oscillations (ENSO) and cyclonic activities on the variability of precipitation. The model predicts an increase of precipitation for the next hundred years, in some regions - especially near the coastal area, by as much as 100mm. The intermodel variation in predicted precipitation magnitude between models and reanalysis, however, severely restrict the reliability of these projections, and highlight the need for improved polar models in future.



**S13 – 160: Past Antarctic Ice Sheet Behaviour and Response to External Forcing**

***Temperatures in the Ross Sea during the Middle Miocene Climatic Optimum from Clumped Isotope Analyses of Andrill-2a Carbonates***

Taviani, M.<sup>1</sup>; Eagle, R.<sup>2</sup>; Riesselman, C.<sup>3</sup>; Tripathi, A.<sup>2</sup>; ANDRILL SMS Team<sup>4</sup>

ISMAR, Bologna, Italy<sup>1</sup>; UCLA, Los Angeles, United States<sup>2</sup>; University of Otago, New Zealand<sup>3</sup>; ANDRILL SMS Team<sup>4</sup>

Recently published proxy evidence from foraminiferal B/Ca and leaf stomata indicate that pCO<sub>2</sub> may have been sustained at 350-450 ppm during the Middle Miocene Climatic Optimum (MMCO). On Antarctica, the MMCO has been identified mainly from ecological and sedimentological descriptors, with approximate estimates of temperature derived from these and other proxies. Here we present the first thermodynamic estimates of temperatures in the near-shore coastal Antarctic using 'clumped' isotope thermometry, a technique that is founded on the measurement of <sup>13</sup>C-<sup>18</sup>O bond abundances in carbonate minerals. It has an advantage over traditional oxygen isotope thermometry as 13C-18O 'clumping' is independent of the d<sup>18</sup>O of the fluid from which the mineral formed, and there are apparently no complications from biological influences on isotope distributions. We have measured marine carbonates from the SMS ANDRILL-2A borehole and obtained preliminary calcification temperatures of 7.2 ± 1.1°C (1 standard error) from 10 analyses of 5 bivalve samples. These results support conditions on Western Antarctica during the MMCO that were considerably warmer than today, with temperatures in the Ross Sea that were similar to modern-day temperatures from sub-polar environments.



### S13 – 233: Past Antarctic Ice Sheet Behaviour and Response to External Forcing

#### *Variability of Antarctic Ice Sheets versus Northern Ice Sheets at Orbital Timescales*

Roychowdhury Rajarshi<sup>1</sup>; Deconto Rob<sup>1</sup>

University Of Massachusetts, Amherst, United States<sup>1</sup>

#### Background:

The variability of Antarctic versus Northern hemispheric ice sheets has been a mystery for a long time. Global proxy records such as benthic  $d^{18}O$  capture the alternating glacial and interglacial conditions during the late Pliocene - early Pleistocene (0.8-3.1 Ma), showing primary periodicity at obliquity periods (41 kyr), instead of the 23 kyr precessional cycle which controls local insolation. The two competing theories (Huybers 2006 & Raymo et al. 2006) trying to explain this 41-kyr anomaly in global ice volume records, contradict each other in terms of variability of Northern hemispheric and Antarctic ice sheets. Huybers proposed that glacial cycles are driven by the total integrated summer insolation, which does not vary at precessional periods. Thus the Northern and Antarctic ice sheets vary in-phase and are driven by obliquity alone. Raymo proposed that glacial cycles are driven by local summer insolation, which varies mainly at precessional periods, but is out-of-phase between the hemispheres. Thus Antarctic and Northern ice sheets vary out-of-phase, and the effects cancel each other at precessional periods.

#### Objectives:

An improved understanding of the how the earth's response to orbital forcing varied in the past with respect to the different orbital parameters namely eccentricity, obliquity and precession has provided an opportunity to study the pulsation of the Antarctic ice sheets along with the Northern ice sheets. Using sophisticated global climate and ice-sheet models, we aim to find whether the Northern and Antarctic ice sheets vary in-phase or out-of-phase, and whether this behavior changed with variation in the earth's orbital parameters.

#### Methods:

In this study, we use a top down approach and physically based models to gain insight into the variability of the Antarctic ice sheet and the Northern ice sheet and if any relation can be identified between them. In the first part of the study, we carry out an ensemble of GCM simulations using a range of orbital forcings to calculate a summer metric (sum of positive degree days), which is a good indicator of air temperature's influence on annual ablation at high latitudes. In the next part of the study, we run a coupled GCM - ice sheet-shelf model at a very high temporal resolution to simulate the evolution of Antarctic ice sheets through different orbital forcings at precessional and obliquity periods.

#### Results:

GCM results show obliquity response between northern and southern hemisphere is in-phase at all eccentricities. Interestingly, the hemispheric response to precession changes with eccentricity. At low eccentricities ( $e < 0.015$ ) the effect of precession is minimal, and the summer metric varies in-phase between the two hemispheres. Thus, Northern Hemisphere and Antarctica have in-phase ice-sheet variability, forced by northern insolation intensity, and it varies primarily in the obliquity band. At higher eccentricities ( $e > 0.015$ ) precessional effects are important, and the summer metric varies out-of-phase between the two hemispheres. Consequently, Northern and Antarctic ice-sheets vary out-of-phase with each other, the primary variance in each hemisphere being in the precessional band. These results are confirmed in the coupled GCM - ice sheet-shelf model covering a period of 130 kyr covering MIS 31 (1010 - 1140 ky bp). At low eccentricity period (1120 - 1133 ky bp), simulated Antarctic ice volume follows northern hemisphere insolation. At higher eccentricity, simulated Antarctic ice volume follows local southern hemisphere insolation.



**Conclusion:**

The response of Antarctic ice sheets to orbital forcing depends on eccentricity. At low eccentricities, Antarctic ice sheets are forced by Northern Hemisphere insolation, and vary in-phase with northern ice sheets. At higher eccentricities, Antarctic ice sheets are forced by local southern hemisphere insolation, and vary out-of-phase with northern ice sheets. This switch in the forcing of Antarctica ice sheets from southern hemisphere insolation to northern hemisphere insolation at low eccentricity periods causes it to miss a beat in the glacial-interglacial cycles at 23 kyr periods. Thus, depending on the orbital conditions, Antarctic either has a long glacial or interglacial period following a low eccentricity orbit. When Antarctica has prolonged interglacial type conditions, it creates a preconditioning for a strong interglacial like MIS 11 or 31, which are indicated by deep sea warming and reduced global ice volume. Indeed, it has been observed that most strong interglacials follow a period of low eccentricity.



### **S13 – 251: Past Antarctic Ice Sheet Behaviour and Response to External Forcing**

#### ***Reconstructing the Glacial History of the South Orkney Islands, NE Antarctic Peninsula***

William Dickens<sup>1</sup>; Alastair Graham<sup>2</sup>; James Smith<sup>1</sup>; Julian Dowdeswell<sup>3</sup>

British Antarctic Survey, United Kingdom<sup>1</sup>; University Of Exeter, United Kingdom<sup>2</sup>; Scott Polar Research Institute, United Kingdom<sup>3</sup>

Advances in the coverage and quality of marine geophysical and geological data over the past 15 years have led to significant improvements in our understanding of ice dynamics during former glacial periods across the Antarctic Peninsula and sub-Antarctic. Despite these advances, very little is known about the history or past behaviour of ice caps that once dominated the South Orkney Islands (SOI), northeast of the Antarctic Peninsula. Here we present new analyses of geophysical and geological data collected on cruise JR244 of the RRS James Clark Ross to the South Orkney continental shelf in 2011. These data are used to (i) construct a new regional bathymetry for the SOI, (ii) provide detailed insights into past ice cap behaviour from landform assemblages, and (iii) reveal ice dynamics through combined sediment, landform and geochronological studies.

A gridded compilation of new and existing echo-sounding (multibeam and singlebeam) data depicts the regional bathymetry of the SOI in greater detail than was previously possible. From the new dataset, broad-scale ice drainage patterns during former glacial periods are revealed. The new bathymetry indicates that the continental shelf is dominated by at least seven glacially eroded troughs. Trough morphologies demonstrate that grounded ice extended to the shelf break to the north of the islands at least once, and likely on numerous occasions. A large, c. 250 km long sediment depocenter, visualised for the first time by bathymetric data, and in newly-collected single-channel seismic data, is interpreted as a maximum former ice limit of one or more Cenozoic glaciations. The lack of glacial morphology seaward of the depocentre suggests that ice was only ever grounded to the c. 300 m contour in the South and did not extend beyond.

Alongside regional constraints on palaeo-ice cap extent, we also present results from the detailed mapping of glacial bedforms from a number of trough and inter-trough areas which are used to infer information about the former ice cap dynamics and the style of deglaciation. Mapped landform-sediment assemblages differ markedly between the northern and southern parts of the continental shelf. On the northern shelf, glacial lineations indicate the presence of fast flowing ice; this may have been enhanced by high volumes of basal meltwater, as inferred from the presence of bedrock eroded by subglacial meltwater. In contrast, the southern continental shelf shows little evidence of fast ice flow or meltwater activity, but an abundance of deglacial moraines indicates that ice retreat occurred progressively, with varying retreat rates and dynamics. These contrasts are discussed together with ongoing sediment core analyses which aim to test inferred rates of deglaciation and constrain the timing of ice cap retreat following the Last Glacial Maximum. Further work aims to synthesise the geophysical, geological and chronological information in order to provide a holistic understanding of past ice cap change on the SOI.



### S13 – 257: Past Antarctic Ice Sheet Behaviour and Response to External Forcing

#### ***Neogene Quaternary Terrestrial Environmental History in Coastal Eastern Marie Byrd Land Based on Volcanic and Associated Outcrops at Mt Murphy***

John Smellie

University of Leicester, Britain

The stability of the marine-based West Antarctic Ice Sheet (WAIS) and how it may contribute to future sea-level rise is a continuing concern under global warming. Knowing its configuration and how it reacted to past environmental conditions is an important way of assessing its future climatic susceptibility and identifying the principal forcing factors. Our knowledge of the pre-LGM environmental history of the WAIS in Marie Byrd Land is overwhelmingly biased toward the marine record through offshore geophysical and sedimentary studies, and largely for Quaternary time. However, although successful in documenting fluctuations in ice sheet extent, the marine record is unable to reconstruct many other important environmental aspects, especially those useful for reconstructing ice sheet configuration. For example, they cannot determine how thick past terrestrial ice was, or reliably infer the basal regime, or identify if there were ice-free periods.

An alternative approach is to examine neglected onshore outcrops which, in Marie Byrd Land, are mainly volcanic. Marie Byrd Land hosts the largest concentration of Neogene and younger volcanoes (< 28 Ma) in Antarctica. Many exceed 3 km in summit elevation. However, sections cut deeply into volcano interiors and therefore capable of yielding evidence for past environmental evolution, are frustratingly few. Mt Murphy is the jewel in the crown in the region. It is a large late Miocene (c. 9 Ma) basalt-trachyte shield volcano with several small basaltic satellite centres (c. 7-5 Ma) and late-stage pyroclastic cones (< 1 Ma). Because the outcrops are situated in coastal Marie Byrd Land, they have been extensively eroded by a combination of marine and glacial action. The few published studies have documented a relatively simple environmental history comprising past ice sheets with surfaces that fluctuated widely. A putative glaciolacustrine deposit was also identified whose high elevation was interpreted (incorrectly) to indicate a very thick regional ice sheet in late Pliocene time.

A reconsideration and reappraisal of the evidence suggests that the published studies are incorrect in many aspects. Moreover, a much more complicated environmental history is preserved than was previously recognized, with evidence for at least 14 temporally discrete glacial and ice-poor events. Although the information is patchy, with many gaps, it is not obtainable any other way and is therefore a uniquely important window into the long-term terrestrial environmental evolution of coastal Marie Byrd Land. In addition to imprecisely dated ice-poor periods represented by reworked diatom assemblages in the supposed lacustrine deposit, the results of this new study indicate that the Neogene WAIS was mainly a thin (few hundred metres) regional wet-based ice sheet. It thickened enormously in the Quaternary on at least two occasions, when the surface elevation of the ice increased to c. 600 - > 1400 m higher than at present and it was also wet-based until the advent of modern local cold-based conditions. The volcanic rocks also document at least two hitherto-unrecognized periods of ice-poor or ice-free conditions. Studies are underway to date those events that are currently undated.



### S13 – 275: Past Antarctic Ice Sheet Behaviour and Response to External Forcing

#### ***Testing the Extent and Timing of Past Glaciations Offshore of the Sub-Antarctic Island of South Georgia***

Alastair G.C. Graham<sup>1</sup>; Gerhard Kuhn<sup>2</sup>; Claus-Dieter Hillenbrand<sup>3</sup>; Dominic A. Hodgson<sup>3</sup>; Werner Ehrmann<sup>4</sup>; Ove Meisel<sup>5</sup>; Robert D. Larter<sup>3</sup>; Colm A. Cofaigh<sup>6</sup>

College of Life and Environmental Sciences, University of Exeter, UK<sup>1</sup>; Alfred-Wegener-Institut Helmholtz-Zentrum für Polar- und Meeresforschung, Bremerhaven, Germany<sup>2</sup>; British Antarctic Survey (Natural Environment Research Council), Cambridge, UK<sup>3</sup>; Institute of Geology and Geophysics, University of Leipzig, Leipzig, Germany<sup>4</sup>; Department of Earth Sciences, VU University Amsterdam, Amsterdam, Netherlands<sup>5</sup>; Department of Geography, Durham University, Durham, UK<sup>6</sup>

There has been a long history of debate over the extent and timing of past glaciations on the small but climatically-sensitive islands of the sub-Antarctic. The largest of these islands, South Georgia, has been the focus of contention with two conflicting models proposed for the peak of the last glaciation (the Last Glacial Maximum, c. 21 k yrs B.P.): one suggesting an ice cap of restricted extent that saw tidewater outlets limited to the coastal basins of radial fjords; the other proposing an extensive shelf-wide ice cap based on well-preserved though as yet un-dated or un-sampled sea-bed geomorphology. It has been suggested that these two models form comparative end-members of 'South American' (restricted) and 'Antarctic' (extensive) modes of glaciation, and thus establishing whether the pattern of glaciation on sub-Antarctic islands follows one of these modes, or is in itself entirely different, can provide potentially important insight into past climate forcing of an otherwise poorly-constrained Southern Ocean region. The extent of island glaciation can also provide valuable far-field constraint for Antarctic ice sheet models, and forms vital information for biologists seeking to understand benthic marine communities around South Georgia, whose evolution and structure are intimately linked to the long-term history of ice advance and retreat.

Here we investigate the geological record offshore of South Georgia to improve understanding of the extent and timing of past glaciation. Marine geophysical data from new and previous research cruises have been compiled and analysed to advance knowledge of palaeo-ice cap dynamics on the island's submerged sea bed and subsurface. We have also sought an independent verification of the glacial history of the island by linking new geomorphological analyses with dated marine sedimentary records recovered by coring, for the first time, on the continental shelf.

We present results of new landform mapping on the sea-bed of the South Georgia block. Mapped moraine belts demarcate a minimum of three shelf limits of former glaciation: (1) a shelf edge maximum, (2) an outer basin/fjord mouth limit, and (3) an inner basin moraine position. In addition, numerous spatially-discontinuous moraines must represent further intermediary ice-marginal extents. Geomorphological observations are consistent with the larger configurations of the palaeo-ice cap being highly dynamic, reflected in the pattern, geometry, and sedimentary sequences of cross-shelf glacial troughs, extensive depositional moraine systems, subglacially-generated bedforms, and meltwater-carved channels mapped from multibeam bathymetric survey and sub-bottom echo-sounder data. Reconstructed limits suggest a complex offshore glacial history, and provide hitherto unrivalled insight into the spatial configurations of past sub-Antarctic ice caps. A key question is whether the most prominent moraines were formed during successive Cenozoic glaciations or during retreat and readvance(s) since the last glaciation. We present preliminary chronological investigations of marine gravity cores from the Cumberland Bay and Royal Bay areas of the north-eastern shelf that provide tests of the restricted vs extensive ice-cap hypotheses. We show additional sedimentological and physical properties data from the suite of sediment cores that give insight into fjord and shelf depositional environments, patterns of Holocene glacier behaviour, and contribute more broadly towards a better characterisation of South Georgia's long-term marine environmental history.



**S13 – 289: Past Antarctic Ice Sheet Behaviour and Response to External Forcing**

***Bayesian Determination of Thwaites Catchment Internal Age Structure Using Radar Stratigraphy***

Gail Gutowski<sup>1</sup>; C. S. Jackson<sup>1</sup>; D. D. Blankenship<sup>1</sup>; D. A. Young<sup>1</sup>

University of Texas, Austin, United States<sup>1</sup>

Information about the history and dynamics of ice sheets is contained in basin-scale radar sounding surveys. Englacial, isochronous radar horizons traced throughout the sampled domain of these basins can give a three-dimensional picture of past ice flow by revealing significant details of deformation within the ice column. However, the value of this stratigraphy is increased if we can assign absolute dates to the horizons from ice cores. We focus our efforts in the Thwaites Glacier catchment, West Antarctica, which previous studies have shown to be a bellwether for future WAIS deglaciation scenarios. The closest source of in situ age data is the WAIS Divide and Byrd ice cores, in the adjacent Ross Sea Embayment catchment.

Here we present a Bayesian determination of the age-depth profile at the 1968 Byrd ice core, Antarctica, based on robust uncertainty estimates in ice core ages and radar sounding depths. A simple ice flow model is used to determine the age-depth relationship near the ice core and a Markov Chain Monte Carlo technique is used to sample a posterior distribution of age as a function of depth to within uncertainty. This age-depth profile is further constrained by the published chronology of the more recent WAIS Divide ice core, which can be connected to the Byrd ice core chronology through direct comparison because of continuity of radar layers between the two drill sites. Drilled 40 years later, the WAIS Divide ice core chronology is expected to be of higher quality than Byrd ice core measurements due to advances drilling technology and scientific methodology.

We propagate the age-depth information, including uncertainty, for several prominent radar reflectors from the Byrd and WAIS Divide ice-coring sites in the Ross Embayment across the ice divide and throughout the Thwaites Glacier catchment using extensive airborne ice-penetrating radar data collected and processed by the University of Texas Institute for Geophysics (UTIG) and the Center for Remote Sensing of Ice Sheets (CRaSI).



**S13 – 299: Past Antarctic Ice Sheet Behaviour and Response to External Forcing**

***Enhanced Seismic Resolution Created by Attribute Analysis Suggests Significant E.A.I.S Contribution to Miocene Ice Sheet Flow in West - Central Ross Sea***

Seth J. Brazell<sup>1</sup>; Louis R. Bartek<sup>1</sup>

University of North Carolina at Chapel Hill, United States<sup>1</sup>

Interpretation of the glacial history of stratal units in the subsurface of west-central Ross Sea were aided by seismic stratigraphic analysis of single (SCS) and multi-channel seismic (MCS) data. A unique glaciogenic feature, that suggests northeasterly ice sheet flow, was identified in SCS data in the central Ross Sea, Antarctica. Adjacent seismic lines, that cross this feature, are lower resolution, MCS data. Unfortunately, critical details, identified in higher resolution, SCS data are obscured in the MCS data. Application of seismic attribute analysis enhanced the resolution of the MCS data, revealing facies characteristics at a scale that is comparable to that found in SCS data. Complex trace analysis provided enhanced visualization of reflection geometries that were unrecognizable in standard amplitude sections. Application of spectral decomposition made it possible to delineate thin beds that previously were amalgamated into single reflections within the MCS data.

To summarize, use of seismic attribute analysis on seismic data, of various resolutions, from the Ross Sea, resulted in an enhanced understanding of the geometry and internal facies heterogeneity of a glaciogenic feature in west-central Ross Sea. The characteristics revealed by the attribute analyses suggest that during the Miocene there was ice stream flow from the southwest toward the northeast in west-central Ross Sea. This observation suggests that the East Antarctic Ice Sheet made a significant contribution to ice sheet flow in the western Ross Sea during the Miocene.



### S13 – 302: Past Antarctic Ice Sheet Behaviour and Response to External Forcing

#### ***Uncertainties arising from Different Climate and Ocean Scenarios for Modeling the Contribution of Antarctic Ice Sheets to Sea Level Rise during Termination I***

Then F<sup>1</sup>; Bernales J<sup>1</sup>; Rogozhina I<sup>1</sup>; Stroeven AP<sup>2</sup>

Helmholtz Centre Potsdam - GFZ German Research Centre for Geosciences, Potsdam, Germany<sup>1</sup>;  
Department of Physical Geography, Stockholm University, Bolin Centre for Climate Research, Stockholm University, Stockholm, Sweden<sup>2</sup>

During the Last Glacial Maximum (LGM, 26 to 19 thousand years ago) continental-scale ice sheets covered most of North America, northern Europe and parts of Asia. The Antarctic and Greenland ice sheets were also more voluminous than today and extended across most of their continental shelves. The growth of ice sheets towards the LGM caused global sea level to fall with 120-130 m relative to today. The rise in sea level during Termination I, the transition from the Weichselian glacial period to the Holocene interglacial, occurred in several pulses as massive volumes of melt water from retreating and disintegrating ice sheets and glaciers were routed to the oceans. Current ice sheet models still struggle to obtain the rates of ice mass loss needed to explain the large difference between late glacial and interglacial sea levels. Some 20% of the observed sea level rise cannot be attributed to any known former ice mass, indicating that these arise from the deficiencies in the modelled reconstructions of ice sheet volumes and postglacial rebound. In particular, the contribution of the Antarctic ice sheets (AIS) to the sea level rise is one of largest unknowns due to the lack of constraining geological and geophysical data and because of uncertainties in the regional climate history. While geological investigations have yielded the chronology of marginal retreat since the LGM for large tracts of the Antarctic continental shelf, the former ice sheet geometry remains mostly a matter of speculation. The uncertainties in climate history and, therefore, model-derived ice sheet thicknesses, are especially pronounced close to the continental margins, which are remote from constraints offered by ice core sites. Reconstructing regional changes in the AIS geometry and dynamics during Termination I is important, since it will shed light into the responses of different ice sheet sectors to global climate changes and their contributions to global sea level rise. This study presents a detailed analysis of uncertainties in the regional retreat history of the AIS arising from insufficiently-well constrained regional evolutions of climate and ocean conditions since the LGM. We have designed a series of high-resolution deglaciation simulations of AIS using SICOPOLIS, driven by a wide range of climate and ocean scenarios and calibrated against present-day observations. This temporal forcing is based on 18 outputs of global circulation models for the LGM and the mid-Holocene combined with information derived from ice core and sediment records.

We derive maps of regional uncertainties in ice sheet thickness and estimate the limits for the regional contribution of AIS sectors to global sea level rise during major stages of Termination I. The performance of the applied climate and ocean scenarios is evaluated according to the spatial resolution of the input fields and the degree of convergence between the simulated ice sheet retreat and the retreat history inferred from geological evidence. For the best-fit simulation of the AIS history, we also demonstrate a gradual alteration in ice stream dynamics during Termination I, following the retreat of ice masses across the continental shelf.



### **S13 – 359: Past Antarctic Ice Sheet Behaviour and Response to External Forcing**

#### ***Constraints on Transient Fast Flow at South Pole in the Last Glacial Cycle***

Cavitte M. G. P.<sup>1</sup>; Blankenship D. D.<sup>1</sup>; Johnson J. V.<sup>2</sup>; Siegert M. J.<sup>3</sup>; Young D. A.<sup>1</sup>; Carter S. P.<sup>4</sup>; Gutowski G. R.<sup>1</sup>; Jackson C. S.<sup>1</sup>

UTIG, Austin, Texas, USA<sup>1</sup>; University of Montana, Missoula, USA<sup>2</sup>; Bristol Glaciology Centre, Bristol, UK<sup>3</sup>; Scripps, San Diego, USA<sup>4</sup>

Many parts of the East Antarctic Ice Sheet remain to be explored: in particular the South Pole region, where the lack of satellite data has limited our understanding of a key part of the East Antarctic interior. South Pole has been assumed to be a very stable part of the ice sheet, which drove the siting of the IceCube neutrino detection experiment. However, airborne radar data collected by the University of Texas Institute for Geophysics (UTIG) between South Pole and the Trans-Antarctic Mountains has revealed a history of fast flow transients as evidenced from the disturbed radar layer record (Bingham et al, 2007). We further constrain the spatial and temporal extent of these perturbations in the ice sheet flow through the tracing and analysis of a set of extensive radar layers. This radio-stratigraphy has been age correlated with the IceCube dust age-depth record and the SPRESSO core timescale; vertical variations in age depth across the South Pole region indicate enhanced flow at the height of the last glacial maximum, between 51 ka and 17 ka. Dating uncertainties are constrained for each radar layer as a function of the resolution of the radar system and the SNR of the layer record (Cavitte et al., in prep.). The South Pole radio-stratigraphy shows distinct ice stream margins with an asymmetry suggestive of a complex temporal evolution of the margins. Paleo-accumulation rates reconstructed from the radar layers via 1D strain modeling show anomalous linear accumulation features, suggestive of localized enhanced melt rates, consistent with the presence of subglacial lakes in the area (Peters et al, 2008). The dynamic relationship between accumulation rates and melt rates due to ice streaming is used to reconstruct potential ice streaming velocities in the past at likely upstream domes.

We numerically investigate a variety of ice stream geometries as well as the spatial migration of their margins through time, using a simple transverse 2D flow model, in which we compare and contrast discrete vs. continuous margin evolution, and hypothesize the distribution of basal melt corresponding to these scenarios. Presence of fast flow reaching deep into the interior of the Antarctic Ice Sheet has crucial ramifications for ice sheet stability with implications for rapid sea level rise; our study will also support the SPICECORE intermediate ice coring in the South Pole area where the complex flow history will need to be understood in order to obtain a reliable age-depth reconstruction.



**S13 – 399: Past Antarctic Ice Sheet Behaviour and Response to External Forcing**

***Holocene Marine-Based Ice Sheet Instability in the Ross Sea***

Rob McKay<sup>1</sup>; Nicholas Golledge<sup>1</sup>; Sanne Maas<sup>1</sup>; Tim Naish<sup>1</sup>; Richard Levy<sup>2</sup>; Gavin Dunbar<sup>1</sup>; Gerhard Kuhn<sup>3</sup>

Victoria University of Wellington, Australia<sup>1</sup>; GNS Science, New Zealand<sup>2</sup>; Alfred Wegener Institute, Germany<sup>3</sup>

Given the hypothesized instability of marine-based ice sheets to future warming, constraining the rate of retreat under past natural warming regimes can provide new insight into the mechanics of ice sheet retreat and their sensitivity to environmental change. However, the timing of this retreat in Antarctica is variably well-constrained. In part this is due to a paucity of suitable post-LGM records, but also due to the well-documented difficulties in reliably dating marine deposits with the <sup>14</sup>C method around Antarctica due to a lack of suitable carbonate material. Most chronologies from the marine realm in the Ross Sea are largely dependent on Acid Insoluble Organic radiocarbon ages from bulk sediments that inherently overestimate the timing of glacial retreat ages due to pervasive reworking of older carbon on the continental shelves of the Antarctic. Here, we report a lithofacies-based retreat history from the ANDRILL Coulman High drill site in the Central Ross Embayment. This site was located within the paleo-drainage path of the Byrd Glacier, the largest East Antarctic Ice Sheet outlet glacier draining in to the Ross Sea at the LGM. Planktic and benthic foraminiferal-based radiocarbon dates from a laminated-diatom- and ice-rafted debris-bearing glaciomarine mud constrain the retreat history of the Last Glacial Maximum (LGM) ice sheet in the Ross Embayment. During post-LGM retreat of the ice sheet margin in western Ross Sea, the calving line became 'pinned' in the Ross Island region and the grounding line continued its retreat toward its present day location. This establishes that the modern-day calving line location of the Ross Ice Shelf was established by the Early Holocene, and that the ice sheet retreat was initiated in the Ross Sea prior to this time, but also continued through into the mid-Holocene. We examine our results in the context of oceanic drivers and marine instability mechanisms for the LGM retreat of the ice sheets in the Ross Embayment.



**S14 – 27: The Himalayan Cryosphere - Global Versus Regional Climate Forcing**

***Reconstructing Glacier Fluctuations Post - Little Ice Age (LIA) in the Ravi Basin, North-Western Himalaya***

Pritam Chand<sup>1</sup>, Milap Chand Sharma<sup>1</sup>

JNU, Delhi, India<sup>1</sup>

The Himalaya encompasses one of the largest glacier-covered areas outside the polar-regions. Studies suggest that the Himalayan glaciers had responded to the global cooling associated with the Little Ice Age (LIA). However, there is no realistic estimate to suggest how the recession occurred after the termination of this globally important climatic event barring exceptions. Pattern of deglaciation following the LIA is important towards understanding the role of natural versus anthropogenic contribution in glaciers' response in the age of modern mechanization and development (IPCC, 2007). Thus, the present study documents, analyses and reconstructs fluctuation of valley glacier in the Ravi basin of North-Western Himalaya, one of the highly sensitive transitional regions of the Himalaya, since LIA maximum using historical records/maps, remote sensing data and field observations. Geomorphological evidence, i.e., trimlines, perseverance of recessional and latero-frontal moraines, are used to construct quantitative data on the glaciers' morphological characteristics and the changes since the LIA. The study also highlights the glacier fluctuation since the LIA maximum glacier advance for the other valley glaciers in the Himachal Himalaya, in particular. The preliminary results show a general state of glacier retreat since the end of LIA with varying rates between one glacier and the other. Such behaviour can be attributed to the influence of micro climate, topographical factors, glacier morphology and the nature of debris cover. Additionally, centennial climate fluctuation using the available reanalysis data for the Himachal Himalaya is also discussed.



## S14 – 38: The Himalayan Cryosphere-Global Versus Regional Climate Forcing

### *Snow accumulation and ablation processes in the Himalayas*

Sarita Tiwari<sup>1</sup>; S.C.Kar<sup>1</sup>; R.Bhatla<sup>1</sup>

National Centre for Medium Range Weather Forecasting, Noida, Ghaziabad.<sup>1</sup>

Himalaya is the source of India's major river system. About 10 to 70% annual discharge comprises of melt water in Indus and its tributaries. More than 50% of the annual flow of Satluj River is contributed by snow and ice melt in Himalaya. Estimation of the rate and volume of snow and glacier runoff during spring and summer seasons is needed for the efficient management of water resources, including flood forecasting. Therefore it is important to understand the mechanism of snowfall and snowmelt in the Himalayan region. Winter precipitation over Himalayan region is interlinked with many large scale ocean and atmospheric phenomenon like North Atlantic Oscillation (NAO), Arctic Oscillation, El Nino Southern Oscillation and Western Disturbances. Skill of hydrological models for stream flow prediction depends on how accurately the model input variables and parameters have been entered. Snowmelt factor is one of the important input parameter in hydrological models that governs the melting of snow and ice. It can change about 10 % in output of Hydrological model that is used to predict stream flow for a snowy river basin.

Another important input parameter is snow depletion curve which shows relation between snow cover area (SCA) and snow water equivalent (SWE). A linear relation between SCA and SWE assumed in hydrological modes may not always be correct. Therefore it is important to study these model input parameters.

Reanalysis data (CFSR) and ERA-Interim from 1979 to 2007 have been used in this study. In addition to above, monthly remotely sensed snow water equivalent data from SSMR and SSM/I from 1979 to 2007 are also used. Snow cover data (8-day) from MODIS from 2001 to 2008 have been used in this study. Monthly mean and seasonal mean snow amount, snow melt amount and melt factor have been computed. Composite analyses have been made to understand the accumulation and ablation processes. Observed climatology of seasonal mean precipitation (mm/day) for December, January and February (DJF) over the north and northwest parts of India and adjoining regions shows a northwest-southeast oriented precipitation patch extending from northern parts of Pakistan, Afghanistan up to some parts of Jammu and Kashmir (J&K), Himachal Pradesh (HP) and Uttarakhand (UK). As the western disturbances approach the Indian region, they offload most of the moisture over Hindu Kush and Western Himalayas in the form of snowfall and rainfall. As the western disturbance moves further east, their intensity weakens and moisture available for causing more precipitation also gets reduced. Some amount of precipitation is received over the mountains of Himachal Pradesh and Uttarakhand. Averaged accumulated SWE (per month) climatology based on data from 1979 to 2007 for DJF from NSIDC, CFSR and ERA-I have been examined. The large-scale pattern of SWE from all the three sources is similar. In reanalysis (CFSR & ERA-I), the SWE values are grossly underestimated as compared to remotely sensed data with ERA-I having the minimum values. In order to understand the mechanism of snowfall and snow accumulation variability in winters in interannual cycle, composite analyses of SWE as well as several atmospheric and surface parameters have been done. Composite analysis for winds and temperature for DJF at 500hPa and moisture convergence for excess and deficient snowfall years and their differences are examined. This study suggests that larger amount of snowfall during winters over the study area occurs when there is a deep trough in winds at 500hPa, moisture convergence occurring over the region with moisture transport from the Caspian Sea and the Arabian Sea, and in the presence of colder air at 500hPa. In April, snowmelt mostly occurs in Afghanistan and northern parts of Jammu and Kashmir. Along the Pir Panjal range, snowfall continues in April and it is seen that the snow amount is more in April than in May over this region. From May onwards drastic decrease in snow is seen with melting of snow increasing with increase in temperature. . In June and July, most of the snow in the region melts and is available as snowmelt runoff. Thus, it is found that maximum runoff from snowmelt in J&K, Himachal and Uttarakhand



occurs in the months of June and July, whereas maximum snowmelt occurs in Afghanistan and adjoining regions in April and May. The melt rate (cm per degree per day) averaged over 29 years have been computed and variation of melt rate with elevation and month has been examined. The melt rate ranges from 0.02 to 0.6 cm/°C/day. Using the computed melt factor, a snowmelt model has been developed and its skill and issues have been examined.

There is considerable interannual variability in snow over the region. For snow fall and its accumulation, colder upper air temperature along with presence of a westerly trough and moisture convergence are required. It has been observed that the SCA-SWE relationship in the Himalayas is not linear as assumed in many studies.



**S14 – 41: The Himalayan Cryosphere - Global Versus Regional Climate Forcing**

***Region-Wide Summer Mass Balance of Chandra Basin Glaciers, Lahaul Spiti Valley, Western Himalaya***

Parmanand Sharma<sup>1</sup>; Lavkush K. Patel<sup>1</sup>; Ajit T. Singh<sup>1</sup>; Thamban Meloth<sup>1</sup>; Rasik Ravindra<sup>2</sup>

National Centre for Antarctic and Ocean Research (ESSO-NCAOR), Goa, India<sup>1</sup>; Ministry of Earth Sciences (MoES), Government of India, New Delhi, India<sup>2</sup>

The glaciers of Himalaya are used as a proxy to understand local and regional climate variation and widely acknowledged as climate change indicators. However, the behaviour of Himalayan glaciers remains poorly known. To estimate the region-wide summer mass balance of Chandra basin glaciers for ablation period of 2014, a network of stakes were established over six glaciers (Sutri Dhaka, Batal, Samudra Tapu, Bara Shigri, Gepang and Kunzam) and measurements were made from June to October in 2014 at fortnightly /monthly interval. The Chandra basin falls in the monsoon-arid transition zone which is alternatively influenced by the summer Asian monsoon and the mid-latitude westerlies, bringing precipitation in winter. However, this basin experience leeward effect which prevents part of the monsoon flux from reaching the valley. The six above mentioned glaciers cover almost 40% of the glacier area of this basin and represent most of the aspects of the glaciers of this basin. During the 2014 ablation period, the overall region-wide summer balance of glaciers of Chandra basin has been estimated to be  $1.18 \pm 0.21$  m w.e., which is two to three times less negative than the global average for alpine glaciers. Maximum negative balance ( $3.58 \pm 0.6$  m w.e.) has been observed at east facing C- type glacier (clean ice) while minimum balance ( $0.45 \pm 0.6$  m w.e.) has been observed on small glaciers above 5000m altitude. One of the biggest glaciers, Bara Shigri of this basin has experienced less negative glacier wide summer balance of  $0.8 \pm 0.16$  m w.e. than the average of Chandra basin. Contrasting ablation results among the studied glaciers suggested that summer balance in this basin is mainly controlled by a combined impact of solar radiation, glacier flow direction and debris cover. However energy budget investigations are still needed to confirm this.

Key word: Glacier, Himalaya, Chandra basin, Mass balance, Ablation



## S14 – 45: The Himalayan Cryosphere - Global Versus Regional Climate Forcing

### ***Accuracy Assessment of tModerate Resolution Imaging Spectroradiometer (MODIS) Fractional Snow Products for Eastern Himalayan River Basin***

A. Bhadra<sup>1</sup>; P. Mishra<sup>1</sup>; K. T. Tayal<sup>1</sup>; V. V. Zaphu<sup>1</sup>; N. Monica<sup>1</sup>

NERIST, Arunachal Pradesh, India<sup>1</sup>

MODIS fractional snow cover products are appealing for hydrological applications because of their good accuracy and daily availability at free of cost. The NASA Earth Observing System (EOS) Moderate Resolution Imaging Spectroradiometer (MODIS) provides improved capabilities to provide fractional snow cover from space and has been successfully used to get the global, automated binary maps of snow cover. The NDSI is a spectral band ratio that takes advantage of the spectral differences of snow in shortwave infrared and visible MODIS spectral bands to identify snow versus other features in a scene. Researchers evaluated whether there is a signal in the NDSI that could be used to estimate the fraction of snow within a 500 m MODIS pixel and thereby enhance the use of the NDSI approach in monitoring snow cover. They have developed fractional snow cover algorithms for global-scale use with MODIS. The accuracy of fractional MODIS snow products must be known in order to optimize their use in eastern Himalayan region.

: Accuracy assessment of the MODIS fractional snow covered maps with measurements of snow cover from higher resolution LISSIII/AWiFS data, which are considered to be the truth for this work.

: The Nuranang river basin located in Tawang district of Arunachal Pradesh, India is selected as study area. The entire basin is dominated by seasonal snow. Snow starts accumulating from October and ends in March. Melting of snow starts in February and completely depletes by June. Three snow block year of 2006-07, 2008-09, and 2009-10 of MODIS daily fractional snow cover products are downloaded from (<http://reverb.echo.nasa.gov/>). The Nuranang basin comes under the tile identifier h26v06 i.e., horizontal 26 and vertical 6. These data are in HDFEOS format and gridded in a sinusoidal map projection. This sinusoidal projection is re-projected to Geographic Lat/Long and WGS84 datum. Fractional snow cover (FSC) mapping achieve a more precise estimate of areal snow cover extent by estimating the fraction of a pixel that is snow covered. The most common snow fraction methods applied to MODIS images are spectral un-mixing and an empirical NDSI. MODIS (both Terra and Aqua) Snow Cover Daily L3 Global 500 m Grid (MOD10A1 and MYD10A1) contains snow cover and quality assurance (QA) data in HDFEOS format along with corresponding metadata. MODIS Re-projection Tool (MRT) (version 4.1) is used to convert the HDFEOS to GeoTIFF. The MRT is downloaded from the site [https://lpdaac.usgs.gov/tools/modis\\_reprojection\\_tool](https://lpdaac.usgs.gov/tools/modis_reprojection_tool). Using ERDAS IMAGINE 2011, all the converted GeoTIFF images are subset for the study area. After the completion of the subset, comparisons are made between the clipped MOD10A1 and MYD10A1 images to select a cloud free or minimum cloud covered image. Selecting the image between MYD10A1 and MOD10A1 having minimum or zero cloud pixels serves the purpose. The images having cloud cover area (CCA) percentages more than 5% are not considered for the analysis. Snow cover area percentages from cloud free MODIS images (CCA% <5%) are used for comparing with LISSIII/AWiFS images.

Satellite images (LISSIII/AWiFS) for the same snow years are procured from NRSC, ISRO, Hyderabad, India. A NDSI model is coded in ERDAS using Model Maker for discrimination of snow pixel. First, the geo-rectified multi-spectral satellite images (LISSIII/AWiFS) are used as the input file to the NDSI model. Then, the band 2 and band 5 images are separated from the input image. By executing the NDSI model, the image obtained by 10 bit sensor is rescaled to eight bit float image first. Next, the DN values for each band are converted into radiance. Further, the radiance values are converted into reflectance. Finally, the NDSI image is obtained and NDSI values greater than 0.4 is considered as snow plus water. Then the water pixels are removed by masking the water bodies which are marked in the pre-winter image. The



coefficient of determination ( $r^2$ ) is used as performance indicators for comparison of MODIS with LISSIII/AWiFS.

Snow cover area (SCA) percentage from MODIS fractional snow cover products are compared with the SCA% derived from LISSIII/AWiFS images of IRSP6 for the snow years 2006-07, 2008-09, and 2009-10 on specific dates. For the snow year 2006-07 (October to May), first peak is observed in the month of November with SCA% as 13.85% under MODIS and 35.55% under IRS/P6, whereas, second peak, higher than first one, is in the month of February with 86.13% under MODIS and 98.53% under IRS/P6. Overall performance of MODIS considering all eight months of 2006-07 is satisfactory with  $r^2$  of 0.94. For the snow year 2008-09 (October to May), three peaks are observed; first one in the month of November with SCA% as 32.16% under MODIS and 20.97% under IRS/P6, second peak, higher than first one in the month of January with 64.41% under MODIS and 58.78% under IRS/P6, third peak highest among three peaks in the month of April with 77.75% under MODIS and 73.89% under IRS/P6. Overall performance of MODIS for 2006-07 is also satisfactory with  $r^2$  of 0.98. Performance of MODIS in the snow year of 2009-10 is acceptable with  $r^2$  of 0.75 but poorer than other two snow years may be because of cloud. In this snow year, peaks are not obtained in the same month for MODIS and IRS/P6. In case of MODIS only one peak is observed in the month of March with SCA% of 30.66%. Under IRS/P6, first peak is in the month of December with SCA% of 5.10% and second peak, i.e., larger one in the month of April with 21.51%. In general, the obtained SCA% in this particular snow year is lesser than other snow years because of cloud which is responsible for poorer matching of MODIS with IRS/P6 in 2009-10.

The derived SCA% from MODIS fractional snow cover products match satisfactorily with truth for this work i.e., high resolution IRSP6 satellite images, so, it can be concluded that MODIS fractional snow cover product can be used for reliable snow cover mapping in Eastern Himalayan region.



## S14 – 46: The Himalayan Cryosphere - Global Versus Regional Climate Forcing

### ***Analysis of Temporal Variations of Snow Albedo at Different Elevation Zones of an Eastern Himalayan River Basin***

Arnab Bandyopadhyay<sup>1</sup>; N. Chiphang<sup>1</sup>; P. Mishra<sup>1</sup>

NERIST, Arunachal Pradesh, India<sup>1</sup>

Snow albedo is an important climate parameter as it governs the amount of solar energy absorbed by the snow and hence can be considered as a major contributor to the surface radiation budget. Albedo varies in space and time as a result of both natural processes and human activities and is a sensitive indicator of environmental vulnerability. The remote sensing approach has the potential to provide detailed information on how landscape albedo varies through space and time. A detailed knowledge of spatiotemporal changes in albedo is crucial if the global radiation balance and its influence on climate are to be adequately understood

: Present study deals with estimation of temporal variation of snow albedo at different elevation zones in Mago Basin of Arunachal Pradesh which falls in eastern Himalayan region.

Estimated area of selected glaciated Mago river basin is 839 sq. km. Highest and lowest elevations are 6430 m and 2588 m, respectively. The MODIS Daily Snow Products (MOD10A1 and MYD10A1) which provide daily snow albedo for the selected study site, having spatial resolution of 500 m are used in the study. Both the MODIS Daily Snow Products for ten snow years (200313) and Digital Elevation Model (DEM) of the study area were downloaded from NASA Distributed Active Archive Centre (DAAC) (<http://reverb.echo.nasa.gov/reverb/>). The downloaded MODIS data were converted from HDFEOS to GeoTiff format, extraction of the daily albedo layer was performed and to simplify the analysis process subset of the study area was done. Further, the DEM of the study area was subdivided into four zones, Zone 1 (25883500m), 2 (35004500m), 3 (45005500m), and 4 (55006430m) having elevation difference of 1000m. The area (%) under different snow types (dry snow, wet snow, firn and ice) for Whole Basin, i.e four zones were determined by masking DEM model into the albedo images for the 10 block years (October 2003- September 2013). A typical MOD10A1/MYD10A1 scene of 1200 km by 1200 km tiles is subset based on Area of Interest (AOI) layer i.e., study area boundary. Since the number of GeoTiff files to be processed is very large, a Batch Command File (.bcf) file was prepared for each block year in order to perform batch processing.

In the whole basin, almost all the months show a decreasing trend in area (%) of dry snow, wet snow, firn and ice over time. Monthly slopes show a decreasing trend in area (%) of dry snow, wet snow, firn and ice for the entire basin, Zone 3 and Zone 2. While in Zone 4, the average of monthly slopes shows decreasing trend in area (%) of dry snow and wet snow and an increasing trend for firn and ice. 10 years analysis shows that the monthly slopes of snow cover area (%) for all types of snow are decreasing for lower elevation, however at the higher elevation, it shows a mixed trend. The 10 year average variation in area (%) for the whole basin and different zones show that whole Basin, Zone 4 and Zone 3 follows a similar trend with firn occupying the highest area (%) followed by ice then wet snow and the least area (%) by dry snow. In case of Zone 2, ice has higher area (%) over firn and a marginal area (%) of wet snow is detected with no dry snow. Zone 1 does not contain any type of snow.

The average monthly variation in area (%) depicts that firn, ice, wet snow and dry snow start to accumulate from late December till early April, and begins to decrease from late April to the end of August which indicates that this period is the main snow melt season in the study area. Another period of accumulation though lesser in volume starts from September till early November and melts off in the period between late November and December. Yearly spatial variation in dry snow indicates that the existence of dry snow is confined mostly in the Zone 4 and comparatively a very small area (%) in the



Zone 3. Yearly spatial variation of wet snow shows that Zone 4 experienced the highest area (%) of wet snow followed by zone 3 and a very small area (%) in Zone 2. Yearly spatial variation of firn shows that Zone 4 has the highest area (%) which is well over 35% for the entire study period. Ice also exhibits similar spatial variation pattern as the other snow types: Zone 4 with the highest area (%) followed by Zone 3 and then Zone 2. The most persistently snow cover region is Zone 4 which occupies the highest elevation area. In this zone, all the four types of snow are found throughout the year. Zone 1 does not contain any type of snow as such elevation below 3500 m cannot sustain any type of snow.

It can be concluded that effect of climate change is more prominent in lower elevation zone as the areas (%) for all types of snow are decreasing over time in the lower elevation. Over the different elevation zones as well as the whole basin, firn seems to be the dominating type of snow followed by ice after which comes wet snow and the least area (%) is occupied by dry snow. The monthly variation shows that the highest snow area (%) is in the month of March and April. Another peak though lesser one is in the month of September and November. Most of the firn, ice, wet snow and dry snow are confined within Zone 4 and Zone 3. Only a small percentage is in Zone 2 and no snow of any kind was found in Zone 1.



## S14 – 50: The Himalayan Cryosphere - Global Versus Regional Climate Forcing

### *Velocity and Thickness Estimation of Siachen Glacier Using Optical Remote Sensing Data*

H S Gusain<sup>1</sup>; Kanav Barotra<sup>2</sup>; Kamal Kumar<sup>2</sup>; Kavita Mitkari<sup>2</sup>; M K Arora<sup>2</sup>; Ashwagosha Ganju<sup>1</sup>

SASE (DRDO), Chandigarh, India<sup>1</sup>; PEC University Chandigarh, India<sup>2</sup>

Siachen glacier is one of the largest glaciers outside Polar region having length of more than 70 km. It lies in Karakoram Himalayas between 35.2°-35.6°N latitude and 76.8°-77.3° E longitude with an elevation range of 4000 m to above 7000m mean sea level. This valley glacier having width of 1-8 km is fed by many tributary glaciers including two large tributary glaciers Teram-Sher and Lolofond. Nubra river which is a part of Indus drainage system originates from Siachen glacier. Study of glacier dynamics and geometry is very important in assessment of the glacier sustainability and catchment hydrology. However keeping in view the inaccessibility of the Siachen glacier, remote sensing seems to be a promising tool to study this glacier.

Optical remote sensing data of Landsat Thematic Mapper (TM) and Landsat 8 OLI (Optical Land Imager) with spatial resolution of 30 m have been used to estimate the velocity of the glacier. Data of 23-August-2010 and 3-November 2013 was acquired to perform sub-pixel correlation between images. To achieve good correlation it was insured that the images are free of cloud cover and having same path and row. Near Infrared (NIR) Band of both the images was used for co-registration.

COSI-corr a freely available add on tool of ENVI downloadable from [www.tectonics.caltech.edu](http://www.tectonics.caltech.edu) was used for finding correlation. Correlation patches of size 32 x 32 pixels corresponding to .96 x .96 km on the ground were chosen. Correlation mask parameter was set at  $m=0.9$  for initialisation and four robustness iterations were performed and a sliding step of 4 pixels (120x120m) was used. After performing above steps we obtained three output images i.e. North/South displacement image, East/ West displacement image and a signal to Noise ratio Image (SNR). SNR image defines the quality of correlation and all pixels having SNR values  $< 0.9$  were discarded. Finally eulerian norms were used to obtain the resultant velocity. Resultant velocity ranges from nearly 1.4-62 m per annum ( $\text{ma}^{-1}$ ) in the accumulation zone and around 18-38  $\text{ma}^{-1}$  near snout. However maximum velocities of the order of 150-230  $\text{ma}^{-1}$  were observed in the middle region of the glacier. The glacier ice thickness estimates were made using glacier velocities as given by Cuffey and Paterson (2010) and used by many researchers e.g. Gantayat et al. (2014), Linsbauer et al. (2011) etc. Glacier thickness was observed to be varying between 400-700m in accumulation zone and middle part, 100-300m and in the lower part in ablation zone and 50-100 meters near snout. Unfortunately we don't have the ground data of surface velocity and depth measurements of the glacier to validate our results. However results published in the literature using other techniques were found to be in good agreement with this study.



**S14 – 55: The Himalayan Cryosphere - Global Versus Regional Climate Forcing**

***Velocity and Thickness Estimation of a Small Glacier in Great Himalaya Using Optical Remote Sensing Technique***

H S Gusain<sup>1</sup>, Sunita<sup>2</sup>, Kamal Kumar<sup>2</sup>, H S Negi<sup>1</sup>, Kavita Mitkari<sup>2</sup>, M K Arora<sup>2</sup>, Ashwagosha Ganju<sup>1</sup>

SASE (DRDO), Chandigarh, India<sup>1</sup>; PEC University Chandigarh, India<sup>2</sup>

Correlation of sub-pixels between two images acquired at different time using optical remote sensing has been used widely for estimation of glacier velocity recently. The technique has been proven for large glaciers with fairly reasonable estimate of glacier velocities as published by many researchers. However, the technique has not been applied to estimate velocities of small glaciers with glacier length of less than 10 km. In this paper we are analysing the results of this technique on a small glacier of Great Himalaya named Zing-ZingBarâ. The co-ordinates of the middle of the glacier are 32° 46' 02" N latitude and 77° 20' 26" E longitude. Glacier is having N-E Aspect and lies in the elevation range 4607 m to 5531 m from mean sea level. This glacier is of rapidly retreating type glacier due to climate change as reported earlier. To measure ground displacement using remote sensing images, we have selected Landsat-5 Thematic Mapper (TM) and Landsat-7 Enhanced Thematic Mapper Plus (ETM+) of 30m spatial resolution. Satellite images of the period September 2004 and August 2009 were downloaded from USGS website (<http://glovis.usgs.gov/>). In order to obtain good correlation between images, it was ensured that images were of same path and row, and were free of cloud cover. The ASTER digital elevation model (DEM) has been used for topographic analysis. For Co-registration of images band 4 of Landsat TM as well as Landsat ETM+ was used. This band represents near infrared region (NIR) in both the images. We have used COSI-corr (freely available add on tool of ENVI) downloadable from [www.tectonics.caltech.edu](http://www.tectonics.caltech.edu) tool for finding correlation between subpixels of the images. Using correlation image we obtained three output images: a North/South displacement image, an East/West displacement image and Signal to Noise ratio image (SNR). SNR image defines the quality of the correlation. Pixels of correlation having value < 0.9 were moved out. Finally Eulerian norms were used to calculate the resultant velocity. Resultant velocity in the accumulation zone ranges from 1-58  $\text{ma}^{-1}$  and in the middle region of the glacier, velocities of the order of 2-20  $\text{ma}^{-1}$  are observed. Velocities around 1-5  $\text{ma}^{-1}$  are observed near snout of the glacier. An attempt has been made to estimate the thickness of the glacier using surface velocities. Assuming basal velocity to be 25 percent of the surface velocity, thickness has been estimated by the relation given by Cuffey and Paterson (2010). Ice thickness of the glacier has been estimated in the range of 27-42 m near terminus, The thickness increases to 150 m in the middle part and the accumulation zone of the glacier.



**S14 – 79: The Himalayan Cryosphere - Global Versus Regional Climate Forcing**

***The Monsoon Induced Aggradations in the Three River Valleys of NW Himalayas during MIS 3-A Comparative Evaluation on Spatial Variability in the Timing of Deposition***

Saini, H.S<sup>1</sup>; Mujtaba, S.A.I.<sup>1</sup>, Pant, N.C.<sup>2</sup>; Bhattacharya, S.<sup>1</sup>

Geological Survey of India, Faridabad, India<sup>1</sup>, University of Delhi, Delhi, India<sup>2</sup>

The precipitation in the Ganges and the Indus basins are largely controlled by the summer monsoon in the eastern basin and by the "westerlies" in the western basin. Climate record preceding the last glacial maximum (LGM) and during the Marine Isotope Stage 3 (MIS 3) in the western and central Himalayas is represented by the fluvial records of the Indus, the Sutlej and the Alaknanda valleys.

The river morphology, thickness and architecture of late Quaternary deposits in the mid to upper reaches of these valleys have been studied and the timings of major depositional phase in each valley has been constrained using quartz OSL dating of about 40 samples from critical sections.

In Indus valley, fluvial terrace are rare. A 20m thick patch of gritty sand over the lacustrine clays near Spituk (3200m RL) has given a depositional age of ca. 49-46 ka. A prominent patch of semi-loose, non stratified, massive of rounded to sub rounded, poorly sorted pebble to boulder with lenses of coarse sand occur along Tangste river as middle terrace (T2) in Darbuk area (3400m RL). It has yielded a dispositional age of 45-39ka. Satluj Valley has numerous patches of 40-80 m thick gravelly and sandy terrace deposits preserved downstream of Rampur (RL of river bed 1200m) from where river widens and meanders. Important patches are present around Datt Nagar, Nogli, Bihad, Luhree etc. The top of terrace is occupied by a meter thick mud which constitute the main habitation surface. The sequence was aggraded during ca. 49-27 ka. The Alaknanda valley also shows the development of 80-100m thick gravelly terrace deposit downstream of Pipalkoti (RL of river bed 1300m) near Gauchar, Nathaur and Srinagar etc. At places the top is oxidized. The sequence was laid down during ca.50-34 ka.

The above mentioned deposits of three valleys comprise loose to semi-consolidated gravel-boulder casts deposited by high energy river flow in the wide, meandering stretches of river and indicate a prominent aggradational phase during MIS 3 under intensified monsoon. The lithology of terrace suggests that during the last interstadial, the Alaknanda, Satluj as well as Indus basins in Ladakh experienced warm and wet conditions due to strengthening of SW monsoon. It led to strong fluvial activities over the NW Himalayas with spatial variation from east to west. In western part, in Indus and Tangste valley, this monsoon phase was weak, erratic and lasted for the minimum duration of 3-6 ka. In Satluj and Alaknanda, the phase was strong and fairly consistent for about 15 ka. Our data indicate that, strengthening of monsoon had commenced at the same time around 49-50 ka in Indus, Alaknanda and Satluj valleys but lagged behind in Tangste valley by around 5 ka.

There is a close similarity in valley morphology, aggradation style and depositional timing in Alaknanda and Satluj valleys which suggests that for ca.15 ka period, both valleys witnessed high intensity monsoon and responded in similar fashion which led to 80m valley fill during last interstadial. In arid Ladakh, impact of this phase was in short pulses mainly during ca. 49-46 ka in Leh area and ca. 45-39 in Darbuk area. Thus, it is inferred that the precipitation influences during MIS 3 were similar to the present time.



## S14 – 95: The Himalayan Cryosphere - Global Versus Regional Climate Forcing

### ***Mass Balances of Chhota Shigri Glacier (Benchmark Glacier, Western Himalaya), India since 2002***

AL Ramanathan<sup>1</sup>; Mandal Arindan<sup>1</sup>; Azam Mohd. Farooq<sup>1</sup>; Wagnon Patrick<sup>2</sup>; Vincent Christian<sup>2</sup>; Linda Anurag<sup>3</sup>; Sharma Parmanand<sup>4</sup>; Angchuk Thupstan<sup>1</sup>; Singh Virendra Bahadur<sup>1</sup>; Pottakkal Jose George<sup>5</sup>; Kumar Naveen<sup>1</sup>

JNU, Delhi, India<sup>1</sup>, LGGE, Grenoble<sup>2</sup>, CU, HP<sup>3</sup>, NCAOR<sup>4</sup>, NIH, India<sup>5</sup>

Several studies on Himalayan glaciers have been recently initiated as they are of particular interest in terms of future water supply, regional climate change and sea-level rise. In 2002, a long-term monitoring program was initiated on Chhota Shigri Glacier (15.68 km<sup>2</sup>, 9 km long, 5830-4050 m a.s.l.) located in Lahaul and Spiti Valley, Himachal Pradesh, India. This glacier lies in the monsoon arid transition zone (western Himalaya) and is a representative glacier in Lahaul and Spiti Valley. We present here the updated glaciological mass balance (MB) of Chhota Shigri Glacier, the longest continuous annual mass balance record in the HKH region. Additionally, four years of seasonal mass balances are presented and analyzed using the data acquired at an automatic weather station (AWS) installed in 2009 on a lateral moraine (4863 m asl). Chhota Shigri Glacier lost mass between 2002 and 2014 with a cumulative glaciological MB of -6.75 m w.e. corresponding to a mean annual glacier-wide MB (Ba) of 0.56 m w.e. a<sup>-1</sup>. Ba were negative except for four years (2004/05, 2008/09, 2009/10 and 2010/11) when it was generally close to balanced conditions. The winter glacier-wide mass balance (Bw) between 2009 and 2013 ranges from a maximum value of 1.38 m w.e. in 2009/10 to a minimum value of 0.89 in 2012/13 year whereas the summer glacier-wide mass balance (Bs) varies from the highest value of 0.95 m w.e. in 2010/11 to the lowest value of 1.72 m w.e. in 2011/12 year. Equilibrium line altitude (ELA) for steady state condition is calculated as ~4950 m asl corresponding to an accumulation area ratio (AAR) of ~61%. An analysis of the seasonal MBs between 2009 and 2013 with air temperature from AWS and precipitation from the nearest meteorological station at Bhuntar (1050 m asl.) suggests that the summer-monsoon is the key season driving Ba of this glacier. The intensity of summer snowfall events controls the Ba evolution via controlling Bs. Mass balance is strongly dependent on debris cover, exposure and the shading effect of surrounding steep slopes.



## S14 – 96: The Himalayana Crosphere - Global Versus Regional Climate Forcing

### *Styles of Fluctuation in Gangotri Glacier Through the Holocene*

Milap Sharma<sup>1</sup>; V K Raina<sup>2</sup>; Ishwar Singh<sup>3</sup>; Pawan Kumar<sup>4</sup>

JNU, Delhi, India<sup>1</sup>, Formerly With GSI<sup>2</sup>, Project Staff JNU, Delhi, India<sup>3</sup>, Research Scholar<sup>4</sup>

The largest glacier of the Indian Himalaya, having an immense social, historical and cultural relevance, has fluctuated throughout the late Quaternary as elsewhere. The IPCC projection of an increasing trend of temperature rise throughout the 21st Century would adversely affect the freshwater scenario at least in areas where it emanates from a glacier source. Therefore, the assessment of glacier mass, i.e., and the total fresh water reserve needs to be quantified in order to meet the future requirement; based on the trend and styles of fluctuations derived from historical and proxy records. We present here a record of However, the 19th and 20th Century fluctuation is atypical, compared to the other glacier across the mountain chain. It appears that the response time of the glacier mass transfer in this part is in centennial scale; therefore, the ice limit at Bhujbas; constrained with  $440 \pm 0.09$  and  $210 \pm .06$  ( $\text{Be}^{10}$ ) may be one of the advances that occurred  $>1.5$  ka. However, this extent has always been referred to as the Little Ice Age elsewhere. Glacier has since been retreating in varied rates over these years, since the available historical records from 1817. It appears ironical to state but the Gangotri had a substantial advance at 1.5 ka that resulted in the deposition of three ridges at Tapovan; the shape being determined and modified by the Meru overburden. It means that the snout of this glacier was on a higher altitude as compared to contemporary snout at  $\sim 4000\text{m}$ . The arcuate shapes of the ridges are but the proof of the advance that resulted in deposition of erratic on the ridges at Tapovan with exposure ages constrained within  $1.62 \pm 0.15$  and  $1.32 \pm 0.13$  ka. Had there been secular retreat, this arcuate shape would not have developed.

Large concentrations of erratic around Gangotri village have been dated between  $3.27 \pm 0.47$  and  $3.72 \pm 0.47$  ka ( $\text{Be}^{10}$ ). Initial interpretation of the site, based on exposure age, was that the glaciers vacated this area around 3.5ka. But these have now been re-interpreted as exposure of erratic after a mega-flood that removed the overburden in a single episode. The Gangotri has fluctuated within  $\sim 4.2$  km for much of the Holocene, with varied behaviour and dynamics. The Chanturangi and Raktavarn, two of its separated tributaries, are now showing a little signs of expansion past 25 years. However, it may be premature to conclude that these glaciers would once again be joining the Gangotri in foreseeable time, given the dynamics of glacier based on size and other environmental factors.



## **S14 – 103: The Himalayan Cryosphere - Global Versus Regional Climate Forcing**

### ***Late Quaternary Climate Variability in the Indian Himalaya: An Over View***

Navin Juyal

Physical Research Laboratory, Gujarat, India

The major component of the tropical climate system is the Indian summer monsoon, which is a result of differential land-sea thermal contrast, producing seasonal reversal in wind direction and intense rainfall during the summer. During winter, dry cold winds from the Asian continent flow offshore, whereas in central Asia westerly winds flow around the Tibetan Plateau. The forcing factors controlling the monsoon variability on multi-millennial timescales (10<sup>3</sup>-10<sup>5</sup> years) are incoming solar radiation, interhemispheric transport of heat, and high-latitude glacial and interglacial boundary conditions. Short term climatic fluctuations were probably caused by variations in cross-equatorial heat transport by ocean surface currents (thermohaline circulation), particularly in the monsoon dominated region, and were probably independent of insolation changes.

The Himalaya and Tibetan plateau play an important role in global climate change in general and the Asian monsoon system in particular. However, climate change in the higher Himalaya is poorly documented because of the lack of well preserved stratigraphic records. Glacial deposits are valuable indicators of past environment; however, palaeoclimatic interpretation based on moraines is subject to major temporal and spatial gaps. Compared to this, sedimentation in proglacial lakes is more continuous and, hence, can be used to reconstruct a more complete record of past climatic variability particularly the minor glacial advances and retreats which otherwise is not possible from the moraines.

In this presentation it has been attempted to summarize the current understanding of the late Quaternary glaciation in Indian Himalaya with emphasis on the lake sequences.



## S14 – 121: The Himalayan Cryosphere-Global Versus Regional Climate Forcing

### *Some Studies of Climate Variables over Antarctica and West Himalaya*

Krishna Kumar<sup>1</sup>, Gyan Prakash Singh<sup>1</sup>

Banaras Hindu University, Uttar Pradesh, India<sup>1</sup>

This paper examines the seasonal pattern of tropical climate signals over Antarctica and west Himalaya snow and discusses these linkages between them. Snow covered west Himalaya region has spatial and temporal variation in snow surface temperature because of its topography and climate change. Snow surface temperature (SST) is one important parameter responsible for the physical processes taking place between snow pack and atmosphere and play an important role in avalanche related studies. Temperature and snow cover of Himalaya and Antarctica region which are mainly influenced by El Nino Southern Oscillation (ENSO), Southern Annular Mode (SAM), Southern Oscillation Index (SOI), and East Pacific Sea surface Temperature (EPSST). The Antarctica and west Himalaya snow temperature is an important factor of the glacial system: melt water, erosion and deposition rates are directly related to thermal characteristics of the glacier, especially of its bed. An Antarctica snow is always below the melting point at the temperature surface. These glaciers do not produce any melt water. However, as in the case of Antarctic ice sheet, they can be warm-based as well. Sub-polar glaciers warm to the melting point at their surface in summer time and thus produce melt water. Antarctica sea ice affects the tropical climate viz. (1) Sea-Ice has potential to modify the Earth-climate system by perturbing the radiation budget through ice-albedo feedback. (2) On inter-annual time scale, sea ice concentration (% cover of sea-ice) (SIC) is related with two dominant patterns of atmospheric variability (a) Southern Annular Mode (SAM) and (b) high latitude atmospheric response to ENSO. (3) The southern hemisphere high latitude atmospheric response to ENSO is dominated by a more wave like structure.



**S14 – 124: The Himalayan Cryosphere - Global Versus Regional Climate Forcing**

***Flash Floods and Fluvial Processes in Glaciated Terrain of Gangotri and Kedarnath Region, Garhwal Himalaya***

Dhruv Sen Singh

Geology Department, University of Lucknow, India

Himalaya, the abode of snow, ice and glacier is the sustainable sources of fresh water and birth place of all the perennial rivers hence assist in the sustainable growth of agriculture and energy sectors of India. Gangotri Glacier and Chorabari Glacier located in the Garhwal Himalaya, are characterized by tributary glaciers, supraglacial moraines, supraglacial lakes, crevasses, moraines, outwash plains etc. These landforms preserve a complete record of the climate/environmental changes on geological time scale. However, there are some catastrophic events which modify it. For the last few decades, Himalaya has witnessed many casualties including the flash floods and heavy snow fall. The events are natural however, the loss of life and property are increasing due to human intervention in the cycle of the natural system. It has been observed and identified that the pre-existing landforms are modified by tributary glaciers, snow melt ephemeral streams and by the flash floods also. Flash floods, caused by bursting of glacial lakes, slope failures and landslides are well known in the Himalayas. The flash floods and associated surface processes differentially erode the sediments from mountain wall, moraines, outwash plains, valley wall, river banks and deposit 1-3 m thick poorly sorted sediments on the outwash plain and river valley. The redistribution of enormous amount of sediments results in the modification of pre-existing glacial landforms/landscapes. The modification of landforms and distribution of diamictons everywhere in these glaciated areas creates confusion in the identification of different types of landforms. The remotely sensed satellite data indicate that these areas are covered with snow during winter (accumulation period). The ephemeral streams are initiated when snow melts during summer (ablation period). The ephemeral streams erode the fine grained sediments from the pre-existing landforms and changes its facies from matrix supported boulder to clast supported boulder. Therefore, the flash floods and snow melt ephemeral streams have played important role in the landscape/landform evolution of this region.



**S14 – 131: The Himalayan Cryosphere - Global Versus Regional Climate Forcing**

***Flash Floods and Fluvial processes in Glaciated Terrain of Gangotri and Kedarnath Region, Garhwal Himalaya***

Anil D. Shukla<sup>1</sup>; Naresh Rana<sup>2</sup>; Pinky Bisht<sup>2</sup>; Yogesh Ray<sup>3</sup>; Yashpal Sundriyal<sup>2</sup>; Umesh Sharma<sup>4</sup>

Physical Research Laboratory, Ahmedabad, India<sup>1</sup>; H.N.B. Garhwal University, Srinagar, Uttarakhand, India<sup>2</sup>; National Centre for Antarctic & Ocean Research, Goa, India<sup>3</sup>; Department of Science & Technology, Government of India, New Delhi, India<sup>4</sup>

The Trans-Himalayan glaciers provide unique opportunity to understand the Quaternary climate history in comparison to the monsoon subjugated central Himalaya, where the high surface erosion, constrain the preservation of older glacial deposits. One of the most spectacular glaciated Khardung valley which is located in the north of Leh town, was carved by the Khardung and its tributary glaciers during the late Quaternary period. At present the Khardung glacier has shrunken towards the northwest and occupies the Khardung ridge which is the Ladakh Batholith at an elevation of ~5400 m. Based on detailed field mapping supported by total station survey, two generations of lateral moraines have been identified. The older event is marked as the Khardung Glacial Advance-I (KGA-I), which descended down to a distance of ~14 km and terminated near Ganglas village (3783 m). The evidences of KGA-I can be identified in the form of a distinct laterofrontal moraine ridge and can be traced upstream at an elevation of ~4000 m.

In comparison with the older event the younger KGA-II advance, terminates around South Pullu (4507 m). The paraglacial processes like the frost shattered debris flow fans have significantly modified the evidences of this expansion. Optical chronology of glacial events was ascertained by dating the sand bodies associated with the moraines in the Khardung valley. Three samples from KGA-I and two from KGA-II have been dated by OSL dating technique for quartz grains. The older KGA-I is bracketed between  $35 \pm 5$  ka to  $24 \pm 2$  ka whereas the younger KGA-II lasted between  $21 \pm 3$  ka and  $18 \pm 3$  ka. The age estimates imply that the Khardung glacier responded to the winnowing phase of the humid Marine Isotopic Stage-3 (MIS-3) and the expansion persisted during the early part of the MIS-2. Interestingly, the younger advance (KGA-II) broadly corresponds to the Global Last Glacial Maximum (LGM). Our observations are at variance with the exposure ages obtained by the earlier workers and suggest that in the mid-latitude westerlies dominated Trans Himalayan glaciers responded synchronously with the global LGM. The presentation will discuss the climatic implications of the new chronology obtained from the Khardung valley.



## S14 – 136: The Himalayan Cryosphere - Global Versus Regional Climate Forcing

### ***Snow Cover Variability in Western Himalaya: An Analysis from a Few Meteorological Stations and Satellite Data***

H S Gusain<sup>1</sup>; Ashwagosh Ganju<sup>1</sup>; Manish Kala<sup>1</sup>; V D Mishra<sup>1</sup>; Dhiraj Kumar<sup>1</sup>; Vaibhav Sharma<sup>1</sup>

Snow and Avalanche Study Establishment, DRDO, Chandigarh, India<sup>1</sup>

Snow and Avalanche Study Establishment (SASE) has been observing snow and meteorological parameters in the cryospheric regions of Western Himalaya since 1970. These snow-meteorological parameters are an indicator of the climate of the Western Himalaya and have impact on dynamics of the glaciers in the region. In this paper we are presenting an analysis of the snow cover variability in Western Himalaya using ground observations and satellite data. Western Himalaya is delineated into three principal zones e.g. Lower, Middle and Upper Himalaya. Pir Panjal and Shamsabari ranges lie in the Lower Himalaya, Great Himalayan range lies in the Middle Himalaya and Zaskar, Ladakh and Karakoram ranges lie in the Upper Himalaya zone. Lower, Middle and Upper Himalaya zones span areas of 41000 km<sup>2</sup>, 85000 km<sup>2</sup> and 50000 km<sup>2</sup> (approx.) respectively. In-situ data of more than last two decades from two to three observation stations in each zone has been used for the analysis. Moderate Resolution Imaging Spectroradiometer (MODIS) sensor images of past one decade have been used for estimation of snow covered area in all the three zones. Lowest temperature has been observed in the Upper Himalaya zone and seasonal average (November to April) of daily minimum temperature was recorded -32° C at an observation location in this zone. Spatial and temporal variations in snow covered area and snow cover thicknesses have been analyzed. Out of the three zones, Lower Himalaya zone receives maximum snowfall during winter months (November to April) due to orographic effect. Dhundi observation station in this zone recorded highest snowfall of 1945 cm in one season. In comparison, Middle and Upper Himalaya zones receive quite less snowfall (less than 1000 cm during a season in each zone).

Higher snow cover thickness has been observed in the Lower Himalayan zone compared to Middle and Upper Himalaya and highest snow cover thickness recorded at Dhundi was 4.5 m. Snow cover thickness on mountains is modified by wind-erosion, wind deposition, slope angles, aspect, and avalanche activities, which results in large spatial variability. Binary maps of snow covered area have been generated using Normalised Difference Snow Index (NDSI) and reflectance in Near Infrared Region (NIR) in MODIS images. Snow covered area has been calculated in each zone of the Western Himalaya and its temporal variability has been monitored. Permanent snow covered areas (which also include glaciers) in all the three zones are less than 20%. Snow covered area varies during the winter months from November to April and it peaks during the months of February and March. Snow covered area varies from less than 20% (before onset of winter) to more than 60% (during peak winter period) in each zone. Time series analysis of snowfall amount, highest snow cover thickness and area covered under snow show a decreasing trend during past decade. Snow cover characteristics and snow cover duration also vary in the three zones. While moist and wet snow dominates major part of the season in Lower Himalayan zone, dry snow dominates in the Middle and Upper Himalaya zone. Snow cover duration in Lower Himalaya zone is comparatively shorter due to early ablation. Satellite and in situ data analysis show a large spatial and temporal variability in snow covered area, snow thickness and snow characteristics in all the three zones of Western Himalaya.



## S14 – 150: The Himalayan Cryosphere - Global Versus Regional Climate Forcing

### ***Ascertaining the Role of Indian Summer Monsoon and Mid-latitude Westerlies in Driving the Glaciation in Sarchu Plain, Zaskar Himalaya***

Shubhra Sharma<sup>1</sup>; Pinky Bisht<sup>2</sup>; Pritam Chand<sup>3</sup>; Anil D. Shukla<sup>4</sup>; S. K. Bartarya<sup>1</sup>; Y. P. Sundriyal<sup>2</sup>; Navin Juyal<sup>4</sup>

Wadia Institute of Himalayan Geology, Dehradun, India<sup>1</sup>; HNB Garhwal University, Srinagar, India<sup>2</sup>, Jawaharlal Nehru University, New Delhi, India<sup>3</sup>, Physical Research Laboratory, Ahmedabad, India<sup>4</sup>

Sarchu plain lies in the Tethyan sedimentary sequence and is dominated by Paleozoic phyllite, quartzite, schist and the Triassic limestone. The U-shaped valley, with elevation ranging between 4200 to 6000 m asl, is carved on an anticline. The southern end of the valley is demarcated by a north dipping Lingti-Sarchu fault. Precipitation is dominantly contributed by the mid-latitude Westerlies (~64.4%) with subordinate contribution of the Indian Summer Monsoon (~35.6%) (Source: [http://www.esrl.noaa.gov/psd/data/grid\\_ded/data.ncep.reanalysis.html](http://www.esrl.noaa.gov/psd/data/grid_ded/data.ncep.reanalysis.html)). Compared to the northern ranges, large number of glaciers can be found on the south-western (north facing) slopes having mean elevation of 5500 m and elevation range between 5100 to 6000 m asl. Quaternary sediments are dominated by ~100 m thick glacio-fluvial outwash sediments, lateral moraines, drumlins and moraine dammed lakes.

Primary objectives of the study are (i) to establish temporal evolution of various late Quaternary landforms in Sarchu plain and (ii) ascertain the relative roles of ISM and mid-Westerlies in driving the glaciation. The study is primarily based on detailed geomorphological mapping supported by Optical Stimulated Luminescence (OSL) chronology. Based on the nature of occurrences of the Quaternary landforms, it appears that the U-shaped valley of Sarchu plain was carved by an older glacial event termed as Sarchu Glacial Stage-I (SGS-I). This was followed by a major phase of deglaciation which caused the valley-fill aggradation. A renewed phase of glacial advance is observed in the form of sharp crested lateral moraine ridges, corresponding to the Sarchu Glacial Stage-II (SGS-II) which terminates at the valley margin. The third and the last glacial stage viz. the Sarchu Glacial Stage-III (SGS-III) is represented by the drumlins and ground moraine which are preferentially preserved in the upper reaches of the Sarchu plain and directly overlies the outwash glacio-fluvial terraces. The moraine dammed lake is located in the upstream gorge section and is overlain by well-rounded and imbricated outwash fluvial gravel. The optical chronology of the lateral moraine is dated to  $19.6 \pm 1.3$  ka and  $19.8 \pm 1.8$  ka respectively. The drumlins have been dated between  $6.9 \pm 0.6$  ka to  $2.6 \pm 0.2$  ka; the outwash gravel above the moraine dammed lake is dated to  $4.7 \pm 0.3$  ka. Based on the above ages a tentative landform evolution and inferred climatic scenario is reconstructed. The valley-fill aggradation occurred on a pre-existing glaciated valley implying a glaciation predate the Last Glacial Maximum (LGM). It may be inferred that the oldest glaciation (SGS-I) occurred during the cold and wet Marine Isotopic Stage-4 (MIS-4; ~60 ka). This was followed by a major phase of deglaciation which is ascribed to the pluvial MIS-3 (50-'30 ka). The SGS-II advance is dated to the LGM, during which the tributary glaciers mostly from southern and western flanks descended down to an elevation of ~4200 m whereas, the SGS-III is dated to the early to mid-Holocene. This was followed by second phase of incision that was initiated ~5 ka and has continued till date. The study would help in understanding the implications of climate variability in the landform evolution around Sarchu plain, Zaskar Himalaya with emphasis on the role of the ISM and mid-latitude Westerlies in driving the late Quaternary glaciation in this transitional climatic zone.



**S14 – 151: The Himalayan Cryosphere-Global Versus Regional Climate Forcing**

***Snow Cover Variability of Chandra and Miyar Basin from 2010 to 2014 using Multi Temporal Data***

Purnesh Jani<sup>1</sup>; B P Rathore<sup>2</sup>; I M Bahuguna<sup>2</sup>; A S Rajawat<sup>2</sup>; Anjana Vyas<sup>1</sup>

CEPT University, Gujarat, India<sup>1</sup>, Space Application Centre, Gujarat, India<sup>2</sup>

Snow is an important natural Resource in Himalayan Region and monitoring of it on large scale has become essential because it is highly sensitive to climatic fluctuation. It has been observed that snow cover pattern shows significant variations in Himalayan region due to different climatic zones and anthropogenic activities. It is also a vital parameter to study availability of water in Himalayan River, forecast & assessment of avalanche and various other applications. Currently, Remote Sensing is the most promising method for studying snow cover. Various satellite sensors like LISS-I, LISSIII, AWiFS, AVHRR, MODIS are used for Snow cover monitoring. In this study an algorithm based on Normalized Difference Snow Index (NDSI) was used to map snow cover using AWiFS Data. NDSI is calculated using ratio of green band (band 2) and Short wave infra-red (Band 5) channel of AWiFS (Automatic wide Field Sensor) Sensor. Snow cover monitoring is carried out for the interval of 5 days and 10 days from the month of October to June for Chandra and Miyar sub basins of Chenab basin. Approximately 600 scenes are analyzed to observe changes in snow cover from 2010 to 2014. Every year shows different accumulation and ablation pattern in Chandra and Miyar sub-basins. Accumulation takes place in early winter i.e. in mid October. Then Areal extent reaches to 100% in Chandra basin (2010-11,2013-14) where as in Miyar basin it reaches to 80% (2010-11). Afterwards, significant snow melting is observed in both of the basin for all four years. Later on snowpack remains stable from December to May in Chandra basin whereas in Miyar basin it remains stable from December to April for all the four years. The results show that both sub-basins show almost similar ablation trend during summer.

Key Words: Remote Sensing, Snow, NDSI, AWiFS



## S14 – 184: The Himalayan Cryosphere-Global Versus Regional Climate Forcing

### *Fluctuation in Equilibrium Line Altitude*

Rupal M. Brahmabhatt<sup>1</sup>; B. P. Rathore<sup>2</sup>; I. M. Bahuguna<sup>2</sup>; S. K. Singh<sup>2</sup>; R. D. Shah<sup>1</sup>

M.G. Science Institute, Gujarat, India<sup>1</sup>, Space Application Centre, Gujarat, India<sup>2</sup>

Glaciers are important natural resource to human kind because they are fresh water in frozen state and sensitive indicator of climate change. Temporal monitoring of mountain glaciers extents is an important element of cryospheric studies to understand glacier responses to climatic variations. The studies accelerated in the last two decades owing to the large amount of satellite data made available from multiple active and passive sensors operating in Visible-Near Infrared (VNIR), Thermal Infrared (TIR) and Microwave (MW) region by several orbiting missions of international space agencies and the concern shown by geoscientists on the retreat of glaciers as a result of global warming.

High altitude of the Himalaya is engraved with multitudes of glaciers, ranging in size from less than one sq km to tens of sq km. Though the glaciers advancement and retreat are related to long term climatic variations but there has been a serious concern on the general state of the health of glaciers not only in Himalayas but also world over. Health of glaciers is studied by monitoring its mass balance which means the total gain and loss of ice at the end of ablation season. However, snow line altitude at the end of the ablation season which is known as equilibrium line altitude can be used as indicator of the glaciers health. This paper represents the knowledge and information about the variation in equilibrium line altitude (ELA). The study shows that the glaciers having similar altitude show great level of variation in ELA. Warwan-Bhut sub-basin of Chenab basin, H. P. has been considered for this study. A series of satellite images of AWIFS sensor were analyzed for extraction of snowline on the glaciers for the period of 2010- 2011. Furthermore, using Aster data, altitude of ELA was computed and it has been found that within the basin it shows the significant variation in altitude. Thus, influencing parameters such as slope of glaciers and its orientation was derived using Aster data and visual interpretation respectively. These parameters were analyzed with ELA to understand its role. However, it was found that the glaciers having Northern orientation found having relatively lower ELA. Moreover, the glaciers having steep or high slope have shown lower ELA as well. Therefore, the glaciers having steep slope and Northern orientation found to be favorable for the glaciers health.

Key word: ELA, glaciers, slope, aspect



**S14 – 213: The Himalayan Cryosphere - Global Versus Regional Climate Forcing**

***Himalaya-Karakoram Glaciers Monitoring using Remote Sensing***

Rakesh Bhambri<sup>1</sup>; D P Dobhal<sup>1</sup>; A K Gupta<sup>1</sup>; B Pratap<sup>1</sup>

Centre for Glaciology, Wadia Institute of Himalayan Geology, Dehradun, India<sup>1</sup>

The Himalaya-Karakoram has one of the largest concentrations of glaciers outside the polar regions. The melt water discharge from these glaciers is of interest for several reasons (e.g. irrigation, sustaining ecosystem and hydropower generation). For water resource planning and management in northern India, it is essential to monitor the Himalayan glaciers. Ground based glaciological work is highly recommended but time and capital intensive as well as involves enormous risks in remote and rugged mountainous areas. Multi-spectral and multi-temporal remote sensing data can be used to monitor several glaciers simultaneously. Therefore, satellite images and digital elevation models (DEMs) were used to map clean-ice, debris-covered ice and planimetric and volumetric glacier changes in Himalaya-Karakoram (HK) region. A semi-automated mapping method for the debris-covered glaciers of the Garhwal Himalaya based on an Advanced Space-borne Thermal Emission and Reflection Radiometer (ASTER) DEM and thermal data were developed. A detailed inventory for surging glaciers in Karakoram was completed and surge dynamics was also examined using spatial and temporal observations from DEM differencing and time series of surface velocities from satellite images. The analysis provides a hint that the overall glacier area of Shyok valley slightly decreased until 1989 (area 1973:  $1613.6 \pm 43.6 \text{ km}^2$ ; area 1989:  $1602.0 \pm 33.6 \text{ km}^2$ ) followed by an increase (area 2002:  $1609.7 \pm 51.5 \text{ km}^2$ ; area 2011:  $1615.8 \pm 35.5 \text{ km}^2$ ). Although, the overall change in area is very less but advances in glacier tongues since the end of the 1980s are clearly visible. Detailed estimations of length changes for individual glaciers since the 1970s and for Central Rimo Glacier since the 1930s confirm the irregular retreat and advance. Conversely, in Garhwal Himalaya glaciers area decreased from  $599.9 \pm 15.6 \text{ km}^2$  (1968) to  $572.5 \pm 18.0 \text{ km}^2$  (2006), a loss of  $4.6 \pm 2.8\%$ . Glaciers in the Saraswati/Alaknanda basin and upper Bhagirathi basin lost  $18.4 \pm 9.0 \text{ km}^2$  ( $5.7 \pm 2.7\%$ ) and  $9.0 \pm 7.7 \text{ km}^2$  ( $3.3 \pm 2.8\%$ ), respectively, from 1968 to 2006. This suggests that glaciers in the Karakoram show long-term irregular behaviour with comparatively frequent and sudden advances as compared to central and eastern Himalayan glaciers.



**S14 – 224: The Himalayan Cryosphere - Global Versus Regional Climate Forcing**

***Sedimentary Architecture, Paleoenvironment and Provenance of Fluvio-Lacustrine Sequence in Leh: Records of Late Pleistocene Climatic Fluctuation***

Syed Ali Imam Mujtaba<sup>1</sup>; Lal, R.<sup>2</sup>; Kumar, P.<sup>1</sup>; Pant, N.C.<sup>2</sup>; Saini, H.S.<sup>1</sup>; Dutta, S.<sup>1</sup>

Geological Survey of India<sup>1</sup>, Delhi University, Delhi, India<sup>2</sup>

Late Pleistocene sedimentary sequences in the upper Indus basin in Ladakh region of North-western Himalaya represents natural repository to study climate change. The area lying 3200m amsl represents climatically sensitive rain shadow zone where moraines, alluvial fans, fluvial, aeolian and lacustrine deposits are ubiquitous. Amongst these, sporadically distributed relict lacustrine deposits around Lamayuru, Leh, Shey, Mahe, Nyoma etc are important in inferring the cold climate and tectonic or climatically induced river damming. A 60 m thick section exposed on the right bank of Indus River has been divided in three major units viz., lower fluvio-lacustrine, middle lacustrine and upper alluvial. Our studies show that the deposition of lower fluvio-lacustrine unit commenced around 79 +5 ka under warm and relatively humid environment of MIS-5a (interglacial). The middle lacustrine unit consists of laminated clay which was laid down during MIS-4 between ~ 72-57 ka under cooler environment. The upper alluvial unit was deposited between ~ 49 to < 46 ka during Isotope stage 3 interglacial. The heavy mineral assemblage in lower unit is dominated by garnet, staurolite and zircon which indicate dominant supply of sediments from metapelitic Pangong-Tso Formation (Tangse valley). However, the absence of these minerals in the upper part of section suggests a shift in the provenance from metapelitic to granite dominant source. The change of source occurred at 70+ 6 ka during the transition of MIS 4 and MIS 3. The middle clayey unit has low detrital heavy minerals and high evaporatic carbonate minerals. It shows the presence of illite (clay mica) and chlorite as major phases and smectite, occasional kaolinite, feldspar and quartz as minor phases in the clay fraction. The dominance of illite and chlorite in the middle layers suggests physical weathering in cold/ dry conditions. The mineralogy indicates a closed lake environment with low detrital influx. Occurrence of relict lacustrine patches along the valley margin (both along left and right banks) upstream of Spituk (mapped for about 30 km distance up to Shey-Ranbirpura) suggests that a major lake had existed in the Indus valley during Late Pleistocene. The upper part of lake deposits is present along 3300m counter from Spituk to Ranbirpura. A possible site of the damming of river which gave rise to lake has been located near the confluence of Indus-Zaskar Rivers downstream of Leh. Our integrated sedimentological approach including lithology, heavy and clay mineral analysis supported with OSL chronologies of a well developed Late Quaternary sedimentary section at Spituk allows us to decipher climatic variations during MIS-5a to MIS-3.



**S14 – 230: The Himalayan Cryosphere - Global Versus Regional Climate Forcing**

***Records of Late Quaternary Glacial Interglacial Transitions and Abrupt Holocene Climate Change along Baspa River Valley, Northwest Himalaya, India***

Sharat Dutta<sup>1</sup>; Kumar, P<sup>1</sup>; Mujtaba, S. A. I.<sup>1</sup>; Chunchekar, R<sup>1</sup>; Saini, H.S.<sup>1</sup>

Geological Survey of India<sup>1</sup>

The Baspa River valley (tributary of Satluj R.) presents amphitheatre of late Quaternary glacial, fluvial, lacustrine and alluvial fan landscapes in the form of moraine, fluvial terrace, glacio-fluvial fan and lacustrine deposits that are result of profound influence of Late Quaternary climate variability. Geomorphologically the 75km stretch between source to Karcham (confluence of Baspa and Satluj River) of Baspa valley can be divided into three sectors viz. Sector-I (source to Chitkul) comprises of U-shaped valley with average river gradient of 15o mainly consists of lateral moraines and fan/slope wash material from tributary glaciers. Sector-II (Chitkul to Sangla) comprises of wider valley where fluvial terraces, lacustrine deposits and intermittent debris fans are prominent. Sector-III (Sangla to Karcham) is entrenched V-shaped valley which is devoid of fluvial/lake sediment and the river flows in this segment as bedrock channel. A prominent nickpoint has been observed in the river profile at Sangla with sudden change of gradient from 10° in the upstream to 14° upto Karcham (confluence of Baspa and Satluj). We carried out detailed sedimentary facies analysis together with optically stimulated luminescence chronology (OSL dating) of Late Quaternary deposits to constrain the valley aggradation and incision phases and to gain insight to the nature of fluvial responses to Late Quaternary glacial interglacial transitions and Holocene climate change. The geomorphology, lithostratigraphic arrangement and OSL chronology of sediments shows that the parts of Baspa river valley aggraded under lacustrine environment owing to river damming at Sangla and Rakcham area by huge landslides induced by abnormal monsoon conditions during end of MIS-3 (>23ka). The lacustrine deposition continued throughout LGM (>23ka~11.5ka) whereby achieved >120m thick lacustrine sedimentation at Sangla and upto 40m at Rakcham from present day river bed. The lacustrine deposition phases, at both the areas are contemporary and continued till the beginning of Holocene (~11.5ka). Lake breaching and reestablishment of fluvial regime started during early part of Holocene under warm and humid climatic conditions. The fluvial sediments younger than marine oxygen isotope stage-2 (MIS-2) are present in the form of terrace deposits resting over erosional remnants of lacustrine facies. This reflects the minor pulses of aggradation during major incision in response of Holocene climatic fluctuations. In the valley reaches that are beyond palaeolake limits, fluvial aggradation continued till ~19ka (i.e. MIS-3 to MIS-2) indicating coeval span of fluvial and lacustrine aggradation phase in the valley. The geomorphic attributes and chronostratigraphic framework of aggradation and incision phases suggest that the glacial fed Baspa River is highly sensitive to glacial-interglacial transitions and abrupt Holocene climate change thereby responding rapidly to these allogenic forcing.



## S14 – 235: The Himalayan Cryosphere - Global Versus Regional Climate Forcing

### **Operational Algorithm for Estimating Snow - Cover Fraction using MODIS Data in Himalayan Region**

Kavita Mitkari<sup>1</sup>; Arora Manoj K.<sup>1</sup>; Mishra V. D.<sup>2</sup>; Gusain Hemendra S.<sup>2</sup>; Gupta Naveen K.<sup>3</sup>

PEC University of Technology, Chandigarh, India<sup>1</sup>, Snow and Avalanche Study Establishment – RDC (DRDO), Chandigarh, India<sup>2</sup>, Indian Institute of Technology Roorkee, Uttarakhand, India<sup>3</sup>

**Background:** Varied inputs in the form of snow and weather parameters are required in scientific models pertaining to avalanche and weather forecasting. These are usually collected from various field observatories at different locations in the snowbound regions; however, the vast snow-covered areas generally occur at high altitudes, which are remote and inaccessible. As a result, the feedback of snow-cover information on snow cover and snow volume from field based scientific models is usually incomplete in various Himalayan zones. Remote sensing techniques therefore have been used for the retrieval of a number of snow cover parameters and properties such as depth, density, velocity, volume, snow water equivalent, areal estimates etc. Among these parameters, the accurate mapping of snow cover at an operational level is extremely important as it forms a crucial input for climate change models.

Until recently snow-cover mapping and monitoring was being carried out using satellite sensors such as NOAA AVHRR, Landsat MSS and TM, which unfortunately have become saturated for snow due its high reflectance in most of their spectral regions. Availability of data from new sensors such as MODIS on-board Terra and Aqua satellites has not only helped in overcoming the saturation problem due to their high radiometric resolutions but also facilitated the effective monitoring of large snow covered areas as a result of high temporal resolution and wide swath coverage.

As it is well known, raw digital numbers (DN) derived from satellite optical systems cannot confidently be used for engineering studies, since they include effects derived from sensor calibration, as well as atmospheric and topographic interferences. Therefore, calibrating the DN values to sensor radiance is a crucial process, which must be performed in order to extract high quality information from remote sensing data.

Further, the prevalent techniques of snow cover mapping such as manual delineation, spectral ratios and indices in their present form encounter serious limitations. The per-pixel classification techniques fail for areas having mixed problem and therefore sub-pixel classification techniques need to be studied for accurate mapping of snow. Among the sub-pixel classification techniques for mapping of snow, linear mixture model is the most effective and widely used. However, for the sensors which have been planned for operational snow-cover mapping, the empirical relationship techniques are useful. A technique based on empirical relationship between snow cover fraction and NDSI to accurately map snow has not been effectively used in Indian Himalayas.

Thus, in order to map snow cover accurately from other land covers, appropriate reflectance models, sub-pixel techniques and empirical relationships between the fraction snow cover and NDSI need to be developed at operational level. Objectives

1. Reflectance modelling of MODIS data to understand various factors that influence the satellite measured reflectance.
2. Develop and analyze the relationship between snow cover fractions derived from Linear Mixture Modelling and Normalized Difference Snow Index (NDSI) using MODIS.
3. Assessment of the accuracy of snow cover fraction.



**Methods:** Reflectance Modelling (Image based Correction Methods): Original C-Correction, Modified C-Correction, SCS + C-Correction and Smooth C-Correction.

Snow-cover fraction: Empirical relationship based method using results from Linear Mixture Model (LMM) and Normalized Difference Snow Index (NDSI).

**Results:** This article describes an attempt to map snow cover accurately from other land covers by developing appropriate reflectance models, sub-pixel techniques and empirical relationships between the fraction snow cover and NDSI at operational level. Various reflectance models have been compared statistically using coefficient of correlation (R) and coefficient of determination (R) which revealed that smooth c-correction method gives most accurate results compared to others. Further, evaluation of efficacy of the methods by comparison with field data also reveals that the reflectance of snow corrected using smooth c-correction method is more nearer to the ground reflectance of snow as compared to other methods implemented here. Further study of different smoothing factors (3,5 and 7) shows that smaller the smoothing factor, more accurate is the reflectance corrected by smooth c-correction method. Regression relationships have been developed between NDSI and snow cover fractions produced from LMM based on two criteria namely, snow cover fraction greater than 0.0 and greater 0.1. The best regression equation has been selected by examining their respective graph plots, correlation coefficients and RMSE. The selected regression equation is as follows:  $SCF = 0.25 + 0.35 \cdot NDSI$  This equation has been tested on other area and validation efforts show that the pixel-level, fractional snow cover relationship provides useful results as measured in independent tests against fractional snow cover, actual snow fraction obtained from IRS P6 AWIFS scene covering a substantial range of snow cover quantified by measures as correlation coefficients and RMSE. The mean absolute error was less than 0.1, correlation coefficient was near 0.9 and the corresponding RMSE value was less than 0.5. The validation has been performed on a small scene whose corresponding high resolution AWIFS data was available. It has been applied on two other full MODIS, but due to the non-availability of corresponding high resolution scenes the validation of the results obtained was not possible.

**Conclusion:** Based on the results obtained from the methodology adopted for retrieving fractional snow cover from the data of Terra MODIS sensor for the Western Himalayas consisting of some parts of Jammu & Kashmir and Himachal Pradesh, following broad conclusions have been drawn:

1. The statistical comparison of the image-based correction methods as well as validation of the reflectance of snow derived from all the correction methods with ground truth shows that the reflectance derived from smooth C-correction method is most accurate. Further examination of the smoothing factors (3,5 and 7) shows that smaller the smoothing factor, the more accurate is the reflectance derived.
2. The snow cover fraction used for developing regression relationship has been produced from LMM. However, further research may be conducted to explore the utility of other non-parametric classifiers such as artificial neural networks (ANNs) for mapping snow cover.



**S14 – 246: The Himalayan Cryosphere - Global Versus Regional Climate Forcing**

***Regional Prevailing Climatic Conditions and Analysis of Meteorological Parameters of Chorabari Glacier Valley, Central Himalaya, India***

Kesarwani K.<sup>1</sup>; Dobhal D.P.<sup>1</sup>; Gupta A.K.<sup>1</sup>; Mehta M.<sup>1</sup>; Durgapal A.<sup>2</sup>

Centre for Glaciology, Wadia Institute of Himalayan Geology, Dehradun, India<sup>1</sup>; Department of Physics, D.S.B. Campus, Kumaun University, Nainital<sup>2</sup>

Mountain glaciers are widely recognized as sensitive indicator to the climate change. Although the interaction between glaciers and climate is a complex process, the global as well as regional meteorology plays a significant role in controlling the glacier health. In order to enhance the knowledge of various weather components responsible for fluctuations in glaciers, a continuous meteorological investigation was carried out in Chorabari Glacier valley (63.8 km<sup>2</sup>) of Mandakini basin, Central Himalaya, India. We have analyzed the seasonal (Winter: November to April; Summer: May-October) and synoptic variations in meteorological parameters, radiative fluxes and precipitation patterns for the two consequent glaciological years (01 November to 31 October of the next year) of 2011-12 and 2012-13. The meteorological variables were collected from three Automatic Weather Stations (AWSs) classified as K1 (Glacier camp; 4270 m a.s.l), K2 (Base camp; 3820 m a.s.l) and K3 (Rambara; 2760 m asl). These stations represent the three distinctive regimes of the valley viz. glacierized, transitional and non-glacierized. Results show that the mean air temperature of K1, K2 and K3 were -1.4° C, 2.4°C and 7.7°C respectively. Calculated seasonal and annual variations in near-surface air temperature lapse rate were ranging from 4.2°C to 6.7°C km<sup>-1</sup> with an average rate of 5.3°C km<sup>-1</sup> between K2 and K1. Similarly, between K3 and K2, it was ranging from 3.3°C to 7.3°C km<sup>-1</sup> with an average rate of 5.8°C km<sup>-1</sup>. These variations were observed highly subjective to the amount of precipitation pattern. The mean relative humidity was calculated 57.9%, 62.4% and 58.3% for K1, K2 and K3 respectively which was relatively high in the summer (73% for K1, 75% for K2 and 73% for K3) due to the influence of Indian summer monsoon and low in dry winter periods (50% for K1, 51% for K2 and 52% for K3). Interannual variations in incoming shortwave radiation flux were small depending on the cloud cover whereas outgoing shortwave radiation was highly variable subjective to the snowfall. The mean incoming shortwave radiation was recorded 339, 329 and 234 W m<sup>-2</sup> and outgoing shortwave radiation was 174, 127 and 49 W m<sup>-2</sup> for K1, K2 and K3 respectively. Outsized variations in albedo during the winter season were recorded due to the frequent snowfall and daily values varied between 10 and 100. Likewise, during the melt season, changes in albedo were relatively small and ranged between 11 and 21. Variability in the energy balance of the valley is greatly controlled by the net radiation and is the most important energy source for melting of the snow and ice. Average net radiation was calculated 15, 40 and 25 W m<sup>2</sup> for K1, K2 and K3 respectively. The wind speed and direction of the area are highly influenced by the valley characteristics and orientation. The average wind speed was observed high at K2 (2.3 m s<sup>-1</sup>) followed by K3 (2.1 m s<sup>-1</sup>) and low at K1 site (1.6 m s<sup>-1</sup>). However, the diurnal and seasonal analysis of wind speed suggests that it was high in the day time (1200-0200 hr) during the summer and in the morning (0600-0800 hr) during the winter. The frequency distribution analysis of wind direction shows that the fraction of annual katabatic wind (68%) was more prominent than the anabatic (32%), resulting inadequacy in the surface melting produced by the turbulent sensible heat flux. Seasonal variations in the atmospheric pressure show tendency to be high in the summer and variably low in the winter. The average atmospheric pressure was calculated 606, 640 and 727 h Pa for K1, K2 and K3 respectively. Precipitation during the winter season is received in the mixed form of snow, sleet, hail and liquid water. The total fresh snowfall calculated from snow depth measurements was 24.04 m (2221.5 mm w.e.) in 2011-12 and 25.59 m (2507.5 mm w.e.) in 2012-13. Monthly distribution of summer rainfall was very erratic and the highest rainfall was recorded in the month of August (391 mm) for 2012 and June (519 mm) for 2013. The total summer rainfall was recorded 1033.5 and 1488.5 mm during 2012 and 2013 respectively. Annual precipitation records indicate that the winter precipitation is more than the summer one in the region.



Analysis of meteorological records suggests that the general climate of the valley is humid-temperate in the summer and dry-cold in the winter. The spatial-temporal analysis of meteorological data based on the three distinctive regimes suggests K1 site is principally controlled by the glacierized regime whereas K2 has a mix effect of glacierized as well as non-glacierized zone. Moreover, the study provides a comprehensive introduction to weather processes and climatic conditions of the region which would be useful to understand the influence of fluctuations in regional meteorology on glacierized regime.



**S14 – 247: The Himalayan Cryosphere - Global Versus Regional Climate Forcing**

***Response of Glaciers Towards the Changing Climate: A Case Study of Chandra-Bhaga Basin, Western Himalaya, India***

Farjana Birajdar<sup>1</sup>; G. Venkataraman<sup>1</sup>; I.M Bahunguna<sup>2</sup>; H.P. Samant<sup>3</sup>

Centre of Studies in Resource Engineering, Indian Institute of Technology Bombay<sup>1</sup>, Geosciences Division, ISRO-Space Applications Centre, Ahmedabad<sup>2</sup>, Department of Geology, St. Xavier's College Autonomous, Mumbai<sup>3</sup>

The Himalaya has been a great spectator of the warming environment and climate change over the years. Signals of warming atmosphere and changing climate can easily be identified through monitoring of glaciers as they respond directly in terms of change in mass, terminus and runoff. In order to quantify the fluctuations of Himalayan glaciers over the past half century (1963-2013), an attempt has been made towards monitoring the changes in glacierized area lying between 3800 and 6500 m asl of Chandra-Bhaga basin (~4147.43 km<sup>2</sup>), Western Himalaya, India. Monitoring of glacier extent, length and terminus altitude of 13 glaciers (Bada Shigri, Chhallopathang, Chhota Shigri, Gangring, Gepang Gath, Hamtah, Kalas Buk, Mulkila, Panchinala-A, Panchinala-B, Patsio, Samudra Tapu, Shamshargang) (varies in length between 2.8 km and 28 km) have been carried out on 1:50,000 scale using Survey of India topographical maps and the false-colour composites generated by multi temporal satellite data of IRS LISS III, Landsat-TM, Landsat-8 OLI/TIRS data using visual interpretation techniques in GIS environment. Terminus altitude for 1963 is extracted by utilizing the toposheet DEM (for all 13 glaciers), generated using 3D analysis tool of ArcGIS-10.1 and for 2013 ASTER GDEM Version-2 (Acquisition date: 17/10/2011) is used. Results indicate that the glaciers of Chandra-Bhaga basin are showing continuous retreat in terms of area and length. During 1963, total area of glaciers was estimated 304.44 ± 3.43 km<sup>2</sup> which was reduced to 281.86 ± 3.40 km<sup>2</sup> in 2013 showing a loss of 22.58 ± 3.41 km<sup>2</sup>. The estimated areal retreat of glaciers shows 7.41% ± 1.44% reduction in area with an average rate of retreat 0.45 km<sup>2</sup> a<sup>-1</sup>. 12 glaciers (except Patsio glacier) are showing longitudinal retreat with an average rate of retreat 283.12 ± 19.38 m a<sup>-1</sup>. Kelas Buk Glacier (this glacier is undergone a process of fragmentation) showed the maximum retreat rate (59.31 m a<sup>-1</sup>) while the minimum by Chhallopathang Glacier (0.38 m a<sup>-1</sup>). Further, 12 glaciers (except Patsio glacier) are showing the average terminus upliftment of 32 m with a mean rate of 09.66 m<sup>-1</sup>. Mulkila Glacier showed the highest terminus upliftment of 48 m whereas lowest by Panchinala-B Glacier (4.0 m). Due to the continuous icemass loss and shrinking of glaciers, the fragmentation of glaciers was also marked leads to a more number of glaciers from 13 (1963) to 15 (2013). Since local climates are heterogeneous, therefore, all the glaciers are reflecting different rate of retreat. The dynamic nature of retreating glaciers of Chandra-Bhaga basin are indicating the change in climatic conditions during past half century as the glaciers respond to climate variation and reveal the effects of climate change.



## S14 – 270: The Himalayan Cryosphere - Global Versus Regional Climate Forcing

### **Quantifying Annual Mass Balance Gradient (12 Years) and State of Dokriani Glacier, Central Himalaya, India**

Pratap B<sup>1</sup>; Dobhal D P<sup>1</sup>; Gupta A K<sup>1</sup>; Bhambri R<sup>1</sup>; Mehta M<sup>1</sup>

Centre for Glaciology, Wadia Institute of Himalayan Geology, India<sup>1</sup>

Knowledge about different aspects of glacier dynamics is important to understand the variety of glaciological processes and its characteristics in response to climatic variations. Therefore, a detail ground based measurement of annual mass balance gradient has been carried out on Dokriani Glacier for the period of 12 balance years between 1992 and 2013. Dokriani Glacier in Bhagirathi basin is a small NNW exposed glacier (area 7 km<sup>2</sup>) in the Western part of central Himalaya, India. Our study describes the results of the annual balances, mass balance gradient and length changes observed during first decade of 21st century (2007-2013) and compare with the previous observations of 1990s (1992-2000). For mass balance estimation, a network of 30-35 ablation stakes were drilled into the ice at particular points over the glacier surface along with different altitudinal zones for every studied year. These stakes are specifically installed for the ice ablation for which density of ice is assumed to be 850 kg m<sup>-3</sup>. Whereas, annual accumulation was determined using hand-dug pits, crevasse stratigraphy and by probing. Pits were performed nearby at the same location each year in the centre-line of glaciers accumulation zone where external factors like wind erosion and avalanching are minimal. Thickness measured was extrapolated to the higher mountain reaches to accommodate total snow accumulation that falls into bergschrund area. Extrapolated and measured thickness of annual snow accumulation was adjusted with density measured at every sample points varied from 530 850 kg m<sup>-3</sup> to 570 850 kg m<sup>-3</sup>. Residual accumulation and annual ablation were added for annual balance ( $ba = m^3 \text{ w.e.}$ ). The average annual balance from 1992 to 2000 with the gap years of 1996 and 1997 and from 2007/08-2012/13 was 0.32 m w.e. a<sup>-1</sup>. The spatial variability of two different periods mass balance gradients is very high, ablation and accumulation shows different order of melting magnitude than the average melting. Although, having larger accumulation area, the glacier has faced strong mass wasting with average annual ablation of -1.82 m w.e. a<sup>-1</sup> in the ablation zone compare to residual average annual accumulation of 0.41 m w.e. a<sup>-1</sup>. In spite of the high order of ablation rate compare to less accumulation rate, glacier has only -0.32 m w.e. a<sup>-1</sup> of surface mass loss. This attributed to the 30% of the total glacier area faced ablation process. This also shows that Dokriani Glacier is losing mass as a result of stronger summer ablation, particularly due to the exposition (WSW) direction of the lower ablation zone. The equilibrium line altitude (ELA) was fluctuated between 5030 and 5100m asl. The derived time averaged ELA (ELAn,) and balance budget ELA (ELA0) were 5075 and 4965m asl respectively. The observed time-averaged accumulation area ratio (AARn) and balance budget AAR (AAR0) were 0.67 and 0.72 respectively. The higher value of AAR comprises due to flat and broader accumulation area (4.67 km<sup>2</sup>) of the glacier. The recession rate of 21.3 m a<sup>-1</sup> during 2007-2013 is much higher than the retreat rate of 16.5 m a<sup>-1</sup> (1962-91), 17.8 m a<sup>-1</sup> (1991-2000) and 15.5 m a<sup>-1</sup> (2000-2007) respectively. The progressive retreat of the glacier affects its extension and volume and is covered by continuous enhancement of debris in the lower ablation zone.



**S14 – 282: The Himalayan Cryosphere-Global Versus Regional Climate Forcing**

***Debris Control on the Glacier Thinning Case Study of Batal Glacier, Western Himalaya***

Lavkush Patel<sup>1</sup>; Parmanand Sharma<sup>1</sup>; Meloth Thamban<sup>1</sup>; Ajit Singh<sup>1</sup>; Rasik Ravindra<sup>2</sup>

ESSO-National Centre for Antarctic and Ocean Research, Ministry of Earth Sciences, Goa, India<sup>1</sup>, Earth System Science Organization, Ministry of Earth Sciences, Delhi, India<sup>2</sup>

Complex factors like climate, glacial geometry, topographical features and debris cover have significant influence on the dynamics of the Himalayan glaciers. Presence of debris cover on the surface of glaciers can significantly alter the surface energy balance and influence the climatic response of glaciers. In this study, influences of debris cover were analyzed by in situ data collection over glacier surface of Batal glacier in Chandra Basin, Western Himalaya. Almost 90% of the ablation zone of Batal glacier is covered by debris, 35% of which is thick debris (> 10 cm). Fourteen stakes with increasing altitude and with varying debris thickness were installed to cover whole ablation zone. Among 14 installed stakes, 2 stakes represent clean ice, 4 stakes represent 15 cm debris thickness, 3 stakes represent 525 cm debris thickness, 2 stakes represent 2550 cm debris thickness, and 3 stakes represent > 50 cm debris thickness. These stakes were monitored at 15 days interval during August-October 2014 (ablation season). Our study has revealed high surface melting (84.7 cm w.e.) in the debris free glacier while low surface melting observed in thick debris covered ice (30.5 cm w.e.). This observation revealed a significant difference in the rate of surface melting as per the increasing debris thickness. Contrasting to normal ablation pattern over glaciers, Batal have experienced inverse retreat rate of ablation along with increasing altitude. This inverse relation is attributed to the control of debris thickness on ablation rate. A high degree of negative correlation ( $r^2 = 0.82$ ,  $p < 0.05$ ) between ablation rate and debris thickness suggest a significant control of debris thickness over ablation rate.



## **S14 – 331: The Himalayan Cryosphere-Global Versus Regional Climate Forcing**

### ***Understanding the Complex Changes in the Himalayan Cryosphere***

Shakil Ahmad Romshoo

University of Kashmir, India

There is lack of credible knowledge about Himalayan cryosphere as is evident from the contradictory reports about the status and dynamics of the glaciers in the region. Glacier behavior in Himalaya has to be understood and interpreted in light of the significant variation in the topography, climate and anthropocene across Himalayas. The observed changes in Himalayan glaciers, analyzed by studying 30 glaciers in the North Western Himalaya, indicated that the glacier response varies as a function of changing climatology, topography and emission regimes. We used time series of satellite images from 1990-2011 and DEM, supported by selective field campaigns, to map the changes in glacier boundaries, snout, ELA, AAR, volume, debris cover and several other glacier parameters. It was observed that the glaciers in Karakoram range showed the least recession in glacial area (1.59%) during the period due to the prevalence of extreme cold average temperatures of 18°C (Oct-April). Other glacial parameters like snout, ELA, AAR and glacier volume also showed very little changes in the Karakoram during the period. The glaciers in the Ladakh range, with an average temperature of 6° C (Oct-April), have shrunk, on an average, by 4.19 % during the 2 decades of the observation, followed by the glaciers in the Zaskar range where the glaciers have shown a loss of 5.46% in area during the same time. The highest glacier retreat of 7.72% and 6.94% was observed in the Greater Himalayan and Shamshabari range with the average temperature of 1.3°C and 6.2°C (Oct-April) respectively. In the Pir Panjal range, almost all the glaciers have vanished during the last 67 decades due to higher mean winter temperatures. The analysis of the glacial retreat and other glacial parameters in all the six ranges showed a very strong influence of the climatic and topographic regimes. It was found that the maximum recession of glacial area was observed in the mountainous ranges with altitudes below 4500m asl followed by the glaciers in the altitudinal range of 4500-5000m. The glaciers above 5000m showed the lowest rate of glacial retreat in the region. The other parameters like snout retreat, ELA changes, volume and other parameters observed in all the six observed ranges also showed strong correlation with topography.

The glaciers in the Kashmir valley surrounded by the Pir Panjal, Shamshabari and Greater Himalayan ranges showed an overall recession of 36.72% in area during 1980-2010. Detailed analysis of the topographic, climatic and emission data was carried out to understand the enhanced glacial recession observed in the Kashmir valley. The climate change signals are quite loud and clear in the region and the higher rates of recession could be due to the significant increase in the minimum winter temperatures observed in the region. Further, the analysis of the spatiotemporal observations of black carbon across these three ranges (42 sites) showed significant altitudinal, climatic and latitudinal variability. The highest concentration of BC (1600 to 18000 ngm<sup>2</sup>) was found in the plains of the Kashmir.



**S14 – 341: The Himalayan Cryosphere-Global Versus Regional Climate Forcing**

***Regional Climate Modeling over the Himalayas Glacier***

A P Dimri

Jawaharlal Nehru University, New Delhi, India

Regional Climate Model(s) (RCMs) are sensitive towards presentation of regional climate of Indian winter monsoon (IWM) over the western Himalayas (WH). They illustrate robust nature in representing regional climate at mountain scale and even at event scale. While downscaling outputs, from these models, at basin level for hydrological and glaciological studies, it is found that RCMs fail to provide realistic figures. And hence, in the present paper, using the Siachen glacier basin as a reference, debate and deliberation on RCMs uncertainly and high order of deviation from real observations is presented. Results from RCMs thus need a further tuning if they are used for hydrological and glacier studies. Reasons for such uncertainties could be due to the improper representation of topography, missing sub-grid scale processes, surface flux characteristics, various physical processes etc. at such finer model resolution and scale. At present, this paper only deliberates and bring out issues pertaining to such complexities to provide an insight for future course of studies, if understood correctly.



## S14 – 363: The Himalayan Cryosphere-Global Versus Regional Climate Forcing

### ***Spatial and Temporal variability of Accumulation Area Ratio (AAR) of Glaciers in Nubra, Chandra and Bhagirathi Sub-Basins in the Himalayan Region***

Sandhya Rani Pattanaik<sup>1</sup>; S.K.Singh<sup>1</sup>; I.M.Bahuguna<sup>1</sup>; A.S.Rajawat<sup>1</sup>

Space Application Centre, Indian Space Researcrch Organisation, Gujarta, India<sup>1</sup>

Accumulation area or zone is the part of a glacier which is above equilibrium line or the line of zero mass balance. Accumulation Area Ratio (AAR) is the ratio of accumulation area to total area of respective glacier. AAR can be used to determine the mass balance of glaciers at a reconnaissance level if the value of AAR is known for zero mass balance based on linear relationship developed between AAR and mass balance of glaciers for the corresponding years. This linear relationship can be further used to determine mass balance of glaciers without going to field. AAR can be derived in the field based on data of accumulation and ablation over a hydrological year. However, it is not practically possible to determine the mass balance of each glacier in Himalayan terrain as the Himalayan glaciers are remotely located in rugged and hazardous terrain imposing difficult environment in conducting research due to their inaccessibility, poor weather, cost and limited point measurements. Therefore satellite images with high temporal and radiometric resolution can be used to extract snow line at the end of ablation season. Snow line (SL) at the end of ablation period can be approximated as equilibrium line. Similar relationship between this line and mass balance of each year can be used to estimate mass balance. Increase or decrease in AAR values indicate the fluctuations in mass balance and can support as a good indicator to understand the variations in mass balance. In view of the above, a study was taken up to compare the AAR of glaciers in three sub-basins viz. Nubra, Chandra and Bhagirathi. The objective of this study is to understand the spatial and temporal variability of AAR of glaciers three sub-basins in the Himalayan region.

Identification of SL at the end of ablation season requires multi-temporal satellite data with high frequency. The best suited satellites are those which have Visible and Infrared (VIS) channels at the geostationary platform to identify SL each day. However current configurations of geostationary satellites allow resolution of the order of a Km or few Kms. So polar orbiting satellites with a better temporal resolution can be highly useful in this kind of study but the frequency of revisit time is of the order of 5 days or less. One of such sensor is AWiFS onboard Resourcesat1& 2 satellites with a resolution of 56m, swath of 700 km and at 5 days interval is a highly useful sensor for this work. Repeativity of 5 days enhances the opportunity to collect the minimum snow cover images during ablation period from July to September months. Reflectance of bright surface like snow does not get saturated over snow due to high radiometry of AWiFS data.

In this study, snow line at the end of ablation period was delineated using AWiFS data. AAR was estimated for more than 333 glaciers in identified sub-basins such as Nubra (a part of Indus Basin), Chandra (a part of Chenab Basin) and Bhagirathi (a part of Ganga Basin). These sub-basins are located in different climatic zones. Nubra basin is situated in Karakoram region with dry climate, Chandra basin is located in moist to dry climate and Bhagirathi basin is situated in moist or monsoonal climatic region. Eighty glaciers from Nubra basin covering 419 sq km, 106 glaciers in Chandra basin covering 265 sq km and 141 glaciers in Bhagirathi basin covering 715 sq km were used in this analysis. The AAR was generated from year 2008 to 2013. Glacier boundaries were delineated using moderately high spatial resolution LISSIII data and overlaid on AWiFS images for delineation of snow line. After delineating snow line, accumulation area was estimated for each glacier and AAR was derived using accumulation and total area of respective glaciers. Empirical relationship was used to derive mass balance of all glaciers in the identified sub-basins. Variation in the snow line altitude was also analysed and compared for all glaciers at sub-basin's scale.



The date of end of ablation season also varies on spatial and temporal scale. The maximum, minimum, mean and standard deviation of AAR for each year was calculated for each basin. These statistics indicated more variability in the Bhagirathi sub-basin than in other two sub-basins. The mean AAR of the glaciers of the Chandra and Nubra basins indicate the positive mass balance whereas the glaciers of the Bhagirathi sub-basin indicated negative mass balance in all years except in year 2010-2012. The variance has been noted minimum in Nubra sub-basin in all years; however, no significant trend of increase or decrease in AAR of glaciers of Chandra and Nubra sub-basins has been noted. This method can be used to understand in a limited time to assess the overall health of glaciers at a reconnaissance level. In future, with the availability of similar resolution data from geostationary platforms, monitoring of snow line could be done on daily basis and auto extraction of snow line will indicate the relative health of glaciers in terms of mass balance for entire Hindukush-Karakoram-Himalaya (HKH) region. The following figure shows the comparative values of AAR for three sub-basins from year 2008 to 2013.



## S14 – 389: The Himalayan Cryosphere-Global Versus Regional Climate Forcing

### *Monitoring of Snow Cover Variability in Chenab Basin using IRS AWiFS Sensor*

B. P. Rathore<sup>1</sup>; S K. Singh<sup>1</sup>; Purnesh Jani<sup>2</sup>; I. M. Bahuguna<sup>1</sup>; Rupal M. Brahmhatt<sup>3</sup>; A. S. Rajawat<sup>1</sup>; Anjana Vyas<sup>2</sup>

Space Application Centre, Indian Space Research Organisation, Gujarta, India<sup>1</sup>, CEPT University, Ahmedabad, Gujarat, India<sup>2</sup>, M.G. Science Institute, Gujarat, India<sup>3</sup>

The cryosphere is an integral part of the global climate system with important linkages and feedback generated through its influence on surface energy and moisture fluxes, precipitation, hydrology, atmospheric and oceanic circulation. Snow cover is a very dynamic component of the cryosphere which collectively includes those portions of Earth system where water is in a solid form and includes sea ice, river and lake ice, glaciers, ice caps and ice sheets, frozen ground and snow. Several fundamental physical properties of snow modulate energy exchanges between the surface and the atmosphere. This makes monitoring of seasonal snow cover important for many applications such as melt runoff estimation, climate change studies and strategic requirements. In terms of the spatial extent, snow is the second largest component of the cryosphere and covers almost 40 per cent of the Earth's land surface during Northern Hemisphere winter, which makes albedo and areal extent of snow as important component of the Earth's radiation budget. The most important properties of snow are high reflectivity, thermal insulation and ability to change physical state. The higher albedo of snow causes rapid shifts in reflectivity in autumn and spring at high latitudes. Reduced reflectivity of snow generates negative feedback to air temperature and increased air temperature raises the temperature of snowpack which accelerates the melting. It results into reduced snow cover areal extent and albedo of the region. Snow cover exhibited the greatest influence on the Earth radiation balance in the spring (April to May) period when incoming solar radiation was greatest over snow cover areas. In this investigation, AWiFS (Advanced Wide Field Sensor) data of RESOURCESAT- 1 and 2 satellites were used. AWiFS is an advanced version of earlier Indian satellite sensor WiFS (Wide Field Sensor) the study area was prepared using reference points from Landsat TM data. All AWiFS scenes from October to June for 2004-14 were geocoded using master image. 5 & 10 days snow cover product of Chenab sub-basin for consecutive ten years from 2004-14 for October to June months were generated to understand the accumulation and ablation patterns of snow. Snow cover product has been generated using Normalized Difference Snow Index (NDSI) using digital analysis technique and Geographic Information System (GIS). NDSI was calculated using the ratio of reflectance of Green (Band 2) and SWIR (Band 5) channel of AWiFS sensor. To estimate NDSI, DN numbers were converted into TOA (Top of Atmosphere) reflectance. This involves conversion of digital numbers into the radiance values, known as sensor calibration, and then estimation of reflectance from these radiance values. Various parameters needed for estimating spectral reflectance are maximum and minimum band pass spectral radiances and mean solar exo-atmospheric spectral irradiances in the satellite sensor bands, satellite data acquisition time, solar declination, solar zenith and solar azimuth angles, mean Earth-Sun distance etc. Sub-basins boundaries were overlaid on snow cover product to extract the areal extent of snow for Chandra, Bhaga, Miyar, Bhut, Warwan and Ravi. SRTM data was used to estimate altitude wise areal extent of snow cover for all three sub-basins. DEM is converted into contour map at 500 m interval using ARC GIS. The 10 days snow cover products were converted to polygon layer using raster to vector conversion. Intersection analysis of GIS is used between snow product and altitude zone to get snow cover area in each altitude zone. Snow cover area under each altitude zone was estimated using GIS for their comparative analysis. Average monthly snow line altitude was estimated for all the sub-basins using hypsographic curve. Snow cover monitoring of Chandra, Bhaga, Miyar, Bhut, Warwan and Ravi sub-basins were carried out for consecutive 10 hydrological years from 2004- 14 (October to June) using RESOURCESAT-1 & 2 AWiFS data. Accumulation and ablation patterns of snow cover have also been analyzed for the six sub-basins. It is observed that areal extent of snow in 2004-05, 2011-12 and 2013- 14 were higher than the average of all years of observations for all basins. Minimum and maximum snow cover were observed to be 26 %, 21 %, 12 %, 18 %, 13 % and 3 %



corresponding to 638, 359, 552, 397, 590 and 147 sq. km, and 100%, 100 %, 100 %, 100 %, 100 % and 97 % corresponding to 2432, 1680, 4449, 2208, 4658 and 4747 sq. km for Chandra, Bhaga, Miyar, Bhut, Warwan and Ravi sub-basins respectively during the observed period. Accumulation and ablation pattern of snow cover from 2004 to 2014 have shown slightly increasing trend for all the sub-basins. Hypsographic analysis for each sub-basin has shown it's influence on the accumulation and ablation pattern of snow cover area. This was prominently observed as the fluctuations in snow cover during winter months were high in low altitude Ravi sub-basin due to ablation of snow in accumulation months itself.



## S14 – 430: The Himalayan Cryosphere-Global Versus Regional Climate Forcing

### ***Monitoring Accumulation Zone of Glaciers in the Alaknanda River Basin using IRSP6, AWIFS Satellite Imageries***

Swati Tak<sup>1</sup>; Ashok K. Keshari<sup>2</sup>

M.D.S. University, Ajmer, India<sup>1</sup>, Department of Civil Engineering, I.I.T Delhi, New Delhi, India<sup>2</sup>

A number of perennial rivers in India originate from Himalayan ranges and have significant contributions from the glaciers in its stream flow which support water, food, energy and livelihood of millions of people along its course. The high altitude snow fields supply fresh snow to glaciers throughout the year where accumulation takes place. The addition of snow and ice leads to accumulation and it occurs through the snowfall occurring directly over the accumulation zone, resulting from wind blown snow, and the firnification taking place in the prevailing climate condition. The accumulation zone covers the area above the snow line because snow and ice must survive all year round in this zone. The monitoring of the accumulation area draws paramount significance in order to assess the health status of the glaciers, to carry out mass balance study, to understand the glaciers retreat, to understand the triggering of avalanches, and to assess the availability of water in the glacier fed river basin.

In this paper, medium resolution satellite remote sensing data was analysed to monitor the accumulation area of the Alaknanda glaciers for the improved understanding of the present health condition of glaciers and its contribution in the river steam flow. The analysis of satellite imageries of IRS-P6 AWiFS and SRTM DEM data was carried out using image processing and GIS tools for deriving five significant glacier parameters for assessing the relative health status of glaciers in the Alaknanda sub-basin of Ganga river basin, India. The glacier morphology map and data sheet were prepared based on IRS-P6 AWiFS data of 2004–07, SRTM DEM and other ancillary data. The various parameters, namely, glacier area, length, orientation, elevation and ice exposed are derived from these remote sensing data. The study shows that the Alaknanda sub-basin of the Ganga river basin spreads over 10882 km<sup>2</sup> area, and it has 253 glaciers, covering 39% as the glaciated area.

Results obtained from the study shows that the total accumulation area of the Alaknanda glaciers is 787.07 km<sup>2</sup>, ablation area debris is 349.79 km<sup>2</sup> and the ablation area ice is 193.07 km<sup>2</sup>. The estimated total volume of glacier ice in the Alaknanda sub-basin is 183.85 km<sup>3</sup>. The study also reveals that these are only 11 numbers of relatively healthy glaciers covering an area of 26 km<sup>2</sup>. These glaciers show values of composite health index more than 440. The less number of healthy glaciers may be of concern with reference to the sustainability of water resources on the longer term in the glaciers fed river basins and also with reference to glacier retreat as a consequence of the climate change.

**Keywords:** Snow Hydrology, Glaciology, Glacier Health, Remote Sensing, GIS, Alaknanda, Ganga



**S14 – 451: The Himalayan Cryosphere-Global Versus Regional Climate Forcing**

***Evidence of Formation and Breaching of Two Palaeo Lakes around Leh in Upper Indus Valley During Late Quaternary***

Lal Ravish<sup>1</sup>; Pant N.C<sup>1</sup>; Saini H.S<sup>2</sup>; Mujtaba SAI<sup>2</sup>; Kumar Pawan<sup>2</sup>; Tom Christy<sup>1</sup>

Department of Geology, University of Delhi, India<sup>1</sup>, Geological Survey of India, Faridabad, India<sup>2</sup>

The upper Indus basin along the Indus Tsangpo suture zone (ITSZ) in Ladakh region of Northwestern Himalaya lies in a climatically sensitive rain shadow which receives dominant precipitation by westerly disturbances. A number of Late Quaternary deposits like morains, alluvial fans, alluvial and lacustrine terraces and dunes are scattered in the valley at different levels offering scope to infer the palaeoclimatic changes and understand surface processes. Among them, lacustrine clays are common in the arid zone of NW Himalayas in Indus and Spiti valleys. In Indus valley, lamayuru paleolake is the most outstanding deposit. We have mapped two zones of palaeolake deposits around Leh using systematic traverses along the Indus River between Nimoo and Karoo in Indus valley downstream and upstream of Leh, respectively. Zone A, located downstream of Leh, is of few hundred meter aerial extent in a narrow valley, just upstream of the confluence of Zinchan nalla with Indus River. It consists of deformed laminated clays sandwiched between coarse fluvial sand beds. The top part of lake deposit is defined by a 3260m counter. The quartz OSL dating from fluvial sand below and above of the lacustrine clays suggest the clay deposition between ca. 125±11ka and 87±8 ka during stage 5. No evidence of the damming of the river is preserved in the valley. This lake is likely have formed and breached during MIS 5.

Zone B, a wider zone beginning from near Phyang nalla downstream of Leh extends from Phey to Shey villages and possibly further upstream for a length of >15 km along the Indus river. It is characterized by ~20m thick, relatively undeformed laminated clays near Spituk and about 10m thick siltyclay near Shey. Small patches of clays occur on left and right banks of Indus at several places between these two locations.

The palaeolake of Zone B was developed during a major alluviation phase of Indus valley that started ca. 79±5 ka. It is best developed in Spituk section in which three units (fluviaolacustrine, lacustrine and fluvial) have been identified earlier. The lacustrine unit was deposited due to the damming of the Indus river by alluvial fan emerging from Phyang nulla on the right bank, possibly between ca. 74±5 ka and < 58±2 ka during the cold stage 4 (MIS 4). The Phyang alluvial fan consists of rounded pebbles of granites with lenses of sand representing Ladakh granite which it drains. These sediments also occur on the left bank of Indus river suggesting that, the river was blocked by this fan and allowed the sediments to cross over to the left bank terrace. At other places such transgression is absent. This lake was oval and deepest near the damming site i.e Spituk and gradually tapered towards upstream in a manner that it formed laminated siltclay near Shey village. The lake appears to have breached before 49±2 ka.

Like Spituk section, the ~33 m thick section at Shey also shows three lithological units. The basal unit (~10m thick) comprises alternating layers of laminated sand, siltyclay and clay (fluviolacustrine). The middle unit (~10m) represents a stable lacustrine phase consisting mainly of laminated clays. The top unit (~13m) is a sandy fluvial unit.

Heavy mineral assemblages from the sediments of Shey and Spituk sections show similarities in having typical metapelitic assemblages in lower fluvial unit and their absence in middle and upper units. With Zone B lithological and sedimentological similarities allow correlation of composite lithological sections which are widely separated indicating presence of a single water body within which these deposits formed. Assuming no post depositional disturbance, top of lake can be marked at 3324 msl at Ranbirpor on the right bank and on the left bank it goes upto 3330 msl. A contour drawn at this 3330 msl height



provides the limiting minimum water level for the paleolake in Zone B. This contour describes an area of 161 sq km for this megapaleolake. The formation and breaching of paleolakes during MIS 4 and 5 is discussed in the context of global climate signatures and a significant influence of local climate control is observed.



**S14 – 481: The Himalayan Cryosphere-Global Versus Regional Climate Forcing**

***Estimation of Snow Cover Area by Remote Sensing Data Sets “A Case Study of Chorabari Glacier Basin, Garhwal Himalaya, India”***

Anshuman Misra<sup>1</sup>; Amit Kumar<sup>1</sup>; Rakesh Bhambri<sup>1</sup>; D.P. Dobhal<sup>1</sup>; Rajeev Upadhyay<sup>2</sup>

Centre for Glaciology, Wadia Institute of Himalayan Geology, Uttarakhand, India<sup>1</sup>, Department of Geology, Kumaun University, Uttarakhand, India<sup>2</sup>

Snow cover play an important role in energy balance on earth by reflecting back the solar radiation to space and also contribute significantly in overall runoff. Snowmelt in turn acts in seasonal energy exchange between atmosphere and ground, affecting soil moisture and runoff. Earlier the snow cover was determined by field based methods. These methods were cumbersome, highly expensive and provided very rough estimation. In early 70s, unprecedented developments in the field of remote sensing techniques and availability of a wide range of spatial, temporal, and spectral satellite data, Snow Cover Area (SCA) can be mapped in different spatial scales throughout the year. This consequently helps to monitor the dynamic nature of the snow cover. In the present study an attempt is made (i) to estimate the SCA over the Chorabari Glacier basin (elevation range ~ 3,799m to 6,893 m.asl, length 6.5 km and basin area 17.8 km<sup>2</sup>) and (ii) its variability during summer months at different elevation zones for selected years of study. The Landsat TM 5 satellite data are acquired from the Earth Explorer site, for the years 2009 and 2010. Normalized Difference Snow Index (NDSI) and Band Rationing methods were used to extract SCA from the Landsat TM data. To estimate SCA, elevation wise zones were created with the help of ASTER DEM. Results show that, snowmelt begins by the end of March and the snowline at 3799 m ascends up to 4,800 m by the end of the melt season. Nearly 97% of the catchment area is covered with snow during winter months, out of that only ~46% remains at the end of summer. Subsequently, the SCA for each elevation zone is plotted against the elapsed time in order to construct the depletion curves for the different elevation zones. The high variability found in SCA (Cv = 0.03 to 1.98) between higher and lower elevation zones. At higher elevations it is significantly less (above 5500 m asl) in comparison to lower elevation zones (below 5000 m asl), indicating depletion of SCA more rapidly during summer months, and contributes melt water discharge. Daily snow cover area derived from the interpolation of depletion curve using polynomial equation of 2 order ranges between R<sup>2</sup>=0.8 and 0.9 which in turn helps to relate with hydro-meteorological data during the study period. Such relationship provides a good input to prepare hydrological model for the estimation of melt water discharge annually. The methodology developed during the present study, can be applied to understand basin wide variability in SCA.



**S14 – 485: The Himalayan Cryosphere-Global Versus Regional Climate Forcing**

***Black Carbon and Aerosol Chemistry Over Manora Peak in Central Himalayas***

Kirpa Ram

Institute of Environment and Sustainable Development, Uttar Pradesh, India

Black carbon (BC), derived from variety of anthropogenic emission sources, have a direct effect on regional air quality, hydrological cycle and climate through the modification of atmospheric radiative forcing. BC is mainly hydrophobic in nature and can affect the cloud formation processes through the modification in the cloud-condensation nuclei (CCN). The indirect effects of BC are poorly known, partly because it requires the knowledge of the microphysical and optical properties of black carbon. The pristine regions like Himalaya and Arctic are also influenced by the long-range transport of atmospheric aerosols which may contain a significant amount of the absorbing BC. The radiative forcing of BC aerosols and changes in snow-albedo strongly depends on the ambient BC concentration and amount of BC deposited on to snow surfaces. The deposition of aerosols, especially BC, leads to a decrease in the snow albedo which subsequently may enhance melting of the glaciers. A recent study have reported that deposition of BC aerosols during the summer/ pre-monsoon (April-June) can cause a reduction of ~2 to 5% in the snow albedo which can lead to an increase of ~70% ( 204 mm) runoff of water drainage. A detailed understanding and knowledge of the chemical composition of aerosols, their size-distribution and optical properties (absorption coefficient, single scattering albedo, SSA and aerosol optical depth, AOD) is of utmost interest for the assessment of aerosol radiative forcing and air-quality over the Himalayan region. Our study conducted during 2005-2008 indicate that aerosol optical depth values exhibit significant variability (range: 0.04 to 0.45) with higher AOD values in summer mainly due to an increase in mineral dust contribution. In contrast, single scattering albedo (SSA) varied from 0.74 to 0.88 with relatively lower SSA values during summer, suggesting an increase in absorbing BC and mineral dust aerosols. As a result, a large positive atmospheric radiative forcing (about  $+28 \pm 5 \text{ Wm}^2$ ) and high values of corresponding heating rate ( $0.80 \pm 0.14 \text{ Kday}^{-1}$ ) has been found during summer. During the entire observation period, radiative forcing at the top of the atmosphere varied from 2 to  $+14 \text{ Wm}^2$  and from 3 to  $50 \text{ Wm}^2$  at the surface whereas atmospheric forcing was in the range of 3 to  $65 \text{ Wm}^2$  resulting in a heating rate of 0.1 to  $1.8 \text{ Kday}^{-1}$ . The present study provides an additional evidence for the presence of absorbing aerosols in summer in central Himalayan region which may influence the local atmospheric circulation and monsoon activities.



## **S14 – 516: The Himalayan Cryosphere-Global Versus Regional Climate Forcing**

### ***Himalayan Glaciers – Climate Change and Their Heterogeneous Behavior***

Deepak Srivastava<sup>1</sup>; Rasik Ravindra<sup>2</sup>; N. C. Pant<sup>3</sup>

Geological Survey of India (Retd), India<sup>1</sup>; Earth System Science Organization, Ministry of Earth Sciences, New Delhi, India<sup>2</sup>; University of Delhi, New Delhi, India<sup>3</sup>

The role of Himalaya in global cryosphere is very important. Himalayan glaciers influence the climate as well as they are impacted by the climate. The glaciers in the Himalaya feed 10 rivers supporting livelihood for about 1.4 billion people whose very survival depends on them. Concern for Himalayan glaciers emanate from their not only being store house of fresh water but the seasonal release of fresh water for survival. Himalayan glaciers prominently figured when impact of global warming was over emphasized on them. Initial studies on few glaciers lead to certain conclusions which were later debated.

Himalayan glaciers do not act like a monolithic body. They show heterogeneous behavior. That is why understanding the Himalayan glaciers in totality are of utmost importance. Himalaya spread between latitudes 25° N and 35°N and longitudes 60° and 106° E for about 2500kms in west to east direction and 230 to 350 kms in south to north, consists of several ranges which are north west to south east oriented. They are all store house of more than several thousand glaciers. The widespread distribution of glaciers both longitude wise and latitude wise encounters variety of climatic regimes as well as they have their altitudinal distribution. To understand Himalayan glacier behavior, therefore, it is important to understand different sources of precipitation regimes of Himalaya, temperature variation trend over different altitudes, impact of radiation over different parts of the glacier with debris cover and clean areas besides orographic disposition and microclimate of the basin. Length change response of a glacier is impacted by several factors which may be specific for that glacier. That is why retreat of a glacier may not represent an overall scenario. Studies have indicated that recession of glacier in southern part of Himalaya is more compared to those in the northern part of the Himalaya. Glaciers in Karakoram both in western and eastern part are showing advance as well as surging behavior. There is an increase in glacier area in Karakoram region whereas in western, central and eastern Himalaya the glacier area has decreased.

Heterogeneity in behavior of Himalayan glaciers need to be understood in terms of spatial distribution of glaciers, different climatic regimes prevailing over the vast distributed area, altitudinal distribution of the glaciers, specific orographic position, pattern of debris cover on the glacier and microclimate prevailing in the basin.



### S15 – 23: Palaeoclimate Records from Antarctic Drilling Projects

#### ***Let's get to the bottom of West Antarctic Ice Sheet Evolution: An Initiative to Drill Sediment Drifts on the Amundsen Sea Continental Rise.***

Gabriele Uenzelmann-Neben<sup>1</sup>; Dr. Claus Dieter Hillenbrand<sup>2</sup>

Alfred-Wegener-Institute, Germany<sup>1</sup>; British Antarctic Survey, United Kingdom<sup>2</sup>

The Antarctic ice sheets have moved into the focus of public and scientific interest because of modern global warming and their possible contribution to sea level rise and resulting flooding of low lying coastal areas. Research has predominantly concentrated on recent short term dynamics of the ice sheets in order to understand their vulnerability to a changing climate by collecting multidisciplinary data. However, little is known about their long term evolution, especially about that of the West Antarctic Ice Sheet (WAIS). The WAIS is a marine based ice sheet and assumed to respond more sensitively to both atmospheric and oceanic warming than the largely terrestrial East Antarctic Ice Sheet (EAIS). Information on the early stage of WAIS formation and the Cenozoic glacial history in its Amundsen Sea sector is scarce. Drilling offshore from the George V. and Adelie Land drainage sectors of the EAIS has shown that mid Eocene cooling there was initiated by early flow of the cold Antarctic Counter Current across the Tasman Gateway (IODP Expedition 318). Seismic data indicate that this cold Antarctic Counter Current has also bathed the Amundsen Sea continental margin implying a cold climate in this area during the Palaeogene. The timing of WAIS formation and possible collapse events thereafter are still under debate and little is known about the Cenozoic WAIS dynamics in the Amundsen Sea region, where the east setting Antarctic Circumpolar Current (ACC) bathes the continental rise. The ongoing discussions about the glacial history of West Antarctica resulting from both on and offshore studies include topics such as (i) the first appearance of mountain glaciers, ice shelves and local ice caps, (ii) the build up of a large WAIS, (iii) the cooling of surface waters, (iv) the variability of bottom water circulation, and (v) the instability of the WAIS during the Neogene. Ground truthing is difficult because most of the corresponding palaeo records were recovered in the Ross Sea sector, thus providing an integrated picture of WAIS and EAIS history, while the only available deep sea drill site from the Amundsen Sea, DSDP Site 324, extends back to not more than 4 Ma. We suggest the development of an IODP proposal to address the following objectives:

1. Develop a general age depth model for the whole sedimentary column on the Amundsen Sea continental rise down to the oceanic basement, identify its basal age and reconstruct changes in depositional regimes in response to palaeo-environmental changes from sedimentological analyses on the drill cores.
2. Identify the first supply of glaciogenic sediments to the Amundsen Sea for reconstructing WAIS formation.
3. Search for indicators for WAIS collapses during the Neogene.
4. Identify the oldest documented bottom current activity on the continental rise and study its relation to WAIS formation.
5. Decipher the history and southward protrusions of Circumpolar Deep Water (CDW).
6. Document the interaction of along slope and downslope sediment transport and distinguish between times with high detrital input from the continent and times with low material input for reconstructing ice sheet advance and retreat and changes in bed conditions (temperate vs. polar) on land through time and for determining forcing mechanisms.
7. Reconstruct the variability in the direction and velocity of bottom current flow in the Amundsen Sea and infer changes in bottom water production in the source areas (Ross and Weddell seas)

We invite and welcome further ideas and contributions.



## S15 – 81: Palaeoclimate Records from Antarctic Drilling Projects

### *Future Plans and Strategy of IODP Drilling in Antarctica and the Southern Ocean*

Gohl, K.

Alfred Wegener Institute, Helmholtz-Centre for Polar and Marine Research, Germany

The International Ocean Discovery Program (IODP) states in its current IODP Science Plan for 20132023 that the polar regions are one of the primary target areas for scientific drilling using the drill vessels Joides Resolution and Chikyu as well as various drilling options in so-called Mission-Specific Platforms. In particular this is expressed in the Science Plans Key Theme Climate and Ocean Change and its Challenge 1 How does Earth's climate system respond to elevated levels of atmospheric CO<sup>2</sup> and Challenge 2 How do ice sheets and sea level respond to a warming climate : The response of ice sheets to a warmer climate can be reconstructed from sedimentary records of relatively recent interglacial episodes when ice extent was similar, or slightly less than at present, and from much earlier times (343 Ma) when climate was several degrees warmer than today. Analysis of recently recovered ocean sediment cores suggests that the West Antarctic Ice Sheet (WAIS), with a potential of 4 m sea level rise, is particularly sensitive to climate change and may have collapsed many times over the last 5 million years. Estimates of sea level rise during warm intervals about 3 million years ago suggest the possibility of even larger changes. The Greenland Ice Sheet and WAIS together account for only about 12 m of potential sea level, so estimates greater than 12 m imply a significant loss of ice from the much larger East Antarctic Ice Sheet, containing the equivalent of about 52 m of sea level. Some of the major questions to be urgently addressed are: Did large sections of the West and East Antarctic Ice Sheets collapse the last time when atmospheric CO<sup>2</sup> levels reached 400 ppm? What are the time spans over which past ice sheet collapses occurred, and how much warming was required to push them past their tipping points ? To answer these questions, sediment cores are needed from the Antarctic shelves and slopes where sediment accumulates rapidly. This information is needed, along with land-based records, to constrain numerical ice sheet models that attempt to predict how ice sheets melt under warmer conditions. Drilling of continental rise and deep-sea sediments at sites close to past ice sheets will provide more direct information regarding regional ice melt history and the timing of ice advance and retreat. Ultimately, the combination of these ice-proximal and ice-distal data with modelling techniques can be used to work out the relative contributions of different ice sheets to past sea level change, providing more realistic scenarios for testing predictive models and a better understanding of ice sheet behaviour in climate change situations.

The general drilling strategy in IODP is to target locations ranging from polar seas to low-latitude upwelling zones to explain the behaviour of the climate system during past episodes of global warmth. This is well in line with the SCAR-PAIS approach to development of ice-to-abyss data transects, extending from the ice sheet interior to the deep sea in order to link ice core, ice sheet-proximal, offshore, and far-field records of past ice sheet behaviour and sea level, yielding an unprecedented view of past changes in ice sheet geometry, volume, and ice sheet-ocean interactions.

About 10 drilling proposals for Antarctica and the Southern Ocean, at various stages from pre-proposals to revised and mature full proposals, are currently in the IODP evaluation and implementation system. Some have been forwarded to the Facility Boards for scheduling, and one proposal is already scheduled for drilling. This presentation will give an overview of these proposals and their progress stages, also with regard to the future perspectives and challenges of IODP, and will discuss strategies that may help successful proposals to be considered for drilling.



**S15 – 84: Palaeoclimate Records from Antarctic Drilling Projects**

***New Environmental Magnetic and Organic Geochemical Insights into the Pliocene Warm Period from New Harbor Drill Cores***

Christian Ohneiser<sup>1</sup>; Catherine Beltran<sup>1</sup>; Gary Wilson<sup>1</sup>; Joe Prebble<sup>2</sup>

University of Otago, Department of Geology, New Zealand<sup>1</sup>, GNS Science, New Zealand<sup>2</sup>

We present a record from the Taylor Valley, DVDP 11 drill core, which paints a new picture of the warm Pliocene period in Southern Victoria Land, Antarctica. Paleomagnetic data provide robust age control of the successions and indicate that below 200 m the successions is of early Pliocene to latest Miocene age and the upper portion dates from the mid Pleistocene to modern times. Sediments comprise thin mudstones and massive to stratified diamictites. Sedimentary and paleo-ecological evidence indicates that during the latest Miocene to early Pliocene, wet based glaciers filled the Taylor fiord and that glaciers retreated during the Pliocene warm period leaving open marine conditions and a deep fiord (>300 m).

We conducted environmental magnetic and organic geochemical analyses to characterize the terrestrial environment around the fiord. Magnetic analyses revealed oxidized magnetic minerals, which indicate that soils likely formed at the edges of the fiord. Soil formation requires warm and wet conditions and a significant increase in the number of above-freezing days compared with today. In order to further test the hypothesis of Pliocene soil development we conducted geochemical analyses in which we identify significant concentrations of n-alkanes and fatty alcohols indicative of higher order, vascular plants. Pollen analyses of the same samples yielded only a handful of recognizable palynomorphs possibly because sediments were winnowed, therefore pollen data do not provide supporting evidence of a Pliocene plant community. However, the concentrations and composition of organic biomarkers exclude advection from low latitude landmasses or from an older, local source, suggesting the development of local plant community.

We suggest that conditions were significantly different during the Pliocene warm period and possibly warm enough to support higher order plants. Such a setting would require a significant reduction in Antarctic ice volume in line with recently published results from IODP Expedition 318, the ANDRILL MIS core and computer simulations which suggest East Antarctic ice volume were probably much lower than previously thought.



**S15 – 153: Palaeoclimate Records from Antarctic Drilling Projects**

***Potential for Drilling Cainozoic Sediments below the Ekstram Ice Shelf, Dronning Maud Land, East Antarctica***

Gerhard Kuhn<sup>1</sup>; Kristoffersen<sup>2</sup>; Eisen, O.<sup>1</sup>; Jokat, W.<sup>1</sup>

Alfred-Wegener-Institute, Germany<sup>1</sup>; University Bergen, Norway<sup>2</sup>

The Explora Wedge (Hinz and Krause, 1982; Hinz et al., 2004) represents a prominent morphological and structural feature of Earth crust in the north eastern Weddell Sea. Marine geophysical data reveal that it constitutes East Antarctica's volcanic rift margin, with seaward dipping reflectors buried below sediments and floating ice shelves on the continental margin of Dronning Maud Land. Using a vibroseis source on the Antarctic continent for the first time, together with regional aeromagnetic data, these new results show the southward extent of the more than 1000 m thick Explora Wedge (EW) volcanic deposit below the Ekstram Ice Shelf (Kristoffersen et al., 2014). While up to now the landward extent of the wedge had been less clearly defined, the new data indicates the top of the wedge outcrop to be about 36 km landward off the shelf edge, or 14 km south of Neumayer III station. One target of the geo-scientific studies will be the top of the EW sequence, which represents the final phase of the initial continent break up and is presumed to be of an Upper Jurassic age. Genesis, magma differentiation, and precise age of the EW volcanics are largely unknown and high-ranking research objectives. The upper boundary of the EW forms a distinct unconformity to the overlying younger, wedge-shaped sedimentary unit, which reaches about 800 m in thickness close to the Neumayer III station.

The age of these sediments is unknown and could be all from Mesozoic to Recent. Considering this largely unexplored Antarctic continental margin, any high latitude palaeo-environmental information about the Mesozoic and lower Cainozoic greenhouse world prior to the start of Antarctic glaciation, the onset of glaciation, and up to the glacial/interglacial variability of the East Antarctic Ice Shield during the Quaternary can best be gathered through drilling at the proposed site. Perhaps we will be able to drill one never reached target of former ODP Leg 113, the Cretaceous black shales that sparsely were dredged from the scarps of the Wegener Canyon close by (Fetterer et al. 1990).



**S15 – 154: Palaeoclimate Records from Antarctic Drilling Projects**

***Clues for Late Cenozoic Antarctic Ice sheet and Bottom Current Dynamics from a Seismostratigraphic study in the Central Basin (ROSS SEA SLOPE)***

S. Kim<sup>1</sup>; L. De Santis<sup>2</sup>; J.K. Hong<sup>1</sup>; Y.K. Jin<sup>1</sup>; R. Geletti<sup>2</sup>; N. Wardell<sup>2</sup>; L. Petronio<sup>2</sup>; E. Colizza<sup>3</sup>; R. McKay<sup>4</sup>; S.H. Kang<sup>1</sup>

Korea Polar Research Institute, South Korea<sup>1</sup>; OGS, Italy<sup>2</sup>; Univ. Trieste, Italy<sup>3</sup>; Victoria Univ. Wellington, New Zealand<sup>4</sup>

The Ross Sea embayment is one of the main glacial drainage outlets of the Antarctic Ice Sheet (AIS). The AIS evolution and ocean current dynamics during the mid-late Cenozoic time could be extracted from sedimentary sequence of the outer Ross Sea continental margin, that have minimum hiatus compared to the inner shelf region. The aim of this study is to contribute to the understanding of AIS and ocean current dynamics by reconstructing the paleo-depositional environment evolution, based on the seismic stratigraphy from the outer shelf to lower slope of the Central Basin (west of the Iselin Bank), from mid Miocene to the present.

Multi-channel seismic (MCS) profiles were acquired in the Central Basin during the 2012-2013 and 2014-2015 Antarctic expeditions with RV/IB Araon.

The new data were combined with the existing MCS lines that were previously collected by the Italian Antarctic research program (PNRA) and other data that were available from the Antarctic Seismic Data Library System (SDLS), in order to extend major ANTOSTRAT seismic horizons from inner shelf to continental slope and rise. The seismic grid was used for seismic sequence mapping (1) to reconstruct paleo-bathymetry at RSU4 (mid-late Miocene) and RSU2 (late Pliocene-early Pleistocene) times and (2) to calculate sedimentation rates since RSU4 time.

The seismic profiles show well-stratified aggradational sedimentary sequence from the outer shelf to the lower slope between RSU4 and RSU2 horizons.

Above RSU2 horizon, prograding wedges developed in the outer shelf and upper slope. Well-developed sediment drift features are observed along the slope of the Central Basin. The paleo-bathymetry at RSU4 and RSU2 appears to be similar to present-day topography. Sedimentation rate between RSU2 and the present seafloor is 23 times higher than between RSU4 and RSU2. Paleo-shelf break and depocenter at the mouth of Joides Basin migrated basin ward throughout the mid-late Cenozoic time. The preliminary results of this study document the advance of the AIS over the shelf edge of the Central Basin region after RSU2 time. In addition, the new seismic profiles are crucial sites survey for the IODP proposal 751-full aimed at investigating ocean-ice sheet interactions during the mid-late Cenozoic time.



## S15 – 214: Palaeoclimate Records from Antarctic Drilling Projects

### ***"Beyond EPICA": Potential sites where to find a 1.5 Million Year OLDEST ICE record of Climate and Greenhouse gases from Antarctica.***

Massimo Frezzotti<sup>1</sup>

ENEA, Italy<sup>1</sup>

After the success of EPICA (European Project for Ice Coring in Antarctica), which at Dome C (East Antarctica) has provided access to climate and environmental records covering the last 800 ka, the international community, under the auspices of International Partnerships in Ice Core Sciences (IPICS), is now engaged in the challenge to obtain the oldest possible ice core record from Antarctica.

An ice core record reaching towards 1.5 Ma ago would be a major step forward in understanding Quaternary climate, and would further our understanding of the relationship between greenhouse gases and climate.

Throughout the EPICA era, climate cycles of roughly 100 ka years held sway. Marine sediments show that just before this time, cold and warm periods alternated instead on a timescale of 40 ka. By observing the transition into the so-called 100 ka world in the first ice core reaching back 1.5 Ma, we will be able to constrain the origin of this fundamental Earth System threshold and unravel the linkages between the carbon cycle, ocean overturning, ice sheets and climate. By studying this so-called mid-Pleistocene transition we can further constrain our knowledge of both the transient and equilibrium response to carbon emissions. Only an ice core covering this transition will provide direct evidence of associated CO<sub>2</sub> changes and of the possible role played by this and other greenhouse gases in setting the Earth's climate at a different pace.

In order to attain the goals, two or more cores will be required in order to provide replication in a regime where flow disturbance is possible. Horizontal ice flow should be avoided as much as possible, as ice transported long distances in the bottom hundred meters of ice is prone to flow disturbances. Based on ice thickness, bedrock topography, accumulation rate and basal temperature, the likely search region is the highest part of East ice divide Antarctica, with a region south of Dome C provoking particular interest; Other areas should also be researched (Dome F, Dome B, Dome A and their ice divide area).

After the current planning stage, a broad area geophysical survey and a season of shallow drilling are needed in any candidate regions. This will provide enough data for a more targeted modelling effort that candidate sites. Multinational consortia would be expected to form in order to tackle each candidate site. Before being confirmed as an oldest ice site, each candidate should undergo more detailed local survey and also a rapid access to entire record using new drilling probes before heavy equipment is committed.



## S15 – 244: Palaeoclimate Records from Antarctic Drilling Projects

### *The Sorting Centre of the National Antarctic Museum-Trieste Section-an Italian Repository for Marine Geological Materials Collected in Antarctica*

Ester Colizza<sup>1</sup>; Giorgio Fontolan<sup>1</sup>; Ioanna Protopsalti<sup>1</sup>; Gianguido Salvi<sup>1</sup>; Cristiano Landucci<sup>1</sup>; Giudo Travaglia<sup>1</sup>; Michele Ferneti<sup>1</sup>

University of Trieste-MNA Trieste Section, Italy<sup>1</sup>

Italy ratified the Antarctic Treaty in 1981, and from 1985 Italian scientists have participated in research activities regarding the Antarctic continent in the framework of the Programma Nazionale di Ricerche in Antartide-PNRA (National Antarctic Research Program). Since this time, many different Italian scientific groups have outlined and carried out basic and applied research studies and projects in various scientific fields. The diffusion of information regarding these studies has led to the formation of the Museo Nazionale dell'Antartide MNA (National Antarctic Museum) dedicated to the memory of Felice Ippolito, a prominent geologist and the first president of the museum. The mission of the Museum is the conservation and study of samples collected during Italian scientific expeditions, the promotion of the results achieved by the Italian scientific community and any activity (specifically related to exploration) as a result of the Italian presence in Antarctica. The Museum is a centre set up by the Universities of Genoa, Siena and Trieste. Each of the three sections is made up of a permanent exhibition, a study and sorting centre, and a documentation centre.

The University of Genoa has been tasked with promoting research in the field of biology and ecology and preservation of marine and terrestrial biological samples. The University of Siena is responsible for the preservation of samples connected to geology, mineralogy, lithology and glaciology, and raising public awareness. The University of Trieste collects findings connected to the history of the exploration of the Antarctic continent and preservation of marine geological and sedimentological samples.

The Sorting Centre of the Triestine section of the National Antarctic Museum is the national site for the collection of that geological-marine material sampled in Antarctic and Magellan marine areas during the Italian PNRA Antarctic Expeditions since the early 1990s. The facility houses over 1.000 meters of core sediment, over 1.400 kg of dredge and grab samples and over 50 meters of box-cores of Antarctic and Magellan marine areas as well as of Antarctic lakes and beach samples. The samples are stored in cold rooms at a temperature of 4 degrees centigrade (cores and sediments considered archive), freezers and on shelves at room temperature (subsamples obtained for the study of sediments).

Sorting Centre facilities for marine geology include:

1. The preservation of the collections (piston cores, gravity cores, interface gravity cores, trigger cores, box-cores, grab sediment samples);
2. The acceptance and conservation of new cores and marine geological samples, core X-rays and their description;
3. An updated GIS database of the samples which display metadata (PNRA expedition, core label, collected data, latitude and longitude, water depth (m), etc) and a link to more data such as digitalized X-rays and their preliminary description and images.

The aim of the existence of the Sorting Centre is to provide tools for scientists to complete their research objectives and to promote international collaboration between research centres and universities. Samples can be distributed worldwide upon request for a specific Antarctic research project.



## S15 – 249: Palaeoclimate Records from Antarctic Drilling Projects

### ***Ostracoda record from Quaternary biogenic carbonate sediments off Cape Adare (NorthWest Ross Sea, Antarctica)***

Gianguido Salvi<sup>1</sup>; Ester Colizza<sup>1</sup>

Department of Mathematics and Geosciences University of Trieste, Italy<sup>1</sup>

Increasing attention has been paid to environmental and climatic change in the scientific literature with a focus on organisms which provide a proxy record of changes. Ostracods (a group of small crustaceans), have an excellent fossil record and are among the few groups that can be (palaeo) environmentally informative in the marine realm, and as such are widely employed as a palaeoenvironmental and palaeoclimatic indicator. Research on benthic ostracods in the Antarctic region started with expeditions at the end of 19<sup>th</sup> century. The earliest paper described ostracods collected on the H. M. S. Challenger expedition from the region around Kerguelen, Marion, and Prince Edward Islands. Since these early studies, knowledge on recent and fossil Antarctic ostracods has significantly improved. All these studies indicate a high level of endemism of the Antarctic ostracoda fauna, with the exception of several species living both in Antarctica seas and along the southernmost coast of South America. In contrast, investigations on ostracods in past records (sediment cores) of the Antarctic seas are rare, as a consequence of the poor preservation of ostracod valves in the fossil records. The NW Ross Sea area off Cape Adare shows carbonate rich litho-facies, consisting of poorly sorted sandy and gravelly skeletal remains, with a good presence of biological remains. The high abundance of fossils pertaining to different taxa, including ostracoda fauna, is related to the water mass circulation with related changes of nutrient content, salinity, sea ice cover and CaCO<sub>3</sub> saturation. Moreover, accumulation factors are granted when the carbonate output surpasses the dilution by terrigenous compounds. In addition, the fossil assemblages, as well as textural and geochemical characteristics of marine limestone, contain invaluable proxies that make it possible to reconstruct the evolution of marine ecosystems.

Analyses on ostracoda fauna aims: a) to define different accumulation patterns in selected cores from the western Ross Sea area, where carbonate rich sequences associated with glacial marine sediments were recovered; b) to locate the more or less favourable periods when carbonate factories operated in order to produce carbonate sediment c) to exploit qualitative and quantitative variations of the ostracod species together with compositional data (texture, organic Carbon, CaCO<sub>3</sub> contents) to reconstruct the ice shelf front oscillation phases and the connected paleo-environmental / climatic changes.

Six gravity cores (ANTA 98 c25, ANTA02 NW1, NW2, NW5, NW6, and NW12) were collected in 1998 and 2002 respectively during two PNRA cruises and were investigated from the micropaleontological point of view in the framework of the GEOSMART project. Cores were split into two halves, X-rayed and sampled. Several measurements (analyses) were performed on sediment including water content, grain size, organic and CaCO<sub>3</sub> content, microfossil assemblages. A significant number of levels were C14 dated.

Sediment samples used for ostracod analyses were disaggregated in warm water and gently washed through a 62.5 µm sieve and subsequently dried and weighed. The >62.5 µm fraction was examined for benthic ostracods, and the 62.52 mm jam fraction was stored for future study. Ostracods were picked, identified and counted. Percentages of each species were calculated from data expressed as the number of individuals / gram of dry sediment.

The north-western sector of the Ross Sea continental shelf presents a wide zone characterized by a rich carbonate deposit occurring during the late Pleistocene, and likely contemporaneous with the basal till and glacialmarine deposits on almost the whole continental shelf. The radiometric age, ranging from 26 to 1.2 ky BP, produced by these deposits revealed that the sedimentation took place simultaneously with the



late Quaternary glacial phases and subsequently during the phases of withdrawal of the West Antarctic Ice Sheet (WAIS). The carbonate deposits located along the western margins of the banks of the NW Ross Sea Shelf yielded the ostracod population analyzed in this work. Studies of ostracod assemblages from six sediment cores showed some interesting micropaleontological results, particularly those obtained from ostracod assemblage changes (species appearance and disappearance, test fragmentation evidence of displacement phenomena) which were useful for the reconstruction of the climatic history of the area and for improving our understanding of the carbonate deposition in polar environments.

In this research on fossil ostracods, the preliminary results of the cores in the outer shelf showed strong qualitative and quantitative variations on the ostracod populations probably linked to specific glacial fluctuations. The species which are almost constantly present throughout the cores are: *Australicythere* sp., *Cativella bensoni*, *Cytheropteron antarcticum*, *Echinocythereis* sp., *Loxoreticulatum fallax*, *Krithe* sp., *Pseudocythere* cf. *P. caudate*, *Patagonacythere* sp. These species have been frequently recorded as dominant elements in modern Antarctic shelf environments. Although the cryobiology of these species is poorly understood, changes in temperature and salinity appear to have little influence on the distribution of these species across the Antarctic seas. Some levels of the logs, characterized by high terrigenous inputs, show an evident decrease of the number of ostracods, mainly on *Echinocythereis* sp., *Loxoreticulatum fallax* and *Krithe* sp.

On the contrary, cores collected on the top banks usually show a gradual increase in ostracod diversity, a trend that continues more uniformly from the bottom to the top at the same time highlighting high percentages of test fragmentation thus reflecting reworking phenomena.

The first results provided information which confirms that micropaleontological analyses, based on the ostracode fauna of the Ross Sea will help to improve our understanding of the carbonate deposits in polar settings and will be an excellent instrument to obtain a sharper interpretation of the paleo-environmental and climatic changes which affected the Ross Sea area during the last glacial events.

In particular, the qualitative / quantitative assemblage changes together with compositional settings (sediment texture, organic Carbon, CaCO<sub>3</sub> contents), were able to identify specific moments of crisis and environmental improvement probably related to the stages of glacial advance or retreat.



**S15 – 276: Palaeoclimate Records from Antarctic Drilling Projects**

***Multichannel Seismic Investigations of Sediment Drifts on the west Antarctic Peninsula Pacific Margin: Preliminary Results from Research Cruise JR298***

Alastair G.C. Graham<sup>1</sup>; Robert D.Larter<sup>2</sup>; James E.T. Channell; Claus-Dieter Hillenbrand<sup>2</sup>; David A. Hodell<sup>4</sup>; Javier Hernandez-Molina<sup>5</sup>; Karsten Gohl<sup>6</sup>; Gabriele Uenzelmann-Neben<sup>6</sup>; Michele Rebesco<sup>7</sup>; Kelly Hogan<sup>2</sup>; JR298 Shipboard Party<sup>11</sup>

College of Life and Environmental Sciences, University of Exeter, United Kingdom<sup>1</sup>; British Antarctic Survey (Natural Environment Research Council), Cambridge, United Kingdom<sup>2</sup>; Department of Geological Sciences, University of Florida, Gainesville, Florida, USA<sup>3</sup>; Department of Earth Sciences, University of Cambridge, Cambridge, United Kingdom<sup>4</sup>; Department of Geology, Royal Holloway, University of London, Egham<sup>5</sup>; Alfred-Wegener-Institute Helmholtz-Zentrum für Polar- und Meeresforschung, Bremerhaven, Germany<sup>6</sup>; OGS, Istituto Nazionale di Oceanografia e di Geofisica Sperimentale, Sgonico, TS, Italy<sup>7</sup>

Observations across both the West Antarctic and Antarctic Peninsula ice sheets over recent decades have confirmed that the region is warming and undergoing major and potentially rapid changes as a result. These changes have manifested in the form of significant ice-sheet thinning and retreat, and in dramatic short-lived events such as ice-shelf collapses. The longer-term backdrop to this recent change is vital information for our understanding of future ice and climate evolution, and for wider knowledge of ice-sheet function and sensitivity.

Providing context on geological timescales, such records can be obtained from two main sources: (1) from ice cores extracted from the ice sheet interiors and

(2) from continuous marine sedimentary sequences recovered from the sea floor surrounding the Antarctic continent. Whilst ice cores provide a very high-resolution archive of palaeo-climate, they offer data over only a relatively short window of time (<1 million years) and provide little information on how the ice and oceans were changing at the ice sheet periphery. By contrast, sediments derived from the Antarctic continent have discharged continuously to the continental slope and deeper ocean over millions of years, and are sensitive recorders of both ice sheet and oceanographic variability. Repeated continental margin-derived turbidity currents, in combination with the activity of along-slope currents, have led to the accumulation of large hemi-pelagic depositional bodies, termed sediment drifts that are, today, oriented orthogonal to the continental margin and record continuous sedimentation on the continental rise since at least the Miocene. Along the Antarctic Peninsula Pacific margin, a chain of twelve large sediment drifts separated out by channels eroded by turbidity currents provide unique archives of environmental changes in Antarctica's ice sheets and the Southern Ocean. IODP proposal 732FULL2 aims to recover drill cores extending back into the Pliocene from the crests of a number of the drifts, as well as from the top of the Belgica trough mouth fan, during a future leg to the region. Two further sites will recover older strata that can be accessed at relatively shallow depth by drilling through eroded drift flanks where the overburden is particularly thin. However, before recovering sequences from these bodies, a full understanding of their geometry, internal architecture, age and stratigraphic evolution is required. We present preliminary results from recent Natural Environment Research Council (UKIODP Programme) funded site survey cruise JR298 that obtained high-resolution multichannel seismic (MCS) reflection data over the proposed drill sites and adjacent working areas. A first look at the seismic data from several of the drilling targets will be presented, and some initial interpretations regarding the (i) sedimentary processes that operated during the formation and evolution of the drifts and fan, and (ii) links between depositional systems on the continental rise, palaeo-ice-sheet dynamics and past oceanographic processes within the datasets will be discussed. Further geophysical analyses, in combination with marine sediment cores retrieved from the proposed sites, will aim to shed light upon continental margin sediment delivery, Antarctic ice-sheet history and stability, and Antarctic margin palaeo-oceanography that form the key scientific objectives of the planned drilling campaign.



### S15 – 283: Palaeoclimate Records from Antarctic Drilling Projects

#### ***Implication of grain size analysis and U ratio in interpretation of Palaeoenvironment-a case study from the ocean sediments off the coast of Wilkes Land, East Antarctica***

Pandey Mayuri<sup>1</sup>, Pant Naresh C.<sup>1</sup>, Shrivastava Prakash<sup>2</sup>, Biswas Paromita<sup>1</sup>

Department of Geology, University of Delhi, India<sup>1</sup>, Geological Survey of India, Faridabad<sup>2</sup>

East Antarctic ice sheet is a terrestrial ice sheet grounded predominantly over large interior basins. Large fluctuations in its motion including advances into southern ocean and periodic retreats have been reported during last several million years. The advancement and retreat has contributed variably to the sediment supply in adjacent depocenters. Conversely, analysis of these sediments can be used to infer the past movement of the ice sheet. Grain size is a function of the energy of the depositional medium and this energy can be considered as a function of the movement of the ice sheet in form of decreased flow during advancement and vice versa.

The Adélie and George V Coasts of the eastern Wilkes Land margin drain the EAIS with a mostly divergent flow pattern. Ice cliffs and two prominent outlet glaciers, the Mertz and the Ninnis, characterize the present coastline. These outlet glaciers extend seaward as ice tongues and have an important role in ice drainage and sediment delivery to the ocean. The eastern Wilkes Land margin receives sediment delivered through the Wilkes subglacial basin where the EAIS is partly grounded below sea level and thus may have been more sensitive to climate changes in the late Neogene.

Turbidity surface currents initiated by movements of the ice sheet along with erosion and the re-deposition of fine-grained sediments by bottom currents have been considered main processes for sediment supply from the shelf and slope to the Wilkes Land continental rise. The Antarctic Bottom Water produced in the Ross Sea flows westward along the Wilkes Land continental slope and rise, where it mixes with the Antarctic Bottom Water produced in the Adélie Depression. The sandy and gravely materials inside the massive mud can be due to the deposition of IRD associated with hemipelagic sedimentation.

U ratio is defined as ratio of sediment weight percentages between 44 and 16  $\mu\text{m}$  and between 16 and 5.5  $\mu\text{m}$ . Grain size analysis shows that the silt size sediment dominates throughout the depth of site U1359 with an average of 82% with the minimum and maximum values varying between 45% and 100% respectively. In the calculated statistical parameters for representative samples from Pleistocene to Miocene at this site three modes at 7 $\mu\text{m}$ , 16 $\mu\text{m}$  and 33 $\mu\text{m}$  were obtained. We have used these mode values for redefining two ranges of U ratio from 7  $\mu\text{m}$  to 16  $\mu\text{m}$  and 16 $\mu\text{m}$  to 33  $\mu\text{m}$ . U ratio shows strong antipathic relation with clay size content.

U ratio when compared with clay minerals abundances for sediments representing Plio-Pleistocene time shows positive correlation with smectite content. Also high U ratio corresponds to the time of ice retreat phases interpreted from clay mineral analysis. In heavy mineral fraction the pyroxene content corresponds positively with the higher values of U ratio. The clay mineral assemblages of Plio-Pleistocene sediments show strong relation with U ratio but similar relation for Miocene sediments is not observed. It has been proposed that the suspended fine-grained sediments from the turbidity-current flows are entrained in a nepheloid layer associated with the westward flowing bottom currents, and then deposited in sediment mounts. Possibly high smectite content corresponding to high U ratio in Plio-Pleistocene sediments is a result of two sourcing for smectite i.e. one from nepheloid layer by bottom water intensification in Ross Sea and other as pyroxene alteration and possibly due to retreat of ice sheet and intensification of surface currents. U-ratio of ocean sediments can, therefore, be a useful tool for paleo-environmental interpretation.



**S15 – 305: Palaeoclimate Records from Antarctic Drilling Projects**

***Subglacial Exploration from a PAIS Perspective***

Powell, R.D.<sup>1</sup>

Northern Illinois University, USA<sup>1</sup>

Over the last decade or more there has been increasing interest in and development of technology for, accessing subglacial environments even though such endeavours pose significant challenges. The main scientific problems driving these developments include: (i) better constraining Antarctica's geological and tectonic history, which are the least known of any continent due to ice cover, because the Antarctic plate plays an important, though poorly understood role in global tectonic architecture. (ii) Recovering sedimentary records housed within subglacial sedimentary basins (Subglacial lakes, West Antarctic rift basins, East Antarctic basins) because they contain valuable libraries of deep time paleo-climatic change and past ice sheet dynamics from the continental interior. (iii) Sampling the ice sheet bed because it is a critical boundary condition for ice dynamics, especially of ice streams and grounding zones, and so the data are needed to better predict future ice sheet behaviour. (iv) Coring to collect exposure dates of subglacial bedrock and for palinspastically reconstructing sediment mass and paleogeography in order to determine past ice surface elevations and land surface paleo-topography which then are used to constrain past sizes and volumes of the ice sheet. (v) Sampling subglacial microbial ecosystems and biogeochemistry to determine their phylogenetics and physiology, genomic recycling, and environmental controls on biotic diversity, and to better our understanding of the evolution of Antarctic biology and our predictions for extra-terrestrial life. Various countries have, or are developing new technologies to achieve these scientific goals. Some subglacial exploration has already been achieved and other projects are approaching fruition. But more capabilities are needed for: (i) conducting surveys to determine particular access points, (ii) creating mobile, energy-efficient platforms, (iii) continuing the evolution of instrumentation, and (iv) further the development of clean access in deep boreholes where temperatures are very cold. The current state of these programs will be reviewed.



## S15 – 371: Palaeoclimate Records from Antarctic Drilling Projects

### *Insights into changing East Antarctic paleoenvironments since the Eocene based on first-ever seismic imaging and coring on the Sabrina Coast shelf*

S.P.S. Gulick<sup>1</sup>; A. Montelli<sup>1</sup>; B. Frederick<sup>1</sup>; E. Domack<sup>2</sup>; A. Shevenell<sup>2</sup>; C. Sjunneskog<sup>3</sup>; S. Bohaty<sup>4</sup>; A. Leventer<sup>5</sup>; D. Blankenship<sup>1</sup>; R. Fernandez<sup>1</sup>; F.T. Sangiorgi<sup>6</sup>

University of Texas at Austin, USA<sup>1</sup>; University of South Florida, USA<sup>2</sup>; Florida State University, USA<sup>3</sup>; University of Southampton, United Kingdom<sup>4</sup>; Colgate University, USA<sup>5</sup>; Utrecht University, Netherlands<sup>6</sup>

Key to understanding Antarctic paleoenvironments is locating preserved sedimentary sequences with diagnostic indicators of climate. High-resolution seismic reflection images and piston cored sediments acquired during the 2014 expedition of the RVIB Nathaniel B. Palmer to the Sabrina Coast (NBP1402) provide the first data on a well-preserved record of the Eocene to Miocene climate evolution of East Antarctica in the form of four megasequences with distinct paleoenvironmental indicators.

For the deepest of these units, seismic images reveal a thick sequence of continuous interbedded sediments that represent a north-northwestward progradation of the shelf. The upper section of this unit includes two deltas with clear topsets and foresets that suggest a fluvial, near sea-level environment. Based on preliminary pollen and foraminifer biostratigraphy, sediment core NBP-1402 JPC-55, collected from a unit stratigraphically below the shallowest delta is likely middle to late Eocene. Core JPC-54, retrieved from a unit just above the younger delta, includes ice-rafted debris indicative of the presence of marine terminating glaciers on the shelf; biostratigraphic studies are ongoing.

Upsection from these deltas, the seismic facies of the next megasequence change dramatically and include a basal undulatory erosional surface indicative of grounded ice. This surface is overlain by an interbedded, unconformity free interval interpreted as non-glacial. This non-glacial unit is overlain and partly eroded by at least three additional glacial erosional surfaces, some of which include diagnostic Subglacial tunnel valleys. Moving up-section, the glacial unit is overlain by a relatively thick (10s of m) prograding, likely non-glacial unit, that is overlain and partly eroded by two to three additional glacial erosion surfaces with tunnel valleys. These six to eight glacial erosion surfaces suggest polythermal glaciations based on the presence of tunnel valley and related Subglacial meltwater-derived landforms.

Above the megasequence with abundant evidence of intermittent grounded ice on the shelf, lies a thick (>100 m) NNW prograding section. This unit contains no evidence for renewed glacial erosion. The prograding units are likely conformable with those that extend to the modern shelf edge based on regional correlations with shelf-edge dipping strata previously identified along the East Antarctic margin.

The three stratigraphic megasequences described above display a general seaward tilt and are all truncated by a regional landward-dipping angular unconformity above which lies the shallowest unit. Core JPC-30 recovered sediments including diatomites from just below and JPCs-29 and 31 from just above this regional unconformity. Work to identify the age of the angular unconformity is on-going but JPC-31 from above this surface recovered a late Miocene-to-earliest Pliocene diatom assemblage. Additional sediment cores indicate that the 10s of m thick chaotic units above the unconformity are predominantly till sequences. Additional inter-till reflectors are present that likely represent an incomplete record of late Miocene to Recent glacial advances. We interpret the till dominated unit lying above the regional angular unconformity to represent polar conditions.

In summary, we hypothesize that the Sabrina Coast section contains: 1) an Eocene and older non-glacial sequence that terminates with fluvial deltaic deposits, 2) a transitional sequence immediately up-section from the deltas (likely late Eocene to early Oligocene) that contains ice-rafted debris indicative of marine



terminating glaciers and evidence of the first grounded ice on the continental shelf, 3) a non-glacial sequence followed by at least three glacial intervals, which are likely of early to middle Oligocene age, 4) a non-glacial sequence that may represent the Oligocene climatic optimum, 5) a sequence that includes at least 2 glaciations (late Oligocene to early Miocene), 6) an extended non-glacial unit that prograded the shelf to its present extent and may reflect deposition during the Miocene Climate Optimum, 7) the development of a large cold-based East Antarctic Ice Sheet (EAIS) during the middle Miocene, and 8) fluctuations of the ice front potentially signaling EAIS instability in the late Miocene to early Pliocene based on the presence of diatomite layers within the till sequence. Polythermal-style glacial landforms, including tunnel valleys and preserved morainal structures, suggest that the Sabrina Coast region must have experienced a more humid environment and glacial conditions similar to those presently observed at Northern Hemisphere glaciated margins. The Sabrina Coast sequence is an unprecedented high-resolution Paleocene to Neogene sequence of East Antarctic Ice Sheet and climate evolution. As such, this sequence is an important future drilling target that will: 1) improve understanding of Cenozoic cryosphere development, 2) provide important near-field insights to Cenozoic ice sheet and climate evolution presently inferred from deep-sea sediments, and 3) inform/improve ice sheet models.



## S15 – 450: Palaeoclimate Records from Antarctic Drilling Projects

### *Recent Progress on Chinese Deep Ice-Core Drilling Project DK-1 at DOME A*

Nan Zhang<sup>1</sup>; Chunlei An<sup>2</sup>; Xiaopeng Fan<sup>1</sup>; Cheng Yang<sup>1</sup>; Bing Li<sup>1</sup>; Da Gong<sup>1</sup>; Shimeng Wang<sup>3</sup>; Pavel Talalay<sup>1</sup>; Youhong Sun<sup>1</sup>; Yuansheng Li<sup>2</sup>

Polar Research Center, Changchun, Jilin University, China<sup>1</sup>, Polar Research Institute of China, Shanghai, China<sup>2</sup>, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou, China<sup>3</sup>

The oldest ice core now extends over 0.8 Ma years into the past indicating that we are currently living in a relatively mild interglacial phase within a series of warm/cold oscillations occurring every 100 ka. However, from marine sediments, we know that just before this time the pattern of climate variability was different, with cycles of only 40 ka length. If we are to understand the state our climate is in now, we need to understand what caused the length of the cycles to change. Therefore, the search for ice core climate record extending at least 1.2 Ma and preferably 1.5 Ma, into the past is an active and key question for the Quaternary science community. One of the most promising areas for retrieving the longest possible Antarctic ice core climate record is Dome A, the highest plateau of Antarctic Ice Sheet. The annual mean temperature (measured at 10 m below the surface) at Dome A is  $\sim 58.5$  °C, the lowest annual mean temperature ever recorded on the surface of the Earth. Horizontal movement of the ice is minimal and the snow accumulation rate is as low as 16 mm w.e. The Kunlun Station (80°25'01' S, 77°06'58' E, 4092 m a.s.l.), China's third Station in Antarctica, was officially set up at Dome A in January 2009. The station is located where the thickest ice (30-90 m) occurs on the gently sloping summit region of Dome A. There is no consensus about the age of the near-bottom ice at Kunlun Station. First estimation of a depth temperature distribution with a steady-state ice-dynamics model indicates that the near-bottom ice might be >1.1 Ma old. However, recent modelling found that the Kunlun site would provide a record of the past only 0.6-0.7 Ma. The real situation is planned to be revealed by deep ice-core drilling, and China started deep drilling project DK-1 at Dome-A in season 2011-12, when the pilot hole was drilled and a 100 m deep fiberglass casing was installed. In the next season 2012-13, the deep ice-core drilling system was set down, and all the auxiliary equipment was connected and commissioned. After filling the hole with drilling fluid (n-butyl acetate), wet ice-core drilling was started. During last season 2014-15 drilling was continued to a depth of 303 m. In season 2014-2015, 54 drill runs with total depth of 172.7m had been drilled in 10 days. In each run, the lengths of cores were in the range from 3.15 to 3.85 m. The number of pieces in the core increased with depth from one to 56. At the end of the season, 2.9 m<sup>3</sup> of drilling fluid was added into the hole and liquid level raised to the depth of 104 m which can balance the ice-overburden pressure at the bottom of the hole. At present, there are no more than 25 days as working time in each season, due to the logistical problems. Therefore, drilling to the bedrock is planned to be completed during a further four seasons.



**S15 – 469: Palaeoclimate Records from Antarctic Drilling Projects**

***Plio-Pleistocene Ice-Sheet, Atmosphere and Ocean Dynamics in the Atlantic Sector of Antarctica***

Weber ME<sup>1</sup>; Clark PU<sup>2</sup>; Kuhn G<sup>3</sup>; Mitrovica JX<sup>4</sup>; Williams T<sup>5</sup>; Allen C<sup>6</sup>; Belt S<sup>7</sup>; Martos YM<sup>8</sup>; Stoner J<sup>2</sup>; Channell JET<sup>9</sup>; Huang X<sup>3</sup>

Institute of Geology and Mineralogy, University of Cologne, Germany<sup>1</sup>; College of Earth, Ocean, and Atmospheric Sciences, Oregon State University, Corvallis, U.S.A.<sup>2</sup>; Alfred-Wegener-Institute Helmholtz Center for Polar- and Marine Research, Bremerhaven, Germany<sup>3</sup>; Department of Earth And Planetary Sciences, Harvard University, Cambridge, U.S.A.<sup>4</sup>; Lamont-Doherty Earth Observatory, Columbia University, Palisades, U.S.A.<sup>5</sup>; British Antarctic Survey, Cambridge, U.K.<sup>6</sup>; School of Geography, Earth and Environmental Sciences, University of Plymouth, Plymouth, U.K.<sup>7</sup>; International Ocean Discovery Program/Texas A&M University, College Station, U.S.A.<sup>8</sup>; Department of Geological Sciences, University of Florida, Gainesville, U.S.A.<sup>9</sup>

We will report on two drilling proposals within the International Ocean Discovery Program (IODP) to address open questions on Antarctic Ice-sheet (AIS) dynamics in a transect from the Weddell Sea to the Scotia Sea on the Atlantic side of the Southern Ocean. IODP proposal 848-pre (Ice-sheet and sea-level history of the Weddell Sea) shall drill three contourite drifts northeast of Riiser-Larson Ice Shelf on the slope of the southeastern Weddell Sea that contain high-resolution Mio-Pleistocene sections.

As the southern extension of the Atlantic Ocean, the Weddell Sea is a key area to study Earth's past climate variability. It constitutes a major source of Antarctic Bottom Water formation, which influences the Atlantic Meridional Overturning Circulation. Moreover, the Weddell Gyre is an important cyclonic circulation system for water-mass communication between the Antarctic Ice Sheet and the Southern Ocean. One of the world's two largest ice shelves, the Filchner-Rønne Ice Shelf, drains into the Weddell Basin.

Ice-sheet dynamics in the Weddell Sea sector of the East Antarctic Ice Sheet (EAIS) are highly susceptible to far-field changes in sea level. Practically all icebergs from the EAIS merge in the Weddell Sea before they exit Antarctica through the Scotia Sea, thereby providing a unique location to study AIS dynamics. Despite these paramount scientific issues that have, over the last two decades, identified the Weddell Sea as a key area to study past and present climate change, there has been no deep scientific drilling for high-resolution reconstruction of the Plio-Pleistocene.

Our scientific objectives aim at achieving the first complete Late Neogene reconstruction for the Weddell Sea. We will address the overarching questions on changing ice-sheet dynamics, interhemispheric phasing of ice-sheet and climate events, ocean circulation, and bottom-water production. Specifically, we wish to unravel whether the formation of the contourite ridges north of Cray Fan were associated with a sea-level drop initiated through intensification of Northern Hemisphere glaciation during the Pliocene. Also, did the drainage pattern change during the Mid-Pleistocene Transition? Can we decipher ice-sheet dynamics on glacial-to-interglacial time scales and during the Last Glacial Maximum? Can we detect far-field sea-level effects and rates of sea-level rise from Iceberg Alley? Can we relate varve thickness variations obtained from counting and dating varved sediment on the contourite ridges to external (solar) or internal (ocean-atmosphere) variability on decadal-to-centennial time scales?

IODP proposal 847-full revised (Plio-Pleistocene reconstruction of ice-sheet, atmosphere, and ocean dynamics in Iceberg Alley) shall drill two deep-ocean sites in the Scotia Sea farther north. We aim at delivering the first well-dated, high-resolution and spatially integrated record of variability in icebergs flux from Iceberg Alley, where a substantial number of Antarctic icebergs exit from the Weddell Sea into the warmer Antarctic Circumpolar Current (ACC). In particular, we will characterize the iceberg flux during the



mid-Pliocene warm interval, the mid-Pleistocene transition, the warm interglacials of the last 800 kyr, and during glacial terminations. We will use the geochemical provenance of detrital material to determine regional sources of AIS mass loss; address inter-hemispheric phasing of ice-sheet and climate events, and the relation of AIS variability to sea level. We will also deliver critical information on changes in Drake Passage throughflow, meridional overturning in the Southern Ocean, CO<sub>2</sub> transfer via wind-induced upwelling, sea-ice variability, bottom water outflow from the Weddell Sea, Antarctic weathering inputs, and changes in oceanic and atmospheric fronts in the vicinity of the ACC by comparing north-south variations across the Scotia Sea.

Comparing changes in dust proxy records between the Scotia Sea and Antarctic ice cores will provide a detailed reconstruction of changes in the Southern Hemisphere westerlies on millennial and orbital time scales for the last 800 kyr. Extending this comparison beyond 800 kyr will help evaluating climate-dust couplings since the Pliocene, its potential role in iron fertilization and atmospheric CO<sub>2</sub> drawdown during glacials, and whether dust and changes in Antarctic ice volume played a role in the mid-Pleistocene transition.



**S15 – 472: Palaeoclimate Records from Antarctic Drilling Projects**

***Next Generation and New PAIS Scientist: Long term Networking and Community Building through Education***

Harwood, D.<sup>1</sup>; Wellner, J.<sup>2</sup>; De-Conto, R.<sup>3</sup>

University of Nebraska, Lincoln, USA<sup>1</sup>; University of Houston, Houston, Texas, USA<sup>2</sup>; University of Massachusetts Amherst, Amherst, Massachusetts, USA<sup>3</sup>

The Past Antarctic Ice Sheet (PAIS) strategy to understand Cenozoic climate and paleo-environmental change through a continent-to-abys strategy of onshore-offshore drilling transects would benefit from a coordinated effort to expose graduate students, postdocs, and early career scientists to methods of data collection and analysis using existing Antarctic and Southern Ocean drill cores and datasets. An educational 3day program at a repository with Antarctic and Southern Ocean drill cores will provide participants with an understanding of: (1) approaches to recover drill core, (2) how paleo-environmental and glacial changes are interpreted and dated from drill core records, (3) how numerical modelling results and data-model integration studies provide guidance on Earth systems sensitivities and thresholds, (4) stages in a project's development from conception to drilling, and (5) current and developing projects to which one could seek involvement. A driver for this educational initiative is to enhance the number of new scientists feeding into a Community for Antarctic Drilling (CAD), working toward PAIS goals to address IPCC questions about ice sheet and Southern Ocean response to past and future high CO<sub>2</sub> conditions. Participants will examine sediment cores, analyze and integrate drill core data sets from a number of geoscience disciplines, develop and discuss interpretations, and build skillsets. This abstract serves as a call for interested young scientists to register their interest in participating, for advisors to alert their students and colleagues to this developing opportunity, and to solicit engagement of active Antarctic geoscientists with PAIS interests to help develop and launch this educational, networking, and community building opportunity. Our goal is to light a path for young and new scientists to take several steps toward, if not into, the PAIS Community for Antarctic Drilling. Early 2016 is the target date for this program. Please contact the authors for more information.



**S15 – 477: Palaeoclimate Records from Antarctic Drilling Projects**

***East Antarctic Ice Sheet Dynamics during the Oligocene-miocene Transition: Insights from IODP Site 1356 Drilling off the Wilkes Land Margin***

Ariadna Salabarnada<sup>1</sup>; Escutia, C<sup>1</sup>; Nelson, C.H.<sup>1</sup>; Damuth, J.E<sup>2</sup>; Jiménez-Espejo F.J.<sup>3</sup>

CSIC-IACT, Granada, Spain<sup>1</sup>; University of Texas at Arlington, USA<sup>2</sup>; JAMSTEC, Japan<sup>3</sup>

IODP Site 1356 was drilled on the flank of a levee deposit at the Wilkes Land continental rise and it recovered a thick section of Oligocene to upper Miocene sediments. A detailed facies analyses and correlations with the grid of multichannel seismic reflection profiles allowed us to reconstruct East Antarctic ice sheet dynamics on this margin. Hemi-pelagic and bottom current deposition dominated during the late Oligocene which indicates a distal environment.

Deposition during the cooling trend leading to the Mi-1 event is characterized by MTDs and turbidite sedimentation from a nearby channel which suggests that ice sheets were advancing onto the continental shelf. Preserved between MTD beds are turbidite deposits, claystones and limestone beds, which we interpret to record times of ice sheet retreat. By the Mi-1 there is a sharp change in the depositional processes, MTDs are restricted to the base of the continental slope with small run-out distances no longer reaching Site 1356, and turbidite sedimentation dominates. The Oligocene/Miocene boundary (23.3 Ma) is marked by a hiatus separating turbidite-dominated sedimentation below from hemipelagic-dominated sedimentation above which suggests an open ocean glacio-marine sedimentation. Our study provides evidence for a highly dynamic East Antarctic Ice Sheet during the late Oligocene-early Miocene Transition.



**S15 – 478: Palaeoclimate Records from Antarctic Drilling Projects**

***Early Holocene Deglaciation Record from the East Antarctic ADELIE Land Margin: IODP Site U1357***

Carlota Escutia<sup>1</sup>, F.J. Jimenez Espejo<sup>2</sup>, A. Salabarnada<sup>1</sup>, J Gutierrez-Pastor<sup>4</sup>, U. Roehl<sup>4</sup>, R. Dunbar<sup>5</sup>

CSICIACT, Granada, Spain<sup>1</sup>, JAMSTEC, Japan<sup>2</sup>, ETH Zurich, Germany<sup>3</sup>, MARUM<sup>4</sup>, Stanford University, California, USA<sup>5</sup>

Drilling at Site U1357 yielded a 185.6 m section of Holocene continuously laminated diatom ooze as well as a portion of an underlying Last Glacial Maximum (LGM) diamict. We present sedimentological and geochemical data of the time of the first Holocene deglaciation. The use of the CT-Scanner has allowed us to characterize in detail four sedimentary facies (Facies 1-4) dominated by silt-clay layers and dark-light biogenic laminations. X-Ray Fluorescence scanning shows that the intervals with high Ba/Al and Si/Al are associated to poor detrital levels allowing to use these ratios along the entire core as detrital/paleo-productivity proxies. Seismic reflection profiles in the region and mega-scale glacial lineations indicate that during the Last Glacial Maximum (LGM) an ice stream flowed directly north of the site. At this time the diamicton (Facies 1) was being deposited. CT-scan images show two intervals within the silt laminations with high Ice Rafted Debris (IRD) content (Facies 2), which suggest two events of effective grounding-line recession off Adelie Land. This is supported by bathymetry charts in the continental shelf that image two grounding events during post-LGM retreat. After ice retreat deposition is dominated by laminated sediments (Facies 3a: silty/sandy and diatom-rich muds; and Facies 3b: diatomaceous oozes). Ongoing radiocarbon analysis, performed in the bulk fraction and in compound-specific show that immediate postglacial ages are impacted by old Carbon likely the result of the steady inclusion of old radiocarbon dead organic materials. However, the age model constrains at this time suggest that the timing of the calving bay re-entrant phase of deglaciation and the deposition of the deglacial sediment facies began before ca. 11.500 yr B.P. potentially contributing mwp-1B. Other east Antarctic margin marine records provide a similar time frame for deglaciation.



**S15 – 505: Palaeoclimate Records from Antarctic Drilling Projects**

***Isotope Fingerprint of Surface Snow and FIRN from ELLSWORTH Mountains Region***

Rodriguez Oroz D<sup>1</sup>, Fernandoy F<sup>2</sup>

Andres Bello University, Metropolitana, Chile<sup>1</sup>, Dept. Of Engineering Science, Andres Bello University, Vaia Del Mar, Chile<sup>2</sup>

During the year 2014 a new Chilean station at Union Glacier, Ellsworth Mountains range (lat. 79°46'10'S, long. 82°54'26'W) was opened for scientific research. The station is located at a key region to study the extraordinary warming phenomenon detected over Central West Antarctica, as this is located between the West Antarctic Ice Sheet (WAIS) and the Ronne Ice Shelf. The WAIS is showing a strong warming, linked to the advection of warm air from the surrounding ocean to the continent. Due to the scarcity of direct long-term meteorological observations (limited to Byrd Station), dynamics of the seasonality and spatial extension of the atmospheric temperature trend are still not well understood. At the moment, most of the climatological data available comes from reanalysis and satellites observations. As consequence of the present warming, WAIS exhibit a negative mass balance contributing to the global sea-level rise. During the first scientific field expedition on December 2014, we retrieved several surface firn cores from the surrounding of Union Glacier, a major tributary to Ronne Ice Shelf over the Weddell Sea. The cores were extracted from Dott Ice Rise (lat. 79°18'38.9"S, long. 81°39'09.3"W - 9.6m depth) at the border of the Ronne Ice Shelf, Schanz-Schneider Glacier divide at the Ellsworth mountains (lat. 79°31'13.9"S, 83°08'56.3"W-14.1m depth) and at the Union Glacier camp (lat. 79°46'10'S, long. 82°54'26'W 9.6m depth). Density profiles show that the snow firn boundary is reached under 15m snow depth, which does not clearly differs from firn cores retrieved on the Ronne Ice Shelf by the Filchner-Ronne Ice Shelf Programme (FRISP) in the 90s. The accumulation rate is estimated to be about 200 to 400 kg m<sup>2</sup> a<sup>-1</sup>, as showed by previous geophysical surveys and snow stratigraphy. This is also slightly above of FRISP cores values from the Ronne Ice Shelf. We observed that the snow surface temperature at the three different places is similar (around 17° C), reflecting similar surface air temperature for the region during summer. Stable water isotope analysis from the cores show depleted values (mean value 251), reflecting the low temperatures at the precipitation location. Using age models from the cores retrieved by previous investigations on the region (e.g.: FRIPS), our cores should cover at least 30 years, however our isotope profiles is yet to be finished. Here we present the preliminary results of our investigation and their implication for climate reconstructions for this region. According to existing geophysical survey for this region, over 900m ice thickness is present at key locations like the Schneider-Schanz divide. Therefore, several thousand years of climate record could be potentially stored within the ice cap, which should reveal information about the recurrence of such warming trends on the past.



## **S16 – 19: Interactions between cryosphere, atmosphere and oceans in coastal Antarctica**

### ***Glacier fluctuations in the Bolivian Andes and its Teleconnections with Antarctic Oscillation***

Bijeesh Kozhikkodan Veetil<sup>1</sup>; Ulisses Franz Bremer<sup>1</sup>; Jefferson Cardia Simões<sup>1</sup>

UFRGS- Universidade Federal do Rio Grande do Sul, BRAZIL<sup>1</sup>

#### Background

The Andes in South America is passing through a large number of temperature and precipitation zones with higher influences of Atlantic circulation patterns in the north and Pacific influence in the south. Both circulation patterns influence the central Andean region. Easterly wind anomalies favor wet condition in the central Andes whereas westerly wind enhances dry conditions. Central Andean glaciers situated on stratovolcanoes were reported to be retreating since 1980s. Even though many climate models exist which predict the future changes that may occur to tropical glaciers, many of them ignore the changes in deep ocean and ocean circulations that contributes El Nino Southern Oscillation (ENSO) and other decadal oscillations that influences the present distribution and frequency of tropical storms. Recent studies suggest a combined effect of ENSO with a long lived, ENSO like, Pacific Decadal Oscillation (PDO) on tropical glaciers. Other southern hemisphere oscillations like Antarctic Oscillation (AAO), which is the counterpart of Arctic Oscillation (AO) in the northern hemisphere, could be considered while studying the influences of complex circulation anomalies in the tropical South America. In this research, we tried to correlate the glacier changes in the central Andes with the frequency of occurrences of AAO.

#### Objectives

This paper emphasize on the observational investigation of two near-by-glaciated mountains in the Central Andes using medium resolution satellite images during the last three decades. Glaciated areas of Nevado Cololo (5859 m asl) and Nevado Huanacuni (5058 m asl) in the Cordillera Apolobamba in Bolivia were studied. The snowline altitudes of selected glaciers radiated from these study sites were calculated using remote sensing data. Changes in the lowest annual snowline altitude is used as an indirect measure of the equilibrium line altitude during this period. LISSIII, CBERS2, Landsat MSS, TM and ETM+ images taken during end of dry season (May-August) were used in this work. We tried to understand the influence of the Antarctic Oscillation on the snow-line-altitude of the selected glaciers. Monthly mean temperature and precipitation data from various gauging stations near the study sites in the form of gridded datasets were also analyzed.

#### Methods

Snowline is calculated using 542 false color composite images. TM4 and TM2 channels were applied with threshold values of 60 to 135 and 80 to 160 respectively before creating the 542 composite image. The resulting images can be used to map the SLA successfully, which is later used as an approximation of equilibrium line altitude (ELA). While using remote sensing techniques, it is difficult to calculate error in the calculation of SLA and it depends on the image co-registration error in relation to the horizontal and vertical DEM resolution as well as depends on the terrain slope. We analyzed the anomalies in precipitation and temperature in the Cordillera using high resolution, gridded, Monthly precipitation and temperature (above 2 m from the ground level) data with a horizontal resolution of 0.5° lat long (between 1945 and 2011) from the University of Delaware. PDO indices were downloaded from Climate Prediction Center (CPC), National Oceanic and Atmospheric Administration (NOAA). The anomalies in precipitation and temperature were calculated in MATLAB using linear interpolation. Finally, the variations in AAO index along with anomalies in precipitation and temperature were tried to correlate with the variations in the snowline altitudes during the study period.

#### Results

From the results obtained from the above methodology, it is seen that the glaciated area and snowline altitudes of the Nevado Huanacuni and Nevado Cololo have been fluctuated between the positive and



negative phases of AAO between 1984 and 2011. We also noticed that negative phase of AAO occurs during El Nino years. It is found that a more rapid retreat has been occurred in the case of Nevado Cololo and Nevado Huanacuni in Bolivia, when compared with mountain glaciers in the Cordillera Oriental in Ecuador. In general, there is an overall increase in the snowline altitude during this period and this indicates that the climate condition in Bolivia is still warming, within the Amazon Basin in particular.

#### Conclusion

Summer months (December-March) accounts for majority of the annual mass variability in Bolivia. Snowfall events often cause underestimation of ELA from SLA using satellite imagery. The selected images towards the end of dry season were excellent to calculate the SLA. In the outer tropics, the highest SLA value during the dry season is taken as the ELA of the year. The suitability of SLA in analyzing mass balance changes with climate variations has been proved in this study. The significant increase in the SLA of the selected glaciers during 1990-1995 confirms the effect of El Nino, which persisted for a long period. A strong negative correlation exists between ENSO and AAO. Other local climatic factors can be taken in to account in order to improve this study in the future. It would be also helpful to consider variations in the southern tropical Atlantic SST variations in order to calculate teleconnections, if any exists, between the tropical atmospheric circulation anomalies and mass balance changes of glaciers in the outer tropics.



**S16 – 83: Interactions between cryosphere, atmosphere and oceans in coastal Antarctica**

***Trends in winter melt periods and analysis of climatological drivers for glacier mass balance changes of the inland ice cap of King George Island, West Antarctica.***

Ulrike Falk<sup>1</sup>; Damien Lopez<sup>2</sup>; Hernan Sala<sup>3</sup>

Center for Remote Sensing of Land Surfaces (ZFL), Germany<sup>1</sup>; Dept. Geology and Minerology, Univ. Cologne, Germany<sup>2</sup>; Direccian Nacional Del Antartico, Buenos Aires, Argentina<sup>3</sup>

The Antarctic Peninsula is amongst the fastest warming places on Earth and further temperature increase is to be expected. Exceptional rates of surface air temperature increases (2.5K in 50 years) are concurrent with retreating glacier fronts, an increase in melt areas, surface lowering and rapid retreat, breakup and disintegration of ice shelves. The South Shetland Islands are located on the northern tip of the Antarctic Peninsula and are especially vulnerable to climate change due to their exposure to transient low pressure systems and their maritime climate. For King George Island/Isla 25 de Mayo, we have compiled a unique meteorological and glaciological data set on the Warszawa Icefield from November 2010 and ongoing. In combination with long term synoptic data sets and reanalysis data, we look at changes in the climatological drivers for glacier melt processes and sensitivity of the inland ice cap with regard to winter melt periods and pressure anomalies. Analysis show a positive trend in minimum air temperatures of central winter months of 5 degree Celsius over four decades, clearly exceeding the published annual mean statistics associated with a decline in mean monthly sea level pressure. This concurs with a positive trend in the SAM index that gives a measure for the strength and extension of the Antarctic vortex, and we connect this with a higher frequency of low pressure systems hitting the South Shetland Islands during austral winter bringing warm and moist air masses from lower latitudes. Due to its exposure, the inland ice cap is especially vulnerable to changes during winter glacial mass accumulation period. In combination with data time series of glacier mass balance stake measurements on several transects, differential GPS kinematic grids in consecutive years, and the application of a glacier melt model, we aim at assessing the impact of the long term climatological changes on the equilibrium line altitude. Glaciological measurements and literature review suggest a change of more than 150m in 15 years. The glacier model is used to give a projection into future mass balance estimates based on the more moderate IPCC scenario of air temperature change. Analysis of area changes in accumulation zone to the total glacier area are used to define a tipping point where the negative trends in glacier mass balance is becoming irreversible. This research is part of the ESF project IMCOAST funded by BMBF. Field work was carried out at the Dallmann laboratory (Jubany, King George Island) in cooperation of the Instituto Antartico Argentino (Argentina) and the Alfred Wegener Institute (Germany).



**S16 – 86: Interactions between cryosphere, atmosphere and oceans in coastal Antarctica**

***Influence of polar cell on Antarctic sea ice Variability***

Praveen Rao Teleti<sup>1</sup>; A.J. Luis<sup>1</sup>

NCAOR, MoES, India<sup>1</sup>

As a responsive pointer of global climate change, Antarctic sea ice variability is known to be influenced by global climatic modes such as El Niño Southern Ocean (ENSO) and Southern Annular Mode (SAM). However, understanding of Southern Polar Cell's impact on sea ice system has been fragmentary. Present study explores modes of variability in Southern Polar Cell and their relationship with known global climate modes and Antarctic sea ice at inter-annual time scale. Using empirical orthogonal function (EOF) analysis on geopotential height anomalies south of 65°S, the dominant circulation patterns in the Polar Cell are highlighted. The Polar Cell is found to be barotropic in nature and 500hPa geopotential height (Z500) field can satisfactorily represent variability in the Polar Cell, with first three leading modes of Z500 accounting for nearly 80% of the observed variability. Dominant mode (PC1500) comprises of high pressure divergence zone over continental Antarctica, while the second mode (PC2500) is low pressure zone covering Amundsen-Bellinghousen Sea (ABS) similar to ABS low feature reported in the literature. A new climate mode called Polar Coastal Index (PCI) is defined, which describes more than 15% and close to 30% variability of circumpolar trough and ABS low, respectively. Out of four modes defined in this study, only PCI and PC2500 show linear trends and clear seasonality. Interestingly, both modes are affected by modulation of ABS low due to tropical ENSO forcing. SAM signature is present in Polar Cell as PC1500 share large variance with it. Largest impact on sea ice comes from PC2500 followed by PC1500 in the Antarctic Dipole regions. However, our results suggest contemporary sea ice trends cannot be sustained, and could reverse given that trends in PCI and PC2500 favour a reversal. These results suggest that the ENSO teleconnection is a key factor influencing Antarctic sea ice as it interacts with other climate modes and lead the combined impact at the inter-annual time scale.



**S16 – 191: Interactions between cryosphere, atmosphere and oceans in coastal Antarctica**

***Changing characteristics of the ice shelf along Princess Astrid coast, East Antarctica***

Kumar P.

Geological Survey of India, India

Princess Astrid coast is a 1200 km long coast line situated between 50° to 200° E and is bounded by ice shelves which experiences a change in the shape of the coast line. The changes in the morphology of this ice shelf margin in contact with the fast ice, drift ice, pack ice as well as the open sea during last four decades was studied by using Archival Landsat data which shows variable patterns in different sectors. There are eight major ice rises oriented perpendicular to the coast line with the width ranging from 6 to 40 km. The flow of the ice shelf is dominated by fast flowing ice streams at many localities at variable pace. The study of the imageries indicate that the ice shelf moves at a rate of 326.5 mts/yr at 70° S: 8° 25' E, where an area of approx. 460 sq. km have been calved from the parent body in two phases within this period. The stress built due to the movement of the ice stream results in the form of transverse as well as longitudinal crevasses within the ice shelf and sometimes shows curvilinear pattern due to multiple ice flow regime as observed towards the eastern part of the study area around 70° S: 18° 30' E where wrappings are observed throughout 60 km length crack. Though dynamic equilibrium is maintained at many localities by outward flow of the ice shelf and its breaking, shrinkages are also observed at many places up to 4 km east-central part of the study area. The coast line is also characterized by having a lesser area of the ice shelf in front of the ice rises which might be due to the influence of the tides helping in the calving of that part. Various meteorological parameters including the rise in the ice shelf surface temperature as well as the sea surface temperature are possible causes for changing the morphology of the ice shelf margin as the temperature rise helps in thinning of the ice shelves as well as their bottom melting.



**S16 – 193: Interactions between cryosphere, atmosphere and oceans in coastal Antarctica**

***Forecasting southern ocean sea ice Variability using Ocean seaice Model: a case study around Indian Antarctic stations***

Anurag Kumar<sup>1</sup>; Siddhartha Chatterjee<sup>1</sup>; Suneet Dwivedi<sup>1</sup>

KBCAOS, Allahabad University, India<sup>1</sup>

The seasonal growth and decay of the Antarctic sea ice influences global climate system. The effect is dominantly seen in terms of changes in the Southern Ocean (SO) circulation and its ecosystem. Therefore, the realistic simulation and prediction of the SO sea ice is of great value. An effort is made here to perform an upper ocean sea ice forecasting for a period of 20 years [2011-2030] using an Ocean circulation model with built in sea ice package. The model uses highest horizontal resolution of nearly 15 km and vertical resolution of 5 m. The sensitivity experiments using closed and open boundary conditions are performed. The quality of the forecast is demonstrated over the domain [9°E78°E; 45°S72°S] covering both the Maitri and Bharti Indian Antarctic stations. The variability of the sea ice concentration and its thickness is studied. The ice drift velocity is computed. Our model results show that the sea ice has been steadily increasing during 2011-2030.



**S16 – 227: Interactions between cryosphere, atmosphere and oceans in coastal Antarctica**

***Recent anomalous retreat of outlet glaciers in Wilkes land, East Antarctica, linked to oceanic Forcing***

B.W.J. Miles<sup>1</sup>; C.R. Stokes<sup>1</sup>; S.S.R Jamieson<sup>1</sup>

University of Durham, United Kingdom<sup>1</sup>

Recent reports have highlighted the potential vulnerability of major East Antarctic marine basins to future climatic warming, but most mass balance estimates indicate a slightly positive mass balance for the entire East Antarctic Ice Sheet. However, there is a clear bimodal distribution with mass gain in Donning Maud and Enderby Land, and mass loss in Wilkes Land. Furthermore, recent analysis of some East Antarctic outlet glaciers has revealed sensitivity to decadal changes in climate. A significant uncertainty is the how the remainders of East Antarctic outlet glaciers are behaving and whether Wilkes Land is anomalous. Here we combine new measurements of glacier terminus position with previous measurements to investigate multi-decadal trends along the entire coast of the EAIS (n = 351) and identify potential forcings. Results show that 65% of EAIS outlet glaciers retreated from 1974-1990, followed by a statistically significant switch to advance from 1990-2000 (67%), with continued advance from 2000-2012 (65%). However, 74% of glaciers in Wilkes Land retreated from 2000-2012, which is the only region to experience this trend. We link this anomalous retreat to reduced sea ice concentrations and associated impacts on ocean stratification, which is likely to increase incursion of warm water at depth.



**S16 – 232: Interactions between cryosphere, atmosphere and oceans in coastal Antarctica**

***Ocean-driven Thinning Enhances Ice-berg Calving and Retreat of Antarctic Ice Shelves***

John Moore<sup>1,2</sup>; Liu Y.<sup>1</sup>; Cheng X<sup>1</sup>; Gladstone R.M.<sup>3</sup>; Bassis J.N.<sup>4</sup>; Liu H.<sup>5</sup>; Wen J.<sup>6</sup>; Hui F.<sup>1</sup>

College of Global Change and Earth System Science, Beijing Normal University, China<sup>1</sup>; Arctic Centre, University of Lapland, Finland<sup>2</sup>; Antarctic Climate and Ecosystems Cooperative Research Centre, University of Tasmania, Hobart, Tasmania<sup>3</sup>; Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie (VAW), Eidgenössische Technische Hochschule Zurich, ETHZ<sup>4</sup>; Department of Atmospheric, Oceanic and Space Sciences, University of Michigan, Ann Arbor, USA<sup>4</sup>; Department of Geography, McMicken College of Arts & Sciences, University of Cincinnati, USA<sup>5</sup>; Department of Geography, Shanghai Normal University, China<sup>6</sup>

Iceberg calving from all Antarctic ice shelves has never been directly measured, despite playing a crucial role in ice sheet mass balance. Rapid changes to iceberg calving naturally arise from the sporadic detachment of large tabular bergs, but can also be triggered by climate forcing. Here we provide a direct empirical estimate of mass loss due to iceberg calving and melting from Antarctic ice shelves. We find that between 2005 and 2011 the total mass loss due to iceberg calving of  $755 \pm 24$  giga-tonnes per year (Gt/yr) is only half the total loss due to basal melt of  $1516 \pm 106$  Gt/yr. However, we observe widespread retreat of ice shelves that are currently thinning. Net mass loss due to iceberg calving for these ice shelves ( $302 \pm 27$  Gt/yr) is comparable in magnitude to net mass loss due to basal melt ( $312 \pm 14$  Gt/yr). Moreover, we find that iceberg calving from these decaying ice shelves is dominated by frequent calving events, which are distinct from the less frequent detachment of isolated tabular icebergs associated with ice shelves in neutral or positive mass balance regimes. Our results suggest that thinning associated with ocean driven increased basal melt can trigger increased iceberg calving, implying that iceberg calving may play an overlooked role in the demise of shrinking ice shelves, and is more sensitive to ocean forcing than expected from steady state calving estimates.



**S16 – 267: Interactions between cryosphere, atmosphere and oceans in coastal Antarctica**

***Instability and Sensitivity of the Amundsen Sea Ice Streams***

I.J. Nias<sup>1</sup>; S.L. Cornford<sup>1</sup>; A.J. Payne<sup>1</sup>

University Of Bristol, United Kingdom<sup>1</sup>

Present day ice loss is centered on the Amundsen Sea Embayment (ASE), in West Antarctica. The stability of this area is a key control on global sea level. Within the ASE, ice loss is primarily associated with ice streams draining the area, including Pine Island (PIG), Thwaites (TG) and Smith (SG) glaciers. A perturbed parameter ensemble was performed in order to understand the differences in sensitivity between these three ice streams. This was achieved using BISICLES, a vertically-integrated higher-order flow model with adaptive mesh refinement, which provides fine resolution in the region of the grounding line and shear margins, while applying a coarse mesh elsewhere. Latin hypercube sampling was used to generate 64 parameter sets in which three physically-based parameters (associated with basal traction, ice rheology and sub-shelf melt rate) were altered. These parameter sets were used to run BISICLES with two bed geometries: one based on BedMap2 and another based on an inverse method, which applies mass conservation to velocity and surface elevation data. The ensemble was run twice, for both a linear and a nonlinear sliding law. This gave a total of 256 configurations, in which the ASE was simulated for 50 years. Initial results show that the ice streams respond differently to changes in the various parameters. Dynamic retreat of the ice streams is particularly sensitive to changes in the viscosity of the ice. The sub-ice shelf melt rate plays a role in the stability of PIG and SG, as they both have constrained ice shelves, which acts as a buttress to the grounded ice.



**S16 – 290: Interactions between cryosphere, atmosphere and oceans in coastal Antarctica**

***Reconstructing the glacial history of the western Dronning Maud land margin***

Jennifer Newall<sup>1</sup>; F Then<sup>2</sup>; J Bernales<sup>2</sup>; I Rogozhina<sup>2</sup>; A Stroeven<sup>1</sup>; J Harbor<sup>3</sup>; N Glasser<sup>4</sup>; O Fredin<sup>5</sup>; D Fabel<sup>6</sup>; C Hattestrand<sup>1</sup>

Stockholm University & Bolin Centre for Climate Research, Sweden <sup>1</sup>; Helmholtz Centre Potsdam GFZ German Research Centre For Geosciences, Germany<sup>2</sup>; Purdue University, Stockholm University & Bolin Centre For Climate Research, Sweden<sup>3</sup>; Aberystwyth University, Wales <sup>4</sup>; Geological Survey Of Norway, Norway<sup>5</sup>; University Of Glasgow, United Kingdom <sup>6</sup>

Given current concern about the stability of ice sheets, and consequent sea level rise, it is imperative that we are able to reconstruct and predict the response of ice sheets to climate change. The Intergovernmental Panel on Climate Change (IPCC), amongst others, have highlighted that our current ability to do so is limited and presents a major weakness in climate science. Numerical models of ice sheet behavior are a central component of the work to address this challenge. These models are tested and improved by comparing model predictions of past ice extents with field based reconstructions from geological and geomorphological data. However, on the East Antarctic Ice sheet, Dronning Maud Land presents a critical gap in the empirical data required to reconstruct changes in ice elevation. In addition, there exist significant uncertainties in regional climate history along the ice sheet margin due to remoteness of these areas from ice core locations where detailed reconstructions of climate history have been performed. This leaves numerical models of regional glaciation history largely unconstrained.

MAGIC-DML is a Swedish-UK-US-Norwegian-German collaboration with a focus on filling the critical data gaps that exist in our knowledge of the timing and pattern of ice surface changes on the Dronning Maud Land margin of the East Antarctic Ice Sheet. We have designed a series of high-resolution modelling experiments of the paleo-glacial history driven by a wide range of climate and ocean histories combining published outputs of 18 general circulation models for the Last Glacial Maximum and mid-Holocene with ice core records. The modelling is designed to help identify those areas across western Dronning Maud Land that is the most sensitive to uncertainties in the regional climate history and the choice of model parameters. The modeling results together with remotely sensed mapping of glacial landforms will inform and guide two field campaigns in western Dronning Maud Land in 2015 and 2016. The field investigations, executed along two inland coast transects (Borgmassivet, and Vestfjella-Heimefrontfjella) and a coast parallel transect along the Heimefrontfjella-Kirwanveggen escarpment, will ground-truth the remotely sensed mapping and collect samples for surface exposure dating. These will be used to reconstruct ice elevation fluctuations and to determine the most probable combinations of climate and ocean forcing and model parameters that best explain the reconstructed history. The anticipated outcome of the MAGIC-DML project is a reconstruction of the long-term pattern and timing of vertical changes in ice surface elevation since the mid-Pliocene warm period, providing the empirical data required to constrain numerical ice sheet models.

Here we demonstrate how the combined use of remotely sensed mapping and numerical modelling experiments are being used to guide the field component of the project.



## S16 – 298: Interactions between cryosphere, atmosphere and oceans in coastal Antarctica

### *A temporal study of greenhouse gases content in Surface waters of the Antarctic Peninsula*

Josefa Verdugo<sup>1</sup>; Laura Farias<sup>2</sup>; Beatriz Diez<sup>3</sup>; Beatriz Fernandez<sup>3</sup>; Ellen Damm<sup>4</sup>; Italo Masotti<sup>5</sup>

University of Concepcion, Chile<sup>1</sup>; Laboratory Of Oceanographic And Climate Processes (PROFC), Department of Oceanography, University Of Concepcion and Center for Climate Change and Resilience Research (CR)2, Concepcion, Chile.<sup>2</sup>; Department of Molecular Genetics and Microbiology and Center for Climate and Resilience Research (CR)2, P. Catholic University Of Chile, Santiago, Chile<sup>3</sup>; Alfred Wegener Institute for Polar and Marine Research, Germany<sup>4</sup>; Faculty of Marine Science and Natural Resources, University of Valparaiso, Valparaiso, Chile.<sup>5</sup>

#### Background

The ocean is a significant source, of biogenic trace gases into the atmosphere, where methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O), both greenhouse gases exert a strong impact on the radiative forcing of the planet and also contribute to the ozone depletion and other photochemical reactions in the stratosphere. Microorganisms are important mediators of processes involved in consumption/production of these gases and act as key players in the carbon (CH<sub>4</sub>) and nitrogen (N<sub>2</sub>O) cycles. We have studied gas cycling in waters of Discovery Bay, South Shetland Islands, Antarctic Peninsula, particularly focused on autotrophic (i.e., nitrification, methanotrophy) processes mediating respectively de production and consumption of these gases. Records of these gases and recycling rates in the Antarctic Peninsula are limited in space and time, even knowing the extreme physical gradients at both, temporal and spatial scale. Moreover, the sea ice cycles at this ecosystem play a pivotal role in gas solubility (surface temperature and salinity) and microbial communities.

#### Objectives

Identify the physical chemical and biological factors responsible for the intra-seasonal variation (daily time series study) in the content of CH<sub>4</sub> and N<sub>2</sub>O and their exchange across air sea interface in surface waters of Discovery Bay, Antarctic Peninsula, during the austral summer (2014).

#### Methods

The study area was located in a coastal area closed to Discovery Bay (62°34'35"S; 59°30'22"S) in Greenwich Island, (South Shetland Islands) Antarctic Peninsula. The time series was performed along 1.5 months from February 9 to March 8 of 2014. The hydrographic variables (temperature and salinity) were measured with a multi-parameter and water samples from surface (5 m depth) and subsurface (30 m depth) were collected directly by Niskin bottles, for nutrients (NO<sub>3</sub>, NO<sub>2</sub>PO<sub>43</sub> and Silicate), gases (CH<sub>4</sub> and N<sub>2</sub>O), Dimethylsulfoniopropionate (DMSP), Chlorophylla and abundance/composition of microorganisms. Moreover, two kinds of experiments were performed. The first one was gas cycling for CH<sub>4</sub> and N<sub>2</sub>O in bags during 24 h of incubation and the second one comprised <sup>15</sup>N (<sup>15</sup>N<sub>2</sub>O) and <sup>13</sup>C (<sup>13</sup>CH<sub>4</sub>) tracer addition to measure biological uptake by autotrophic microorganisms, if they were present, <sup>13</sup>C and <sup>15</sup>N Isotopic enrichment in organic particles was subsequent detected by mass spectrometry.

#### Results

During the austral summer, surface salinity and temperature varied from 32.2 to 34.6 and from 0.3 °C to 0.5 °C, respectively. Nutrients such as NO<sub>3</sub> and PO<sub>43</sub> fluctuated from high initial values as high as 27mol/L and 2.2 mol/L, respectively, to 20.6 and 1.6 mol/L respectively. This pattern could be produced by phytoplankton blooms, which are consuming NO<sub>3</sub> and PO<sub>43</sub> from surface waters. DMSP, a organic molecule produced by phytoplankton and nano-flagellates species and which could act as a substrate for CH<sub>4</sub> regeneration, widely varied, revealing a pick as high as to 78 nm in the middle of the sampled period, after that a decrease up to 28 nm was observed. CH<sub>4</sub> concentrations remain constant during this study with values around 34 nm, and we cannot see a clear relation with DMSP values. N<sub>2</sub>O concentration fluctuated between 9 to 15 nm, showing two maximum values during the sampling period, February 18



and March 3, whereas a minimum value (9 nm) was registered in the middle of the period when high level of DMSP was registered. Bacterial abundance (Flow Cytometry) duplicated from initial time of sampling reach abundance around 220 ( $10^3$  cell/mL) at the end of the period. Similar trend was observed for phytoplankton organisms, dominated by diatoms, as *Pseudonitzschia delicatissima* and *Thalassiosira minuscula*, which show a significant increase of abundance at the end of the sampling period with abundance around 21.400 cell/L and 84.280 cell/L, respectively.  $^{13}\text{C}$  ( $\text{CH}_4$ ) uptake experiments show enrichment in the organic particles, whereas  $^{15}\text{N}(\text{N}_2\text{O})$  doesn't show a clear pattern during this study.

#### Conclusion

Although minimal physical gradient were observed in surface waters of the Discovery Bay, microbial community abundance and phytoplankton community changed during this study and these seem to have influence in chemical variables such as nutrients, DMSP and gases concentration. This study represents a base line of greenhouse gases distribution at the Antarctic Peninsula for future researchers.



**S16 – 314: Interactions between cryosphere, atmosphere and oceans in coastal Antarctica**

***Moisture and sea ice variability in East Antarctica during the last Century***

Rahaman Waliur<sup>1</sup>, Thamban Meloth<sup>1</sup>, Laluraj C.M.<sup>1</sup>

National Centre for Antarctic & Ocean Research, Goa, India<sup>1</sup>

Recent climate change and its impact on cryospheric and atmospheric system in Antarctica are poorly understood due to limited long term observational data. An interesting area of study in this regard is the coastal regions, which provide high resolution proxy records of atmospheric circulation, temperature, precipitation and sea ice conditions. In order to reconstruct these climatic parameters, a high resolution chemical records ( $\text{Na}^+$  and  $\text{Ca}^{2+}$ , methane sulfonic acid (MSA)) and isotope records were studied in an ice core from coastal Dronning Maud Land (cDML), East Antarctica. High resolution study of deuterium excess, sea salt sodium ( $\text{Na}^+$ ) and (MSA), revealed the history of moisture transport and sea ice extent during the last century. Backward trajectory analysis shows that air parcels arrives at this core site are mainly derived from the Weddell Sea with additional sources from the Ross Sea and the Bellingshausen-Amundsen Sea regions. The dexcess profile of this core shows a dramatic shift from an average value of  $7^\circ$  during 1905-1939 to  $1^\circ$  during ~1940. This shift is attributed to reduced moisture supply from the low-mid latitude to Antarctica associated with shifting of SAM (Southern Annular Mode) from positive to negative mode and SAM-ENSO tele-connection. The  $\text{ssNa}^+$  and MSA fluxes used as a proxy for sea ice extent (SIE), show significant temporal variations with a major excursion during 1940-1980; significant increase in  $\text{ssNa}^+$  flux coincided with the decrease in MSA. The annually averaged fluxes of  $\text{ssNa}^+$  and MSA compared with the satellite derived SIE data of the Weddell Sea sector revealed significant positive relationship between  $\text{ssNa}^+$  flux and the winter SIE. Based on this correlation, ~10% higher SIE is expected in the Weddell Sea during 1940-1980 with respect to its average value of the last century. The power spectrum analysis of dexcess and  $\text{ssNa}^+$  flux shows significant periodicity at ~3.5 year which exactly coincide with that of winter SIE in the Weddell Sea and SAM records. This suggests that SAM influences SIE variability in the Weddell Sea sector at ~3.5 year period. Further, wavelet analysis of SAM index and SOI shows the highest common power in 48 year and during 1940-1960 and 1990-2000, overlapping with the period of higher SIE whereas it shows opposite phase in 1016 years band during 1905-1930 and 1990-2005, overlapping with the periods of higher dexcess and positive SAM index. This indicates strong meridional transport of warm and moist air from remote low latitude sources. This study thus suggests the role of SAM and its tele-connection to ENSO in controlling moisture transport as well as sea ice variability in oceanic regions surrounding Antarctica in inter annual to decadal scale. Keywords: Ice core, Antarctica, dexcess, sea salt, sea ice extent, SAM, ENSO.



**S16 – 344: Interactions between cryosphere, atmosphere and oceans in coastal Antarctica**

***Relation between of Calcium and Nitrate in Antarctic Snow possible formation Mechanisms and it's Implications***

K. Mahalinganathan<sup>1</sup>, M. Thamban<sup>1</sup>, C.M. Laluraj<sup>1</sup>

National Centre for Antarctic & Ocean Research, Goa, India<sup>1</sup>

Among the large variety of particulates present in the atmosphere, mineral dust particles have highly reactive surfaces and therefore have a significant role in altering the atmospheric processes. However, very few studies have documented the association between proxy indicators of dust (like  $\text{Ca}^{2+}$ ) and the important trace atmospheric gas (like  $\text{NO}_3$ ) in Antarctic snow and ice. While Rthlisberger et al. (2000) have documented strong associations between  $\text{NO}_3$  and  $\text{Ca}^{2+}$  during the last glacial maximum during which the dust concentrations in Antarctic atmosphere were 20 times the present day, possible physicochemical processes involved are poorly known. Here we present the annual (2008-09) records of soluble  $\text{NO}_3$  and  $\text{Ca}^{2+}$  in snow deposits from two different regions the Princess Elizabeth Land (PEL) and central Dronning Maud Land (cDML) in East Antarctica. A total of 43 snow cores (1 metre long, covering at least one year each) were collected along a coast to inland transect during the Austral summer of 200809 and analysed for major ions. Statistical analyses showed a highly positive correlation between  $\text{NO}_3$  and  $\text{Ca}^{2+}$  in both PEL and cDML transects. Correlation statistics (at 99% significance level) between  $\text{NO}_3$  and  $\text{Ca}^{2+}$  in PEL revealed a strong association both at near coastal ( $r = 0.72$ ) and inland ( $r = 0.89$ ) regions. Similarly, a strong association was observed at near coastal ( $r = 0.76$ ) and inland ( $r = 0.8$ ) regions of cDML. However, there was no such association at sites within the mountainous section of the cDML transect.

Back trajectory analyses using NOAAs HYSPLIT from the sampling locations revealed that most of the air parcels to both the study regions in east Antarctica arrived from the Patagonian region, the seventh largest desert in the world. Studies show that the mineral dust originating from this region is largely composed of carbonate or calcic rich dust (Zarate, 2003). Recent laboratory experiments have demonstrated the conversion of both pure calcium powder and authentic mineral dusts to calcium nitrate in presence of  $\text{HNO}_3$  and have also shown that the hydrolysis on mineral dust components is enhanced in the presence of higher relative humidity (Krueger et al., 2003; Mogili et al., 2006). Thus it is possible that the dust readily react with the nitrogen oxides present in the atmosphere to form  $\text{Ca}(\text{NO}_3)_2$ , possibly formed as a result of heterogeneous reactions of Ca bearing mineral dust with  $\text{HNO}_3$  in the atmosphere, followed by a reaction between the adsorbed  $\text{HNO}_3$  and  $\text{CaCO}_3$  surface site. However, the poor relationship between  $\text{NO}_3$  and  $\text{Ca}^{2+}$  in the snow deposits of the mountainous section of cDML transect is more likely due to masking of the signals by a dominant local dust input from the exposed mountains. Our study suggests that the association between calcium and nitrate apparently occur during the long range transport and not within Antarctica. The study also indicates that the dust-bound  $\text{NO}_3$  could also contribute a significant fraction of the total  $\text{NO}_3$  in east Antarctic snow. The association with  $\text{Ca}^{2+}$  would also reduce the post depositional loss of  $\text{NO}_3$  due to the physicochemical processes like re-evaporation of volatile  $\text{HNO}_3$  and  $\text{NO}_3$  photolysis. Our study has significant implications on the use of  $\text{NO}_3$  and  $\text{Ca}^{2+}$  as paleo-environmental proxies.



**S16 – 348: Interactions between cryosphere, atmosphere and oceans in coastal Antarctica**

***Interannual Variability of Chemical Characteristics of Water Masses in the Shelf and Slope Area of the Commonwealth Sea***

Artamonova K.V.<sup>1</sup>; Maslennikov V.V.<sup>1</sup>

Russian Federal Research Institute of Fisheries and Oceanography (FSBSI , VNIRO), Russia<sup>1</sup>

The region Antarctic shelf continental slope plays an important role in the water and ice regimes formation not only of the Southern, but also the World Ocean. The coldest and densest water mass of the World Ocean Antarctic Bottom Water (AABW) is formed here and exercises a significant influence on the World Ocean global structure and circulation. However this process is observed not in all areas of the Antarctic continental slope, therefore the water structure data of this region, including chemical parameters is important for understanding of the Southern ocean regime and its influence on the climate.

The main objective of present work is to consider the structure of waters above the shelf and the slope in the Commonwealth Sea, analyze chemical indicators of these waters and their interannual variability by results of Russian surveys data led on RV Academic Fedorov .The surveys has been carried out during the austral summers, from January to February. In this study we analyzed the data collected during 2006, 2012, 2013 and 2015. Chemical analysis consisted of determination of dissolved oxygen and nutrients (silicate, phosphates, ammonium nitrogen, nitrate nitrogen, nitrite nitrogen) in the water samples from the oceanological stations and sections in the Commonwealth Sea. All chemical determinations have been carried out in the ship laboratory of RV Academic Fedorov. Studies of the chemical parameters distribution along the oceanological sections showed the vertical structure of the Commonwealth Sea that was constituted by next water masses: the Antarctic Surface Water (AASW) with high content of dissolved oxygen (8.09.0 ml/l) and low concentrations of nutrients; the Upper Circumpolar Deep Water (UCDW) characterized by a minimum of the oxygen content (4,35 5,10 ml/l), and a maximum concentrations of nutrients; The Lower Circumpolar Deep Water (LCDW) primary characterized by a salinity maximum; and bottom waters. In the shelf area of the Commonwealth Sea the modify CDW (MCDW) was observed by the intermediate oxygen minimum and maximums of mineral phosphorus and nitrate nitrogen. In the deep layer of the shelf area of the Commonwealth Sea a local cold, salt and dense shelf water mass (ASW) formed. The ASW was defined by higher content of dissolved oxygen and lower contents of biogenic elements. The ASW mixed with the MCDW and then their mixture (The Bottom Water of the Prydz Bay (BWPB)) moved down along the slope, and reached the bottom.

Inter-annual variability of the chemical characteristics of water masses was observed on the repeated oceanological sections in the Commonwealth Sea. Compare the characteristics of water masses for 2006, 2012, 2013 and 2015 on the repeated section along 70°E we could see that their characteristics changed year by year. The most important changes were showed for the characteristics of the AASW, and the characteristics and volumes of the BWPB undergo year by year. In 2006 the chemical characteristics of the BWPB layer were observed about 5,66,8 ml/l for dissolved oxygen and 110-125 µM for silicate and the thickness of the BWPB layer has been the smallest. In 2012 the BWPB layer was more significant with the highest content of dissolved oxygen (6,47,0 ml/l) and its layer was active moving down near to a bottom of the Antarctic continental slope. In 2013 the BWPB was observed in the Antarctic continental slope only in the range depths from 1000 to 1600 m and its characteristics were close to 2006. In 2015 the BWPB formed again more active and its layer was observed along the bottom of the all the Antarctic continental slope in the Commonwealth Sea with chemical characteristics the same like in 2013. The formations of the ASW of high density in the shelf area of the Commonwealth Sea and the BWPB in the slope area are the important links of the AABW formation in this region. Research of the reasons of so significant inter-annual changes in processes of formation of the bottom water in this area is an important problem.



**S16 – 368: Interactions between cryosphere, atmosphere and oceans in coastal Antarctica**

***Potential of past and future regime shifts in dynamics of the Dronning Maud Land Ice Shelves***

Kenichi Matsuoka<sup>1</sup>; Cesar Deschamps-Berger<sup>1</sup>; Geir Moholdt<sup>1</sup>

Norwegian Polar Institute, Norway<sup>1</sup>

Features surrounded by ice shelf, are known to significantly impact the motion of ice shelves and upstream glaciers. Ongoing rapid retreat of Pine Island and Thwaites Glaciers was presumably initiated by the loss of an ice rumples near the grounding line, which highlights a realistic risk of rapid changes in ice-shelf speed, thickness, calving front position, and eventually regional mass balance triggered by the loss of ice rises and rumples. Delineations and characterizations of past, current, and future ice rises and rumples are thus crucial for predicting ice-sheet evolution, but poorly done primarily because bathymetry data are typically sparse in the vicinity of current ice shelves. Here, we present unique satellite evidence of numerous elevated seabed locations that can potentially accommodate ice rises and rumples embedded in past and possibly future expansions of Dronning Maud Land (DML) Ice Shelves. Satellite imagery acquired between August 2012 and December 2013 show that numerous small icebergs (mostly ~100s meters wide and long) remained at the same positions throughout the period. These lingered icebergs were found almost everywhere within about 50 km from the current calving front, but not in front of two ice shelves extending beyond the continental shelf. In most cases, the stationary icebergs were found close to each other and constitute local clusters. Over the observational periods, the icebergs remained unchanged, while adjacent sea ice changed significantly, so sea ice is not a primary factor to constrain these icebergs. Measured bathymetry available at some of these positions show that the seabed ranges 100-300 m below the sea level. These lines of evidence strongly infer that (at least majority of) these lingered icebergs show positions of anomalously elevated seabed, probably banks, which are possible locations of past and future ice rises and rumples. The current amount of ice rises and rumples in the DML ice shelves is much lower than the population of the stationary icebergs (100-800, depending on the periods). Over the last several years, the DML has been a unique region in Antarctica showing mass gain due to increased surface mass balance. Consequently, the DML ice shelves might expand and thicken in the future. We argue that such expanded ice shelves in the future or in the past during the Holocene deglaciation must have different dynamic regimes than the current ones. Due to inherent dynamic thresholds in ice rises and rumples, these regimes can rapidly shift to more unstable ones, which yield a sudden retreat of the ice sheet and a sudden increase of the sea level contribution from the DML sector of the Antarctic Ice Sheet.



**S16 – 381: Interactions between cryosphere, atmosphere and oceans in coastal Antarctica**

***Seasonal variations of perchlorate concentration in Antarctic and Greenland snow***

Kari Peterson<sup>1</sup>; Jihong Cole-Dai<sup>1</sup>; Thomas Cox<sup>1</sup>; Scott Splett<sup>1</sup>

South Dakota State University, USA<sup>1</sup>

Temporal variations of chemical impurities in polar ice cores are used to document environmental changes and to investigate the causes of the changes. Annual or seasonal variations of some chemical impurities are often the result of cyclic fluctuations in source (emission or chemical production) strength and/or transport from source regions to the polar ice sheets. The seasonal characteristics (seasonality) may depend on the chemical species, polar region (Arctic or Antarctic), and location on an ice sheet, and can be sensitive to source variations (type of source and emission/production rate) and atmospheric circulation impacting transport. For example, in preindustrial ice cores from Greenland nitrate exhibits a reliable annual maximum concentration in the summer. In more recent ice, multiple concentration maxima in a year have been observed, probably due to emissions of nitrate precursors from anthropogenic activities and changes in atmospheric chemical processes of nitrate formation. Recent development in ice core analytical methodology has enabled us to measure perchlorate, a chemical impurity present in ice cores, in both Greenland and Antarctic snow at very low concentrations. Our data indicate that perchlorate in recent (post1980) Greenland snow exhibits a seasonal trend with maximum concentrations in the spring. This seasonal signal is less apparent in Greenland ice samples dated prior to the Industrial Revolution. This may signify that major sources of perchlorate have changed over time, possibly influenced by anthropogenic sources in modern times. However, it is possible that low temporal resolution of our analysis may have contributed to the failure to detect the perchlorate seasonal signal in preindustrial ice samples. We have determined perchlorate concentrations at a sub-annual time resolution in a Greenland ice core (Summit Station) and in snow pit samples from a West Antarctica location (West Antarctic Ice Sheet (WAIS) Divide) using ion chromatography tandem mass spectrometry with electrospray ionization (ICESIMS/ MS). The concentrations of major ions, including chloride, sulfate, calcium, and magnesium, are used to date the samples via annual layer counting and to determine sub-annual (seasonal) timing of snow samples. Our objectives are to determine (1) if the major sources of perchlorate in Greenland have changed over time and (2) if the major sources of perchlorate differ between the Northern and Southern hemispheres. In order to achieve these objectives we are analyzing the seasonal trends in preindustrial revolution Greenland ice samples (at high resolution), in recent Greenland ice samples, and in snow pit samples from Antarctica. Differences in the seasonal trends between preindustrial revolution and recent Greenland ice samples may provide the evidence of a change in the major perchlorate source. In addition, similarity or difference in perchlorate sources in Northern and Southern Hemispheres may be inferred from comparison of the perchlorate seasonality in Greenland and Antarctica snow samples. The detailed data will allow us to examine the variability of perchlorate seasonality in Greenland and Antarctica and assess its implications on major source changes and differences between the Northern and Southern Hemispheres. In addition, we plan to use the data to explore the processes of perchlorate production in the atmosphere. Many of the proposed atmospheric production mechanisms for perchlorate require solar ultraviolet (UV) radiation. The dependence of perchlorate production on solar UV radiation can be assessed using the seasonality of perchlorate concentration; minimum concentrations in the winter, when there is little or no solar UV radiation, and maximum concentrations in the spring summer, when solar UV radiation is available, would reflect a dependence on solar UV radiation. This information could serve as a basis for more in depth studies into the natural production of perchlorate.



**S16 – 388: Interactions between cryosphere, atmosphere and oceans in coastal Antarctica**

***Spatial and temporal variations of organic carbon in Snow deposits of Princess Elizabeth land (east Antarctica) and its implications***

Archana Dayal<sup>1</sup>; Runa Antony<sup>1</sup>; Mahalinganathan K.<sup>1</sup>; Thamban Meloth<sup>1</sup>

ESSO-National Centre for Antarctic and Ocean Research, Goa, India<sup>1</sup>

Polar Regions are an important reservoir of dissolved and cellular organic carbon ( $15.4 \times 10^{15}$  g C) but little information exists about its spatial and seasonal variations in Antarctic snow packs. We present results of high sensitivity analysis of total organic carbon (TOC) in several one metre snow cores along a coast (up to 50 km) to inland (50180 km) transect in the Princess Elizabeth Land (PEL) region, East Antarctica. The snow cores studied represent at least 1 year snow accumulation (2008-09). Results show a well preserved seasonality in TOC concentration, with an average concentration of  $153 \mu\text{g C L}^{-1}$  during summer and  $118 \mu\text{g C L}^{-1}$  in winter for this period. In summer, higher TOC concentration was observed in the coast (mean  $189 \mu\text{g C L}^{-1}$ ) compared to inland (mean  $133 \mu\text{g C L}^{-1}$ ). Higher TOC values in the coastal snow deposits are attributed to biological components (mainly the cellular and noncellular organic components) derived from sea spray. Marine contribution is further explained by the significant positive correlation between sea-salt  $\text{Na}^+$  ( $p < 0.01$ ) and MSA ( $p < 0.01$ ), which are considered to be conservative ionic proxies for sea spray and marine biogenic productivity respectively, in coastal Antarctica. Interestingly, the TOC concentrations within the winter snow samples are not drastically different from the summer samples, with a decreasing trend of TOC concentrations from coast (mean  $122 \mu\text{g C L}^{-1}$ ) to inland (mean  $115 \mu\text{g C L}^{-1}$ ). We suggest that in winter, frost flowers formed on young sea ice and enriched in particulate and dissolved organic matter may be a significant source of organic carbon in the coastal samples. This is also supported by the high sea salt  $\text{Na}^+$  content in the coastal samples during winter, in agreement with the role of frost flowers as a dominant source of sea salt components in coastal Antarctica. However, the TOC in the inland samples has a possible crustal contribution as supported by a strong positive correlation of TOC with nss  $\text{Ca}^{2+}$  ( $p < 0.01$ ). In addition, resident microbial communities also contribute to the organic carbon load in these samples. Thus crustal and microbial contribution to organic carbon appears to be more important in the inland samples in both winter and summer where marine input is minimal. This study in particular highlights the significant seasonal and spatial differences and multiple sources of organic carbon in snow in Antarctica which has important implications for air snow exchange and biogeochemical processes.



**S16 – 391: Interactions between cryosphere, atmosphere and oceans in coastal Antarctica**

***Hydrodynamics of Indian Ocean sector of coastal Antarctica during 2012 and 2013 using in-situ and Satellite data***

Vinit R. Lotlikar<sup>1</sup>; Alvarinho J. Luis<sup>1</sup>; Shridhar D. Jawak<sup>1</sup>

National Centre for Antarctic and Ocean Research, Goa, India<sup>1</sup>

Using in-situ density profiles recorded by deploying Expendable CTD (XCTD) probes and satellite-based fields mapped during the Indian Expedition to Antarctica during austral summers of 2012 and 2013, we explore basic hydrodynamics of the Indian Ocean sector along the Antarctic coast from Prydz Bay 69° 9' S, 75° 36' E) to India Bay (69° 16' S, 13° 46' E) up to a depth of 1000m. Since remote sensing provides large domain with a repeated coverage, we have used sea surface temperature (SST) data of AVHRR, surface chlorophylla concentration from NASA's GeoEye Orbview2 (Sea WIFS sensor) and sea surface salinity (SSS) from Aquarius. Different signature/features in the profiles during 2012 and 2013 were identified which confirms the presence of winter water (WW) layer close to the coast. Vertical section of temperature from both the expeditions did show a well developed mixed layer. During 2012 traces of winter mixed layer (ML) was identified at India Bay region. During both the years, the WW layer was observed near Scott mountain region from 50 m to 300 m. During 2013 this WW layer extended down to 1000 m indicating a downwelling zone near Scoble glacier at around 60°E. In Prydz Bay region a WW layer was observed extending up to 1000m which may be due to the melting of Amery Ice Shelf. In 2012 a upwelling zone was observed at 40°E which is indicated by the warm water of temperatures ranging from 0.5°C to 1°C rising to the surface. During both the years warm waters (> 0Å°C) was observed from ~200 m depth below the ML and WW layer from 20°E to 40°E which represents Circumpolar Deep Water. Salinity section for 2012 and 2013 showed patches of low salinity regions with salinity less than 33.75 psu at the surface. In the deeper section the salinity also showed an increasing trend with salinity exceeding >34.5 psu, except for regions in which there was a presence of cold water with temperature <0.5° C salinity range varied between 34.25-34.5 psu. Low salinity at the surface indicates that the melting of sea ice during Antarctic summers.

During both the years, SST ranged from 1°C to 0.5°C along the cruise track. During 2012, satellite map shows a cold water pocket with temperatures from 0.5° C to 2° C at around 25°E. We found signatures of colder water being advected away from the coast in 2013 with temperatures varying from about 0.5° C to 1.5° C all along the coast, compared to 2012. In-situ data for 2012 confirmed warm temperature pockets of 0.5°-1° C in Prydz Bay. Similarly, cold waters were seen in India Bay region and area near Prydz Bay during 2013 indicating that satellite data matched well with the in-situ measurements. Surface chlorophyll maps for both years indicated low chlorophylla concentration in the coastal Antarctic regions. On a broader domain from 65°S to 70°S, we found comparatively high productive zone with chlorophylla concentration ranging from 1 to 3 mg/l. Sea Surface salinity (SSS) map indicated a saline waters at this region with salinity of 34 psu. Satellite derived chlorophylla during 2013 was almost negligible all along the cruise track, except for the region near Prydz Bay, where traces of chlorophylla concentration in the range of 0.51mg/l was observed. Comparison between satellite derived SST and chlorophylla around 65°S showed that in the cold SST region (0°C) chlorophylla concentration was found to be >0.5 mg/l. SSS indicated relatively saline waters from 10°E to 70°E with salinity range for ~32 to >34 psu. A salinity minimum zone during 2012 is observed in Prydz Bay suggesting that there must be a source of fresh water influx from the coastal region. There is a slight variation in this region during 2013 from 32 to 31.5 psu, compared to 2012.

We computed WW characteristics using in-situ data. The WW layer depth was deeper during 2013 compared to 2012, with maximum depth of ~250 m at 50°E which was detected at 200 m during 2012. While WW minimum temperatures of >2°C was observed in both the years in the Prydz Bay. Warmer WW



temperature of 0°C occurred at 40°E in 2012. For the remaining stations temperatures were observed within the range of 1.5° C to 2° C. The WW salinity peaking to 34.6 psu was observed from 70°E in Prydz Bay during both the years. For the rest of the stations, the WW salinity values ranged between 34.4 psu to 34.2 psu. The thickness of WW layer during 2012 was observed to be highest between 50°E to 60°E with thickness upto 4 m whereas for 2013 the thickness is up to about 5.5 m to 6 m at 4 different stations with highest being 6 m at ~47°E and ~35°E. Heat content was found to be highest  $\sim 844 \times 10^9$  J/m<sup>2</sup> in midlatitude at 40°E which is an upwelling zone. Second region which has highest heat content is from 60°E to 70°E with values approximating to about  $\sim 843 \times 10^9$  J/m<sup>2</sup>. Salt content for coastal Antarctic showed highest values of  $2.66 \times 10^4$  g/kg from 10°E to 40°E, while the region from 40°E to 55°E show low heat as well as low salt content.

Vertical sections help to identify regions of coastal upwelling. Satellite data give a synoptic coverage to monitor small scale features of fronts which is practically not possible with XCTD profiles. To further analyze the reasons for the chlorophylla concentration, nutrient analysis in this particular region will be undertaken in the future.



**S16 – 398: Interactions between cryosphere, atmosphere and oceans in coastal Antarctica**

***Recent thickening of the Blaskimen Ice Rise in western Dronning Maud Land***

Vikram Goel<sup>1</sup>; Kenichi Matsuoka<sup>1</sup>; Joel Brown<sup>2</sup>; Anja Eichler<sup>3</sup>; Elisabeth Isaksson<sup>1</sup>; Taunu Martma<sup>4</sup>; Margit Schwikowski<sup>3</sup>; Carmen P. Vega<sup>5</sup>

Norwegian Polar Institute, Troms, Norway<sup>1</sup>; University Of Montana, Missoula, MT, USA<sup>2</sup>; Paul Scherrer Institute, Villigen, Switzerland<sup>3</sup>; Institute Of Geology At Tallinn University of Technology, Tallinn, ESTONIA<sup>4</sup>; Department Of Earth Sciences, Uppsala Universitet, Uppsala, Sweden<sup>5</sup>

Ice rises are grounded ice bodies (at least partially) surrounded by the floating ice shelf. They provide buttressing to the neighboring ice shelves and hence play a key role in controlling dynamics and mass balance of the Antarctic Ice Sheet. In turn, evolution of an ice rise is affected by the surrounding coastal environment. The Dronning Maud Land coast, East Antarctica, is a 2000km long interconnected system of ice shelves, outlet glaciers and ice rises. We are investigating glaciological settings, recent mass balance, and millennial evolution of the Blaskimen Ice Rise, located west of the Fimbul Ice Shelf, Dronning Maud Land. Data were collected during the 2012-13 and 2013-14 field seasons. We made GPS stake measurements to derive the flow field over the ice rise. Ice penetrating radar is used to map bed topography and englacial layering. A 20 m long firn core was obtained to date radar reflectors and estimate recent surface mass balance. Synthesis of these field data indicate that the ice rise has thickened over the past decades.



**S16 – 401: Interactions between cryosphere, atmosphere and oceans in coastal Antarctica**

***Influence of Indian Ocean Subtropical Dipole on Indian Summer Monsoon Rainfall***

Namendra Kumar Shahi<sup>1</sup>; Shailendra Rai<sup>1</sup>; Dhruva Kumar Pandey<sup>1</sup>

K. Banerjee Centre of Atmospheric and Ocean Studies, India<sup>1</sup>

Many of the previous studies show that the Indian Ocean sea surface temperature (SST) plays an important role in tropical climate variability. The variability in the Indian Ocean have much impact on the society; many studies have been devoted to their understanding. The Indian Ocean Dipole (IOD) is one of the most dominant modes of climate variability in the tropical Indian Ocean, and its mechanisms and climatic impacts have been investigated extensively. There is another important climate mode in the Southern Indian Ocean (SIO) called the Indian Ocean subtropical dipole (IOSD), with mature phase locked to the austral summer, has also been documented by researchers. The influence of the IOSD on the Africa rainfall has been explored by many studies and also shows by many authors that the IOSD affects the South China Sea summer monsoon onset and it can be considered as one of the main factors for the prediction of the rainfall in China. There are only few studies related to influence of the IOSD on the Indian monsoon rainfall and it is at initial stage. We have tried to investigate the influence of IOSD on Indian summer monsoon especially during the progressive phase of monsoon.

In the last several decades, there are many statistical techniques to extract the dominant mode of variability from the observed meteorological parameters. The Empirical Orthogonal Functions (EOF) is one of these techniques and is widely used. The EOF analysis gives us the spatial modes of variability along with its temporal behavior. We have used the EOF analysis in the present work on the SST variability over SIO region. The correlation and regression analysis were also used in this study to see the possible impact of SST in SIO region to the Indian summer monsoon.

We have used monthly mean observed SST data from the Hadley Centre sea ice and sea surface temperature (HadISST). The zonal, meridional wind, geopotential height, air temperature and vertical velocity data have been taken from National Centers for Environmental Prediction National Center for Atmospheric Research (NCEPNCAR) reanalysis data set during the period of 1983-2013. The observed daily rainfall data have been taken from Indian Meteorological Department (IMD) over the land points of India. We have applied EOF analysis on the seasonal SST anomalies over the southern Indian Ocean (60°S 20°N, 30°E 120°E) averaged in December-January-February (DJF) and March-April-May (MAM) respectively. The first EOF mode of the DJF and MAM season explains a variance of 28.2% and 32.3%, respectively. The spatial pattern of first EOF mode of the DJF is almost similar to MAM except with slight variation at few places. We defined an IOSD index as the difference in SST anomalies between the southwestern Indian Ocean (SWIO) and southeastern Indian Ocean (SEIO). The SWIO region for the first EOF mode of the DJF and MAM is selected as region (44°E-64°E, 46°S -36°S). The SEIO region for the first EOF mode is selected as region (80 °E-100°E, 32°S-22°S) for DJF and (56°E-76°E, 17°S-7 °S) for MAM. The correlation coefficient between the principal component of the first mode and IOSD index for DJF and MAM season are 0.81 and 0.84 respectively which indicates that the EOF modes represents the time series faithfully. We have calculated a IMR index by averaging the precipitation anomaly over the land point of India for each month. The inter-annual correlation coefficient between IMR of each month and IOSD index for DJF and MAM season was computed and a significant negative correlation coefficient of 0.41 and 0.44 respectively for the IMR index of June month was found. This suggests that the IOSD index for the DJF and MAM season is related to the Indian monsoon in the month of June. Further, we have computed regression map corresponding to the time series of the normalized DJF and MAM IOSD index with the rainfall of India in June month and a negative pattern is obtained along western ghat and Central India. This also suggests that the SST in the SIO region impact the rainfall over India in the month of June which is the progressing phase of Indian monsoon. The NINO3.4 index has been computed by averaging the SST anomaly for the spatial domain (5°S -5°N, 120°W-170°W) for DJF (MAM)



season and a correlation coefficient of 0.37 (0.37) for the IMR index of June month was obtained. This suggests that the June rainfall over India has a better relationship with IOSD than with ENSO. We have identified the positive and negative IOSD years when the normalized IOSD index for DJF and MAM season is greater (less) than +0.50 (0.50) standard deviation (SD). The years 1984 (1983), 1985 (1987), 1988 (1988), 1991 (1991), 1995 (1994, 1995), 1998 (1998), 2003, 2004 (2005), 2009 (2009), 2010 (2010) and 2013 were identified as positive IOSD index for DJF (MAM) season as per the criteria defined above. Similarly the negative IOSD years were identified as 1986 (1984, 1985, 1986), 1990 (1990), 1994 (1993), 1997 (1997), 1999 (1999), 2001 (2000, 2001) and 2011 (2011) for DJF (MAM) season. The composite precipitation over the land points of India for the years having positive (negative) IOSD index for both the seasons were computed and a deficient (excess) rainfall was obtained throughout the Indian subcontinent. This further strengthens our argument that the IOSD impact the rainfall over India during the progressing phase of monsoon. The study was further extended and it is found that the heating (cooling) in the region covering IOSD change the circulation pattern in the Indian Ocean and hence the impact on the progression of monsoon in India.



**S16 – 413: Interactions between cryosphere, atmosphere and oceans in coastal Antarctica**

***Solar radiation and temperature trends in McMurdo Dry Valleys explained: exploring the role of sulfur dioxide emissions***

Maciej Obryk<sup>1</sup>; A. Fountain<sup>2</sup>; P. Doran<sup>1</sup>; W. B. Lyons<sup>3</sup>

Louisiana State University/Portland State University, USA<sup>1</sup>; Portland State University, USA<sup>2</sup>; Ohio State University, USA<sup>3</sup>

The last published solar radiation record from the McMurdo Dry Valleys (MDVs), Antarctica between 1987 and 1999 showed an increase of 8.1 W m<sup>2</sup> per decade, while surface air temperature decreased by 0.7°C per decade; However, the driving mechanisms behind either trend have not been explained. Here, we provide an up-to-date meteorological record from the McMurdo Dry Valleys and attribute changes in solar radiation trends to anthropogenic sulfur dioxide emissions ( $r = 0.92$ ,  $p < 0.001$ ), which explains 84% of variance. Other influences noted include major natural pulses (influences) such as volcanic eruption and wildfires, and indirectly inferred dimethylsulfide production (a biogenic precursor to sulfate aerosols). Sulfate aerosols are effective cloud condensation nuclei and are extremely efficient at scattering down-welling solar radiation. Numerous reports have attributed anthropogenic sulfur emissions to global solar radiation dimming/brightening, where global is a loosely defined term (as the effect of sulfur aerosols is highly variable on different spatial scales). The pristine nature of the Antarctic continent, due to its isolation from human disturbance and the effect of polar amplification, establishes the McMurdo Dry Valleys as a proxy for a true global monitoring site of anthropogenic and natural sulfur dioxide emissions. Annually, averaged solar radiation increased by more than 20 W m<sup>2</sup> in the MDVs since 1989 as a direct consequence of decreasing anthropogenic sulfur dioxide emissions. Solar radiation is the main driver of surface air temperatures on the Antarctic Plateau, explaining 99% of variance. However, solar radiation in MDVs only explains 86% of variance, suggesting that other minor drivers control surface air temperatures in this region. We postulate that reradiated heat from the exposed bare soils in MDVs and the warming associated with foehn winds explain the remaining variance.



**S16 – 415: Interactions between cryosphere, atmosphere and oceans in coastal Antarctica**

***Controls on a coastal marine ice sheet instability Zone along the Sabrina Coast, East Antarctica***

Greenbaum, J.S.<sup>1</sup>; Blankenship, D.D.<sup>1</sup>; Young, D.A.<sup>1</sup>; Roberts, J.L.<sup>2</sup>; Aitken, A.R.A.<sup>3</sup>; Legresy, B.<sup>4</sup>; Schroeder, D.M.<sup>5</sup>; Warner, R.C.<sup>6</sup>; Ommen, T.V.<sup>2</sup>; Siegert, M.J.<sup>7</sup>

Institute for Geophysics, University of Texas at Austin, USA<sup>1</sup>; Antarctic Climate & Ecosystems Cooperative Research Centre, University of Tasmania and Australian Antarctic Division, Australia<sup>2</sup>; School of Earth and Environment, University of Western Australia, Australia<sup>3</sup>; School of Earth and Environment, University of Western Australia, Australia<sup>4</sup>; Jet Propulsion Laboratory, California Institute of Technology, USA<sup>5</sup>; Antarctic Climate & Ecosystems Cooperative Research Centre, University of Tasmania, Tasmania<sup>6</sup>; Grantham Institute And Department of Earth Sciences and Engineering, Imperial College London, United Kingdom<sup>7</sup>

Leveraging new aero-geophysical data acquired over the last seven years, recent work has shown that the Aurora Subglacial Basin (ASB) in East Antarctica has drained and filled many times since large scale glaciation began and there is evidence that it collapsed during the Pliocene. Recent ice sheet modeling integrating new bed topography data has revealed potential processes controlling ASB evolution that result in retreat scenarios that are consistent with the timing of past high sea level stands. High thinning rates along the coastal margin of the ASB near the grounding line of Totten Glacier suggest that processes governing retreat may be underway. The catchment feeding Totten Glacier is the primary ice sheet outlet of the ASB to the ocean and the observed thinning is the most rapid outside of West Antarctica. The Totten Glacier catchment alone contains enough ice to raise global sea level by at least 3.5 meters, an amount that is roughly equivalent to the likely contribution of the entire West Antarctic Ice Sheet if it were to completely collapse. Here we show that a region of marine ice sheet instability zone lies immediately landward of the modern grounding line along the Sabrina Coast where consistent thinning has been observed since the beginning of the satellite altimetry record. We define the ~ 560 km by 100 km instability zone by where the ice bottom elevation is below the average grounding line depth along the coast and we find that it contains ~10 cm of global sea level potential. This zone is bounded to the north by a minor highland separating it from the rest of the ASB which reaches depths of over 1.7 km below sea level in the interior. We use recent airborne radar data to delineate areas of the grounding line where satellite-derived datasets disagree. Integrated with the latest gravity and magnetic data and informed by recent marine oceanographic and geophysical work along the Sabrina Coast, these results provide the latest sub-glacial and oceanic controls on this previously-unknown area of marine ice sheet instability along the most rapidly changing coastline of East Antarctica.



**S16 – 423: Interactions between cryosphere, atmosphere and oceans in coastal Antarctica**

***Precipitation of silica spherules during regional scale ice melting events***

Massimo Pompilio<sup>1</sup>; Alessio Di Roberto<sup>1</sup>; Paola Del Carlo<sup>1</sup>; Antonella Bertagnini<sup>1</sup>; Ester Colizza<sup>2</sup>; Carmine Lubritto<sup>5</sup>; Fabrizio Lirer<sup>3</sup>; Fabio Florindo<sup>4</sup>;

Istituto Nazionale di Geofisica e Vulcanologia Sezione di Pisa, Italy<sup>1</sup>; Dipartimento Di Matematica E Geoscienze, Universite Di Trieste, Italy<sup>2</sup>; Istituto Per Lâ Ambiente Marino Costiero (IAMC) CNR Napoli, Italy<sup>3</sup>; Istituto Nazionale Di Geofisica E Vulcanologia Sezione Roma 2, Italy<sup>4</sup>; Dipartimento di Scienze Ambientali, Seconda Universita di Napoli<sup>5</sup>

In the last decade considerable effort has been made to reconstruct in detail the palaeo-climate of polar regions. Past climatic conditions can be reconstructed using a combination of proxy indicators including ice and sediment core records, the remains of microbial life such as corals, diatoms and foraminifera, tree rings and fossil pollen, the characteristics of which are affected by prevailing climate conditions at the time of deposition or growth. In particular, sedimentary facies, as well as the nature and composition of materials forming marine sediments, are widely used to interpret past climates.

Concentrically structured silica spherules have recently been identified within Late Pleistocene-Holocene glacio-marine sediments from the Ross Sea and Weddell Sea, Antarctica and there are a number of hypotheses on their origin and meaning. We report on silica spherules identified in Late Pleistocene-Holocene marine sediments from three gravity cores (ANTA99NW27, ANTA99NW31 and ANTA02NW03) recovered from the Ross Sea, Antarctica, during the 1999 and 2000 oceanographic cruises of the Italian Antarctic Research Programme PNRA. These cores were recovered between ~40 and ~80 km off the coast of Daniell Peninsula.

We present data on their depositional environment, morphology, inner texture and major element composition constraining their age through <sup>14</sup>C and <sup>40</sup>Ar/<sup>39</sup>Ar dating of sediments embedding the spherules. Results indicate that spherules are concentrically structured and made of opaline silica. They occur in sediments from the outer continental shelf depositional system and were emplaced under prevalently open sea conditions or during periods in which the extent of sea ice was limited. We suggest that spherules formed by precipitation of silica when important masses of silica rich melt waters mixed with ocean waters during or shortly after regional-scale melting events. On this basis, we argue that the occurrence of silica spherules can possibly be used as a proxy for outbursts of poor subglacial meltwater and/or surging of ice streams into the ocean during ice sheet disintegration.



**S16 – 429: Interactions between cryosphere, atmosphere and oceans in coastal Antarctica**

***Antarctic Sea-Ice Variability Modelling***

David Mendes<sup>1</sup>; Monica Cristina Damiao Mendes<sup>1</sup>

Federal University of Rio Grande do Norte, Brazil<sup>1</sup>

This work aims to study the variability of sea ice in the Antarctic seas using the SPEEDY model coupled to CICE sea ice model. We used the period 1979-2012. The coupled successfully reproduces observation of sea ice concentration, and trends in sea ice over Antarctic seas. Another important factor that may contribute to an approach between the results is that the SPEEDYCICE, captures the inter-annual changes in sea ice cover during the summer, when solar insolation is high, are more critical in terms of ice albedo feedback effects in the southern hemisphere. Results show an interesting similarity between the model and estimated Satellite, demonstrating that the model can capture the dynamics and thermodynamics associated with sea ice. Another important factor related to seasonal variability of sea ice, the CICESPEEDY captures this variability, overestimating this cycle the period of maximum coverage.



**S16 – 441: Interactions between cryosphere, atmosphere and oceans in coastal Antarctica**

***Spatial variability and possible sources of Carboxylate ions in the surface snow samples in Princess Elizabeth land, East Antarctica***

S. Gautami<sup>1</sup>; K. Mahalinganathan<sup>1</sup>; M. Thamban<sup>1</sup>

NCAOR, Goa, India<sup>1</sup>

Carboxylate ions are one of the dominant classes of organic compounds found in the troposphere. Their role in troposphere chemistry through cloud chemistry and precipitation acidity is particularly important especially in remote regions like Antarctica. Carboxylate ions such as acetate and formate were studied in 24 surface snow samples along a coast to inland transect (up to 180 km inland) within the Princess Elizabeth Land in the Indian Ocean sector of Antarctica, using anion exchange ion chromatography. Concentrations of Acetate and Formate ions ranged from 200 ngL<sup>-1</sup> to 90.75 gL<sup>-1</sup>. Acetate ion concentration in the snow samples (2.6 gL<sup>-1</sup> to 90.75 gL<sup>-1</sup> with highly significant values in the fresh snow samples) decreases from the coast to 130 km inland showing a significant correlation with distance ( $r > 0.793$ , 99.99% confidence level), suggesting its direct/indirect source to be the ocean surrounding the continent. This is also supported by the correlation of acetate ions with the Na<sup>+</sup> ( $r > 0.487$ , 96% confidence level). Compared to this, formate ions in the samples (200 ngL<sup>-1</sup> to 3.91 gL<sup>-1</sup>) do not show any correlation with the distance suggesting its origin to be either terrestrial or atmospheric. Significant correlations between nitrate ions and acetate ( $r > 0.646$ ) as well as formate ( $r > 0.421$ ) ions suggests their origin to be photochemical activity which is supported by the presence of organic precursors in the snow samples required for the photochemical reactions. Also, the presence of 10<sup>3</sup>-10<sup>4</sup> cells mL<sup>-1</sup> and a variety of bacteria, fungi and microalgae in the snow samples indicate the possible contribution of microbial activity in the formation of the carboxylic acids.



**S16 – 452: Interactions between cryosphere, atmosphere and oceans in coastal Antarctica**

***Evidence of past climate and ice sheet response from Near-coastal domes in the Weddell Sea Region***

Robert Mulvaney

British Antarctic Survey, United Kingdom

In the past few decades, observations of ice retreat in West Antarctica have been diverse: ice shelves disintegrating, increases in the velocity of glaciers, ice stream grounding lines retreating, and loss of ice mass from the West Antarctic Ice Sheet (WAIS). But are these observations indicative of recent anthropogenic climate change? Local ice cores offer a longer term regional climate perspective and, when taken together with radar observations of the ice sheet, also provide clues to the evolution of the ice domes.

Teams from the British Antarctic Survey and the Laboratoire de Glaciologie et Geophysique de l'Environnement have drilled three ice cores through to bedrock in the Antarctic Peninsula/Weddell Sea region at Berkner Island, James Ross Island and the Fletcher Promontory. Each of these cores penetrates well into the last glacial period, and in the case of Berkner and Fletcher, potentially into the Last Interglacial (LIG, ~125,000 years ago). This suite of cores can be used to assess the regional climate and the extent and thickness of the Weddell Sea ice sheet during the Last Glacial Maximum, and the evolution of the ice sheet and its surrounding ice shelves through the Holocene. As an example, results from James Ross Island support the view that the recent northern Peninsula ice shelf collapse is not a unique event in the Holocene.

Further, these ice cores may provide evidence for the state of the WAIS during the Last Interglacial. East Antarctic ice cores suggest that the local climate was 2-4°C warmer than present day during the while other records point to a global sea level 4-8 meters higher. Recent evidence implies that Greenland did not lose sufficient mass to have added more than 2 m, hinting at the loss of Antarctic ice as a source for the higher LIG sea level. The West Antarctic Ice Sheet (WAIS) is seen as the likely source of major ice loss and some modelling results have suggested that it might have collapsed during the LIG leading to questions about its future stability in a warming world. Sitting close to outlet ice streams from the WAIS, the Fletcher Promontory might provide clues to the state of the main ice sheet during the LIG.



**S16 – 465: Interactions between cryosphere, atmosphere and oceans in coastal Antarctica**

***Impact of the stratospheric ozone hole on Atmospheric perchlorate production***

Thomas Cox<sup>1</sup>, Jihong ColeDai<sup>1</sup>, Kari Peterson<sup>1</sup>, Scott Splett<sup>1</sup>

South Dakota State University, USA<sup>1</sup>

Perchlorate ( $\text{ClO}_4$ ) is ubiquitous in the environment at trace levels. It has been proposed that perchlorate is produced in the atmosphere through natural processes. Little is known about the atmospheric production of perchlorate including the rate of production (strength) and details regarding the important factors of the atmospheric reactions. One of the possible or likely mechanisms of perchlorate formation is oxidation of chlorine species through reactions involving tropospheric ozone and photochemical processes. Perchlorate production may also be affected by stratospheric ozone. We hypothesize that the appearance of the ozone hole over Antarctica leads to increased atmospheric production of perchlorate: the proposed mechanism is that the weakened stratospheric ozone results in increased ultraviolet penetration into the troposphere and causes concentrations of surface level ozone and/or other atmospheric oxidants to increase. This ultimately leads to a higher rate of perchlorate production. The objective of this study is to test this hypothesis by measuring perchlorate in Antarctic snow.

The stratospheric ozone hole appears over Antarctica during the austral spring; thus, according to our hypothesis, high perchlorate concentrations would be expected in spring snow. We are measuring, at high temporal resolution, perchlorate in a shallow South Pole ice core. We are also measuring concentrations of  $\text{Mg}^{++}$  and  $\text{Na}^+$  to date the core, for the concentrations of these ions generally reach a maximum in the austral winter. The high resolution measurement allows the seasons of the core samples to be determined. Measurement of perchlorate in Antarctic snow and ice core samples has begun only recently. The limited data exhibits a sharp decline in perchlorate concentration with increasing depth suggesting either a significant change in the perchlorate source(s) and/or variation in source strength that may occur during the latter half of the twentieth century. Another possible explanation for the trend is that perchlorate experiences post depositional behavior in Antarctic snow. Our analysis of the South Pole core will provide a perchlorate record covering the time period since early twentieth century. This record will also be used to assess the magnitude and long term variability of natural production of perchlorate and to investigate the factors behind the trend. In addition, close examination of the perchlorate deposition patterns over time may reveal the influence of environmental factors, such as climate and ozone chemistry, on perchlorate and can contribute to the interpretation of long perchlorate records from ice cores.



**S16 – 473: Interactions between cryosphere, atmosphere and oceans in coastal Antarctica**

***Estimation of the basal melt distribution beneath ice shelves in a steady state using high-resolution elevation data from Cryosat-2***

Choon-Ki Lee<sup>1</sup>; Byeonghoon Kim<sup>2</sup>; Ki-Weon Seo<sup>2</sup>; Wonsang Lee<sup>1</sup>

Korea Polar Research Institute, Korea<sup>1</sup>; Seoul National University, Korea<sup>2</sup>

Basal melt rates beneath ice shelves have been estimated from flux gate methods since accurate elevation data are mostly limited along flight lines of airborne survey or ground tracks of ICESat satellite altimetry. On the other hand, spatial distributions of basal melt have been derived from the divergence of mass flux usually using the ice thickness data converted from radar altimetry measurements. However, the DEM and ice thickness from previous radar altimetry do not have the resolution and accuracy enough to estimate the detailed basal melt distribution. For the accurate mapping of basal melt in details, we apply the Cryosat-2 radar altimetry measurements to extracting the steady state component of ice shelf topography. In comparison with ICESat elevation, significant biases are observed in the Cryosat-2 elevation in a large portion of ice shelf, since harsh topographic undulations (e.g. ice rumples, flow strips, crevasse and rift) exist on the surface of ice shelf. We first correct the bias of Cryosat-2 elevation dependent on surface roughness in comparison with ICE-Sat elevation. The corrected Cryosat-2 elevations and the InSAR ice velocities are combined to map the divergence of mass flux. Different from the conventional 2D divergence methods, the basal melt rates are estimated along ice flow lines. This approach is useful for narrow ice tongues or ice shelves with severely anisotropic surface undulations where isotropic 2D spatial averaging results in a severe signal loss.



**S16 – 474: Interactions between cryosphere, atmosphere and oceans in coastal Antarctica**

***Molecular evidence for rapid and extensive microbial and photochemical processing of organic matter on the surface of the Antarctic ice sheet***

Runa Antony<sup>1</sup>; Willoughby A. S.<sup>2</sup>; Grannas A. M.<sup>3</sup>; Sleighter R. L.<sup>4</sup>; Thamban M.<sup>1</sup>; Hatcher P. G.<sup>4</sup>

National Centre for Antarctic and Ocean Research, India<sup>1</sup>; Old Dominion University, Department of Chemistry and Biochemistry, Norfolk, Virginia, USA<sup>2</sup>; Villanova University, Department of Chemistry, Villanova, Pennsylvania, USA<sup>3</sup>; FBSciences, Inc. (Research and Development), Norfolk, VA 23508 and Old Dominion University, Department of Chemistry and Biochemistry, Norfolk<sup>4</sup>

Recent studies on glacial dissolved organic matter (DOM) using ultrahigh resolution mass spectrometry have yielded important insights into DOM composition and complexities in these environments. What remains elusive is the reactivity of the various components of this DOM pool and the processes by which they are transformed and cycled in supraglacial environments. We present strong evidence of rapid (order of days) and extensive photochemical and microbial (termed photo-biochemical) alteration of both autochthonous and allochthonous DOM on the coastal Antarctic ice sheet surface. We show that photo-biochemical processing of DOM results in major shifts in the composition and bioavailability of nitrogen, sulfur, and phosphorous bio-molecules with possible consequences for glacial microbial communities. Photo-biochemical processes also appear to be an important mechanism for removing important classes of refractory OM, like dissolved black carbon (DBC) and carboxylic rich alicyclic molecules (CRAM). The possible impacts of such photo-biochemical processing of DBC on surface albedo of snow packs are not known. In some cases, photo-biochemical processing appears to result in altered compounds that are photo and biolabile. The opposite is also observed, converting some components of the DOM to photo and bioresistant forms. Thus, the biogeochemistry of DOM is highly complex and intimately connected with microbial and photochemical processes. This study is unique as it provides new molecular insights on previously undocumented compounds that comprise the photo and biolabile, photo and biorefractory, as well as photo and bioproduced fractions of the DOM pool. The novel insights into new and unforeseen interactions between microbes, light and specific components of the DOM pool highlight the need for focused studies on supraglacial carbon biogeochemistry and its response to a changing climate.



**S16 – 501: Interactions between cryosphere, atmosphere and oceans in coastal Antarctica**

***An unparalleled opportunity to compare the marine Sediment record with a related ice core in coastal Antarctica: Herbertcroft Fjord, James Ross Island***

Rebecca Totten Minzoni<sup>1</sup>; John B. Anderson<sup>1</sup>; Rodrigo Fernandez<sup>2</sup>; Julia S. Wellner<sup>3</sup>

Rice University, USA<sup>1</sup>; University of Texas Institute for Geophysics, USA<sup>2</sup>; University of Houston, USA<sup>3</sup>

Draining the ice dome where the James Ross Island ice core was recently collected, Herbert-Croft Fjord presents an unparalleled opportunity to compare directly related marine and terrestrial climate records in an Antarctic maritime setting, spanning the Holocene. An 11 m drill core was collected as part of the SHALDRIL NBP0502 initiative and is the most highly resolved sedimentary record to date from a fjord setting south of the Antarctic Sound on the eastern side of the AP. Magnetic susceptibility, pebble content, laser particle size, total organic carbon, and diatom abundance and assemblage data were analyzed at centennial scale resolution and interrogated in the context of nearby Holocene icecore, lake, and glaciogenic outcrop data from James Ross Island.

Herbert-Croft Fjord rapidly deglaciated and sustained a floating ice canopy until  $\sim 10 \pm 2.4$  cal kyr BP. The Mid Holocene Hypsithermal commenced  $\sim 7.2$  cal kyr BP when the fjord became open and productive. An extreme peak in productivity  $\sim 6.1$  cal kyr BP indicates an oceanic warming event that is not reflected in atmospheric temperature or lacustrine sediment records. Seaice cover and icerafting Increased  $\sim 2.5$  cal kyr BP, while land-terminating glaciers advanced and atmospheric temperature decreased on James Ross Island, marking the onset of the Neoglacial in the northeastern AP. The historic Medieval Warm Period and Little Ice Age are recognized in Herbert-Croft Fjord, but are not evident in the ice-core record, which documents pronounced warming  $\sim 600$  years ago. Suppressed productivity and greater sea-ice cover  $\sim 100$  years ago in Herbert-Croft Fjord likely resulted from enhanced melt-water contribution of receding glaciers on James Ross Island.

The differences between paleo-environmental signals from Herbert-Croft Fjord and paleo-temperatures from the ice core likely result from marine vs. terrestrial response to climate forcing. Specifically, water mass configuration, seaice, and albedo effects may account for differential timing and magnitude of events in Herbert-Croft Fjord.



**S16 – 510: Interactions between cryosphere, atmosphere and oceans in coastal Antarctica**

***High-resolution Climate information from the northern Antarctic Peninsula as revealed by shallow firn cores and geophysical data***

Francisco Fernandez<sup>1</sup>; Hanno Meyer<sup>2</sup>; Guisella Gacitua<sup>3</sup>; Carlos Cardenas<sup>3</sup>; Ulrike Falk<sup>4</sup>

Universidad Nacional Andres Bello, Chile<sup>1</sup>; Alfred Wegener Institute, Helmholtz Centre For Polar and Marine Research, Potsdam, Germany<sup>2</sup>; Universidad De Magallanes, Punta Arenas, Chile<sup>3</sup>; ZFL Center For Remote Sensing Of Land Surfaces, University Of Bonn, Bonn, Germany<sup>4</sup>

Presently it is broadly recognized that the Antarctic Peninsula and West Antarctica are warming at extraordinarily fast rates. Consequences of the warming can be extensively observed on the ice sheet reduction in this region of Antarctica and on the ice shelf on the surrounding seas. Together West Antarctica and the Antarctica Peninsula exhibit an ice mass loss in the order of  $\sim 85 (\pm 20)$  Gton a<sup>-1</sup> for the last 20 years. At present day conditions, ice shelves around the Peninsula are likely to become unstable and a collapse of the ice shelves might trigger an accelerated ice flow from the continent. While the present-day temperatures are extraordinarily high, setting a new record of +16.5°C for a day maximum during March 2015 (Esperanza station), these are not unprecedented during the Holocene. The forcing mechanisms behind the warming phenomenon are not completely understood, however most likely linked to the perturbation of atmospheric circulation patterns with increased strength of westerlies and rise of sea surface temperatures. The scarcity of long-term meteorological observations made the interpretation of the current events rather-complicated, and year-around automatic weather station data are not abundant. Models do not agree on the temperature increase seasonality. It has been observed that precipitation (and accumulation) has increased due to the greater capacity of warmer air to transport moisture. Ice cores from high-accumulation regions can significantly contribute to understand the undergoing climate variability and expand short meteorological time-series to the past.

Since 2008, we have studied the northern part of the Antarctic Peninsula, where several surface firn cores (up to 20m depth) have been collected from sea level to the divide between west and east coast at the Plateau Laclavere (63°27'15" S / 57°41' 53" W) at ca. 1300 m a.s.l., as it was established after a DGPS survey in 2014 by our research team, improving the previous assumption of an altitude of 1100 m a.s.l. Stable water isotope analysis from these cores reveals that the source of precipitation for this region is mainly located on the southern Pacific ocean, with precipitation events evenly distributed over the whole year. Firn stratigraphy reveals that some melt events are present even at the highest points (MAAT of ca. 7° C). High concentrations of melt layers, centimeters wide, are observed at around 5m and 10m depth on the cores. Stable water isotope determinations (<sup>18</sup>O and D) of the cores were made using classical mass spectrometry (IRMS) and laser cavity ring down spectroscopy (CRDS). The isotope signature of the cores shows a complicated signal to interpret. No seasonality is observed from <sup>18</sup>O (D), most likely due to the restricted temperature oscillation at this region caused by marked maritime influence. Nonetheless the deuterium excess (dexcess D<sup>8</sup> <sup>18</sup>O) can be potentially used as a seasonal marker, reaching minima in summer and maxima during winter. The dexcess reflect most likely the conditions (i.e.: relative humidity) at the moisture source region. Annual layer counting using dexcess yields accumulation rates of around 2.4 m w.e.q. at this region, which roughly approximate 5 m of snow falling per year and also coincide with the melt layers as described above. High-frequency ground penetrating radar survey carried out during the last field campaign in January 2015, further support this estimation made for the accumulation rate. Clear reflectors (stratigraphy) are visible up to 40 m of depth. We postulate that relevant climate information can be retrieved of the ice sheets from this region, when combining different glacio-chemical and geophysical methods. If summer temperatures rise, we expect to see a higher frequency of melt events, while inter-annual isotope signatures reveals air temperature variability. A high accumulation region at the northern tip of the Antarctic Peninsula offers a new insight to study the present accelerated warming in this region. Moreover, the Laclavere Plateau presents a



# *XII International Symposium on Antarctic Earth Sciences*

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location with great conditions for further glaciological and climatic research and drilling of an up to 250 m deep ice core.



## S17 – 118: Southern Ocean Paleoclimatology

### ***Anomalous Extended Southern Ocean Surface Warming Across Marine Isotope Stage 31***

Beltran C<sup>1,2</sup>; Mainié F<sup>2</sup> Sicre M-A<sup>3</sup>; Ohneiser C<sup>1</sup>; Hageman K<sup>2</sup>

Dept. of Geology, University of Otago, PO Box 56, Dunedin. New Zealand<sup>1</sup>; Dept. of Chemistry, University of Otago, PO Box 56, Dunedin. New Zealand<sup>2</sup>; LOCEAN, UMR7159 (IRD, CNRS, UPMC, MNHN), Institut Pierre Simon Laplace, Laboratoire d'Océanographie et du Climat: Expérimentations et Analyses Numériques, Université P. et M. Curie, 4 place Jussieu, 75252 Paris cedex 05, France<sup>3</sup>

Several model simulations have highlighted the prominent role of ocean warming on Antarctic ice stability through sub-ice-shelf melting. Yet, oceanic heat flux thresholds that can lead to significant Antarctic ice loss, as well as the rate and magnitude of ice volume reduction and recovery have not yet been well constrained from geological reconstructions.

This study focuses on the warm Marine Isotope Stage 31 (MIS-31: 1.08-1.06 Ma), during which a dramatic reduction in Antarctic Ice sheets and possibly Northern Hemisphere ice volume resulted in a global sea level rise of more than 7 m. In Southern Ocean sedimentary records, MIS-31 is identified by the abrupt and transient appearance of foraminiferal oozes and coccolith-bearing sediments in the Weddell Sea and Prydz Bay and by the presence of bioclastic limestone in the Ross Sea, indicating Southern Ocean warming coincident with ice shelf retreat and West Antarctic Ice Sheet collapse.

Here we present the first alkenone-based SST reconstruction across the interval encompassing MIS-31 (period between 1.12 and 0.94 Ma) at ODP Site 1094 (53°10.8'S) located South of the Polar Front in the Atlantic sector of the Southern Ocean.

Our data show that during the warmth peak of MIS-31, the SSTs at Site 1094 were on average 5°C warmer than today. This result is likely indicative of a significant southward migration of the Polar Front and subsequent high Southern Ocean heat flux causing sub-ice shelf melt as suggested by ice sheet-shelf and global climate model (GCM) simulations.

Moreover, our long-term alkenone-derived SST record, revealed that the temperatures were on average 3 to 4°C warmer than today up to MIS-25, implying that the Polar Front was and remained located in a rather southern position for a much longer period than previously recognized.

Further work is needed to reconcile simulations, which suggest greater-than-modern ice volume during glacial MIS-32 and MIS-30 under significantly elevated Southern Ocean temperatures.



**S17 – 125: Southern Ocean Paleoclimatology**

***Southern Ocean Mixed Layer Depth Variability and Its Response to Atmospheric Forcing***

Siddhartha Chatterjee<sup>1</sup>; Anurag Kumar<sup>1</sup>; Suneet Dwivedi<sup>1</sup>

Allahabad University; Uttar Pradesh, India<sup>1</sup>

The estimation and understanding of the mixed layer depth (MLD) variability in the Southern Ocean and Antarctic sea ice region is important for wide variety of processes like oceanic productivity, air-sea interaction and for investigating long-term climate change. The MLD variability is controlled directly or indirectly by a number of air-sea forcings, namely - near surface winds, shortwave radiation and air temperature. Efforts are made in this study to examine and estimate the MLD variability using a coupled ocean sea-ice model in the region [9°E, 78°E; 45°S, 72°S]. The horizontal resolution of the model is nearly 15 km whereas the highest vertical resolution near the surface is taken as 5m. Various sensitivity experiments are performed to gauge the relative contribution of the surface winds, shortwave radiation and air temperature on the MLD variability of the region. It is found that most of the MLD variability seen in the Southern Ocean sea-ice region is due to near surface wind variability. It is also observed that in some regions, as a result of strong winds and solar radiation, the MLD may even reach 200 meters.



**S17 – 202: Southern Ocean Paleoclimatology**

***Upper Quaternary Radiolaria from ABP06, Section I (1.1 To 2.10), Central Indian Ocean***

Vandana Khampa<sup>1</sup>; Girish Kumar Sharma<sup>1</sup>

Department of Geology, Kumaun University, Nainital, India<sup>1</sup>

The studies related to radiolaria in the Central Indian Ocean is very scarce. The first work was carried out by Sanfilippo & Riedel (1974) from the western Central Indian Ocean and the Arabian Sea, DSDP Leg 24. Gupta (1988) suggested sub oceanic explosive volcanic eruption during Late Quaternary in the Central Indian Ocean. The studied core ABP06, Station 1 lies at Latitude 110° 44.004` S and Longitude 76° 03.311` E of Central Indian Ocean. The samples were collected at a water depth of 5,232 mbsf (meters below seafloor). The study is carried out on twenty samples from Section I (1.1 to 2.10). These samples have varying depth from 5232 m to 5232.4 m. Objectives: 1. Identification of radiolaria in the section. 2. Systematics of the identified radiolaria was given. 3. To interpret their temporal distribution in all the samples. 4. Establishment of the age of the sections, on the basis of their common presence of radiolaria. Methods: About 34 gm of sediment was first disaggregated in dilute hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>). After disaggregation, heating the samples just below the boiling point, then the sample was sieved through a 63 µm mesh stainless sieve. The residue was dried. The residue material was taken and slides were prepared by using the Canada balsam as mounting medium. About 5000 radiolarian taxa were taken from total radiolarian population for each sample. Results and Conclusion: Twenty five radiolarian species were identified in which fifteen are Spumellarian and ten are Nassellarian. The assemblage belongs to typical Upper Quaternary and is having mixed fauna. Their taxonomic notes and illustrations were given. The studied section is of Upper Quaternary age. The radiolarian assemblage contains warm water species.



## S17 – 203: Southern Ocean Paleoclimatology

### ***Biostratigraphy of Pliocene Radiolaria Leg 119 Site 738b Sections (2h4 To 2h5) of Southern Indian Ocean***

Deepti Tiwari<sup>1</sup>; Girish Kumar Sharma<sup>1</sup>

Department of Geology, Kumaun University, Nainital, India<sup>1</sup>

The area of present study is located on a large sediment drift at the base of the Southern slope of the Kerguelen Plateau at 62°42.54'S and 82°47.25'E. Lithostratigraphically, the sections lie in the subunits IA and consists of diatom ooze, calcareous foraminiferal ooze, radiolarians and nannofossils. The samples were collected at a water depth of 2252.5 mbsf. The total length of studied core is 2.895 m.

#### Background

Investigations on late Cenozoic radiolaria in the Southern Ocean region have been very scanty. Barron et al., 1991 carried out the study on biochronologic and magnetostratigraphic synthesis of sediments from the Kerguelen Plateau and Prydz Bay of the Southern Ocean region. Caulet (1991) did the preliminary study on few samples of Neogene sediments from Kerguelen Plateau. Lazarus (1992) broadly proposed the biozones of Antarctic Neogene radiolaria. Lazarus and Caulet (1991) did the work on radiolarian biostratigraphy, biogeography, diversity and history on Eocene to Recent sediments of Southern Ocean.

#### Objectives

The objectives of the present study are

1. To identify the radiolarian species along with their taxonomic description.
2. To interpret their temporal distribution in the sample.
3. Establish the radiolarian biozones.

#### Methods

Twenty eight samples from two sections (2H4 to 2H5) of Leg 119 Site 738B were used to carry out the present study. Sediment samples of about 3-4 g were disaggregated in dilute Hydrogen peroxide for 1-2 hour followed by heating to just below the boiling point. One teaspoonful of Calgon (Hexametaphosphate) was added to further boil and disaggregate the sediment samples for 1-2 hours and complete the treatment. The samples were sieved through a 63 micron mesh sieve and dried. The strewn slides were prepared by using an eye dropper and Canada balsam as a mounting medium. Generally, minimum 2 – 3 slides (of cover slip size 22:22 mm) were examined for taxonomic and stratigraphic work, depending on their abundance i.e. generally between 950 -1000 individual radiolarians.

#### Results and Conclusion

This work presents the first detailed investigation of Pliocene radiolaria of Antarctic region. Significant assemblage of radiolaria was recovered from two sections (2H4 and 2H5) of 28 samples. Well preserved and varied radiolarian assemblages were found throughout the sections. Thirty Radiolarian taxa were identified and their systematics is given. On the basis of appearance, disappearance and common occurrences of species, the sections lie in the Saturnalis circularis zone of late Pliocene age. This zone is equivalent to NR3 zone. The studied sections show the presence of typical Antarctic and sub Antarctic species.



**S17 – 204 : Southern Ocean Paleoclimatology**

***Upper Quaternary Radiolaria from Abp06, Section I (1.1 To 2.10), Central Indian Ocean***

Vandana Khampa<sup>1</sup>; Girish Kumar Sharma<sup>1</sup>

Department of Geology, Kumaun University, Nainital, India<sup>1</sup>

Background: The work on the Central Indian Ocean is very scarce. The first work was carried out by Sanfilippo & Riedel (1974) who did the work on radiolaria from western Central Indian Ocean and the Arabian Sea, DSDP Leg 24. Gupta (1988) suggested sub oceanic explosive volcanic eruption during late Quaternary in the Central Indian Ocean. The studied core ABP06, Station 1 lies at Latitude 11° 44.004'S and Longitude 76°3.311'E of Central Indian Ocean. The samples were collected at a water depth of 5,232 (mbsf) metres below seafloor. The study is carried out on twenty samples from Section I (1.1 to 2.10). These samples have varying depth from 5232 m. to 5232.40 m.

**Objectives:**

1. Identification of radiolaria in the section.
2. Systematics of the identified radiolaria was given.
3. To interpret their temporal distribution in all the samples.
4. Establishment of the age of the sections, on the basis of the common presence of radiolaria.

**Methods:**

About 34gm of sediment was first disaggregated in dilute hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>). After disaggregation, samples were heated just below the boiling point and then the sample was sieved through a 63µm mesh stainless sieve. The residue was dried. The residue material was taken and slides were prepared by using the Canada balsam as mounting medium. About 5000 radiolarian taxa were taken from total radiolarian population for each sample.

**Results and Conclusion:**

Twenty five radiolarian species were identified in which fifteen are Spumellarian and ten are Nassellarian. The assemblage belongs to typical Upper Quaternary and is having the mixed fauna. Their taxonomic notes and illustrations were given. The studied section is of Upper Quaternary age. The radiolarian assemblage contains warm water species.



**S17 – 287: Southern Ocean Paleoclimatology**

***Enhanced Productivity at the Subtropical Front during the Past Periods of High Aeolian Dust Flux***

Manish Tiwari<sup>1</sup>; Shubham Tripathi<sup>1</sup>; Siddhesh Nagoji<sup>1</sup>; Rahul Mohan<sup>1</sup>

National Centre for Antarctic & Ocean Research, Vasco-da-Gama, Goa, India<sup>1</sup>

A strong link exists between the aeolian dust flux and the climate of the earth. Enhanced dust supply is observed during the past glacial periods that can be two to five times of that during the interglacial periods. Dust can affect the global climate through several ways amongst which fertilization of the HNLC (High Nutrient, Low Chlorophyll) regions (mainly the Southern Ocean, and the North and Equatorial Pacific) by iron bearing dust is an important one. The increase in productivity in such regions would result in additional uptake of carbon in the marine ecosystem resulting in drawdown of the atmospheric CO<sub>2</sub>. Here we present a record of productivity variability from the Subtropical Front of the Indian Ocean sector of the Southern ocean for the past 71 Kyr. The sediment core ABPS1 was collected from a water depth of 3500 m from 42 °S latitude and 48 °E longitude. To reconstruct the past productivity in this region, several isotopic ( $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  of foraminifera,  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  of sedimentary organic matter), geochemical (total organic carbon and nitrogen content) and micropaleontological proxies were studied. The  $\delta^{13}\text{C}$  of the SOM vs. C/N ratio plot clearly indicate that the organic matter is of marine origin with no terrestrial organic matter input. We find that, at the core site, the productivity increases during the colder periods viz. the MIS 2 and the MIS 4. Both the total organic carbon and nitrogen content shows an increase during the MIS 2 and MIS 4 accompanied by enhanced abundance of planktic and benthic foraminifera. The  $\delta^{15}\text{N}$  of the sedimentary organic matter also shows an increase during this period showing relatively higher nitrate utilization. We compare our results with the EDC dust flux representing global dust concentration and ODP1090 Fe mass accumulation rate (MAR) from the Atlantic sector of the Southern Ocean representing iron bearing dust input in the Southern Ocean. During the past 71 Kyr, the dust influx and Fe MAR increases during the MIS 2 and the MIS 4 similar to the periods when the productivity at the Subtropical Front increases drastically. The close correspondence between our productivity record from the Indian Ocean sector of the Southern Ocean with that from the Atlantic sector of the Southern Ocean (ODP 1090 Fe MAR) and the EDC dust flux from Antarctica reveal tight connection between aeolian dust influx and global climate via ocean fertilization.



**S17 – 292: Southern Ocean Paleoclimatology**

***Modern Oxygen Isotope and Salinity Values in Water Masses of Southern and Indian Ocean: Implications to Past Salinity Determination***

Siddhesh Nagoji<sup>1</sup>; Manish Tiwari<sup>1</sup>

National Centre for Antarctic & Ocean Research, Vasco-da-Gama, Goa, India<sup>1</sup>

Several paleoceanographic studies are being carried out in different regions of the Southern Ocean and the Indian Ocean in which oxygen isotopic ratio ( $\delta^{18}\text{O}$ ) of foraminifera are determined. After accounting for temperature, the  $\delta^{18}\text{O}$  of sea water is determined; this is used to quantify past sea surface salinity (SSS) changes related to paleohydrological variability. For this purpose, accurate, region specific  $\delta^{18}\text{O}_{\text{SW}}$ -SSS relationships are required. Specifically, little data exists from the southern Indian Ocean and the adjoining Southern Ocean. Hence, earlier studies had given a single relationship for the Indian Ocean and the adjoining Southern Ocean. Due to the presence of different fronts in the Southern Ocean, the water mass characteristics change very rapidly so single relationship is not suitable. We carried out coupled measurement of  $\delta^{18}\text{O}_{\text{SW}}$  and SSS of seawater to determine specific relationship between them in different water masses of the Indian Ocean and the adjacent Southern Ocean. We further compiled our data with data from all the previous studies listed in the NASA GISS database to arrive at more representative  $\delta^{18}\text{O}$ -SSS relationships. This data set of  $\delta^{18}\text{O}_{\text{SW}}$  and salinity of surface ocean waters collected at every degree latitude during the 4<sup>th</sup> Indian Expedition to the Southern Ocean in the austral summer (January-February) of the year 2010 along a transect from India to Antarctica also helped to trace different hydrological processes active in the Indian and the Southern Ocean. The surface seawater samples were collected using a clean bucket, which was then transferred to 60 ml dry HDPE plastic bottles having a very low permeability to water vapor. The sea surface salinity was calculated using its conductivity, measured by a thermosalinograph (SeaBird Electronics Inc.; model name: SBE 45) installed onboard that uses the 1978 Practical Salinity Scale (PSS78) equations with a precision of  $\pm 0.003$  mS/cm. The resulting precision for salinity is  $\pm 0.005$ . The sea surface temperature (SST) was measured onboard using a bucket thermometer to a precision of  $\pm 0.5$  °C. The oxygen isotope values were measured in the Marine Stable Isotope Lab (MASTIL) at the National Centre for Antarctic & Ocean Research, Goa, India, using an Isoprime dual inlet stable isotope ratio mass spectrometer using the well established  $\text{CO}_2$  equilibration method. The reproducibility of the  $\delta^{18}\text{O}$  measurement is better than  $\pm 0.1\text{‰}$  ( $1\sigma$  standard deviation) as determined by repeated measurements ( $n=25$ ) of the lab standard, which is seawater from 52° 02' S and 57 32' E with  $\delta^{18}\text{O}$  value of  $0.18 \pm 0.05\text{‰}$  with respect to VSMOW. We identified distinct regions in the Indian Ocean and Southern Ocean (Clusters 1 to 5). Cluster 1 represents tropical samples (14° N to 7° N). The 2<sup>nd</sup> cluster shows samples from the northern equatorial and southern tropical Indian Ocean samples (7° N to 17° S). Cluster 3 depicts samples from the subtropical region of the southern hemisphere (24° S to 44° S). Cluster 4 represents Subantarctic/Polar Frontal Zone (44° S to 54° S) and Cluster 5 represents the Antarctic Zone (54° S to 68° S). We determine the relationship between  $\delta^{18}\text{O}$  and SSS pertaining to those distinct water masses by combining our data with those available at the NASA GISS data center. With the help of this relationship, a very clear signature of the domination of evaporation/precipitation process was seen near the tropical and subtropical zone (identified as cluster 1 and 2), while southern ocean (identified as cluster 3 and 4) shows a sea ice melting/freezing dominated zone. The data from the Antarctic Zone (identified as cluster 5) shows an increasingly dominant role played by sea ice melting/freezing. Based on coupled  $\delta^{18}\text{O}$  and SSS data, the signature of the Subtropical Front and Polar Front in the surface waters was observed at 44°S and 56°S, respectively. The last data point at 66.73°S is observed to be affected by continental ice derived melt water. Importantly, this study presents long term values for the  $\delta^{18}\text{O}$ -SSS slope for distinct water masses of the Indian and the Southern Ocean that will help to accurately determine the salinity contribution to oxygen isotopes of carbonates.



**S17 – 294 : Southern Ocean Paleoclimatology**

***Glacial-Interglacial Variability in Antarctic Sea-Ice Extent and Southern Ocean Frontal Systems***

Abhilash Nair<sup>1</sup>; Rahul Mohan<sup>1</sup>; M.C Manoj<sup>2</sup>; Meloth Thamban<sup>1</sup>

National Centre for Antarctic & Ocean Research, Vasco-da-Gama, Goa, India<sup>1</sup>; Birbal Sahni Institute of Palaeobotany, Department of Science and Technology, Lucknow, India<sup>2</sup>

Antarctic sea-ice extent along with Southern Ocean biological productivity varied considerably during glacial-interglacial periods, and both are known to have played a considerable role in regulating atmospheric CO<sub>2</sub> variations in the past. Here we present diatom abundance and their size records for the past ~ 74 ka from two sediment cores retrieved from north and south of polar front for the qualitative reconstruction of glacial-interglacial Antarctic sea-ice extent and Southern Ocean frontal systems. Down core sea-ice diatoms records from north and south of polar front displayed similar variability on a glacial-interglacial time scale, suggesting an increased winter sea-ice extent during glacial periods as opposed to interglacial periods. However, region south of polar front had sea-ice cover of longer duration as compared to the north of polar front during the last glacial maximum (LGM). Higher abundances of Permanent open ocean zone (POOZ) diatoms to the north of polar front during glacial periods indicates a possible northward shift of polar front thereby expanding the POOZ to the present core site. Whereas, the POOZ diatom abundance from south of polar front varied marginal for the last ~ 74ka B. P. However, a slight decrease in POOZ abundance was observed during the MIS 2 in comparison to MIS1, probably indicating decreased POOZ conditions due to the increased influence of Antarctic sea-ice. Down core variation of sub-Antarctic zone (SAZ) diatoms recorded higher abundances at the core site north and south of polar front during the last deglaciation which signifies a possible southward shift of Sub-Antarctic front thereby expanding the SAZ over the core sites. Our records of diatom absolute abundance (valves/g of sediments) suggest two modes of change in total diatom abundance during the last ~30 ka B. P. The higher total diatom abundance north of polar front during LGM as relative to MIS 1 is comparable to the glacial increase in opal and export productivity in Sub-Antarctic zone. This is primarily attributed to various mechanisms such as elevated dust flux, increased terrigenous input from the islands in the vicinity and northward shift of circum-upwelling or opal belt. Whereas, diatom's absolute abundance south of polar front barely shows an increase during LGM. The foremost explanation for such lower total diatom abundance during LGM is the presence of large winter sea-ice cover and stratified water column during the glacial periods. This might have prevented the rise in diatom productivity thereby reducing the diatom concentration in the sediments.



**S17 – 362: Southern Ocean Paleoclimatology**

***Neodymium (Nd) and Strontium (Sr) Isotopic Evidences for the Provenance and Transport Mechanism of Terrigenous Sediment in the Indian Sector of Southern ocean***

N. Lathika<sup>1</sup>; M. C. Manoj<sup>2</sup>; M. Thamban<sup>1</sup>; S.K.Singh<sup>3</sup>

National Centre for Antarctic and Ocean Sciences, Goa, India<sup>1</sup>; Birbal Sahni Institute Of Paleobotany, Lucknow, India<sup>2</sup>; Physical Research Laboratory, Ahmedabad, India<sup>3</sup>

Neodymium (Nd) and Strontium (Sr) isotope records of the terrigenous sediment fraction in two AMS <sup>14</sup>C dated sediment cores from the Indian sector of the Southern Ocean revealed changes in the source regions associated with glacial interglacial climate variations and transport pathways during the late Quaternary. The <sup>87</sup>Sr/<sup>86</sup>Sr and <sup>143</sup>Nd/<sup>144</sup>Nd in the Subantarctic core (SK200/22A) ranges from 0.705 to 0.707 and 0.51245 to 0.51266, respectively. The ε<sub>Nd</sub> records of the SK 200/22A and SK 200/27 cores varied between 0.4 to 3.7 and 0.2 to 5.3, respectively. The study revealed that the ε<sub>Nd</sub> values and Nd concentrations increased during MIS 2 at both core sites and the lowest values were present during the marine isotopic stages (MIS) 1, 3 and 5. The radiogenic isotopic composition of the detritus material in these cores were also compared and correlated with the proximal and distant potential source areas. The data can be explained with a binary mixing of particulates from the distant South Atlantic carried by Antarctic Circumpolar Current (ACC) and particulates derived from the proximal islands (Crozet, Marion, Prince Edward, Bouvet etc.). Wind driven erosion and bottom water processes can be considered as the two important mechanisms of detritus input and transport to the core site. Our data also suggest an increased delivery of the Patagonian dust particles to the study area during glacial periods through enhanced wind as well as ACC transport.



**S17 – 440: Southern Ocean Paleoclimatology**

***Changes in Coccolithophore Abundance in the Southern Atlantic during the Late Quaternary and its Paleoclimatic Significance***

Shramik M. Patil<sup>1</sup>; Sushant S. Naik<sup>2</sup>; Rahul Mohan<sup>1</sup>

National Centre for Antarctic and Ocean Research, Vasco-da-Gama, Goa, India<sup>1</sup>; National Institute of Oceanography, Goa, India<sup>2</sup>

The sub-Antarctic zone of the Atlantic sector is potentially important for glacial/interglacial CO<sub>2</sub> changes and is characterized by higher productivity during ice ages leading to lower atmospheric CO<sub>2</sub> and storage of carbon in the ocean interior. In this study, we utilize the ODP Site 1090 located in the sub-Antarctic zone, to reconstruct surface water conditions of southeast Atlantic during the late Quaternary. We discuss the contribution of coccolithophores to the production of calcium carbonate and their paleoecological significance. The highest coccolith diversity and abundance was recorded during the late Holocene followed by Last Glacial Maximum (LGM) and lowest during the last glacial termination. The decrease in coccolith diversity, increase in heavily calcified *Calcidiscus leptoporus*, *Gephyrocapsa* spp. and *Helicosphaera carteri* during the last glacial termination is attributed to intermediate to low nutrient conditions during this period. Further, the surface water stratification, productivity and coccolithophore dissolution index (CEX) for this region is calculated and discussed. A CEX calculated in this study based on dissolution behavior of *E. huxleyi* and *C. leptoporus* indicates deepening of coccolith lysocline from LGM to late Holocene period. The southward-northward shifts of oceanic frontal regions were judged based on occurrence of subtropical coccolith species at this site.



**S18 – 56: Paleoenvironmental changes in Antarctica and Southern Oceans since the last Glacial Maximum**

***Geochemical records from the Indian sector of Southern Ocean since the last glacial maximum and its palaeoclimatic linkages***

M. C. Manoj<sup>1</sup>; Thamban Meloth<sup>2</sup>

Birbal Sahni Institute of Palaeobotany, Lucknow<sup>1</sup>; National Centre for Antarctic and Ocean Research, Goa, India<sup>2</sup>

**Abstract:**

Paleoceanographic reconstruction based on high resolution geochemical proxy parameters in the sediment cores SK200/22a and SK200/27 from the Subantarctic front (SAF) and Polar front (APF) regime of the Indian sector of Southern Ocean depict variation in the deposition of terrigenous, biogenic materials and redox condition during the last 22,000 years. The records reveal significant glacial-interglacial as well as millennial scale changes in the deposition of biogenic and terrigenous materials existed at the APF compared to the SAF region. Supply of detrital materials to the cores sites has dominantly been attributed to glacial period and mainly influenced by bottom water processes and transport. The latitudinal and depth regimes of SK200/22a and SK200/27 also played a role in the temporal records of geochemical components. Terrigenous proxies like Al, Ti, Fe and K records in both cores show that increased terrigenous input during MIS 2 and must have sourced from diverse source areas and was ultimately controlled by the climatic fluctuations. The high terrigenous and biogenic (Ba/Al, Sr/Al, Ca/Al, Ni/Al, Cu/Al and Zn/Al) elemental concentration are most likely the result from a combination of high terrigenous supply and biological productivity. In the core SK200/22a, the high U/Al, Mo/Al, and Cd/Al observed during MIS 2, which supports the existence of suboxic bottom water during these intervals. Whereas at the deeper water depth core SK200/27, LGM period shows the low enrichment of redox sensitive elements like U/Al, Mo/Al, Cu/Al and Ni/Al suggest that strong redox conditions may not have associated with the late glacial sediments in deeper parts of the Southern Ocean. Enhanced terrigenous input and increased productivity, and oxic/redox conditions in the study area synchronously linked and the shifting of the ACC fronts and the variation in the deep water masses (NADW, CDW and AABW) during the glacial periods control the climatic variations at the core sites.



**S18 – 176: Paleoenvironmental changes in Antarctica and Southern Oceans since the last Glacial Maximum**

***Late Quaternary variability of an East Antarctic outlet glacier: Insights from sedimentary Beryllium-10 in Prydz Channel***

Michelle Guitard<sup>1</sup>; Amelia Shevenell<sup>2</sup>; Eugene Domack<sup>2</sup>; Brad Rosenheim<sup>2</sup>; Yusuke Yokoyama<sup>3</sup>

College of Marine Science, University of South Florida, USA<sup>1</sup>; College Of Marine Science, University Of South Florida, USA<sup>2</sup>; Atmosphere And Ocean Research Institute, University Of Tokyo, Japan<sup>3</sup>

Background: Ongoing retreat of Antarctica's marine based glacial systems is associated with the presence of warm (~2° C) modified Circumpolar Deep Water (mCDW) on Antarctica's continental shelves. This observation suggests that Southern Ocean temperatures may influence Antarctic ice sheet stability. Understanding how Antarctica's ice sheets respond to oceanic heat is important for developing accurate projections of sea level rise expected in a warming world. Ice proximal marine sediments from Antarctica's margins are essential for understanding the potential influences of ocean and atmosphere dynamics on cryosphere evolution.

Late Quaternary sediments are not often preserved on Antarctica's margins due to glacial advance and retreat cycles. However, records from this time interval are critical for reconstructing the Antarctic cryosphere's role in and response to climate variations interpreted from detailed ice core and deepsea sedimentary archives. Late Quaternary sediments are preserved in Prydz Channel, a cross shelf trough in Prydz Bay, East Antarctica, which was formed by a paleo ice stream associated with the Lambert Glacier Amery Ice Shelf (LG-AIS) system. This system presently drains ~15% of the East Antarctic Ice Sheet. However, preservation of Late Quaternary age sediments in Prydz Channel suggests that the LGAIS ice stream did not extend to the continental shelf edge during the Last Glacial Maximum.

Sediment cores collected on the United States Antarctic Program cruise NBP0101 contain an alternating sequence of siliceous mud ooze (SMO) and glacial marine sediments. Previous interpretations suggest that individual SMO units reflect either the presence of open water at the front of the LG-AIS system or sub-ice shelf advection of marine diatoms. Granulated sediments, sandy muds and silty clays suggest sub-ice shelf to ice proximal deposition. Foraminifer and ramped pyrolysis prepared bulk acid insoluble organic carbon AMS <sup>14</sup>C dating of Prydz Channel sediments suggest that these fluctuations of the LG-AIS system occurred during the Last Glacial Maximum and deglaciation (27 to 20 <sup>14</sup>C kyr).

Objectives: Resolving the depositional environment of the SMO units is central to reconstructing the past location of the LGAIS calving front, with important implications for East Antarctic Ice Sheet stability. This study reconstructs the Late Quaternary advance and retreat of the LGAIS system using the relative abundance of meteoric beryllium-10 (<sup>10</sup>Be) in Prydz Channel sediments. Meteoric <sup>10</sup>Be enters the surface ocean through direct atmospheric fallout or the release of sequestered isotopes from glacial meltwater. The nuclides adsorb onto clay particles and sink through the water column to the sea floor. The flux of <sup>10</sup>Be into the surface ocean is higher during periods of open water than those with permanent ice cover. Generally, sediments with high concentrations of <sup>10</sup>Be reflect Open marine conditions at the time of deposition, while sediments with lower <sup>10</sup>Be concentrations reflects periods of more persistent ice cover.

Methods: Three jumbo piston cores (JPCs) were collected during USAP cruise NBP01-01. Thirty three samples from the distinct sedimentary lithologies preserved in jumbo piston cores (JPCs) 34, 35, and 36 were analyzed for <sup>10</sup>Be. Sediments were freeze dried, homogenized, and, approximately 100 ppm of <sup>9</sup>Be carrier was added as a yield tracer to each ~100 mg sediment sample. <sup>10</sup>Be was then extracted from the silt to clay size fraction of carbonate free sediments using a total digestion procedure (HF/HCL/HNO<sub>3</sub>) and evaporated to dryness. Samples were re-dissolved in 0.5 M HCL and purified using cation exchange chromatography. Beryllium Hydroxide (Be(OH)<sub>2</sub>) was then precipitated with NH<sub>4</sub>OH at pH 9 and the cation



exchange step was repeated (3x). The resulting precipitate was fumed at 850°C to form a beryllium oxide (BeO) powder. The resulting product was analyzed by Accelerator Mass Spectrometry (AMS) at the Micro Analysis Laboratory, Tandem Accelerator, University of Tokyo.

Results: Prydz Channel Sedimentary  $^{10}\text{Be}$  concentrations, corrected for radioactive decay and production rate fluctuations, range from  $0.73 \pm 0.04 \times 10^8$  to  $14.6 \pm 0.22 \times 10^8$  atoms  $\text{g}^{-1}$ . In the SMOs,  $^{10}\text{Be}$  concentrations range from  $4.88 \pm 0.09 \times 10^8$  to  $14.6 \pm 0.22 \times 10^8$  atoms  $\text{g}^{-1}$  and there is an increase in  $^{10}\text{Be}$  abundance upcore.  $^{10}\text{Be}$  concentrations become progressively lower in the transitional to glacial facies, ranging from  $0.73 \times 10^8 \pm 0.04$  to  $2.12 \times 10^8 \pm 0.05$  atoms  $\text{g}^{-1}$ , which suggests correspondence between  $^{10}\text{Be}$  and lithology.

Conclusions: Within Prydz Channel, there is a correlation between sedimentary lithologies and  $^{10}\text{Be}$  concentrations. The SMO units generally exhibit higher  $^{10}\text{Be}$  concentrations relative to glacial proximal sediments. The general increase in  $^{10}\text{Be}$  concentrations in younger SMOs suggests increased delivery of  $^{10}\text{Be}$  to the sediment, likely as a result of retreating ice. We interpret higher relative  $^{10}\text{Be}$  concentrations as periods of open water in Prydz Channel. Our results support previous studies that correlate  $^{10}\text{Be}$  concentration to depositional environment in the Ross Sea and demonstrate  $^{10}\text{Be}$  can also be utilized in East Antarctic margin sediments. Lithologic and relative  $^{10}\text{Be}$  abundance variations in Prydz Channel SMOs imply larger scale fluctuations in the LG-AIS system during the LGM and deglaciation. This variability within the largest marine based East Antarctic outlet glacier system suggests that the East Antarctic Ice Sheet is not as stable as traditionally viewed, even during periods of ice retreat. Furthermore, this variability occurred prior to sea level rise associated with deglacial meltwater pulses. Although the driver of recent LG-AIS thinning and retreat is unknown, the observed retreat of marine based glaciers concurrent with upwelling of mCDW supports the hypothesis that ocean temperatures influenced past ice shelf and marine based outlet glacier stability.



**S18 – 186: Paleoenvironmental changes in Antarctica and Southern Oceans since the last Glacial Maximum**

***Vulnerability of the Lambert Glacier Amery Ice Shelf System during deglaciation***

Amelia Shevenell<sup>1</sup>; Michelle Guitard<sup>2</sup>; Dr. Eugene Domack<sup>2</sup>; Dr. Brad Rosenheim<sup>2</sup>

University of South Florida College of Marine Science, USA<sup>1</sup>; USF College of Marine Science, USA<sup>2</sup>

Ice proximal marine sediments from Antarctica's continental margins contain unique near field information about the timing and response of glacial systems to climate forcings not available from ice core and deep-sea sedimentary archives. Understanding the Quaternary response of Antarctica's glaciers to such forcings (e.g., ocean temperature) depends on 1. The preservation of Quaternary sediments on Antarctica's continental shelves and 2. a robust chronology. Prydz Channel, in Prydz Bay, East Antarctica, was carved by a fast flowing paleo-ice stream that was last grounded at the shelf edge at ~750 ka before it collapsed and rapidly retreated. Geomorphologic evidence for ice stream retreat is muted landward by a ~10 meter late Quaternary drape of alternating hemipelagic and ice-proximal siliciclastic sediments. Based on bulk acid insoluble organic matter (AIOM) <sup>14</sup>C ages, the sequence records the late Quaternary (>50 ka) variability of the Lambert Glacier Amery Ice Shelf (LGAIS) system, a large marine-based outlet glacier system that drains 15% of the East Antarctic Ice Sheet. Thus, the Prydz Channel sedimentary sequence provides a unique opportunity to investigate the timing and potential oceanic forcings of late Quaternary East Antarctic Ice Sheet variability and retreat. Chronologic control in Antarctic margin sediments is complicated by poor calcium carbonate preservation.

To circumvent this difficulty in late Quaternary to Recent sediments, radiocarbon (<sup>14</sup>C) dates are often obtained from bulk AIOM. However, the potential for organic carbon to derive from multiple sources of different ages complicates glacial marine AIOM based chronologies and often results in an average AIOM <sup>14</sup>C age that is hundreds to thousands of years older than the deposition age. The recently developed ramped pyrolysis/oxidation (Ramped PyrOx; RP) preparation technique may improve AIOM-based Antarctic margin <sup>14</sup>C chronologies by exploiting differences in the thermochemical stability of different pools of organic carbon in glacial marine sediments. Radiocarbon analyses of multiple carbon aliquots from a single sedimentary horizon reveal that low temperature RP <sup>14</sup>C ages are younger than bulk AIOM ages by as much as 10,000 years.

In this study, we employ the RP method to develop a detailed <sup>14</sup>C chronology for the Prydz Channel sedimentary sequence. Such a chronology is the first step towards understanding the mechanisms forcing LGAIS variability and retreat during the late Quaternary.

We prepared and dated twelve glacial marine sediment samples from a variety of facies recovered in three jumbo piston cores (JPCs) collected in Prydz Channel on USAP cruise NBP0101. Sediments were freeze dried, homogenized, acidified in 2N HCl, rinsed with DI water to a pH of ~7, and dried at 65°C. For RP, ~100 to 300 mg of sediment was placed into a pre-combusted quartz reactor tube and pyrolyzed using a smooth 5° C/min ramp. The evolved CO<sub>2</sub> was collected sequentially at five intervals of approximately 1015 mol. Intervals were determined by the total CO<sub>2</sub> concentration of the sample, which is related to the total amount of organic carbon in the sample and the overall thermochemical stability of the major constituents. Each CO<sub>2</sub> aliquot was cryogenically separated from water and non-condensable gases, sealed into borosilicate glass tubes with pre-combusted copper oxide and silver wire, re-combusted, and submitted for AMS <sup>14</sup>C analysis at Lawrence Livermore National Laboratory. Radiocarbon ages were corrected for blank contamination using published methods, resulting in uncertainties of ±100 to ±300 <sup>14</sup>C years.



Each  $^{14}\text{C}$  date was then converted to calendar age using Calib 7.1, the Marine13 calibration curve, and a constant regional reservoir correction of 1300 years. A chronology for the Prydz Channel sequence was then developed using the Bacon Bayesian age depth modelling software.

We generated 24 AIOM AMS  $^{14}\text{C}$  dates from low and high temperature RP aliquots. Radiocarbon ages from high temperature aliquots range from  $7.1 \pm 40$  to  $38.7 \pm 1700$   $^{14}\text{C}$  kyr, while those from low temperature aliquots constrain the age of the Prydz Channel sequence to between  $5.3 \pm 35$  and  $26.8 \pm 1000$   $^{14}\text{C}$  kyr. Low temperature RP ages improve the accuracy of the Prydz Bay chronology by 2 to 15  $^{14}\text{C}$  kyr. Smaller improvements upon bulk AIOM  $^{14}\text{C}$  are associated with hemipelagic siliceous mud and ooze (SMO) intervals, while larger improvements are associated with lithologies containing more terrigenous provenance, suggesting a higher relative proportion of old authochthonous carbon in these intervals. Sedimentation rates are high ( $\sim 37$  cm/kyr) between 27 and 20  $^{14}\text{C}$  kyr and decline upsection. SMO intervals, indicative of open water conditions in Prydz Channel, are centered at  $\sim 5$ , 20, 25, and 27  $^{14}\text{C}$  kyr with an average error of  $\pm 470$  kyr.

The RP technique significantly improves the bulk AIOM-based late Quaternary chronology in Prydz Channel, providing support for the method's utility in East Antarctic margin sediments. High sedimentation rates between 27 and 20  $^{14}\text{C}$  kyr reflect the proximity of the LGAIS grounding line to the Prydz Channel sites, while the three SMO units suggest periods of open water that may reflect variations in the position of the LGAIS calving front during the LGM. The timing of marine-based LGAIS variability and retreat is coincident with regional terrestrial glacial thinning as well as millennial-scale warm events recorded in Antarctic ice cores. The RP-based chronology indicates that variability of the LGAIS system precedes Meltwater Pulse 1a. This observation suggests that forcings other than sea level rise contributed to deglaciation in Antarctica. Given the observed vulnerability of key marine-based Antarctic glacial systems to incursions of warm modified Circumpolar Deep Water onto the continental shelf via cross shelf troughs, it seems likely that such a process played an important role in late Quaternary variability and retreat of East Antarctic outlet glaciers.



**S18 – 206: Paleoenvironmental changes in Antarctica and Southern Oceans since the last Glacial Maximum**

***Pelagic sedimentation and paleoenvironment of Pliocene radiolaria from Leg 119 Site 745, Southern Ocean region***

**Deepak Dayal**<sup>1</sup>, G.K. Sharma<sup>1</sup>

Department of Geology, Kumaun University, Nainital, India<sup>1</sup>

This work presents detail investigation of Pliocene radiolaria from the Antarctic region. Significant assemblage of radiolarians were recovered from thirty nine samples of three sections (12H to14H) from Leg119 Site 745 of the Kerguelen Heard Plateau in the Southern Ocean region. The study area is located on a large sediment drift at the base of the Southern slope of the Kerguelen Plateau at 59°35.71'S and 85°57.60'E. The samples were collected at a water depth of 4082.5 meters. The interval between the samples are 1.5 meters but varies if lithology changes. The total length of the studied core is 28.02 m and composed of diatom ooze along with radiolaria in traces. Lithostratigraphically, the sections lie in the subunits IB only.

**Background:**

Ehrenberg (1844b) began the study on Southern Ocean radiolarians by describing 20 species from Antarctic sector of the Indian Ocean. Haeckel (1887) and Haecker (1908) primarily dealt with radiolarian systematics of the Southern Ocean region. Caulet (1991) included 2 new genera and 17 new species from the Neogene of the Kerguelen Plateau. Lazarus (1992) reported on Neogene Radiolaria from ODP legs 119 and 120. Sharma et al. (2004) presented first comprehensive account of Pleistocene radiolarians from the Tasman region. They identified and described 83 radiolarian species and encountered few new taxa. Sharma et al. (2006) established two radiolarian zones namely the Chi and Psi from this region. Sharma and Takahashi (2007) recognized the Chi zone which is further subdivided into lower and upper subzones of the Pleistocene sequence of Antarctic region. Sharma and Bora (2006, 2007, 2009) presented the detail work on Pliocene - Pleistocene radiolarian systematics, Biostratigraphy and distribution in the leg 119 site 745.

**Objectives:**

To identify the radiolarian species along with the taxonomic and illustration for each of the taxa. To interpret the temporal distribution of radiolarian species in the studied sequence. To study the nature of assemblage and paleoceanographic setting of the region.

**Methods:**

About 34 g of sediment was first disaggregated in dilute hydrogen peroxide for 12 hours, followed by heating to just below the boiling point. One teaspoonful of Calgon (R) was added to further disaggregate the samples and complete the treatment. The sample was then sieved through a 63 μ mesh stainless sieve. The strewn slides were prepared by using an eyedropper and Canada balsam as a mounting medium.

**Results and Conclusion:**

It is observed that deposition at this site was essentially of a mixed siliceous pelagic terrigenous character with no carbonate accumulation. Further, most of the time interval, the sections represents sedimentation which was essentially dominated by diatoms ooze and clay with a significant quartz, feldspar and silt



component. The sedimentary structures are poorly developed and most of the stratification appears to be of diagenetic origin. Although, the presence of bioturbation is evident and is of diffuse nature in the studied samples. Further, the sections show alternations of more or less clay rich zones. These clay rich zones when plotted against depth show distinct cyclicity from glacial to interglacial which could have occurred. This cyclicity was further confirmed by the presence of abundant radiolaria i.e. *Cycladophora davisiana*. It is interpreted that the high productivity of opal silica/radiolaria are accumulated near south of the polar front of this region.



**S18 – 231: Paleoenvironmental changes in Antarctica and Southern Oceans since the last Glacial Maximum**

***Dynamic response of Antarctica Ice Shelves to bedrock uncertainty***

John Moore

College of Global Change and Earth System Science, Beijing Normal University, China

Bedrock geometry is an essential boundary condition in ice sheet modelling. The shape of the bedrock on fine scales can influence ice sheet evolution, for example through the formation of pinning points that alter grounding line dynamics. Here we test the sensitivity of the BISICLES adaptive mesh ice sheet model to small amplitude height fluctuations on different spatial scales in the bedrock topography provided by bedmap2 in the catchments of Pine Island Glacier, the Amery Ice Shelf, and a region of East Antarctica including the Denman and Totten Glaciers. We generate an ensemble of bedrock topographies by adding random noise to the bedmap2 data with amplitude determined by the accompanying estimates of bedrock uncertainty. We find that the small amplitude fluctuations result in only minor changes in the way these glaciers evolve. However, low frequency coherent noise generates broad spatial scale (10s of km) errors in topography with relatively gently slopes are more important than higher frequency noise having steeper slopes over smaller spatial scales even when the features have the same height amplitudes and the total noise power is maintained. This provides optimism for credible sea level rise estimates with presently achievable densities of thickness measurements. Pine Island Glacier appears the most sensitive to errors in bed topography, while Lambert Amery is stable under the present day observational data uncertainty. Totten Denman region may undergo a retreat around Totten ice shelf, where the bedrock is lower than the sea level, especially if basal melt rates increase.



**S18 – 255: Paleoenvironmental changes in Antarctica and Southern Oceans since the last Glacial Maximum**

***Decoding geochemical signals in Antarctic corals: paleoceanographic proxies of Southern Ocean water masses***

Paolo Montagna<sup>1,2</sup>; Malcolm McCulloch<sup>3</sup>; Alessandro Remia<sup>2</sup>; Stefano Schiaparelli<sup>4</sup>; Marco Taviani<sup>2</sup>; Julie Trotter<sup>3</sup>

Institute of Marine Sciences<sup>1</sup>; CNR-ISMAR, U.O.S. Bologna, Via Gobetti 101, 40129, Bologna, Italy<sup>2</sup>; School Of Earth & Environment, University Of Western Australia, Fairway Entry 1, Crawley WA 6009 Australia<sup>3</sup>; Department Of Earth, Environmental And Life Sciences (DISTAV), University Of Genoa, Genoa, Italy<sup>4</sup>

Attempts to decipher the role of the high latitude Southern Ocean in modulating past climate have been particularly difficult due to the paucity of calcium carbonate precipitating organisms, the skeletons of which can be used as archives of environmental change. The waters south of the Polar Front are under saturated with respect to aragonite and calcite, thereby strongly limiting carbonate accumulation and preservation.

Cold-water corals are one of the few calcifying organisms that can cope with corrosive undersaturated environments and thus are good candidates for reconstructing seawater conditions at a range of temporal scales. Geochemical tracers of the physical and chemical properties of deepwater masses may be encoded within their banded calcareous skeleton, potentially providing centennial records at subdecadal resolution. However, the geochemical composition of coldwater corals can be complicated and difficult to interpret because elemental uptake is often biologically mediated, thereby requiring additional knowledge of coral microstructure and the mechanisms controlling elemental incorporation during calcification.

Scleractinian corals are common within Antarctic intermediate to deepwater benthic communities, but only occur as solitary cup corals. We have selected *Flabellum impensum* for our pilot study because previous studies suggest that this genus is a reliable paleoclimate archive. The two most common extant cup corals in Antarctica, *Caryophyllia antarctica* and *Gardineria antarctica*, which also occur in late Pleistocene and Holocene uplifted deposits, are other potential candidates for similar geochemical studies. Under the umbrella of the PNRA GEOSMART project, modern specimens of *Flabellum impensum* from the Ross Sea were analysed for Li/Ca, B/Ca, Sr/Ca, Ba/Ca and U/Ca ratios, using a laser ablation inductively coupled plasma mass spectrometer (LA-ICPMS). This high resolution geochemical study reveals that most elemental variations along the marginal thecal wall may result from different minor and trace element compositions of different microstructural components, such as the early mineralization zones and fibrous aragonite. Compared to the fibrous aragonite, the early mineralization zones show depleted concentrations of U, B, Ba, and to a lesser degree Sr, as well as an enrichment of Mg and Li, which is likely due to the higher calcification rate within the early mineralization zones.

There is a high degree of reproducibility for most of the elements between adjacent tracks in almost all the coral specimens. These consistent trends likely reflect environmental controls on the uptake of minor and trace elements into the aragonite skeleton, suggesting that *Flabellum impensum* is a promising paleoclimate archive. However, the geochemical variation exhibited by most of the elements, especially along the thecal wall, is too large to be solely attributed to ambient seawater conditions (e.g. near constant physical and chemical parameters). Despite the common general trend between different tracks within the same specimen, some portions of the laser transects are discrepant, implying additional mechanism/s influence the incorporation of minor and trace elements into the skeleton. In particular, Sr/Ca, Mg/Ca and B/Ca, commonly considered as temperature dependent in shallow water corals, show amplitudes roughly comparable to the tropical zooxanthellate corals. However, we found that the septal face of *Flabellum impensum*, which is composed only of fibrous aragonite, displays a more uniform



geochemical composition, with the amplitude of the element variations being consistent with environmental fluctuations. These results suggest that this fibrous portion is most suitable for deriving paleoclimate information and hence the vital effects can be avoided by using careful sampling techniques.



**S18 – 313: Paleoenvironmental changes in Antarctica and Southern Oceans since the last Glacial Maximum**

***Open marine sedimentation in the south-western Ross Sea during the Last Glacial Maximum***

Lee, J.I.<sup>1</sup>; Yoon, H.I.<sup>1</sup>; Yoo, K.C.<sup>1</sup>; Moon, H.S.<sup>1</sup>; Domack, E.<sup>2</sup>; Rosenheim, B.E.<sup>2</sup>; Subt, C.<sup>2</sup>

Korea Polar Research Institute, Korea <sup>1</sup>; University of South Florida, USA <sup>2</sup>.

Growing evidence suggests that the Antarctic ice sheet may not have been in its maximum extent during the Last Glacial Maximum (LGM). Recent radiocarbon results imply that the West Antarctic Ice Sheet (WAIS) retreated from the eastern Ross Sea prior to LGM. In the western Ross Sea, however, it was generally considered that a thick ice sheet was grounded to the sea floor during the LGM and the retreat of that ice sheet did not begin until ~13 ky B.P. Here we show evidence that the ice sheet retreated not only from the eastern Ross Sea but also from the western Ross Sea during the LGM, and then the latest ice sheet advanced into the western Ross Sea, followed by the final retreat. Diatomaceous mud layers underlie stratified diamicton in the southern Drygalski Trough, indicating a seasonally open marine sedimentation prior to the last glacial event in the western Ross Sea. Ramped PyrOx radiocarbon dating of this diatomaceous mud shows that ice sheet on the western Ross Sea retreated at ~24 ky B.P, and advanced at ~21 ky B.P. In order to preserve the diatomaceous mud, we infer that the most recent advance featured a thinner ice sheet than the previous advance.

Multibeam swath bathymetry and subbottom profile data show that the latest ice sheet in the southern Drygalski Trough retreated to the northwest. The flow direction suggests that (1) the latest ice sheet in the SW Ross Sea was the East Antarctic Ice Sheet (EAIS) advanced through the Transantarctic Mountains and (2) the WAIS that can deflect the flow direction to the north did not advance into the study area during the final retreat. The WAIS either retreated much earlier than the EAIS or did not advance into the SW Ross Sea during the last glacial event.



**S18 – 349: Paleoenvironmental changes in Antarctica and Southern Oceans since the last Glacial Maximum**

***Antarctic and Arctic Sea Ice changes during the Holocene and Eemian from Model Simulations***

Mokhov I.I.<sup>1</sup>; Khon V.C.<sup>1</sup>

A.M. Obukhov Institute of Atmospheric Physics RAS<sup>1</sup>

Changes in the Antarctic and Arctic sea ice extent during the Holocene and Eemian warm climate periods from model simulations are analyzed. In particular, long-term simulations with the Kiel climate model were analyzed for different orbital configurations with orbitally induced changes in insolation, including three Eemian (126, 122, 115 ka BP) and three Holocene (9, 6, 0 ka BP) conditions. Differences in Antarctic and Arctic the sea ice changes are discussed. Substantial increase of the Antarctic sea ice extent was obtained for the early Holocene (9 ka BP) and Eemian (126 ka BP) in the austral summer and autumn (from January to May) without significant changes for other months. The Arctic sea ice extent demonstrates stronger seasonal cycle at the early Holocene in comparison to that simulated for preindustrial period. Obtained results are consistent with simulated increase/decrease in insolation over the Northern/Southern Hemisphere during the early Holocene and Eemian relative to preindustrial period.



**S18 – 378: Paleoenvironmental changes in Antarctica and Southern Oceans since the last Glacial Maximum**

***Reconstruction of the East Antarctic deglaciation since LGM: evidence from geomorphology of the Sør Rondane Mountains, Dronning Maud Land***

Yusuke Suganuma<sup>1</sup>; Hideki Miura<sup>1</sup>; Albert Zondervan<sup>2</sup>; Jun'ichi Okuno<sup>1</sup>

National Institute of Polar Research, Japan<sup>1</sup>; Institute of Geological and Nuclear Sciences (GNS) Science, New Zealand<sup>2</sup>

While it is broadly accepted that the Antarctic ice sheets play a major role in the Earth's global climatic system, many questions remain due to the multitude of processes and timescales involved. Reconstructing past variability of the Antarctic ice sheets is essential to understand their stability and to anticipate their contribution to sea level change as a result of future climate change in a high CO<sub>2</sub> world. Especially, the nature of the glacio-eustatic rise following the Last Glacial Maximum (LGM), including the extremely rapid sea-level rise event Meltwater pulse 1A (MWP1A), remains elusive. The current lack of data from East Antarctica, especially Dronning Maud Land, makes it difficult to estimate the location(s) of melting ice responsible for this prominent feature of the last deglaciation. In this study, we reconstruct magnitude and timing of ice sheet retreat at central part of the Sør Rondane Mountains in Dronning Maud Land, East Antarctica, based on detailed geomorphological survey and cosmogenic exposure dating. The data show since the Last Glacial Maximum the ice surface has lowered less than ca.50 m and probably started after ca. 14 ka. This suggests that the EAIS in Dronning Maud Land is unlikely to have been a major contributor to postglacial sea-level rise and Meltwater pulse 1A.



**S18 – 396: Paleoenvironmental changes in Antarctica and Southern Oceans since the last Glacial Maximum**

***Was South Georgia ice free during the Last Glacial Maximum?***

Duanne White

University of Canberra, Australia

Reconstruction of past landscape changes, particularly in glacial environments, requires techniques for mapping the age of sediments and landforms preserved in the terrestrial environment. Cosmogenic exposure age dating is presently the gold standard in many cases, but is time consuming and expensive, so difficult to apply on a landscape scale. Further, results are only known long after returning from a field campaign, and repeat sampling to follow up unexpected results is especially problematic in logistically difficult sub-Antarctic regions. A range of field based relative dating techniques have been used to fill this void, such as lichenometry, soil development and landscape relaxation. However, many of these techniques are difficult to apply systematically across a range of geomorphic environments and timescales in the sub-Antarctic. For example, the rate of soil development is strongly influenced by nutrient and habitat gradients that vary strongly with elevation and/or slope, and lichen sizes do not appear to increase beyond the last few hundred years in many sites. New data using Schmidt hammer rebounds suggest it has the potential to be a robust and widely applicable relative dating tool in sub-Antarctic environments. Results from South Georgia Island indicate that for stable landscapes, it is broadly applicable across a range of altitudes and geomorphic environments. Further, initial results from the application of this technique on outer Lewin Peninsula, South Georgia Island, suggest that the 600 m high peaks on were covered by ice around the time of the last global glacial maximum, c. 2030 ka BP. If validated by absolute dating techniques, this would imply substantively greater ice coverage than presently assumed at this time for South Georgia, and perhaps other sub-Antarctic islands.



**S18 – 470: Paleoenvironmental changes in Antarctica and Southern Oceans since the last Glacial Maximum**

***Antarctic contribution to Meltwater Pulse 1A new deglacial perspective and implications for future sea-level rise***

Weber ME<sup>1</sup>; Clark PU<sup>2</sup>; Lohmann G<sup>3</sup>; Gladstone R<sup>4</sup>; Mitrovica JX<sup>5</sup>; Sprenk D<sup>1</sup>; Timmermann A<sup>6</sup>; Ohlwein C<sup>7</sup>; Menviel, L<sup>8</sup>

Institute of Geology and Mineralogy, University of Cologne, Germany<sup>1</sup>; College Of Earth, Ocean, And Atmospheric Sciences, Oregon State University, Corvallis, U.S.A.<sup>2</sup> Alfred-Wegener Institute Helmholtz Center for Polar and Marine Research, Bremerhaven, Germany<sup>3</sup>; Arctic Centre, University Of Lapland, Rovaniemi, Finland<sup>4</sup>; Department Of Earth And Planetary Sciences, Harvard University, Cambridge, U.S.A.<sup>5</sup>; School Of Ocean And Earth Sciences And Technology, University Of Hawaii, Honolulu, U.S.A.<sup>6</sup>; Meteorological Institute, University Of Bonn, Bonn, Germany<sup>7</sup>; Climate Change Research Centre, Centre Of Excellence, University Of New South Wales, Sydney, Australia<sup>8</sup>

The response of the Antarctic Ice Sheet (AIS) to past climate changes was based on only a few near-field sediment sequences, which limited our understanding of the dominant feedbacks between the AIS, Southern Hemisphere and Northern Hemisphere climate, and global sea level. Most shallow marine and terrestrial Antarctic sequences cannot be dated adequately, reveal only the final stage of ice retreat, or resolve only local responses to climate forcing, leaving much room for speculation on what happened on a continental scale.

Here, far-field records from the Scotia Sea advance our knowledge substantially and revise our current understanding of ice-sheet dynamics for three reasons. First, the sites can be precisely dated using well-established couplings of atmospheric dust as time markers between Antarctic ice cores and deep ocean cores (Weber et al. 2012, Quaternary Science Reviews). Second, the sites contain a very long, continuous, and detailed record of deglaciation. Third, the sites are located in the center of Iceberg Alley, where the majority of icebergs are routed, after calving from the Antarctic margin (Stuart and Long 2011, Deep-Sea Research II) and travelling counter-clockwise around Antarctica within the Antarctic Coastal Current. Melt rates remain low until the warmer Antarctic Circumpolar Current is reached, after which icebergs ablate rapidly in the study area. Marine records of iceberg-rafted debris have been widely used to reconstruct variability in Northern Hemisphere ice sheets, but comparable records from the Southern Ocean of the AIS were previously lacking. The Scotia Sea sites fill this gap. Since icebergs account for ~half of the total Antarctic ice mass loss (Depoorter et al. 2013, Nature), iceberg-rafted debris provides a nearly continuous signal of ice-sheet dynamics and captures and integrative signal of Antarctic ice mass loss (Weber et al. 2014, Nature).

The sediment record from Iceberg Alley indicates, for the first time, multiple phases of enhanced iceberg routing during the last deglaciation that commenced abruptly (within a decade!) and lasted from centuries to a millennium. These periods are termed Antarctic Ice-sheet Discharges (AID) 8 to 1. AID8 occurred during (~19 – 20 ka) the initial deglaciation, likely in response to Northern Hemisphere deglaciation and associated with far-field sea-level forcing (Weber et al., 2011, Science). It is synchronous with Meltwater Pulse 19 ka. AID7 occurred ~17 – 16 ka and is accompanied by beginning Antarctic temperature rise and sea-ice retreat, while the Northern Hemisphere experienced cold conditions during Heinrich Event 1. Southward shifting Southern Hemisphere westerlies and/or retreating sea ice increased primary production, leading to enhanced opal accumulation of in the Scotia Sea and elsewhere in the Southern Ocean. Increased upwelling of carbon-rich deep waters may have released additional CO<sub>2</sub> to the atmosphere (Schmitt et al. 2012, Science), which may have further amplified warming. We hypothesize that AID7 represents the turning point for Southern Hemisphere climate after the last Ice Age and that it is of key importance to reconstruct Antarctic deglacial history.



AID6 (~15 – 13.9 ka) constitutes the peak of deglaciation. The largest flux of iceberg rafted debris occurred 14.76 – 14.4 ka, providing the first direct evidence for an Antarctic contribution to Meltwater Pulse 1A (14.65 – 14.31 ka), the single largest sea-level rise of ~16 m in ~350 years at the onset of the first warm period in the Northern Hemisphere, the Bølling-Allerød at ~14.65 ka (Deschamps et al. 2012, *Nature*). The next four iceberg-rafted debris events (AID5-AID2) are of similar amplitude and duration to each other, and show a pacing of ~800 – 900 years. AID2 attained its peak iceberg-rafted debris flux at ~11.3 ka, which corresponds to the age of MWP-1B recorded at Barbados, for which the magnitude of sea-level rise is unclear (Bard et al. 2010, *Science*). The final slowdown in sea-level rise occurred 8 – 7 ka, after AID1.

Previous scenarios identified the main AIS retreat as occurring after Meltwater Pulse 1A and continuing into the late Holocene (e.g., Bentley et al. 2010, *Geology*; Mackintosh et al. 2011, *Nature Geoscience*). However, given the vast size of the continent and the little accessibility for sampling, any of the near-field studies will contain large uncertainties and little data constraining them to reconstruct ice recession on a continental scale. Moreover, Weber et al. (2011, *Science*) challenge these scenarios and indicate that the advance to (at 29 –28 ka) and retreat from (at 19 ka) the maximum extent of AIS was nearly synchronous with Northern Hemisphere ice sheets. Finally, the highly dynamic AIS disintegration record from Iceberg Alley for which the major characteristics are reproduced by independent simulations of Golledge et al. (2014, *Nature Communications*), tells a very different story and indicates that Antarctic deglaciation accelerated at ~17 ka, peaked at Meltwater Pulse 1A around 14.5 ka, and declined thereafter until ~8 ka.

Deciphering past sea-level changes is key to understanding current and future climate change. Here, the role of the AIS is crucial, yet poorly understood, because AIS collapse in a warming world leads to rapid sea-level rise. West Antarctica may now be locked in an irreversible collapse caused by human warming (Rignot et al. 2014, *Geophysical Research Letters*). Also, Mengel and Levermann (2014, *Nature Climate Change*) simulate that the marine-based Wilkes Land region could also collapse and discharge ice for centuries to millennia.

Despite the mounting evidence for present-day and future ice-sheet instability in Antarctica, and increasing concerns about global sea-level rise, there has previously been no example of past instability that could resolve the timing, magnitude, source, and related processes of ice-sheet collapse events in Antarctica, all of which are essential to provide sound projections for the future course of the AIS. Our recent findings in Iceberg Alley demonstrate, for the first time, that eight collapses occurred during the last natural climate transition, and lasted for centuries to millennia. Therefore, we need to be concerned that we are currently facing another AIS collapse that will again last for centuries and lead to higher sea-level rise than currently projected by the Intergovernmental Panel on Climate Change (Church et al. 2013, IPCC 5th Assessment Report).



**S18 – 476: Paleoenvironmental changes in Antarctica and Southern Oceans since the last Glacial Maximum**

***The early middle Holocene of Adélie land (East Antarctic margin): a high resolution record from IODP site U1357.***

Jimenez Espejo F.<sup>1</sup>; Etourneau J.<sup>2</sup>; Dunbar R.<sup>3</sup>; Escutia C.<sup>4</sup>; Salabarnada A.<sup>4</sup>; Yamane M.<sup>5</sup>; Ohkouchi N.<sup>1</sup>; Crosta X.<sup>2</sup>; Yokoyama Y.<sup>5</sup>; Gutierrez Pastor, J.<sup>4</sup>

Depart. Biogeochemistry, JAMSTEC, Yokosuka, Japan<sup>1</sup>; EPHE, UMR 5805 EPOC, University Of Bordeaux, Talence, France<sup>2</sup>; Stanford University, Stanford, USA<sup>3</sup>; IACT, CSICUGR, Armilla, Granada, Spain<sup>4</sup>; Atmosphere And Ocean Research Institute, University of Tokyo, Japan<sup>5</sup>

The East Antarctic Ice Sheet (EAIS) has long been viewed as very stable, but recent works doubt on this view. In this sense, the role of Antarctica during the last deglaciation and Holocene and its contribution to the melt water pulses and major climate variations during this period remains poorly known. This poor knowledge is related with the complex shelf sedimentation, low sedimentation rates, large reservoir age and dating problems among others. In order to reconstruct in detail the last deglaciation paleoenvironmental changes in EAIS domain we selected marine site U1357 and applied a wide range of geochemical, paleontological and sedimentological techniques. This site was recovered from the Terre Adélie margin during the IODP Expedition 318 contain an unique ~200 m sequence of likely annually layered sediments of the Holocene for at least the past 11 ky. The laminated sediments consist predominantly of diatom and radiolarian remains and cyclic coarse detrital layers in the lowermost part. Geochemical studies have been conducted on cores from holes U1357A and B at ultrahigh (seasonal to decadal) resolution using X-Ray Fluorescence scanning, allowing reconstruction of detrital input, paleoproductivity and redox conditions. The ratio of the concentrations of highly branched isoprenoid (HBI) diene/triene (D/T), a diatom specific biomarker, also has been used as a proxy for relative inputs of sea-ice algae and open water phytoplankton that gives indication on past sea-ice cover. The use of CT scanner allowed to characterize at high detail the presence and relationship between iceberg raft debris, silty layers and the biogenic lamination. Aluminium perfect correlation between lamination and geochemical changes, indicate that XRF Scanner is an appropriate instrument for this mainly biogenic sediments. In general: Dark colour lamina indicates high detrital content and light colour is associated to low detrital content and higher diatom presence. Changing relations between elements point to a complex sedimentation process during certain intervals. U/Th (redox conditions) and Ti/Al ratio (detrital input) are sensitive to major Holocene climate variations recognized In the Antarctic climatic realm (e.g., Hypsithermal 1 and 2 and Neoglacial).

Deepest levels (between 176 to 185 mbsf), associated with deglaciation, are characterized by the presence of E. Antarctica spores with values >15%. This diatom indicates strong water column stratification. High values in D/T and ice sea proxy species (e.g. Fragilariopsis curta + F. cylindrus) indicate abrupt variations in sea-ice during this interval and shows a good correlation with bottom redox proxies (U/Th), pointing to lower oxygen availability when sea-ice is present. Comparison between CTScan images and geochemical data demonstrate that the intervals with high Ba/Al and Si/Al are associated to poor detrital levels (Fig. 2), allowing to use these ratios along the entire core as detrital/paleoproductivity proxies. CT Scan images also corroborate an erosional character for these silty layers. Detrital proxies (e.g., Zr content) are anticorrelate respect to bottom redox conditions proxies (U/Th), pointing to well oxygenated deep waters as generator for silty layers. All these preliminary evidences allow us to recognize an unprecedented high resolution ice fjord like sequence in the studied region with strong water column stratification and pulsational detrital input acting as a main forcing for environmental variations. Ongoing radiocarbon analysis, performed in the bulk fraction and also in compound-specific, will allow us to recognize timing, cycles and if major variations occurred in the reservoir age during the deglaciation. After this fjord-like environment preliminary data indicate less stratified waters and silty layers almost disappear. Detrital proxies (e.g., Ti content) are associated only to



summer conditions and allow distinguish multiannual lamination. Preliminary interpretations based on diatoms analysis indicate high occurrences of sea ice related diatom species (e.g. *F. curta* + *F. cylindrus*) together with high D/T values, allowed us to distinguish periods of long persistence of sea ice during the year (> 9 months per year) with late spring melting from those with shorter duration of sea ice cover (< ~8 months per year) with high occurrences of open ocean diatom species (large centrics, *F. kerguelensis*, *Chaetoceros* Resting Spores CRS) and low D/T values. The obtained robust age model will allow us to conduct a cyclostratigraphic analysis where paleoclimate cycles at under decadal scale will be identified.



**S18 – 500: Paleoenvironmental changes in Antarctica and Southern Oceans since the last Glacial Maximum**

***Holocene behaviour of Antarctic Peninsula glaciers reveals vulnerability to modern warming***

Rebecca Totten Minzoni<sup>1</sup>; John B. Anderson <sup>1</sup>; Julia S. Wellner <sup>2</sup>; Rodrigo Fernandez <sup>3</sup>

Rice University<sup>1</sup>; University Of Houston, USA <sup>2</sup>; University of Texas Institute for Geophysics, USA <sup>3</sup>

Ongoing seismic and coring efforts in the Antarctic Peninsula have yielded an extensive database of glaciomarine sediment records, which together reveal a complex history of glacial behaviour following the Last Glacial Maximum. Here we present new and updated records from fjords and bays of vastly different climatic and oceanographic settings to better understand the variability of glacial response during known climate events. Paleoclimate records are obtained by conducting centennial scale-resolution, multi-proxy analyses on well-dated cores, including: grain size, magnetic susceptibility, diatom and foraminiferal assemblages, organic carbon content, and stable isotopes. Our study builds on the published record by re-sampling cores for additional proxies and adding several new study areas that meet the criteria of having expanded Holocene stratigraphy and well-constrained chronology. Multi-proxy analysis facilitates consistent comparison across fjord sites, while supplementary sites of varied oceanographic and climatic settings provides a means to test relative consequence of local forcings on tidewater glacial environments through time. Study areas include: Herbert-Croft Fjord, Firth of Tay, Maxwell Bay, Lapeyrère Bay, Collins Bay, Neny Fjord, and Ferrero Bay. These records are scrutinized closely with the Late Pleistocene-Holocene- age ice core from James Ross Island and with open shelf records from Palmer Deep and Bransfield Basin. This comparison reveals that both initial fjord deglaciation and response of tidewater glaciers to major warm events during the early and mid Holocene were characterized by great variability in timing and magnitude across the peninsula. Synchronicity of glacial response increased during the Late Holocene, indicating that glaciers may have become increasingly more vulnerable to climate change during the Holocene. Ongoing research is aimed at addressing the manifestation of recent warming in the fjord sediment record.



**S19 – 53: Lake Sediment Records of Past Changes in sea level and climate during the Late Quaternary**

***Inverted sediments in coastal Antarctic lake: Evidence of paleostorm?***

Rajeev Saraswat<sup>1</sup>; Atif Raza<sup>2</sup>; Dinesh K. Naik<sup>1</sup>; N. Khare<sup>3</sup>; Pawan Govil<sup>4</sup>; Abhijit Mazumder<sup>4</sup>

National Institute of Oceanography, India<sup>1</sup>, Geological Survey of India <sup>2</sup>, Ministry of Earth Sciences, ESSO, Govt. of India<sup>3</sup>, Birbal Sahni Institute of Paleobotany, India<sup>4</sup>

Faunal and sedimentological analysis was carried out on two cores collected from a coastal lake in the Vestfold Hills region of Antarctica. Radiocarbon dating revealed that the sediments were inverted, with two sequences of younger sediments overlain by older sediments. Increased abundance of marine microfossils, including foraminifera and diatoms in inverted layers shows that the sediments were transported from the adjacent shelf region. It is further confirmed by the presence of a few planktic foraminiferal shells in the sediments. The transport of older marine sediments from the nearby shelf, into the lake against gravity is inferred as a result of storm/cyclone. Two such past storm/cyclone events are inferred as the core includes two sets of inverted sediments. The study suggests that faunal and sedimentological analysis in conjunction with dating can be applied to infer past instances of extreme events in high latitude regions.



**S19 – 215: Lake Sediment Records of Past Changes in sea level and climate during the Late Quaternary**

***Holocene palaeoenvironmental changes: evidenced from fresh water lakes in Schirmacher Oasis, east Antarctica***

Pawan Govil<sup>1</sup>; Abhijit Mazumder<sup>1</sup>; D. S. Singh<sup>2</sup>; R. Asthana<sup>3</sup>; A. Swain<sup>4</sup>; R. Raghu<sup>4</sup>

Birbal Sahni Institute of Palaeobotany<sup>1</sup>; Department of Geology, Lucknow University<sup>2</sup>; Geological Survey Of India, H.R.D., H.Q., Kolkata<sup>3</sup>; Geological Survey Of India, NH5P, N.I.T., Faridabad<sup>4</sup>

Detailed investigations have been carried out on sediment cores from proglacial, land-locked and epi-shelf lakes of Schirmacher Oasis, east Antarctica to understand the paleoenvironmental variations from three different realms of depositional environment. Proxies such as biogenic silica, grain size analysis, Total Organic Carbon etc. have been analyzed for the three sediment cores. Cumulative dataset from proglacial as well as epi-shelf Lake shows change in percentage of sand and BSi around 4.5 ka. Epishelf Lake exhibits a sudden decrease of sand percentage and increase of BSi percentage prior to 4.2 ka, whereas proglacial lake shows a decrease of sand percentage and increase of BSi percentage prior to 4.7 ka. Hence, these two cores suggest a sudden turnover from colder to warmer climatic conditions during mid- to late-Holocene. One of the landlocked lakes also reveals the warming period initiated at ~4ka to recent based on total organic carbon concentration and Mg/Ca ratio. The increase of sand in both land locked lakes prior to ~10 ka demarcates another warming episode in the study area. The early- to mid-Holocene period consequently shows the low energy environment and colder phase. Whereas, mid to late-Holocene experienced high energy environment due to warming in the Schirmacher Oasis.



**S19 – 386: Lake Sediment Records of Past Changes in sea level and climate during the Late Quaternary**

***Paleoenvironmental variations from lake sediments of Schirmacher Oasis, East Antarctica: A multi-proxy Approach***

Anish Warri<sup>1</sup>; Mahesh Badnal<sup>1</sup>; Rahul Mohan<sup>1</sup>; R. Shankar<sup>2</sup>; Rajesh Asthana<sup>3</sup>; Rasik Ravindra<sup>4</sup>

ESSO-National Centre for Antarctic and Ocean Research<sup>1</sup>; Mangalore University, India<sup>2</sup>; Geological Survey of India<sup>3</sup>; Earth System Sciences Organization (ESSO), Ministry Of Earth Sciences, India<sup>4</sup>

In this study, we present a detailed rock magnetic record of paleoenvironmental/paleoclimatic variations in the Schirmacher Oasis, East Antarctica. We determined environmental magnetic properties and interparametric ratios ( $\chi_{if}$ ,  $\chi_{fd}$  %,  $\chi_{ARM}$ , SIRM,  $\chi_{ARM}/SIRM$ ,  $\chi_{ARM}/\chi_{if}$ ,  $\chi_{ARM}/\chi_{fd}$ ,  $SIRM/\chi_{if}$ , S-ratio and HIRM) for sediment samples of a 68 cm sediment core from Sandy Lake. Five  $^{14}C$  dates were obtained on the organic matter from bulk sediment samples using an accelerator mass spectrometer (AMS). The sediment core spans the past ~ 42.5 cal. ka B.P. Based on the magnetic properties, it is evident that the magnetic minerals are mainly detrital and catchment-derived, as there is no presence of authigenic greigite, bacterial magnetite or diagenetic dissolution. High S-ratio values and isothermal remanence magnetisation (IRM) acquisition curves suggest the presence of low-coercive minerals like magnetite, titanomagnetite etc. which are coarse grained in terms of magnetic grain size. The magnetic mineralogy is also confirmed by SEM-EDS observations on magnetic extracts. The last glacial period is characterized by a high concentration of ferrimagnetic minerals such as titanomagnetite (high values of  $\chi_{if}$ , SIRM etc.) and coarse magnetic grain size (low  $\chi_{ARM}/SIRM$  and  $\chi_{ARM}/\chi_{if}$  values and high S-ratio values). Deglaciation in the Schirmacher Oasis began around 21 cal. ka B.P. as suggested by the low magnetic mineral concentration. The Holocene period is characterized by relatively warm climatic events as seen in the low values of magnetic susceptibility which is primarily contributed by fine-grained titanomagnetite resulting from pedogenesis (high  $\chi_{fd}$  % values). Several of the relatively warm and cold events that we deciphered from the environmental magnetic data are correlatable with lake sediments from the Schirmacher Oasis and other ice-free areas in East Antarctica and from ice-core records on the Antarctic Plateau.



**S19 – 390: Lake Sediment Records of Past Changes in sea level and climate during the Late Quaternary**

***Holocene climatic history of Larsemann Hills, East Antarctica: A diatom based study from Stepped Lake***

Aniruddha Avadhani<sup>1</sup>, Abhilash Nair<sup>2</sup>, Anish Kumar Warriar<sup>2</sup>, Mahesh Badanal<sup>2</sup>, Rahul Mohan<sup>2</sup>

Mangalore University, India<sup>1</sup> ; ESSO-National Centre for Antarctic and Ocean Research, Goa, India<sup>2</sup>

The timing of the deglaciation in Larsemann Hills displays a regional variation in the past, wherein western Larsemann Hills (Stornes Peninsula) is known to have deglaciated during mid- to late-Holocene. However, some areas of eastern Larsemann Hills (Broknes Peninsula) deglaciated since ~ 40 ka BP. Therefore, an attempt is made to decipher the paleo-depositional environment and the response of the Stepped Lake in Larsemann Hills towards the climatic variations for the last ~ 7 cal. ka B. P. Overall, a higher concentration of diatom valves were observed throughout the sediment core. This suggests increased diatom productivity in Stepped Lake since the last 7 ka BP which may possibly indicate an ice free (no perennial ice cover) region in and around the lake. Down-core diatom assemblages comprised a mix of marine and lacustrine diatoms, with former dominating the sediment core. Higher abundance of sea-ice diatoms such as *Fragilariopsis curta* (40 to 50%) and *Fragilariopsis cylindrus* (~46%) between ~ 4,300 and 5,800 cal. ka BP possibly suggest an open lake system, where spatial and temporal distribution of sea-ice could have been more than the modern day. Abundance of lacustrine diatoms such as *Planothidium quadripunctatum*, *Amphora veneta* and *Navicula* sp. displayed an increasing trend between ~ 6,957 and 7,078 cal. ka BP which is also complemented by decrease in an abundance of sea-ice diatoms. This sort of increase in lacustrine diatoms in the lake sediment during ~7 cal. ka BP suggests that the Stepped Lake was more of a closed system and cut off from the marine environment.



**S19 – 419: Lake Sediment Records of Past Changes in sea level and climate during the Late Quaternary**

***Holocene environmental changes in Byers Peninsula (South Shetland Islands, Antarctica) based on a multiple dating method approach to lake sediments***

Marc Oliva<sup>1</sup>; Dermot Antoniades<sup>2</sup>; Santiago Giral<sup>3</sup>; Ignacio Granados<sup>4</sup>; Sergi Pla<sup>5</sup>; Manuel Toro<sup>6</sup>; Jorge Sanjurjo<sup>7</sup>; Emma Liu<sup>8</sup>; Gonçalo Vieira<sup>1</sup>

Institute of Geography and Spatial Planning, University of Lisbon<sup>1</sup>; Dept. Géographie & Centre d'Études Nordiques, Université Laval, Canada<sup>2</sup>; Institute of Earth Sciences Jaume Almera, CSIC, Spain<sup>3</sup>; Peñalara National Park, Spain<sup>4</sup>; Centre de Recerca Ecològica i Aplicacions Forestals (CREAF-CSIC)<sup>5</sup>; Centro de Estudios Hidrográficos (Centre for Hydrographic Studies) (CEDEX), Spain<sup>6</sup>; Department of Earth Sciences, University of Bristol, Wills Memorial Building, Bristol, BS81RJ, UK<sup>7</sup>; Department of Earth Sciences, University of A Coruña<sup>8</sup>.

The present day ice-free environments of the South Shetland Islands are a consequence of the long-term Retreat of the ice caps that covered most of these islands. The warmer periods recorded during the Holocene have led to a gradual shrinking of the ice masses, which in turn favored the expansion of periglacial processes in the newly exposed areas.

This is the case of the Byers Peninsula, the largest ice-free environment in this archipelago (ca. 60 km<sup>2</sup>) in the westernmost part of Livingston Island. Today, the environment here shows a high biodiversity with active periglacial processes. Until now, the knowledge of the deglaciation process of the Byers Peninsula was based only on a few radiocarbon dates from the bottom sediments of several peninsula lakes. Moreover, inferences drawn from these dates may be tenuous, since the diamicton was not reached and therefore these ages do not reveal the age of deglaciation of these environments.

The present research introduces a multiple dating approach to four lake sequences from the Byers Peninsula that complements and greatly expanded the scarce number of dates existing for the area. The cored lakes are: Chester, Escondido, Cerro Negro and Domo. The complete sedimentary sequence was retrieved from these lakes in November 2012. The chronological framework for environmental changes was established using thermoluminescence dating, tephrochronology, Pb-210 and C-14.

Five different, visually evident tephra layers were identified in the lake sediments from Byers Peninsula. The geochemical and textural properties of these tephras point to Deception Island as the volcanic source of these eruptions, and independent dating methods suggest that they occurred at 5.0, 4.8, 3.9, 2.3 and 1.8 ka BP.

Lake sediments also suggest the chronology of deglaciation in this ice-free peninsula. The onset of the deglaciation of the Byers Peninsula started during the Early Holocene in the eastern fringe of the peninsula according to the basal dating of Limnopolar Lake (8.3 ka cal BP). The glacial shrinking also exposed the highest parts of Cerro Negro nunatak in the SE corner of Byers, where Cerro Negro Lake is located. This lake was glacier free by 7.5 ka. During the Mid-Holocene, the retreat of the Rotch Dome glacier cleared the central part of the Byers plateau of ice, and Chester and Escondido lakes formed at 5.9 ka and 5.1 ka cal BP, respectively. Finally, in Domo Lake, cored at only 300 m from the present day glacier front, we report an age of 2.3 ka BP for the basal sediments, which suggests that the deglaciation of the westernmost part of the Byers Peninsula is of Late Holocene age.

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# *XII International Symposium on Antarctic Earth Sciences*

*13 - 17 July 2015, Goa, India*



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**S19 – 462: Lake Sediment Records of Past Changes in sea level and climate during the Late Quaternary**

***Regional Differences in Late Holocene Relative Sea-level Changes in Lutzow Holm Bay, East Antarctica***

Verleyen E.<sup>1</sup>; Tavernier, I.<sup>1</sup>; Hodgson D.A.<sup>2</sup>; Whitehouse P.<sup>3</sup>; Kudoh, S.<sup>4</sup>; Satoshi, I.<sup>4</sup>; Roberts, S.J.<sup>2</sup>; Bentley, M.J.<sup>3</sup>; Sabbe, K.<sup>1</sup>; Vyverman, W.<sup>1</sup>

Lab. Protistology & Aquatic Ecology, Ghent University, Ghent, Belgium<sup>1</sup>; British Antarctic Survey, Cambridge, UK<sup>2</sup>; Durham University, Durham, UK<sup>3</sup>; National Institute of Polar Research, Tokyo, Japan<sup>4</sup>

Compared to the other continental ice masses, the East Antarctic Ice Sheet (EAIS) has few field data to constrain its past volume and contribution to global sea-level changes since the Last Glacial Maximum. We developed relative sea-level (RSL) curves for four regions separated maximum 80 km apart in Lutzow Holm Bay (Dronning Maud Land, East Antarctica) by using marine to freshwater transitions in sediment cores from isolation lakes and published new <sup>14</sup>C dating of macrofossils in raised beaches. These data were combined with radiocarbon dating of the transitions from glaciogenic to organic richer sediments in three glacial lakes to obtain the minimum age of deglaciation and the maximum sea-level high stand. The RSL curves were compared with the output of Glacial Isostatic Adjustment (GIA) Models. In West Ongul Island, the maximum marine limit was 17 m at 10,500 14C yr BP (10,170 to 10,400 cal yr BP after correction for the marine reservoir effect). RSL fall was relatively rapid (15 mm/yr) between c. 5000 cal. yr BP and 4800 cal. yr BP. The RSL fall equaled 2.1 mm/yr during the past c. 4800 cal. yr BP, which was similar to that in Skallen (2 mm/yr during the past 4690 ± 100 cal. yr BP). In Skarvsnes, the maximum marine limit was 32.7 m at 5410 ± 40 <sup>14</sup>C (5265 4653 cal. yr BP). RSL fall was very rapid (14.5 mm/yr) between c. 3670 and 1905 cal. yr BP. Between c. 1905 and 1500 cal. yr BP, RSL fall dropped to 2.1 mm/yr and from c. 1500 cal. yr BP onwards, it was c. 1 mm/yr. The RSL changes on West Ongul Island and Skallen are broadly in agreement with previous findings from the region and with GIA models. By contrast, the RSL curve for Skarvsnes strongly differs in shape and the maximum marine limit from previous reconstructions, the GIA output, and those from nearby regions and elsewhere in East Antarctica. One possible way to explain these regional differences would be the reactivation of faulting.



**S19 – 463: Lake Sediment Records of Past Changes in sea level and climate during the Late Quaternary**

***Lake sediments from Antarctica and the sub-Antarctic Islands as recorders of past changes in Regional climate and ice sheet dynamics***

Verleyen E.<sup>1</sup>; Hodgson D.A.<sup>2</sup>; Roberts, S.J.<sup>2</sup>; Van Nieuwenhuyze, W.<sup>1</sup>; Tavernier, I.<sup>1</sup>; Imura, S.<sup>3</sup>; Kudoh, S.<sup>3</sup>; Sabbe, K.<sup>1</sup>; Vyverman, W.<sup>1</sup>

Lab. Protistology & Aquatic Ecology, Ghent University, Ghent, Belgium<sup>1</sup>; British Antarctic Survey, Cambridge, UK<sup>2</sup>; National Institute of Polar Research, Tokyo, Japan<sup>3</sup>

Recent changes in climate and ice-sheet dynamics in Antarctica and the surrounding islands are regionally variable in both amplitude and rate, which makes it crucial to understand their response to natural forcings during the Holocene. Here we review how past variations in climate and deglaciation are preserved in lake sediments along the East Antarctic coastline and the Sub-Antarctic islands in the form of changes in biological, geochemical and sedimentological proxies. We focus on our most recently studied records from Lutzow Holm Bay (East Antarctica) and South Georgia (Sub-Antarctica) and integrate them with existing records from the region and elsewhere. In Lutzow Holm Bay, we compared lake records from the West Ongul Island with those from Skarvsness. The available <sup>14</sup>C dates suggest that both regions deglaciated asynchronously as organic matter started to accumulate in lakes in West Ongul Island around 11.2 ka BP, while our study site in Skarvsness only became ice-free around 7.2 ka BP, narrowing down available cosmogenic isotope dates that placed deglaciation of this peninsula roughly between 10 and 6 ka BP. Increased lake primary production and changes in sedimentological variables likely related to meltwater input revealed the presence of a Late Holocene climate optimum between c. 4 and 1 ka BP. There is no evidence for a Medieval Climate Anomaly, Little Ice Age or twentieth century warming in our East Antarctic records. In South Georgia, we compared multi-proxy data from lake and peat cores at two sites, Annenkov Island and Prince Olav Harbour, on either side of the orographic barrier on the island. Deglaciation appears to be synchronous at both sites, but occurred 1500-2500 years later than in other available records from the region. After deglaciation a low nutrient/low productivity environment persisted until c. 4.3 ka BP and c. 4.7 ka BP in respectively Fan Lake (Annenkov Island) and the lake in Prince Olav Harbour. This suggests that retreating glaciers probably remained in their catchments well into the mid Holocene. Proxies for primary production were relatively high between 4.3 and 1.5 ka BP and 4.7 and 2 ka BP in Fan Lake and the lake in Prince Olav Harbour respectively, which is likely related to warmer summer temperatures and/or catchment processes related to regional glacier dynamics. This period coincides with the late Holocene climate optimum generally observed in Antarctica. It was followed by an alternation of cold and warm conditions during the past two millennia which are more or less coincident in both sediment cores and broadly follow patterns observed in the Northern Hemisphere and lower latitudes in the Southern Hemisphere. Combined, our data revealed that paleoclimatic events in South Georgia shifted c. 2 ka BP from being synchronous with Antarctica to a pattern broadly similar with records north of the Antarctic polar front, while past climate changes in East Antarctica appear to be different to records from elsewhere. We conclude that additional high resolution data from other Sub-Antarctic islands and the Antarctic continent are urgently needed to confirm these regional differences in deglaciation and paleoclimate changes.



## S20 – 67: Break up of Gondwana and Vertebrate evolution

### *The early Paleogene biota of southern Pakistan, and the early history of the Indus drainage*

Métais, Grégoire<sup>1</sup>; Guillot, Stéphane<sup>2</sup>; Bartolini, Anachiara<sup>1</sup>; Lashari, Rafiq<sup>3</sup>; Merle, Didier<sup>1</sup>; Rage, JeanClaude<sup>1</sup>; Solangi Sarfraz<sup>3</sup>

Centre de recherche sur la paléobiodiversité et les paléoenvironnements CR2P, MNHN, Paris<sup>1</sup>; ISTerre, University of Grenoble, France<sup>2</sup>; CPAG, University of Sindh, Pakistan<sup>3</sup>

Paleocene terrestrial mammals are not yet known from the Indian subcontinent. Yet, they are of utmost importance to test various paleobiogeographic hypotheses related to the Island insolation of the Indian subcontinent, before the lithospheric collision with the Asian mainland by the early Eocene.

The Ranikot Group (classically considered as entirely Paleocene in age) spans an important interval of tectonic and sedimentary history that records the latest episode of the 'Indo-Pakistani Island' that just predates the collision between the Indian and Asian plates, which began near the Paleocene/Eocene transition, ~55 Ma. The Ranikot Group is widely exposed throughout the Laki Range and the Lakhra Dome, and consists of coastal, deltaic and fluvial sediments that have yielded sparse fossil data, including some vertebrates. In the frame of a joint Franco-Pakistani research program, a survey of the Laki Formation, Ranikot Group, was initiated in 2009, and below we present preliminary results of geological and paleontological investigation carried out in several localities of both the Laki Range and Lakhra Dome. The main objectives of the Ranikot Project are:

1. To document for the first time the Paleocene vertebrate fossil record in the Indian Subcontinent,
2. To better constrain the chronostratigraphic framework of the different units of the Ranikot Series with high resolution biostratigraphy,
3. Characterise the depositional environments in this area just before the beginning of the collision with Asia, and how they relate to the early History of the Indus drainage.

We have carried out a general survey of the three formations included in the Ranikot Group. They display different lithologies and sedimentary structures based on which the depositional environments are characterized. Several stratigraphic levels yielding fossil data along the sections have been identified, but the poor assemblages of fauna and flora hamper extensive comparisons with the few contemporaneous localities of the Gondwanan landmasses. The identified madtsoiid snake *Gigantophis* sp. reveal biogeographic affinities between the Indian Subcontinent and Africa, thus suggesting dispersal between these areas during the Paleocene or earlier. The marine Lakhra Formation (upper Ranikot Group) is of interest as it has registered the isotopic excursion that characterizes the Paleocene-Eocene boundary, suggesting that part of the Lakhra Formation is Eocene in age. This hyper thermal event is correlative with a peak in mollusc biodiversity.

Besides, we present an overview of the results from an integrated provenance analysis using strontium (Sr) neodymium (Nd) isotopes and detrital zircons in Paleogene to Neogene sedimentary rocks from Indus basin in order to understand the paleodrainage of Indus River and its tectonic control. Our isotopic data revealed that the greatly extended Greater India between the leading margin of Indian plate and the Indian craton was occupied by a fluvial deltaic system that was transporting sediments from the Asian plate by 50 Ma, suggesting that the hard India Asia collision was accomplished by then.

The precollision biotas remain poorly known in the Indian subcontinent, and the biogeographic affinities of the area during the 'Island stage' remain elusive, and a matter of speculation. The provenance analysis of



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sediments of various age exposed in the Pakistani thrust belts clearly indicate an early exhumation of the investigated stratigraphic units, and the installation of a drainage by the early Eocene.



## S20 – 74: Break up of Gondwana and Vertebrate evolution

### ***Guelb el Ahmar, Morocco, first Middle Jurassic fossil assemblage including mammals from Africa: Pangean or Laurasian affinities?***

Emmanuel Gheerbrant<sup>1</sup>, Ronan Allain<sup>2</sup>, Hamid Haddoumi<sup>3</sup>, Said Meslouh<sup>4</sup>, Gregoire Metais<sup>2</sup>, Michel Monbaron<sup>5</sup>, Denise Pons<sup>2</sup>, Jean Claude Rage<sup>2</sup>, Romain Vullo<sup>6</sup>, Samir Zouhri<sup>7</sup>

CNRS, Muséum National d'Histoire Naturelle, Paris<sup>1</sup>, CR2P UMR 7207, Muséum National D'Histoire Naturelle, CNRS, UPMC, Paris, France.<sup>2</sup>, Department Geology, Faculty of Sciences, University Mohammed 1er, Oujda, Morocco<sup>3</sup>, Ministère De L'Energie, Des Mines, De L'Eau Et De L'Environnement, Rabat, Morocco<sup>4</sup>, Department Geosciences, University of Fribourg, Switzerland<sup>5</sup>, UMRCNRS 6118, Geosciences Rennes, University Rennes 1, Rennes, France<sup>6</sup>, Department Geology (Palaeontology), University Hassan II, Casablanca, Morocco<sup>7</sup>

We report the recent discovery of a new continental fossil assemblage from the Middle Jurassic sites of Guelb el Ahmar (GEA), eastern Morocco (Haddoumi et al., 2015). It includes plants, invertebrates and vertebrates, and is one of the richest continental biotic assemblages found in the Jurassic of Gondwana. The fossiliferous level of GEA belongs to the base of the Anoual Formation that outcrops in the Anoual Syncline, as part of eastern High Atlas mountains. Its Bathonian age is well constrained by several biostratigraphic data coming from the upper member of the Anoual Fm, including charophytes, brachiopods and ostracods. This is confirmed by the palynoflora and the composition of the vertebrate assemblage of GEA sites. The latter recalls especially vertebrate faunas from the Bathonian of Britain with the presence of albanerpetontids, the choristoderan cf. *Cteniogenys*, the anguimorph squamate cf. *Parviraptor*, and an amphitheriid mammal.

The sedimentological facies and the faunal and floral association indicate a lacustrine paleoenvironment and the presence of local forests under rather humid conditions. The flora is most noticeably represented by tree trunks, generally of large size, belonging to three families; the tree trunks form remarkable local accumulations in the Anoual Fm. The flora also includes 13 species of pollen and various charophytes.

The invertebrates include ostracods and gastropods. The vertebrate fauna from GEA is predominated by a microvertebrate assemblage that was recovered by screening washing of about 1.2 tons of fossiliferous marls from the local site GEA2. The recovered vertebrate assemblage is diverse with the presence of 29 species, although the fossil material remains fragmentary. It includes most major groups known during the Middle Jurassic (osteichthyans, lissamphibians, chelonians, rhychocephalians, crocodyliforms, lizards, pterosaurs, non avian dinosaurs, mammals), with the exception of the selachians. The GEA fauna yielded in particular the first Middle Jurassic mammals found in Africa. It also noticeably yielded some of the earliest known representatives of several major taxa such as osteoglossiform fishes, albanerpetontid and urodele amphibians, squamates (scincomorphs and anguimorphs), cladotherian mammals, and probably choristoderans. GEA is the first site yielding choristoderans in Gondwana if the identification is confirmed with additional material. GEA also includes the first Gondwanan occurrence of a Mesozoic anguimorph lizard and one of the very few known albanerpetontid and urodele amphibians from Gondwana. The mammals from GEA, still poorly known, are among the earliest known cladotherians (Amphitheriida and cf. Dryolestida, basal therians) from Gondwana.

The floral and faunal assemblage of GEA is characterized by the presence of both Pangean and Laurasian (and especially European) taxa and also by the paradoxical near absence of Gondwanan taxa. The Jurassic flora includes some Gondwanan taxa both in Morocco (e.g., *Metapodocarpoxyton*, north Gondwanan floral province) and in Africa/Gondwana, but the Gondwanan provincialism was clearly incipient at that time with respect to Cretaceous floras and faunas. Comparison of GEA assemblage with Middle Jurassic contemporaneous continental faunas raises two possible paleobiogeographical interpretations. First, the presence of Laurasian taxa previously unknown in Gondwana suggests a major



Middle Jurassic Gondwanan gap in the fossil record and is consistent with an overall inherited Pangean affinity of GEA fauna, in agreement with the paleogeographical reconstructions. The absence of Gondwanan vertebrate taxon in GEA best fits this hypothesis. Another hypothesis is that the Laurasian and especially the European affinities of the GEA assemblage suggest North-South dispersals between Laurasia (Europe) and Gondwana (Africa). In this hypothesis, the absence of Gondwanan taxa in GEA may result from an intra-Gondwanan provincialism, i.e. a northern African or northern Gondwanan province, which would have taken form before the break up of Gondwana. Such a faunal province, intermediate between the Laurasian and Gondwanan landmasses, more or less recalls the Eurogondwanan province described for the Cretaceous. In any case, the affinities of the GEA fauna with faunas from the Bathonian of Britain remain remarkable, even in an overall Pangean context.

Finally the GEA fauna shows a remarkable faunal continuity with that of the ? Berriasian locality Ksar Metlili, also from the Anoual syncline; this might suggest an alternative earlier (Jurassic) age of the important Ksar Metlili fauna that yielded the most diversified Mesozoic mammal assemblage from Gondwana.



## S20 – 162: Break up of Gondwana and Vertebrate evolution

### Implications of the Procellariiformes (Aves) Fossil Record from the Eocene of Antarctica

Acosta Hospitaleche, C.<sup>1</sup>; Gelfo J.N.<sup>1</sup>; Reguero M.<sup>2</sup>

Consejo Nacional de Investigaciones Científicas y Técnicas CONICET, Argentina<sup>1</sup>; División Paleontología de Vertebrados, Museo de La Plata, Facultad de Ciencias Naturales y Museo de La Plata, La Plata, Argentina<sup>1</sup>; Dirección Nacional del Antártico - Instituto Antártico Argentino, Argentina<sup>2</sup>

Antarctic fossil avifauna is mainly represented by penguins. Thousands of isolated penguin bones and a few skeletons coming from West Antarctica Paleocene and Eocene levels, have been described. It is consistent with other austral marine records; penguins are gregarious birds that settle large reproductive colonies along the coasts today and likely made it in the past. It is translated in great accumulations of bone that are easily preserved due to their dense and compact nature. In contrast, a short list of non-penguin avian is known, including a single and doubtful Ratites and volant birds. Flying bird fossil record includes Gaviiformes, Ciconiiformes, Procellariiformes, Gruiformes, Polyborinae, Pelagornithidae, and Anseriformes from Maastrichtian to Bartonian. Among waterbirds, record of Procellariiformes becomes particularly interesting since living species are almost exclusively pelagic birds mainly distributed across the Southern Hemisphere oceans.

Procellariiformes is an order that includes four extant families with fossil representatives: Diomedidae (albatrosses), Procellariidae (petrels, prions and shearwaters), Hydrobatidae (storm petrels), and, Pelecanoididae (diving petrels), besides the exclusively extinct Diomedoididae with a substantial fossil record including several isolated bones and articulated skeletons from marine Oligocene deposits from Germany, France, Belgium, and Iran, and the early Miocene of Germany. Apparently, the middle Eocene *Murunkus subitus* of Uzbekistan would also belong to this family.

Paleogene record of the group around the world is scarce. Presumptive procellariiforms from the late Paleocene of Asia and early Eocene of Europe are known through fragmentary remains but too incomplete for a reliable identification. Definite Procellariidae are represented by a distal tibiotarsus from the late Eocene of USA, a distal tibiotarsus of *Argyrodyptes microtarsus* from the late Eocene/early Oligocene of Argentina, a humerus of "*Larus*" *raemdonckii* from the early Oligocene of Belgium, and the Antarctic material here described. Finally, the Diomedidae are represented by an incomplete tarsometatarsus from the late Eocene of Antarctica, and a specimen not described from the late Oligocene of South Carolina. During the Neogene, remains became more abundant. Most of records belong to North America, but they are frequent also in South America, Australia, and Africa.

The recent finding of several bones belonging to Procellariiformes coming from the Submeseta (lower Eocene) and La Meseta (middle Eocene) formations (Seymour Island, West Antarctica) motivated the present contribution. New material is here described, and the meaning of the Antarctic record of the group is discussed.

The materials here studied come from three different levels. From Cucullaea I Allomember of La Meseta Formation (upper Ypresian) at DPV 6/84 locality, an ulna (MLP 91-II-4-6) of Procellariidae, and a tibiotarsus (MLP 90-I-20-11), a tarsometatarsus (MLP 88-I-1-5), a pedal phalanx (MLP 92-II-2-7), and a rostrum maxillare (MLP 88-I-1-6) of Diomedidae were recovered. From outcrops of Submeseta II Allomember of Submeseta Formation (Bartonian) at IAA 4/12 locality, a coracoid (MLP 13-XI-28-51) of Procellariidae was collected, as well as from the Submeseta Allomember III of Submeseta Formation (upper Bartonian- Priabonian) at DPV 16/84 locality, a tibiotarsus (MLP 13-XI-28-50) and a tarsometatarsus (MLP 12-I-20-305) of Diomedidae were found.



Procellariidae would be represented in Antarctica at least by two different species. The ulna MLP 91-II-4-6 belonged to a bird a little larger than the Cape Petrel *Daption capense* and with no significant differences in its morphology, whereas the coracoid MLP 13-XI-28-51 that is highly weathered seems to match better to a larger bird.

Diomedeidae are represented by isolated remains, all them smaller than the Black-browed Albatross *Thalasseroche melanophrys* and similar in size to *Daption capense*. The tibiotarsus MLP 13-XI-28-50 has a shaft latero- medially curved with an oval section, a central and broad sulcus extensorius (the pons supratendinous area is broken), a condylus medialis cranially projected, a trochlea cartilaginea tibialis almost flat, and inconspicuous epicondyla lateralis and medialis. The tarsometatarsi (MLP 88-I-1-5 and MLP 12-I-20-305) have a shaft cranio- caudally compressed; both foramina vascularia proximalia located at the same level, a wide sulcus metatarsalis, and a divaricated and caudally projected trochlea metatarsi II. The pedal phalanx has a long cylindrical diaphysis with a rounded caput phalangis and a deep fovea ligamentaris collateralis. The rostrum maxillare MLP 88-I-1-6 is curved, with foramina vascularia well developed and sharp cristae tomialis.

These remains reaffirm the presence of Procellariiformes in Antarctica during the Eocene. Previous Paleogene taxa of the group were found in European and North American fossil sites, even when the main distribution of extant species is in the Southern Hemisphere. Something similar happens with Gaviiformes, whose fossil record is abundant in Antarctica but they are exclusive habitants of the North Hemisphere today.

The association of Sphenisciformes, Gaviiformes and Procellariiformes in Antarctic levels is consistent with previous ideas about the austral origin of the waterbird clade Aequornithes. Around 60 Ma ago, the Paleocene - Eocene Thermal Maximum occasioned an important sea level rise. This global warming could have provided a good opportunity in order that offshore birds expand their habitat into the sea, occupying vacant niches. It could also be closely related to the appearance of an important penguin diversity in the Eocene.



## S20 – 170: Break up of Gondwana and Vertebrate evolution

### ***Additions to the knowledge of Notiolofos (Mammalia: Sparnotheriodontidae) early Eocene of West Antarctica***

Gelfo, J. N.<sup>1,2</sup>; de los Reyes, M.<sup>2,3</sup>; Acosta Hospitaleche, C.<sup>1,2</sup>; Reguero, M.<sup>1,2,3</sup>

CONICET, Argentina<sup>1</sup>; División Paleontología de Vertebrados, Museo de La Plata, Facultad de Ciencias Naturales y Museo de La Plata. La Plata. Argentina<sup>2</sup>; Dirección Nacional del Antártico - Instituto Antártico Argentino. Argentina<sup>3</sup>

One of the most importance significance of the fossil record of terrestrial vertebrates in Antarctica, is settled in the possibility of make inferences about past terrestrial connections with other continents. In this sense the Cretaceous and Paleogene vertebrate record is a major biological evidence of the Gondwana break up. In contrast to flying birds and marine vertebrates, the dispersal of other groups through or into Antarctica, are more constrained by fresh water supply and land connections. Their ancient presence in Antarctica could be used as an independent way of testing plate tectonics and paleogeographic hypotheses. In this sense, since no crocodiles, squamates or amphibians have been found, the information are restricted during Cretaceous to non-avian dinosaurs, and in the Paleogene, to a doubtful and isolated Ratite and, the mammalian record.

Fossil mammals in Antarctica are by now limited to the West Antarctica record in the Eocene outcrops of La Meseta and Submeseta Formations in Seymour Island. The faunistic assemblage has a clear South American imprint and corresponds to endemic genera and species, of groups mostly represented in the Paleogene of Patagonia, Argentina. They include non-therian mammals as a probably Meridolestida dryolestoid and a gondwanathere, closely related to Sudamerica ameghinoi from the Danian of Punta Peligro in Patagonia. Therians are represented by a wide diversity of 'opposum-like' metatherians, referable to 'Didelphimorphia', Microbiotheria, Polydolopimorphia and Derorhynchidae; and, placental mammals, by Xenarthra, Astrapotheria and sparnotheriodontid Litopterna.

The Sparnotheriodontidae were a geographically widespread group of medium to large size herbivorous mammals during the Eocene, and part of the radiation of the so called, South American native ungulates. They were low-crowned browser characterized by a lophoselenodont and bicrescentic lower dentition, a strong lophoselenodont ectoloph and usually a bunoid lingual cusp in the upper molars. Known sparnotheriodontids include Victorlemoinea prototypica (Itaboraian SALMA - Itaboraí, Brazil), Victorlemoinea labyrinthica (Riochican SALMA - Patagonia), Sparnotheriodon epsilonoides (Casamayoran SALMA, Vaca subage - Patagonia), Phoradiadus divortiensis (Casamayoran? SALMA - Mendoza, Argentina), Heteroglyphis dewoletzky, assigned to the family with some doubts (Mustersan SALMA - Patagonia), and Notiolofos arquinotiensis, the most abundant terrestrial placental mammal in the Paleogene of Antarctica. The paleobiogeographic analysis of Sparnotheriodontidae, and also Astrapotheria, yields a widespread ancestral distribution, including South America and Antarctica, since the lower Paleocene up to middle-late Paleocene, when a vicariant event took place. It was recorded through most of the La Meseta Formation allomembers, including from base to top, Acantilados II, Campamento, Cucullaea I, and, Submeseta Formation.

By now Notiolofos was only known by isolated teeth. Here we present the first associated jaw remains of Notiolofos. The material MLP 15-I-10-1 comes from a filling channel at the new locality IAA 2/15 in Acantilados II Allomember. The same unit but stratigraphically higher, than the bearing horizon of the oldest Antarctic mammal, which is the first record of Notiolofos. The jaw is broken in several pieces, due to diagenetic process, and most of them still in a rock matrix. The preliminary technical preparation allows the description of several important features. The largest portion of dentary is a transversal section of the jaw distal to the m3 but mesial to the coronoid fossa. The alveolar portion for the root of the talonid of the m3 is present but no mandibular canal is visible. The height of this section is around 65 mm, similar



to the same portion in the Sparnotheriodon jaw. At least three teeth representing right m1-3 were recognized, and, other enamel portions left to be identified. The m1-2 were preserved in intimate association, and they are interpreted in this locus by the higher position of the labial cingulid and a small portion of their roots in the fore tooth, indicating the earlier eruption of the m1 respect to the m2. The first molar only preserves the labial side of the talonid, with part of the hypoconid and hypocristid enamel and some dentine exposure. In the m2 there is a small elevation and thickening of the labial enamel, in the position of the protocone. The paralophid has a wide dentine surface, the lingual side of the trigonid is not preserved as well as the internal flexid of the trigonid between the paraconid and the metaconid position. Even though the metaconid is not preserved, the labial enamel edge of the cristid obliqua and the protocristid, rise lingually to the position where the metaconid should be, indicating that this cusp was the highest one. The m3 is the best preserved tooth, with almost the complete labial side of the molar. The mesial part of the entoconid obliterated the talonid basin and almost contacts the massive crest which descends distally from the metaconid. At least the mesiodistal length between the protoconid and the hypoconid is longer than those of the other only known m3 of *Notiolofofos* (MLP 01-I-1-1) which came from somewhat younger sediments (Cucullaea I Allomember).

*Notiolofofos* hypodigm comprises only isolated teeth from different locus found in several localities and more important, from distinct stratigraphic levels over a time span of at least 17.5 Ma. Despite their fragmentary preservation, the jaw and the m1-3 series here presented are the more complete finding of a single individual of *Notiolofofos*, and, its second record from Acantilados II Allomember. MLP 15-I-10-1 will allow to test the alleged evolutionary stasis of *Notiolofofos* while improves the faunistic knowledge of this allomember, the lowermost stratigraphic level (Ypresian) in Antarctica where mammals have been found.



## S20 – 173: Break up of Gondwana and Vertebrate evolution

### **Antarctic Paleogene Terrestrial Mammal Biogeography: Vicariance, Dispersal and Geological Events**

Marcelo A. Reguero<sup>1</sup>, María Alejandra Abello<sup>2</sup>, Paula Posadas<sup>2</sup>, Edgardo Ortiz Jaureguizar<sup>2</sup>, Javier N. Gelfo<sup>2</sup>, Laura Chornogubsky<sup>3</sup>, Sergio N. Santillana<sup>1</sup>, Nestor R. Coria<sup>1</sup>

Instituto Antártico Argentino, Buenos Aires, Argentina<sup>1</sup>, Museo De La Plata, La Plata, Argentina<sup>2</sup>, Museo Argentino De Ciencias Naturales, Buenos Aires, Argentina<sup>3</sup>

**Background:** West Antarctica terrestrial mammals were diverse, geographically widespread, stratigraphically long lived and largely terrestrial: they therefore provide an almost 'ideal' case study in Southern Paleogene biogeography. This mammal association includes eutherian (SAANUs Litopterna and Astrapotheria), metatherian (marsupials Polydolopidae, Derorhynchidae and Microbiotheria) and non-therian mammals (Gondwanatheria and Meridiolestida). A more complex picture of the origin of the Cenozoic Antarctic and South American mammalian faunas is starting to emerge, showing integration of faunal elements from different biogeographic events: surviving members of Mesozoic non-therian mammalian lineages, metatherian and eutherian lineages that presumably dispersed to Antarctica in the latest Cretaceous or early Paleocene. These biogeographic events are thought to be linked to geological events of connection and disconnection of these two land masses (Antarctica and South America). From an evolutionary perspective such likenesses and close relationships are difficult to accommodate because, by the end of the Late Cretaceous (~72 Ma), two of the major Gondwanan continental blocks (South America and West Antarctica) were well into the process of breakup and dispersion. Critically, South America (Patagonia) and Antarctic Peninsula (West Antarctica) are commonly thought to have been separated by vast marine barriers. To explain their paleontological linkages, it has thus been proposed that these 'isolated' land masses were connected to one another until as late as c. 58 Ma (Late Paleocene) via long causeways that routed through Antarctica.

**Methods:** The current study has drawn together the most recent and detailed eutherian (Astrapotheria and Litopterna) and metatherian (Polydolopidae) phylogenies, and geographical and stratigraphical range data. This dataset was subjected to the cladistics biogeographical method known as Dispersal Vicariance Analyses and were performed using RASP software for therian mammals (i.e. ungulates and marsupials) in order to test for the presence of the repeated area relationships that are potentially indicative of a vicariance signal. The stratigraphic calibration of eutherian mammal phylogenies indicates the Late Paleocene as the minimum age at which their common ancestor was present on both areas, Antarctica and South America. Examination of ghost lineages of these eutherian mammals currently known to occur in Paleogene rocks of South America and Antarctica indicates that minimum divergence times for these taxa are in the Late Paleocene Astrapotheria (~58-59 m.y.) and Litopterna (~57-58 m.y.) or probably much earlier, thus substantially predating at least 5-6 m.y. earlier than their Early Eocene occurrences in both areas. The analysis of Astrapotheria and litoptern Sparnotheriodontidae yields a widespread ancestral distribution, including South America and Antarctica, since the lower Paleocene up to middle late Paleocene, when a vicariant event took place in ancestral area (West Antarctica Patagonia).

**Results:** Unfortunately, the biogeographical history of some metatherian (marsupials, i.e., Derorhynchidae) groups present in the Paleogene of West Antarctica remains obscure and controversial, partly because of differences in the datasets studied and the methods applied. Many workers have proposed 'vicariance', driven by continental fragmentation, as the dominant factor that determined metatherian distributions, especially during the Paleogene. By the way, the earliest record of marsupials in South America is the ameridelphian *Cocatherium lefipanum* from Paso del Sapo (42° 46'S; 69° 51'W) of Danian age, Chubut Province, Argentina.



The analysis of the Polydolopidae marsupials show a distribution restricted to Patagonia during the lower and middle Paleocene and a dispersal event from Patagonia to Antarctica followed by a vicariance, both of them during the late Paleocene.

The increasing number of Mesozoic mammal lineages now known to have survived into the Cenozoic of Antarctica and South America demonstrates the integration of the non-therian mammalian faunas of the Late Cretaceous into the eutherian and metatherian faunas that made their first appearance in the fossil record of South America during the Paleocene. The following clades will complete this study.

Meridolestida is a diverse group of dryolestoids recorded mostly from Patagonian Cretaceous outcrops, which survived the K/Pg boundary with the youngest representative of the clade coming from the early Miocene. The Antarctic Meridolestida closely resembles to *Barberenia* and *Brandonia* from the Late Cretaceous of Patagonia (Los Alamitos and Allen formations). Gondwanatherians are an enigmatic group of extinct non-therian mammals apparently restricted to the Cretaceous and Paleogene of South America, Africa, India, Madagascar and the Antarctic Peninsula. Gondwanatherians are a strictly Gondwanan radiation, and the Antarctic taxon, cf. *Sudamerica ameghinoi*, belongs to the sudamericids that radiated in the Paleogene of Antarctica and South America (*Sudamerica* and *Greniodon*).

**Conclusion:** From the results obtained we conclude that the biogeographic histories of eutherians (Astrapotheria and Litopterna) were different from those of metatherians (i.e. Polydolopidae), but all of them support the hypothesis of an early stage (late Paleocene) of the paleogeographic event leading to the development of a shallow epicontinental sea which might be interpreted as the earliest tectonic phase (Paleocene) that eventually later led to the opening of the Drake Passage (Miocene).

These analyses reveal biogeographical patterns that closely correlate with palaeogeography. The conclusions drawn from the biogeographical analyses of two eutherian and one metatherian clades reinforce the hypothesis that vicariance and dispersal patterns documented in the early Paleogene between West Antarctica and Patagonia are linked to geological events like an early stage of rifting produced stretching causing crustal thinning and widespread subsidence during the Paleocene leading to the development of a shallow but wide epicontinental sea.



**S20 – 332: Break up of Gondwana and Vertebrate evolution**

***Late Cretaceous Actinopterygians from Vega Island, Antarctica: Preliminary report***

Marcelo A. Reguero<sup>1</sup>, Gouiric Cavalli Soledad<sup>1</sup>, O'Gorman, Jose Patricio<sup>1</sup>, Mars, Thomas<sup>2</sup>, Chornogubsky Laura<sup>3</sup>, Cardenas Magaly<sup>4</sup>; Lopez Guillermo<sup>1</sup>

Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET) And División Paleontología Vertebrados, Museo De La Plata, Universidad Nacional De La Plata<sup>1</sup>, Department of Palaeobiology, Swedish Museum of Natural History<sup>2</sup>, CONICET And Seccion Paleontología Vertebrados, Museo Argentino De Ciencias Naturales Bernardino Rivadavia<sup>3</sup>, Instituto De Investigación en Paleobiología y Geología (IIPG), Universidad Nacional De Río Negro<sup>4</sup>

Antarctic fossil actinopterygians are of particular interest because of their scarcity. The extant Antarctic ichthyofauna diversity is low but it could have been higher during the Mesozoic. Up to date, few Cretaceous localities bearing both chondrichthyan and actinopterygian remains are known from Seymour (Marambio), Vega, and James Ross islands. The material recovered includes several isolated teeth, scales, vertebrae, and skull bones. It is noteworthy to mention that the highest diversity is known for chondrichthyans, whereas only few scattered actinopterygians were recovered. There are only two informative actinopterygian specimens described so far, both are acanthomorphs: the beryciform, *Antarctiberyx* Grande and Chatterjee, represented by a poorly preserved and incomplete anterior region of a head recovered in Maastrichtian levels of the López de Bertodano Formation and one tiny and partially preserved specimen designed as cf. Sphenocephalidae recovered from Maastrichtian levels of the Cape Lamb Member of the Snow Hill Island Formation. Here we report bony fish material collected during the last Antarctic Expedition (January and February 2015) in the lower part of the Cape Lamb Member of the Snow Hill Island Formation (lower Maastrichtian) at Cape Lamb, southwestern part of Vega Island. The material consists of four concretions containing actinopterygian remains. Due to the incomplete nature and poor preservation of the specimens, we are unable to assign them to any finer classification. Nevertheless, due to the dearth of Cretaceous fish material from Antarctica, the putative difference of some of the new findings from the known specimens and the good temporal control, we feel that the description of the material at hand is justified. Furthermore, even in its current state, the new material adds considerable morphological information.

Presently, the more informative material seems to be MLP 15XI711 and MLP 15XI712. MLP 15XI711 consists of disarticulated skull bones associated with articulated, highly imbricated, and large scales, plus part of a vertebral column. The scales are cycloid, oval shaped, and seem to be longer than deep. Their external surfaces show numerous concentric circuli and scarce radiating radii plus a central focus with numerous central pits. The central focus is markedly large in the lateral line scales. Most of the scales are articulated. Part of the opercular series has been recognized, i.e., opercle, subopercle, and preopercle. The opercle is large, more or less triangular, and ornamented with fine radiating lines. The preopercle lacks the distal part of its ventral limb and the posterior margin seems to be smooth and slightly convex. The dorsal limb is elongated and thin. The ventral limb is more or less expanded. There are at least thirteen sensory tubules branching from the main preopercular sensory canal. The tubules are closely arranged in the ventral limb. They are moderately wide, long and seem to reach the ventral margin of the preopercle. The interopercle is broken but it seems to have the same length of the preopercular ventral limb. The subopercle is large. Remains of branchiostegal rays are preserved but their total number is unknown. The material is preliminarily assigned here to Ichthyodectiformes due to similarity in the scales and preopercle morphologies. Ichthyodectiformes is an extinct group of basal teleosts that appeared in the Middle Jurassic, became diverse and successful during almost the entire Cretaceous. They have been collected from marine deposits of North America, Europe, Lebanon, Australia, South America, Asia, Antarctica, and Africa. The group includes big sized fishes (e.g. *Xiphactinus* Leidy, *Cladocycclus* Agassiz), medium sized forms (e.g., *Allothrissops* Nybelin, *Thrissops* Agassiz) and small fishes (e.g. *Ascalabothrissops* Arratia).



MLP 15XI712 consists of a caudal endoskeleton that, as far as it can be observed, is composed of four caudal vertebrae, three preural centra, and one compound ural centra. The vertebrae are heavily ossified, ornamented, and strongly constricting the notochord. The dorsal flexure of the tail begins in the midposterior part of the ural centra. There are two hypurals, the first is well developed and the second is comparatively much reduced. Both hypurals are separated by a marked diastema. There are at least three partially preserved uroneurals. The specimen is preliminary interpreted here as an indeterminate teleost. However it is under study in order to arrive to a more accurate taxonomic designation. MLP 15XI720 consists of a section of a fish of about 8 cm long and 0.8 cm wide that corresponds to the posterior region of its body. The vertebrae correspond to the posterior abdominal ones. There are at least 10 poorly preserved vertebrae that are longer than broad. The notochord is strongly constricted by the autocentra and the vertebrae are amphicoelous. The autocentra are thick and have their external surface ornamented. There are few slightly posteriorly inclined, long neural spines preserved. Where the neural arch is preserved it is possible to observe that it is positioned at the midposterior portion of the autocentra. The isolated vertebra MLP 15XI719 is composed by a thick amphicoelous autocentra that strongly constrict the notochord. Neither hemal and neural arches nor its spines are preserved. The latter two specimens are very poorly preserved and incomplete. Because a thick autocentrum that strongly constrict the notochord is present in most fossils above the phylogenetic level of *Leptolepis coryphaenoides* (Bronn) and in all extant teleosts, the material is designed here as belonging to an indeterminate teleost.

The specimens reported were collected from levels that also yielded other marine and continental vertebrates (i.e., plesiosaurs, mosasaurs, and dinosaurs) together with marine invertebrates (i.e., ammonoids, nautiloids, bivalves, gastropods, bryozoans, crustaceans, and equinoids), and palynomorphs. The actinopterygians described here correspond to medium and/or small sized predators. The putative ichthyodectiform is much more complete and better preserved than the previously reported for Upper Cretaceous levels, being the first record of the group recovered from the Cape Lamb Member. No acanthomorphs were recovered. It is expected that, through comparative studies, a more accurate taxonomic assignment of the material can be made. This study will lead to a better understanding of the diversity and paleobiogeography of the Cretaceous Antarctic ichthyofauna.



**S20 – 334: Break up of Gondwana and Vertebrate evolution**

***Upper Cretaceous Antarctic Plesiosaurs: The heart area of the Weddellian Biogeographic Province***

O’Gorman, J.P.<sup>1,2</sup>; Marta Fernández<sup>1,2</sup>; Marcelo A. Reguero<sup>3</sup>

División Paleontología Vertebrados, Museo de La Plata, Universidad Nacional de La Plata, Paseo del Bosque s/n., B1900FWA, La Plata, Argentina<sup>1</sup>; CONICET: Consejo Nacional de Investigaciones Científicas y Técnicas, Argentina<sup>2</sup>; Instituto Antártico Argentino, Cerrito 1248, C1010AAZ, Capital Federal, Argentina<sup>3</sup>

The Upper Cretaceous plesiosaur record from the Weddellian Province (i.e. Patagonia, Western Antarctica and New Zealand, WP hereafter) extends from the uppermost Coniacian to the uppermost Maastrichtian. The sequence records ~36 ma of evolution of plesiosaur fauna at high latitude across three continents. During this time the WP was affected by a cooling trend of the Weddellian Province which starts in the Coniacian until the end of the Cretaceous. The last 40 years of Antarctic expeditions of the IAA-UNLP have produced the largest collection of Antarctic plesiosaurs and allows the understanding of the main features of this plesiosaur fauna, its main temporal changes and possible correlation with biotic and abiotic factors. The main features of the plesiosaur fauna from the WP are 1) the presence of the aristonectine elasmosaurids since the upper Campanian and 2) the absence of post-Santonian Antarctic polycotyliids, the scarcity of New Zealand polycotyliids records and the restriction to non-marine normal environments in South America. The explanation of these requires an understanding of the stratigraphical distribution, phylogeny and paleobiology of the three main involved groups: elasmosaurids (aristonectine and non-aristonectine) and polycotyliids. This is the general objective and main scope of our current work. Here a general background and preliminary results are commented. The Antarctic plesiosaurs have been collected from three formations: the (upper Coniacian?, Santonian-lower Campanian) Santa Marta Fm., the upper Campanian-lower Maastrichtian Snow Hill Island Fm. and the Maastrichtian-lower Paleocene López de Bertodano Fm. This stratigraphic interval comprises environments from nearshore, transgressive and regressive shelves, deltaic distal wedge and estuary. The plesiosaur record from the Santa Marta Fm. comprises polycotyliids (upper Coniacian?-Santonian) and non-aristonectine elasmosaurids (lower Campanian) but aristonectines have not been already recorded in this unit. The overlying unit, the Snow Hill Island Fm. (Herbert Sound Member) has not yielded any polycotyliid specimen but both groups of elasmosaurids are present. The younger stratigraphic sequence is well exposed at Vega Island where above the uppermost part of the Herbert Sound Member, the Cape Lamb Member of the Snow Hill Island Fm. and the Sandwich Bluff Member of the López de Bertodano Fm. crop out. The plesiosaurs from the Cape Lamb Member belong mostly to non-aristonectine elasmosaurids with a single putative record of aristonectine, again polycotyliids are not recorded. The López de Bertodano Formation (including the Sandwich Bluff Member and the undifferentiated sequence from Seymour Island (Marambio Island)) yield both aristonectines (*Aristonectes* sp.) and non-aristonectine elasmosaurids. This background shows that the appearance of the aristonectines and the disappearance of the polycotyliids during the Santonian-lower Campanian indicate a large scale faunal turnover in Antarctica. This faunal turnover is correlated with the cooling trend of the end of the Cretaceous. New Zealand records show a similar picture, aristonectines such as *Kaiweheke katiki* appears in the record near the limit between lower Maastrichtian and upper Maastrichtian. Additionally, although Upper Cretaceous plesiosaurs have been collected in New Zealand since the XIX century, and the record comprises a large number of elasmosaurids, only few vertebrae are positively recognized as polycotyliid. The South American record shows an almost mirror image. In the Atlantic margin aristonectines appear in the record at the upper Campanian-lower Maastrichtian Allen Formation and *Aristonectes parvidens* is recorded in the upper Maastrichtian horizons of the Lefipán Fm. and additionally a large number of non-aristonectine elasmosaurids are recorded in the mentioned Allen Fm. and the upper Maastrichtian levels of the Jagüel Fm. The main feature is the presence of the polycotyliid *Sulcusuchus erraini* in the upper Campanian-lower Maastrichtian levels of the Allen, Los Alamitos and La Colonia formations. However these stratigraphical units are particular as they



were deposited in a marine marginal to non marine patchy ecosystems and therefore *Sulcususus erraini* is probably not a typical fully marine polycotyloid. Additionally in the marine Lefipán and Jagüel formations polycotyloids are absent. The Pacific margin shows the same pattern, with aristonectines (*Aristonectes quiriquinensis*) recorded from the upper Maastrichtian levels of the Quiriquina Formation, presence of non aristonectine elasmosaurids and completely absence of polycotyloids. Therefore the main pattern observed in Antarctica is observed too from other areas of the Weddellian Province. This great scale faunal feature need to be explained in order to understand the Weddellian plesiosaur fauna. The rise of the aristonectine, with its large skulls and large number of teeth could be related with a trophic change and this with an increase in the primary productivity. The rise of marine productivity could be produced by several reasons but the cooling trend from the maximum in the Turonian could give a large scale explanation because as the water surface become cooler the water column become less stratified and favors periods of vertical mixing. This together with high periods of luminosity, shallow settings and land supply of organic material gives the ideal setting for a high seasonal peak of primary production. Additionally fitoplankton blooms during the Maastrichtian have been inferred to be produced by sea ice melting. These possible changes in primary productivity could partially explain the rise of the aristonectine. The second main recorded feature, the scarcity of polycotyloids, is less clear correlated with other main changes. However the absence of polycotyloids could be explained by the rise and diversification of mosasaurs, which suffered a radiation during the Late Cretaceous. This is supported because the only Weddellian formations with abundant polycotyloid specimens (Allen, Los Alamitos and the middle member of La Colonia formations) are characterized by the absence of mosasaurs, which are abundant in other plesiosaur bearing formations.



**S20 – 357: Break up of Gondwana and Vertebrate evolution**

***Late Cretaceous Mosasaurs (Squamata: Mosasauridae) from the Maastrichtian of Marambio (=Seymour) Island, Antarctica***

Marcelo A. Reguero<sup>1</sup>, Marta Fernández<sup>1</sup>, Marianella Talevi<sup>2</sup>, J.P. O’Gorman<sup>1</sup>, Ari Iglesias<sup>3</sup>, J.J Moly<sup>1</sup>,

Museo de La Plata, UNLP.Instituto Antártico Argentino. Argentina<sup>1</sup>, Instituto De Investigación En Paleobiología y Geología, Universidad Nacional De Río Negro<sup>2</sup>, División Paleontología, Universidad Nacional Del Comahue, Instituto De Investigaciones En Biodiversidad Y Medioambiente INIBIOMA CONICET<sup>3</sup>,

Mosasaurs were highly specialized squamates that invaded the marine realm during the Late Cretaceous. Their fossil records indicate that, after the first appearance about 98 Ma ago, they quickly diversified and radiated into marine environments all over the world. Explanations for their extinction comprise two hypotheses. One invokes a gradualist scenario, in which a widespread regression of epicontinental seas during the Maastrichtian produced a reduction of marine habitats and the decline of mosasaur well before the K/Pg boundary; while the other correlates mosasaur extinction with the big crisis at the K/Pg boundary triggered by a bolide impact. A catastrophic drop in planktonic productivity at the K/Pg would affect species up the food chain, including mosasaurs. If mosasaurs, as well as other apical predators such as plesiosaurs, were gradually driven into extinction it is expected that there would be a reduction in abundance, diversity, and biogeographic range of their fossil records well before the K/Pg. Recent researches carried out in Angola, as well as review of other K/Pg boundary sections containing mosasaurs, suggest a possible diversity decline prior to their extinction. Nevertheless, the collapse of marine productivity at the end of the Cretaceous could have been responsible for their total extinction.

The López de Bertodano Formation exposed on Marambio (=Seymour) Island, James Ross Basin, Antarctic Peninsula, represents the highest southern latitude onshore outcrop (~65°S now and during the Late Cretaceous) containing most of the Maastrichtian and the K/Pg transition. Abundant Mosasaurs recovered from this formation offer an opportunity to analyze how the pattern is observed in lower latitudes, that is if the diversity and abundance decrease prior to their total extinction, and therefore could be interpreted as a more global event. In order to test the abundance and diversity of late Maastrichtian mosasaur assemblages in high southern latitudes, paleontological prospecting under the Vertebrate Paleontological programme of the Instituto Antártico Argentino (Dirección Nacional del Antártico and Museo de La Plata, Argentina), were carried out on this formation. Marine reptile collecting efforts were intensified in this island during the last two summer working seasons (CAV 2014 and 2015). We considered the distribution multielement mosasaurs in stratigraphical intervals 2 to 10 corresponding to the informal units (KLB 210) of the López de Bertodano Formation. The K/Pg boundary has been identified by previous authors at the top of KLB 9 unit. Prospecting included also other marine reptiles (i.e. plesiosaurs). Field trips resulted in the discovery of abundant marine reptile remains. Considering only these two field trips, 33 new multielement marine reptile specimens have been identified. From these, 21 correspond to mosasaurs and the rest to plesiosaurs. The most outstanding feature of distribution of these findings is the concentration of skeletal remains at the top of the KLB 8 and base of KLB 9 units. Tooth materials associated with other cranial and postcranial skeletal bones, permit the preliminary identification of some mosasaurs specimens as *Prognathodon* sp; *Mosasaurus* sp, and *Plioplatecarpus* sp. In agreement with the significant abundance of marine reptile fossils, at the top of KLB 8 (paleomagnetic chron C30n) and the base of KLB 9 (paleomagnetic chron C29r), an increase in the diversity of macro invertebrate faunas has also been documented by other authors. Our results suggest that the last episode in the evolutionary history of southern high latitude mosasaurs was not characterized by a decline in their abundance and/or diversity, in turn a rapid extinction concentrated in the last 0.5 million years of the Maastrichtian.



**S20 – 403: Break up of Gondwana and Vertebrate evolution**

***Eocene whales from La Meseta Formation, Marambio (=Seymour) Island, Antarctica***

Marcelo A. Reguero<sup>1</sup>, Marta Fernández<sup>1</sup>,

División Paleontología Vertebrados, Museo De La Plata, Universidad Nacional De La Plata <sup>1</sup>

The La Meseta Formation, Marambio (=Seymour) Island, NE Antarctic Peninsula, (Antarctica) is one of the world's most diverse fossil assemblages of Eocene age which has produced marine and terrestrial mammals. The cetacean fossil record includes specimens of the paraphyletic group of basal whales Archaeoceti, and the oldest archaic toothed mysticete, *Llanocetus denticrenatus*. All these specimens were collected from Cucullaea I allomembers of the La Meseta Formation and Submeseta Formation (middle Late Eocene). In particular, archaeocete records are based on non-specific material collected in the upper levels of the La Meseta Formation and they were tentatively assigned to Basilosauridae. However, some authors suggest that these materials are too fragmentary to be confidently assigned to family level. During the last thirty years the prospecting field work in La Meseta and Submeseta formations of Marambio Island, organized by the Dirección Nacional del Antártico Instituto Antártico Argentino and Museo de La Plata, resulted in the collection of several new cetaceans remains. The goal of this study is carry out a revision of the Antarctic cetaceans deposited in the vertebrate paleontology collections of Museo de La Plata in order to resolve the taxonomic status of these specimens and thereby gain a better understanding of the cetaceans diversity during the Eocene in the Antarctic Peninsula. Specimens recovered from the La Meseta Fm. (early middle Eocene) could only be identified as Cetacea indet. On the contrary, four specimens (represented by isolated cheek teeth and incisor, an incomplete left mandible, a vertebra, and an innominate pelvic bone, respectively) recovered from the Submeseta Formation (late Eocene) can be confidentially referred to Basilosauridae. These results suggest that the global dispersion of basilosaurids occurred at the earliest stages of their evolutionary history.



**S20 – 431: Break up of Gondwana and Vertebrate evolution**

***A Jurassic australosphenidan mammal from India: Implications for mammalian evolution and distribution in former Gondwanaland***

Guntupalli V.R.Prasad<sup>1</sup>, Varun Parmar<sup>2</sup>, Deepak Kumar<sup>2</sup>

Department of Geology, Centre for Advanced Studies, University of Delhi, India<sup>1</sup>, Department of Geology, University of Jammu, India<sup>2</sup>

**Background:** Continental Jurassic sequences have a restricted occurrence world over with most of the known Jurassic mammals reported from the northern, Laurasian continents. Though in recent years intensive field investigations by different research groups in the southern, Gondwanan continents have improved the Jurassic fossil record of these areas, yet a clear picture regarding the evolution of Mesozoic mammals in these continents has not emerged. However, latest discoveries from the Middle Jurassic of Madagascar and middle Late Jurassic of South America have demonstrated that the former Gondwanaland was inhabited by tribosphenic mammals as old as or older than those of Laurasian landmasses. This led to a debate on the centre of origin for tribosphenic mammals with majority favouring Laurasia, while a few based on the new finds from the Jurassic of Gondwanaland considered the latter as a possible place of origin for tribosphenic mammals. Alternatively, it has been suggested that two independent lineages of tribosphenic mammals, viz., Boreosphenida and Australosphenida, had evolved in Laurasia and Gondwanaland, respectively. In India, continental Jurassic strata are well exposed in the Pranhita Godavari valley where they are formally known by the Kota Formation. This formation is a sandstone, clay, mudstone and siltstone sequence intercalated with limestone horizons and is considered as Early/Middle Jurassic in age. In light of discoveries made in the past from this formation, it is expected that a more diversified assemblage of mammals might be discovered from here. Hence, a thorough palaeontological investigation of Kota Formation outcrops was carried out which brought to light a new tribosphenic mammal from the Jurassic of India.

**Objectives:** To report a new tribosphenic mammal represented by a lower molar recovered from the Lower/Middle Jurassic Kota Formation of Pranhita Godavari valley, peninsular India.

**Methods:** Bulk samples of the grey siltstone associated with the limestone bands of Jurassic Kota Formation exposed near Paikasigudem village in Adilabad district, Telangana were collected and disintegrated using kerosene oil-water immersion method. The samples were screen-washed using different sets of sieves in running water. The residue obtained was dried, sieved and sorted under a binocular microscope that resulted in the discovery of the tooth described here. Scanning Electron Micrographs of the tooth were taken with Zeiss EVOMA10 model SEM.

**Results:** Following bulk screen washing of grey siltstone horizon intercalated with the limestone of Kota Formation, an isolated lower molar characterized by the presence of a trigonid and a talonid basin has been recovered. The trigonid of this tooth bears three cusps, the protoconid, the paraconid and the metaconid, arranged in an obtuse-angled triangle. The protoconid is the voluminous cusp of the trigonid, the paraconid and the metaconid are subequal in size. The paraconid is procumbent and slightly labial in position with respect to the metaconid. The trigonid is open lingually. The tooth has a well developed shelf-like, crenulated lingual cingulid that terminates at the mesiolingual base of the paraconid. The talonid is wider than long, not as wide as the trigonid and is closed lingually. The talonid though partly chipped in the region of hypocristid, it has a heavily worn hypoconid and partly broken hypoconulid. A protuberance in the posterolingual border of the talonid seems to represent the entoconid. The hypoflexid is shallow and the cristid obliqua is not preserved.

In possessing an obtuse-angled and lingually open trigonid, a lingual cingulid, low, wider than long talonid, the new specimen compares well with the australosphenidans reported from the Jurassic of



Gondwanan continents. It differs from pretribosphenic holotherians such as *Peramus*, *Holoclemensia* and *Pappotherium*, in the presence of a broad, fully basined talonid, lingually open trigonid, lingual cingulid and absence of distal metacristid. At present Australosphenida lineage includes *Ambondro mahabo* Flynn et al. 1999 from the Middle Jurassic of Madagascar, *Asfaltomylos patagonicus* Rauhut et al. 2002, and *Henosferus molus* Rougier et al. 2007 from the middle Late Jurassic of South America, and *Ausktribosphenos* Rich et al. 1997 and *Bishops* Rich et al. 2001 from the Early Cretaceous of Australia. The closest allies for the Indian specimen among the known australosphenidans are *Ambondro*, *Asfaltomylos* and *Henosferus*. The new Indian tooth differs from the Australian taxa in the absence of additional cristids on the metaconid and talonid. In the absence of distal metacristid and lingual cingulid mesial to the paraconid, and relatively narrow talonid, the Indian specimen differs from *Ambondro*. In these characters, it is closely comparable with lower molar teeth of *Asfaltomylos* and *Henosferus*. But the former has a weakly developed lingual cingulid as compared to its strong development in the Indian tooth. In *Henosferus*, the talonid is slightly wider than the trigonid and the lingual cingulid terminates just mesial to the mesial edge of the metaconid.

**Conclusion:** The new tooth is the first representative of Australosphenida, the southern group of Mesozoic mammals, from India and is the oldest tribosphenic mammal from the Indian subcontinent. The dental morphology of the present tooth though resembles that of australosphenidans in general and thus justifies its referral to this group, there are subtle differences at generic level with known australosphenidan taxa which warrant erection of a new taxon. However, this is deferred until more detailed analysis of the polarity of dental characters of the new tooth is performed. Among the different australosphenidan taxa reported from Gondwanan continents, the tooth most closely resembles the South American *A. patagonicus*. The new specimen together with *A. mahabo* from Madagascar, *A. patagonicus* and *H. molus* from South America represents basal radiation of the Australosphenida lineage in the southern continents. It also indicates that australosphenidan mammals had pan Gondwanan distribution and future discoveries may reveal its presence in Africa and Antarctica as well. The discovery of australosphenidan mammal from the Kota Formation also demonstrates that the scarcity of fossils from the Jurassic of India is an artifact of sampling bias rather than preservational bias.



**S20 – 443: Break up of Gondwana and Vertebrate evolution**

***Gondwanan India: The cradle of origin and early evolution of modern mammals***

Sunil Bajpai

Birbal Sahni Institute of Palaeobotany, Lucknow

India's physical and biotic links following its breakup from the Gondwana supercontinent continue to be debated intensely in the context of geodynamic plate tectonic models. One of the most profound tectonic events in India's geological history was the early Tertiary initiation of collision between the Indian plate and Asia, which saw the gradual shallowing of the Tethys Sea and eventual suturing of the two landmasses. The timing of the initiation of India/Asia collision is hotly contested, with estimates ranging from 65 to 35 Ma. Major biotic events prior to, and during the collision include the origin and radiation of new mammalian communities in the Indian subcontinent, documented in recent years from the Eocene sedimentary sequences in the Surat area of Gujarat, western India and the Subathu Formation of NW Himalaya. A major recent discovery is the earliest Eocene (~55 Ma) terrestrial vertebrate fauna, discovered from the Cambay Shale Formation (~5455 Ma) in several open pit lignite mines around Vastan, District Surat. This fauna came to light largely due to the concerted efforts made by a group of Indian palaeontologists, and it comprises diverse mammalian orders including artiodactyls, perissodactyls, primates, creodonts, condylarths insectivores, apatotherians, proteutherians, rodents, bats and possible marsupials. The Vastan mammal fauna is globally significant from the evolutionary and biogeographic view points because a) it constitutes the oldest stratigraphic record of Cenozoic terrestrial fauna of South Asia, b) it includes all the modern mammalian orders that appeared almost simultaneously across the northern continents during the intense warming interval i.e. the Paleocene-Eocene Thermal Maximum, around 55 Ma, and c) this fauna nearly coincides with the timing of the India Asia collision. The assemblage dates the earliest Cenozoic faunal exchanges between India and Asia and/or northern Africa and Europe. Although the exact route and the timing of these exchanges is not yet resolved, it appears that a subareal contact of some kind was established between these landmasses by ~55 Ma, possibly during the terminal phase of India's northward drift. Most significantly, the fossil data supports the idea of Gondwanan Indian origin (i.e. the Out of India hypothesis) for several modern land mammal orders such as the perissodactyls (i.e. horses) whose antiquity can now be traced phylogenetically to the Indian genus *Cambaytherium*. A similar scenario is suggested for several groups of primates such as the omomyoids, adapoids and possibly even anthropoids, whose origin/early evolutionary history can be traced back to the Indian taxa *Marcgodinotius*, *Vastanomys* and *Anthrasimias*.



**S21 – 145: Key drivers of Antarctic biodiversity through the Cenozoic: the influence of climate, oceanography and tectonics**

***Impact of Late Cretaceous to Paleogene (~70Ma-64Ma) Climate Change on Antarctic Peninsula Vegetation***

J Francis<sup>1</sup>; Bowman V<sup>1</sup>; Askin R<sup>2</sup>; Riding J<sup>3</sup>

British Antarctic Survey, United Kingdom<sup>1</sup>; Jackson, USA<sup>2</sup>; British Geological Survey, United Kingdom<sup>3</sup>

Late Cretaceous climates were relatively cool following mid Cretaceous warmth and may have generated ephemeral ice sheets on Antarctica. Fluctuations in climate significantly influenced biotic change prior to the K-Pg catastrophe, but their nature, magnitude and timing remain controversial. This paper presents a high resolution dataset of terrestrially derived palynomorphs from Antarctica throughout this period of dramatic global change. Specifically, this is a quantitative spore and pollen analysis of an expanded latest Cretaceous to earliest Paleogene (Maastrichtian to earliest Danian) shallow marine sedimentary succession from Seymour Island, off the northeastern tip of the Antarctic Peninsula, then (as now) located at ~65°S. Using modern analogue techniques, we present detailed vegetation, habitat and climate reconstruction for the emergent volcanic arc at this time, with details of small scale climate variability. We demonstrate trends in floral type, which were influenced by changes in atmospheric temperature and humidity. At this time on the coastal lowlands, a cool to warm temperate rainforest is envisaged growing in a riverine landscape, with both wet (river margin, pond) and relatively dry (interfluvium, canopy gap) habitats. Podocarps and southern beech trees grew alongside aromatic angiosperm herbs and shrubs, and high altitude araucarian forests and ericaceous heathland thrived near the tree line. The closest modern flora is the Andean forests of southern Chile and Argentina. Maastrichtian climate fluctuated from cool, humid conditions through a rapid warming ~2 millions years prior to the K-Pg transition, followed by cooling during the earliest Danian. The data provide unprecedented detail from a terrestrial proxy (akin to marine oxygen isotope records), including the recognition of transient warm spells during the latest Maastrichtian.



**S21 – 146: Key drivers of Antarctic biodiversity through the Cenozoic: the influence of climate, oceanography and tectonics**

***Eocene Greenhouse Roots of the Modern Antarctic Marine Fauna***

Crame, J.A.

British Antarctic Survey, United Kingdom

There is a growing volume of evidence to suggest that some key components of the modern Southern Ocean marine fauna have their origin in the Early Cenozoic greenhouse world. This is particularly so of the extensive neogastropod clade that today comprises one of the most diverse elements within the Antarctic marine invertebrate fauna. Re-examination of the critical K/Pg boundary and Early Cenozoic sedimentary sequence exposed on Seymour Island, NE Antarctic Peninsula indicates that a profound change occurred in the neogastropod fauna in the immediate aftermath of the mass extinction event. Here, seven of the 31 neogastropod species present (= 23%) have a distinctly modern aspect, and this trend is continued upwards into Telms 25 of the La Meseta Formation (Middle Eocene) where 22 out of 55 (= 40%) of the neogastropods can be assigned to modern Southern Ocean genera. The first clearcut signs of regional cooling within the Seymour Island section occur at the Telm 5 - 6 boundary and are currently dated as late Middle Eocene (~42 Ma). We are beginning to understand that both biotic reorganisation in the aftermath of the K/Pg mass extinction and a pronounced phase of global warming from Late Paleocene to late Middle Eocene (i.e. ~57 to 42 Ma) were critical to the formation of high latitude as well as low latitude biotas. Many marine invertebrate taxa established in the Eocene greenhouse world were able to adapt to the gradual onset of global cooling and survive through to the present day.



**S21 – 187: Key drivers of Antarctic biodiversity through the Cenozoic: the influence of climate, oceanography and tectonics**

***Preliminary report of the newly found fossil woods from the early Cenozoic tuff deposit at the Barton Peninsula, King George Island, South Shetland Islands, Antarctic Peninsula***

Oh, Changhwan<sup>1</sup>; Woo, Jusun<sup>1</sup>; Park, Tae Yoon S.<sup>1</sup>; Choi, Han-Gu<sup>1</sup>

Korea Polar Research Institute, South Korea<sup>1</sup>

King George Island is a principal fossiliferous locality of South Shetland Islands in Antarctic Peninsula. Fossils of plants, such as leaves, seeds, woods, and pollens of late Cretaceous to Paleogene in age, have been documented from the island. Studies on fossil woods have been focused mostly on the material from the Fildes Peninsula, and few fossil woods have been documented from the Barton Peninsula. During the 2013/14 and 2014/15 Antarctic summer seasons many fossil woods of Paleocene to Eocene age have been newly collected from the Barton Peninsula. The silicified fossils are pebble, cobble, and rarely boulder grade in diameter. Some specimens were embedded in the tuff deposits overlying the Sejong Formation of the Paleocene to Eocene. Other specimens are sharp-edged frequently containing tuff pieces. Several leaf fossils classified as fernlike foliage and angiosperms have been reported from the Sejong Formation. Therefore, the comparison between the palaeoflora of the Sejong Formation and that of the overlying tuff deposit from which fossil woods were collected for this study will be possible in the future. This study will also provide additional assemblage data of the early Cenozoic wood flora of King George Island, which will eventually help understanding the vegetation changes of Antarctic Peninsula during the late Cretaceous to early Cenozoic.



**S21 – 240: Key drivers of Antarctic biodiversity through the Cenozoic: the influence of climate, oceanography and tectonics**

***Molecular Phylogeny in Nacella (Patellogastropoda: Nacellidae) in the Southern Ocean***

Claudio Gonzalez-Wevar<sup>1</sup>; Mathias Hüne<sup>1</sup>; Nicolás Segovia<sup>1</sup>; Hamish Spencer<sup>1</sup>; Steven Chown<sup>1</sup>; Tomoyuki Nakano<sup>1</sup>; Elie Poulin<sup>1</sup>

Gaia Antártica, Conocimiento y Cultura Antártica, Universidad de Magallanes & Instituto de Ecology, Biodiversidad (IEB), Chile<sup>1</sup>

Background: The biogeography of Southern Ocean biota reflects the complex interaction of geological, climatic, oceanographic and biotic elements at different temporal and spatial scales. Here we focus on an important element in the Southern Ocean marine benthic fauna, the limpet genus *Nacella* (Mollusca: Patellogastropoda), which comprises at least 11 species that are currently distributed in Antarctica, South America and several isolated Subantarctic islands.

Objectives: Using mtDNA and nucDNA data together with an integrative biogeography approach, we aim to elucidate the underlying processes involved in producing the current distribution pattern of this widespread marine benthic group. Material and Methods: Here we present the complete phylogenetic reconstructions in *Nacella* using mtDNA and nucDNA sequences, with special emphasis in species from geographically isolated islands (Marion, Kerguelen, Heard, Macquarie and Campbell). At the same time, a new putative species from southern South America was included in the analyses. Relaxed molecular clock analyses were used for COI + Cytb genes using an uncorrelated lognormal (ucln) model the GTR + I + G substitution model. An age prior with a normal distribution was applied to the most recent common ancestor (tmrca) of Nacellidae (mean-38; SD-3.8). Similarly, two age priors within *Nacella* were included: 1) the tmrca of *N. concinna* (mean-5; SD-0.5) based on the oldest fossil record for this species and 2) tmrca of *N. clypeater* (mean, 4, SD, 0.4) based on *N. clypeater* like fossil from southern Peru.

Results: High levels of genetic divergence among Antarctic and Sub Antarctic lineages are evidence of transoceanic historical discontinuities in the genus. Molecular reconstructions recognized two main lineages, the first one includes Antarctic and Sub Antarctic Islands species and the second one comprises South American ones. Divergence time estimates suggest that soon after the origin of *Nacella* during the mid Miocene, the genus was separated in two main lineages that are currently distributed in (1) South America and (2) in Antarctica and Sub Antarctic islands. The separation of these lineages occurred at the end of the Miocene (9 - 5 Ma), long after the physical separation of the continental landmasses. Our analyses identified two subsequent pulses of diversification in the genus, the first of which occurred during the late Miocene when *Nacella* simultaneously separated into four lineages, one in South America, another in Antarctica, and two in the Kerguelen Plateau. Then, a second pulse of diversification during the Pleistocene includes the colonization of remote Sub Antarctic Islands (Marion, Macquarie and Campbell), as well a radiation of the genus in the southern tip of South America.

Discussion: Our results suggest that major periods of climatic and oceanographic change strongly affected the biogeography of *Nacella* and clearly demonstrate both the long and short term influence of the ACC on the distribution of limpet lineages around the Southern Ocean. Our analyses supported the validity of all recognized *Nacella* species, albeit with important corrections to the recorded distribution of some taxa, and permitted the identification of a new species. This work constitutes the most detailed molecular based study of an ecologically important, nearshore invertebrate genus across Antarctica, South America and Sub Antarctic islands and, as such, constitutes an important step to an improved understanding of the rhythms and trends in the diversification of marine benthic fauna around the globally important Southern Ocean.



**S21 – 241: Key drivers of Antarctic biodiversity through the Cenozoic: the influence of climate, oceanography and tectonics**

***Biogeographical patterns in southern ocean Gastropods with contrasting developmental modes***

Claudio Gonzalez-Wevar<sup>1</sup>; Angie Díaz<sup>1</sup>; Mathias Hüene<sup>1</sup>; Sebastian Rosenfeld<sup>1</sup>; Hamish Spencer<sup>1</sup>; Thomas Saucède<sup>1</sup>; Andrés Mansilla<sup>1</sup>; Elie Poulin<sup>1</sup>

GAIA-Antartica, Universidad de Magallanes & Instituto de Ecology Biodiversidad (IEB), Chile<sup>1</sup>

Background: The evolution of the Southern Ocean marine benthic fauna and its biogeography is the result of complex interactions between abiotic and biotic elements in space and time. Continental drift and major gateway openings shaped past and present oceanographic circulation in this region. The Antarctic Circumpolar Current (ACC), delimited by two main boundaries (the Antarctic Polar Front and the Subantarctic Front), plays a major role in the biogeography of the Southern Ocean. On one hand, the ACC represents an important barrier for many invertebrate taxa between Antarctic and subAntarctic areas. On the other hand, the ACC can transport organisms between geographically distant subAntarctic areas, especially in those species with high active and passive dispersive potential. Recent biogeographical reviews recognized the high level of endemism of the Antarctic biota, as well as the marked differentiation among subAntarctic, low Antarctic and Antarctic/high Antarctic marine species.

Objectives: Here we present new biogeographical comparisons based on mtDNA sequences among provinces of the Southern Ocean (Antarctica, South America, and subAntarctic Kerguelen Island) in different groups of marine benthic mollusks. For this purpose, we selected different gastropod genera with contrasting developmental modes including brooders (*Neobuccinum*, *Trophonella*, *Margarella*, *Kerguelenella*; *Siphonaria*) and broadcasters (*Nacella* and *Yoldia*). Material and Methods: Partial fragments of the mitochondrial genes Cytochrome c Oxidase Subunit I (COI) and Cytochrome b (Cytb) were amplified in populations of the selected analyzed groups from South America, Antarctica, Kerguelen Island. We estimated the average number of nucleotide substitutions and calculated the pairwise percent of divergence (uncorrected pdistances) between lineages of the analyzed provinces. We determine whether the evolutionary rate was constant in the different analyzed taxa using a likelihood ratio test and we performed divergence time estimations among the analyzed groups using a strict Molecular Clock Hypothesis (MCH) and specific substitution rates. Finally, we constructed Median joining genealogical relationships.

Results: Most of analyzed groups (*Nacella*, *Neobuccinum*, *Margarella*, and *Trophonella*) exhibited a high degree of genetic divergence between Antarctic and Subantarctic provinces. Divergence time estimations suggest a separation in these groups for more than 5 million years ago. In *Nacella* and *Trophonella* we detected two main lineages. The first lineage includes species from Antarctica and SubAntarctic islands and the second one those species from South America. In contrast, and surprisingly some of the brooders including *Margarella* and *Kerguelenella lateralis* showed a high degree of genetic cohesiveness among geographically distant subAntarctic areas (South America and Kerguelen Island), showing the importance of long distance dispersal by rafting in the biogeography of these genera.

Conclusions: This study presents new information about the patterns of genetic differentiation between marine organisms of Antarctica and Subantarctica. Divergence time estimations derived from this study indicate that the effective separation between Antarctic and Subantarctic taxa, especially for groups with dispersive potential, occurred between 3.7 and 14.5 Ma, long after the physical separation of these continents and the initiation of the ACC. The separation between lineages of these provinces of the Southern Ocean occurred during the MioPliocene, long after the physical separation of these continents. In this scheme, the geodynamic evolution of Scotia Arc, and particularly the establishment of a full deep ACC after the cessation of central Scotia Sea arc activity and its submergence may represent a major driver of the isolation of marine Antarctic fauna. Finally, the current biogeographical patterns in Southern



## *XII International Symposium on Antarctic Earth Sciences*

*13 - 17 July 2015, Goa, India*



Ocean mollusks are not related to particular taxa but to historical oceanographic/climatic processes, as well as contemporary ones including the likelihood of long distance dispersal.



**S21 – 242: Key drivers of Antarctic biodiversity through the Cenozoic: the influence of climate, oceanography and tectonics**

**Recent Diversification of *Harpagifer* (Perciformes: Notothenioidei) in the Southern Ocean**

Elie Poulin<sup>1</sup>; Mathias Hüene<sup>1</sup>; Javier Naretto<sup>1</sup>; Jean Pierre Feral<sup>1</sup>; Claudio González-Wevar<sup>1</sup>

Gaia-Antartica, Conocimiento y Cultura Antártica, Universidad de Magallanes & Instituto de Ecology Biodiversidad (IEB), Chile<sup>1</sup>

Background: The evolution of the marine benthic fauna in the Southern Ocean has been shaped by geological and climatic atmospheric factors such as the geographic isolation of the Antarctic continent and the subsequent installation of the Antarctic Circumpolar Current (ACC). Recent studies in different taxa have shown, for example, that shallow benthic organisms with long larval stages maintained contact after the physical separation of the continents and divergence may be associated with the intensification of the ACC in the late Miocene to early Pliocene.

Objectives: We performed phylogenetic reconstructions and estimated the level of molecular divergence between congeneric species of *Harpagifer*, a marine notothenioid from the Antarctic Peninsula (*Harpagifer antarcticus*), Marion Island (*H. marionensis*), Kerguelen Island (*H. kerguelenensis* and *H. spinosus*), South Georgia Island (*H. georgianus*) and Patagonia (*H. bispinis*) using the mitochondrial control region (Dloop). Material and Methods: A partial fragment of the Control Region was amplified in species of *Harpagifer* using specific primers. Phylogenetic reconstructions were performed using Maximum Parsimony (MP) and Bayesian Inference (BI), while the divergence time estimations in the evolution of *Harpagifer* were calculated following a relaxed Bayesian approach and assuming a strict molecular clock hypothesis.

Results: Molecular reconstructions recognized two main lineages in the evolution of *Harpagifer*. The first one includes *H. bispinis* from South America while the second one includes the rest of the analyzed species from Antarctica (*H. antarcticus*), South Georgia (*H. georgianus*), Kerguelen (*H. kerguelenensis* and *H. spinosus*), and Marion islands (*H. marionensis*). In fact, the reciprocal monophyly within the species conforming the second lineage was not fully recovered. The divergence between *H. bispinis* and the rest of the species is more recent than expected under a vicariant hypothesis.

Conclusions: We propose that climatic and oceanographic changes during the coldest periods of the Quaternary (i.e., Great Patagonian Glaciation, 1-0.9 Ma) and the northward migration of the Antarctic Polar Front may have enhanced the colonization of *Harpagifer* from Antarctica to Sub-antarctic areas of the Southern Ocean including South America and sub-Antarctic Islands.



**S21 – 281: Key drivers of Antarctic biodiversity through the Cenozoic: The influence of climate, oceanography and tectonics**

***Complex Marine Invertebrate Recovery in Antarctica after the Cretaceous – Paleogene Mass Extinction***

Whittle R. J.<sup>1</sup>; Witts J. D.<sup>2</sup>; Bowman V.<sup>1</sup>; Crame J.A.<sup>1</sup>; Ineson J.<sup>3</sup>; Francis J.E.<sup>1</sup>

British Antarctic Survey, Cambridge, UK<sup>1</sup>; School of Earth and Environment, University of Leeds, Leeds, UK<sup>2</sup>; Geological Survey of Denmark and Greenland (GEUS), Copenhagen, Denmark<sup>3</sup>

The modern Antarctic marine fauna evolved following the Cretaceous-Paleogene (K–Pg) mass extinction event (66 Ma), although details of high latitude biotic recovery in the immediate aftermath are relatively unknown. New extensive collections of macrofossils from Seymour Island (northeast Antarctic Peninsula) have now revealed a complex recovery history within the invertebrate community at southern high latitudes that may have lasted up to 10 million years.

An exceptional (over 2000 m thick) latest Cretaceous to Eocene shallow – marginal marine sedimentary sequence is exposed on Seymour Island, located then and now at ~65°S. The López de Bertodano Formation (uppermost Cretaceous to lowermost Paleocene) contains the K–Pg boundary (identified using biostratigraphy and an iridium anomaly) and is overlain by the Sobral Formation (Paleocene), the Cross Valley Formation (?Late Paleocene) and the La Meseta Formation (Eocene). This study has analyzed the taxonomy, ecology and biostratigraphy of almost 4500 macrofossils, tied to stratigraphic sections throughout this expanded sequence.

The extinction did not affect all ecological groups in the same manner, with epifaunal (living on sea floor) and nektonic (swimming) invertebrates most impacted. This led to an unusual shallow infaunal (living beneath the sea floor) mollusc community dominating marine invertebrate life in Antarctica for ~300,000 years following the extinction event. This low diversity community from the uppermost López de Bertodano Formation exhibited different trophic levels, including deposit feeders, suspension feeders and predators. Many of these infaunal molluscs continued to form a dominant component of the invertebrate community for almost 2 Myrs. A radiation of new molluscan taxa occurred between approximately 65.5 and 65.0 Ma, with an increase in infaunal and epifaunal carnivorous neogastropod species filling vacant ecospace left after the extinction. However predatory nektonic invertebrates are only found again within the La Meseta Formation, at least 10 Myrs after the K–Pg extinction event. Our results suggest that faunal recovery from this mass extinction was a long and complex process that set the stage for the modern Antarctic fauna.



**S21 – 354: Key drivers of Antarctic biodiversity through the Cenozoic: The influence of climate, oceanography and tectonics**

***Bridging the Gap: Otoliths from the Eocene of Seymour Island, Antarctica, Reveal Predominance of Gadiform Fishes (Teleostei)***

Werner Schwarzhans<sup>1</sup>; Kriwet, J.<sup>2</sup>; Mörs, T.<sup>3</sup>; Engelbrecht, A.<sup>2</sup>; Reguero, M.<sup>4</sup>

Natural History Museum of Denmark, Copenhagen, Denmark<sup>1</sup>; Department Of Palaeontology, University Of Vienna<sup>2</sup>; Department Of Palaeobiology, Swedish Museum Of Natural History, Stockholm, Sweden<sup>3</sup>; División Paleontología Vertebrados, Museo de La Plata, Universidad Nacional de La Plata, Paseo del Bosque s/n., B1900FWA, La Plata, Argentina<sup>4</sup>

We present here the first record of fossil otoliths from Antarctica, which were obtained from late Early Eocene shell beds of the La Meseta Formation, Seymour Island. They represent teleosteans of warm to temperate marine environments in Antarctica prior to the onset of the cooling during Late Eocene and later glaciation. Preservation of the aragonitic otoliths has suffered from the extreme climate on the Antarctic Peninsula alternating between freezing and thawing times, and hence only a small number of otoliths obtained warrant detailed examination. A total of 17 otolith-based teleost taxa are recognized, with 10 being identifiable to species level containing nine new species. One species also is known from the Late Eocene of Southern Australia and another species is widespread in the southern oceans of Eocene time and recorded from New Zealand, South Australia and now Antarctica.

The otolith assemblage shows a typical composition of temperate fishes dominated by gadiforms, very similar on genus and family levels to the associations known from younger Eocene strata of New Zealand and South Australia, but also to the temperate northern hemisphere association from the Paleocene of Denmark. Thus, the Seymour Island fauna bridges a gap in the record of global temperate marine teleost faunas during the Early Eocene climate maximum. The dominant gadiforms are interpreted as the main temperate faunal component, as they do in the Paleocene of Denmark. The Seymour gadiforms are represented by the families Moridae, Merlucciidae (Macruroninae), Macrouridae and Gadidae. Moridae, Macruroninae and Macrouridae are nowadays lower shelf to deep-water or mesopelagic fishes with Macruroninae restricted to the Southern Oceans. Gadidae today are predominantly northern hemisphere temperate fishes with only few southern hemisphere species assumed to be the result of relatively recent migration. Their occurrence in the early Eocene of Antarctica indicates that faunal exchange of temperate fishes occurred as well in the geological past at times. The extant endemic Antarctic gadiform family Muraenolepididae is missing, as are today's prime Antarctic fishes of the perciform suborder Notothenioidei. There has been much recent debate on few isolated skull and jaw bones of teleost fishes found in the La Meseta Formation and whether they would represent gadiforms (Merlucciidae in this case) or some early, plesiomorphic notothenioids. Otoliths are known to often complement skeleton finds rather than duplicate. With this in mind we conclude that our otolith data support the presence (in fact dominance) of gadiforms in the Eocene of Antarctica while it does not necessarily rule out the presence of notothenioids at the same time.



**S21 – 416: Key drivers of Antarctic biodiversity through the Cenozoic: The influence of climate, oceanography and tectonics**

***The Cenozoic Cooling Effect on the Bivalves from West Antarctica: A Miocene Episode***

Quaglio F<sup>1</sup>; Whittle R<sup>2</sup>; Griffiths H<sup>2</sup>; Nihei S<sup>3</sup>; Linse K<sup>2</sup>; Gaździcki A<sup>4</sup>; Simões MG<sup>5</sup>

Instituto de Geociências e Ciências Exatas, Universidade Estadual Paulista, Av. 24 A, 1515, 13506-900, Rio Claro, SP, Brazil<sup>1</sup>; British Antarctic Survey, Madingley Road, High Cross, Cambridge, Cambridgeshire, CB3 0ET, United Kingdom<sup>2</sup>; Instituto de Biociências, Universidade de São Paulo, Rua do Matao, Travessa 14 101, Cidade Universitária, 05508 900 São Paulo, SP Brazil<sup>3</sup>; Instytut Paleobiologii PAN, Twarda 51/55, 00-818, Warszawa, Poland<sup>4</sup>; Instituto de Biociências, Universidade Estadual Paulista, 18618-000, Botucatu, SP, Brazil<sup>5</sup>

The Antarctic cooling (~ 37Ma) epitomizes one of the most important climate changes in the Earth's history. Although the triggering mechanism is under debate, it is believed that the marine southern biota was deeply affected by several episodes of glaciation during the Cenozoic. The Cape Melville Formation (CMF) is the only unit in West Antarctica preserving an important fossil record of this Cenozoic glacial history. Hence, its fossil content can be used in order to investigate how marine faunas responded to climatic changes that shaped the modern southern biota. Cropping out along the Melville Peninsula of the King George Island, it comprises the youngest unit of the Moby Dick Group and consists of a 150m thick succession of diamictites and muddy sandstones and mudstones, as well as silty sandstones and sandy siltstones. It was interpreted as a glaciomarine succession that records a maximum glacial event at the base followed by a glacial retreat with distal glaciomarine facies at the top. Available dating methods indicated early Miocene for the upper part of the unit (22.6 Ma). This upper part is the most fossiliferous level, interpreted as deposited during a glacial retreat in a distal marine, hemipelagic environment. This level richly preserves in situ and spatially averaged assemblages of crustaceans, gastropods, bivalves, corals, diatoms, dinoflagellate cysts, fish remains, ichnofossils and reworked Cretaceous belemnites. Molluscs are the most diverse and abundant group in the unit and their taxonomy, paleoecology and paleobiogeography are under study over the last decade. Twelve bivalve genera are recorded in the CMF, including three new bivalve taxa. We analyzed the paleobiogeographic distribution of all identified genera from the CMF along the Cenozoic in the southern oceans. Previous ideas suggest that a shallow marine paleobiogeographic province the 'Weddellian Province' would have existed in the southernmost region from the Cretaceous to the Eocene encompassing the southern Australia, Antarctica, New Zealand and southern South America. The marine fauna of the CMF would have witnessed a scenario of post Weddellian province breakup, in which extensive glaciations caused nearshore taxa to extinct during the Cenozoic. As a result, those taxa would have been restricted to Subantarctic areas until the present day. Recent palaeoecological analysis revealed that the CMF had a possible community structure much similar to the modern benthic community of southern South America, instead of that found in modern Antarctic waters. This corroborates the hypothesis of the Antarctic periphery as a refugium for shallow benthic Neogene forms. In this work, we found that the shallow shelf forms from the CMF were extinct from Antarctic waters after early Miocene or even early Pliocene. The extinctions would have occurred after the expansion of ice shelves, during the Plio-Pleistocene glaciation event. Those Cape Melville genera currently living in Antarctic comprise eurybathic representatives that were not affected by the iceshelf advance during Neogene, with several present day species also thriving in Antarctic periphery. This agrees in some aspects with previous scenarios of extinctions occurring through the Cenozoic, related to the longterm Cenozoic glacial history of Antarctica. They are linked to the long term Cenozoic glacial history of Antarctica and include the Miocene glaciation as an important extinction agent that contributed to the faunal impoverishment in the marine realm. Our data indicate an important extinction event occurred after the extensive glaciation of the Plio-Pleistocene. Those genera currently living in the Antarctic are highly diverse, with several species thriving also in Antarctic periphery.

On the other hand, exclusive Subantarctic genera have much lower species richness and represent relict



taxa that formerly were widespread in Cenozoic southern oceans. It is important to consider that the continental and marine realms had multiple biotic responses, including both flora and fauna, vertebrate and invertebrate taxa. Regarding this, detailed studies must be done for different taxonomic groups in order to access as many as possible distinct biotic responses occurred following one of the most important climate changes in the Earth's history.



**S21 – 426: Key drivers of Antarctic biodiversity through the Cenozoic: The influence of climate, oceanography and tectonics**

***Structure and Function of Fungi in Antarctic Lake Ice***

Priyanka Kudalkar<sup>1</sup>; John Priscu<sup>2</sup>

Montana State University, Bozeman, USA<sup>1</sup>; Advisor<sup>2</sup>

The permanently ice covered lakes of Antarctica harbor a diverse group of microbes that live in unique liquid water habitats. These Dry Valley lakes have a long geological history and the lake ice hosts microbial communities that are unique to this environment. My research focuses on the functional role of fungi in the permanent ice covers of lakes in the McMurdo Dry Valleys. Fungi form a substantial part of this microbial community that greatly influences the dynamics of the icy ecosystem. Laboratory cultures obtained from ice cores taken from selected lakes were tested for growth characteristics under various temperature and nutrient regimes. Partial ITS DNA sequencing was used to screen for functional genes and to identify novel fungal types unique to this region of Antarctica. Our results show that axenic cultures were successfully obtained from the permanent ice cover of the lake ice. Temperature experiments revealed that these organisms were psychrotolerant and grew most rapidly at 20°C. In addition, the isolated organisms possess antifungal activity that has not been previously reported from fungi isolated from Antarctic lake ice. Results from the study will be the first to address the structure and function of fungi in these subzero habitats and the potential for eukaryotic life to exist in icy worlds beyond Earth.



**S21 – 448: Key drivers of Antarctic biodiversity through the Cenozoic: The influence of climate, oceanography and tectonics**

***Biological Persistence through Multiple Glacial Cycles in the Antarctic?***

Convey, P

British Antarctic Survey, United Kingdom

**Background:** It is clear that most currently ice free ground in Antarctica would have been covered and scoured by glacial advances at the Last Glacial Maximum or previous maxima. This has led to a widely held but until recently little tested hypothesis that most life now present on land in Antarctica must have colonized the region relatively recently, and in particular after the Last Glacial Maximum. However, while an increasing number of biological studies in the last decade have drawn conclusions of (very) long term persistence that are inconsistent with this hypothesis, life on land in Antarctica is still surprisingly poorly known in detail. Thus, the generality of these conclusions have not yet been possible to establish with certainty.

**Objectives:** To provide an up to date overview of the state of biodiversity and biogeographic knowledge of the contemporary terrestrial biota of Antarctica, placed in the context of the timescales of its evolution and presence in the region.

**Methods:** This study is a synthesis, across the contemporary biological diversity and regions of Antarctica, of recent classical biogeographic and molecular phylogeographic studies relating to the evolutionary history of life on land in Antarctica on multimillion year timescales.

**Results:** The availability of new baseline biological survey data obtained over the last decade, combined with modern molecular biological analyses, have made it clear that long term persistence and regional isolation typify Antarctica's terrestrial biota. This biota is dominated by cryptogams (lower plants, lichens), micro arthropods (mites, springtails) and other micro invertebrates (nematodes, tardigrades, rotifers), and eukaryotic and prokaryotic microbial groups. Studies of all multicellular groups now show strong evidence of long term presence in Antarctica, the most recent of these relating to the mosses, previously the only group of macroscopic organisms thought to show endemism patterns consistent with recent colonisation (mosses are well known to produce aerially dispersing spores). Various microbial groups are also thought to have high capacity for long distance aerial dispersal and hence the Antarctic microbial flora was expected to be reasonably homogeneous with that of other lower latitude regions. However, increasingly, microbial studies are identifying clear and strong evidence of long term evolution and diversification in representatives of various groups of microbes, as well as presence of the more expected cosmopolitan representatives.

**Conclusion:** As well as creating a new paradigm in which to consider the evolution and adaptation of Antarctic terrestrial biota, this body of work opens important new cross disciplinary linkages in the fields of understanding the geological and glaciological history of the continent itself, and of the climatic and oceanographic processes that can both lead to isolation and support colonisation. This new and more complex understanding of Antarctic biogeography also provides important practical challenges for management and conservation in the region, as required under the Antarctic Treaty System.



**S21 – 460: Key drivers of Antarctic biodiversity through the Cenozoic: The influence of climate, oceanography and tectonics**

***Next Generation Sequencing of Glacial Ice Environmental DNA from North Greenland Ice Core Project***

Ajeeth Adhikari<sup>1</sup>; P Buford Price<sup>1</sup>; Ryan C Bay<sup>1</sup>; Eske Wilerslev<sup>2</sup>; Eddy Rubin<sup>3</sup>; Adam Rivers<sup>3</sup>; Mikkel Winther Pedersen<sup>2</sup>

University of California, Berkeley, United State<sup>1</sup>; Centre for GeoGenetics, Copenhagen<sup>2</sup>; DOE Department of Energy Joint Genome Institute, Walnut Creek, California, USA<sup>3</sup>

**Background:** Aeolian mechanisms transport an immense quantity of microbes worldwide, and polar environments are no exception. Microbes continuously deposit onto polar environments and over time due to snowfall become buried and entombed in networks of liquid water veins within solid ice. Price et. al. has shown previously the preservation of these cells and their genetic material within glacial ice environments, but a more thorough analysis of these bacteria has been out of reach until recent developments in genomics and next generation sequencing.

The North Greenlandic Ice Core Project was completed its goal in 2003 to obtain ice cores dating back to the Eemian period from the center of Greenland. The pristine condition of the ancient ice cores together with modern advances in DNA extraction and sequencing technologies provide an unprecedented opportunity to explore the microbiology of the Arctic, and provide insight on bacterial communities and taxa ranging back to over 100 kya.

**Objectives:** We seek to study the phylogenetic and metabolic potential of the glacial ice core microbiomes of Greenland as far back as 100,000 years. By studying 7 different depths (130m, 253m, 1297m, 1727m, 2049m, 2640m, and 2868m) using modern methodologies in low biomass environmental metagenomics, we hope to shed light on the evolution of microbial species deposited from widespread sources and found within glacial ice. Furthermore, we seek to understand factors contributing to the preservation of nucleic acids over geologically relevant time scales.

**Methods:** All seven core sections were decontaminated using iterative bleach and sterile water ablation under laminar flow hood to remove the outer centimetre of core section exposed to contamination via drilling, handling, transportation, and storage. All further work took place in ultraclean laboratories of the Center for Geo Genetics in Copenhagen, Denmark, which maintains state of the art ancient DNA facilities. Moreover, all surfaces and equipment were treated with either wiped with bleach or exposed to UV irradiation prior to use, and all reagents were filtered to remove contaminants. Negative controls were processed in parallel to samples at every step.

Following ice core melting, centrifugation was used to separate particulate from soluble biomolecules of interest, and both supernatant and retentate were subject to ultraclean DNA extraction. Retentate was subject to alkaline lysis and mechanical agitation followed by filtration by size exclusion centrifugation, while supernatant was subject solely to size exclusion centrifugation. Nucleic acids were quantified if possible by fluorometry using the Qubit dsDNA High Sensitivity Assay (Life Technologies Inc.).

Nucleic acid extracts were used for genomic library preparation using NEBNext kits (New England Biolabs, Inc.) and sequencing on the HiSeq 2000 and MiSeq (Illumina, Inc.) This generated 593,000 reads that were subject to annotation against RefSeq with Rapsearch2. All the reads were mapped against reference genomes to search for high and consistent coverage using bbmap. Sequences were tested for authenticity by observing for damage patterns consistent with post mortem fragmentation and by analysis by a relative rates test assuming a stochastic molecular clock. All samples were processed in parallel with negative controls.



Cell density from ice cores was enumerated using flow cytometry on the LSR Fortessa Flow Cytometer (BD Biosciences, Inc.) using a cell permeant Hoechst 33342 stain (Life Technologies, Inc.).

**Results and Conclusion:** Cell densities by flow cytometry revealed a typical cell density on the order of  $\sim 10^3$ , with the highest density reaching up to over 5000 cells/mL. This remained roughly consistent with DNA concentrations for selected depths quantifiable by fluorimetry.

RefSeq annotations of our shotgun metagenome revealed that just a few taxa were dominant at all depths in the ice core. MapDamage indicated sequences contained damage patterns consistent with post-mortem fragmentation. The alphaproteobacterium *Bradyrhizobium* sp. DFC11 recruited the most reads. Mapping against pathogenic nitrogenfixer recruited the most reads. Mapping against pathogenic nitrogenfixer *Bradyrhizobium* with bmap revealed high and consistent coverage across the reference genome. Other taxa that recruited reads from all depths included *Herbaspirillum*, *Afipia*, and *Ralstonia pickettii*. Interestingly, *Bradyrhizobium* sequences and cultured isolates have been reported by several other research groups studying the biology of the Greenland ice sheet, indicating a potential biochemical significance of these nitrogenfixing microbes.



**S22 – 5: New Frontiers in Remote Sensing in Antarctic Earth Sciences: Cross-disciplinary advances**

***Very High Resolution Satellite Imagery for Cryospheric Geospatial and Geoscientific Information Extraction***

Shridhar D. Jawak<sup>1</sup>; Alvarinho J. Luis<sup>1</sup>

Earth System Science Organization (ESSO), National Centre for Antarctic and Ocean Research (NCAOR), Govt. of India, Headland Sada, Vasco-da-Gama, Goa, India<sup>1</sup>

The study discusses the design and implementation of novel methods to extract essential for semi-automatic extraction of geo-scientific information in cryospheric environments by using very high resolution (VHR) WorldView-2 (WV-2) satellite data the main rationale of this study is to explore the varied applications of VHR imagery in Antarctic earth sciences. We focus on three novel methods developed for such information extraction; (a) an ensemble classification approach for land cover mapping, (b) spectral index ratio-based information mining, and (c) lake feature extraction using novel normalized difference water index (NDWI). The study evaluates the range of applications of spectral remote sensing for rapid information extraction, which would be useful for various polar research applications such as glaciology, environmental and land-cover change monitoring, limnology studies, supraglacial processes, etc. Nevertheless, the semi-automatically extracted information would also be useful for planning Antarctic logistic activities and for providing advisories for safe field campaigns. The study also evaluates 8-band image data as an influential tool for satellite image classification and consequent land cover mapping in Antarctic environment. This research provides new facets to image processing technology. The results indicate that the use of the novel methods on 8-band WV-2 data can significantly improve the semiautomatic extraction of cryospheric features, which can ultimately contribute to an enhanced perceptive of the Antarctic geospatial information in the context of climate change.



**S22 – 6: New Frontiers in Remote Sensing in Antarctic Earth Sciences: Cross-disciplinary advances**

***Interactive Synthesis of Photogrammetry, Laser Altimetry, and Radar Altimetry to Generate Precise DEMs in the Antarctic Environment***

Shridhar D. Jawak<sup>1</sup>; Alvarinho J. Luis<sup>1</sup>

Earth System Science Organization (ESSO), National Centre for Antarctic and Ocean Research (NCAOR), Govt. of India, Headland Sada, Vasco-da-Gama, Goa, India<sup>1</sup>

Existing digital elevation models (DEMs) of Antarctic region in the Antarctic digital database (ADD) indicate elevation variations of up to hundreds of meters, which necessitates the construction of local DEMs. The present study focuses on the achieved improvements in construction of accurate DEMs by fusing multi-sensor, multisource, multitemporal, and multi-technological elevation datasets. The study focuses on two spatially different study regions, (a) Larsemann hills and environ and (b) Schirmacher oasis and environ, where India's Antarctic research stations are established. The study focuses on synergetic fusion of three sensor technologies, (a) photogrammetry, (b) laser altimetry, and (c) radar altimetry. The constructed DEMs were evaluated using differential global positioning system (DGPS) validation points. We also analyzed a suite of interpolation methods for constructing DEMs from multitemporal and multi-technology derived point elevation datasets, in order to determine the level of confidence with which the interpolation techniques can generate a better interpolated continuous surface, and eventually improve the elevation accuracy of DEMs from synergistically fused datasets. This is one of the first international attempts of fusing multitemporal, multisensory and multisource elevation data to generate a DEM of any part of Antarctica, in order to address the ice elevation change and the ice mass balance. This research experiment demonstrates the stability (w.r.t. multitemporal datasets), performance (w.r.t. best interpolation technique) and consistency (w.r.t. all the experimented interpolation techniques) of synergistically fused DEMs over existing DEMs. On the basis of error analyses, the newly constructed DEMs may serve as a benchmark for future elevation models such as from the ICESAT-II mission to spatially monitor ice sheet elevation. Our approach focuses on the strengths of each elevation data source to produce an accurate elevation model.



**S22 – 7: New Frontiers in Remote Sensing in Antarctic Earth Sciences: Cross-disciplinary advances**

***Evaluating Uncertainty Estimates for Kriging Interpolation Using Space-Borne LiDAR Data for Derivation of Digital Elevation Models in Cryospheric Landscape***

Shridhar D. Jawak<sup>1</sup>; Pranita Sambhus<sup>2</sup>; Alvarinho J. Luis<sup>1</sup>

Earth System Science Organization (ESSO), National Centre for Antarctic and Ocean Research (NCAOR), Govt. of India, Headland Sada, Vasco-da-Gama, Goa, India<sup>1</sup>; Geoinformatics Department, Sinhgad College of Science under University of Pune, Ambegaon Bk, Pune, India<sup>2</sup>

This research examines the applicability of four multivariate geostatistical techniques: ordinary kriging (OK), simple kriging (SK), disjunctive kriging (DK), and universal kriging (UK), to assess the uncertainty in estimates for the derivation of digital elevation models (DEM) for the Larsemann Hills region, east Antarctica. Five distinctly different semivariogram models – circular, exponential, gaussian, rational quadratic, and K-bessel – were used for analyzing the performance of aforementioned kriging methods. The test experiment was conducted by using three data sources: satellite-derived laser altimetry data (GLAS/ICESat), Radarsat Antarctic Mapping Project (RAMPv2) DEM-based point elevation dataset, and contour-derived point elevation dataset. Cross validation was used to compare the prediction performances and to ascertain the uncertainty in estimates of the geostatistical interpolation algorithms and semivariogram models using a set of 20 differential global positioning system (DGPS) points. Success of the four methods was evaluated based the difference between the DGPS elevation and the interpolated elevation expressed in terms of root mean square error (RMSE). Based on the RMSE, the overall accuracy of the kriging methods for generating interpolated surface can be ranked as: DK > OK > SK > UK. Quantitative assessment of the continuous surfaces indicates a significant difference (2 to 14 m) between the accuracy of the five semivariogram models. All the kriging methods worked best when coupled with exponential semivariogram model. The accuracy of semivariogram models used for conducting kriging ranked as: exponential > gaussian > rational quadratic > K-bessel > circular. This work suggests that the DK technique for RAMP (RMSE: 7.67 m) and contour point interpolation (RMSE: 10.06 m) and the OK method (RMSE: 15.86 m) for GLAS/ICESat interpolation provide the most accurate elevation surface when compared to other geostatistical techniques in the given cohort.



**S22 – 8: New Frontiers in Remote Sensing in Antarctic Earth Sciences: Cross-disciplinary advances**

***RISAT-1 C-Band Dual Polarimetric SAR Imagery for Classification of Cryospheric Features in the Antarctic Environment***

Shridhar D. Jawak<sup>1</sup>; Satej N. Panditrao<sup>2</sup>; Alvarinho J. Luis<sup>1</sup>

Earth System Science Organization (ESSO), National Centre for Antarctic and Ocean Research (NCAOR), Govt. of India, Headland Sada, Vasco-da-Gama, Goa, India<sup>1</sup>; Indian National Centre for Ocean Information Services, Earth System Science Organization (ESSO), Ministry of Earth Sciences, Government of India, Ocean Valley, Hyderabad, India<sup>2</sup>

Land cover classification is one of the widely used applications in the field of remote sensing. Accurate land cover maps derived from remotely sensed data is the major requirement for many geoscientific applications in polar regions. The present study explores the capabilities of C-band dual polarimetric (HH & HV) level1 SAR image data from Indian Radar Imaging Satellite (RISAT-1) for land cover feature mapping around Larsemann Hills and Schirmacher oasis, Antarctica. We used RISAT-1 Fine Resolution STRIPMAP (FRS-1) mode data having 3m spatial resolution. In order to increase the amount of information in dual polarized RISAT SAR data, a band HH+HV was introduced to make use of the original two polarizations. Transformed divergence (TD) procedure for class separability analysis was performed to evaluate the quality of the statistics prior to image classification along with data calibration. For most of the class pairs the TD values were comparative, which indicates that the classes have good separability. Nonparametric classifier Support Vector Machine (SVM) was used to classify RISAT1 data with optimized polarization combination into three land cover classes consisting of sea ice/snow/ice, rocks/landmass, and lakes/waterbodies. This study demonstrates that C-band FRS1 image mode data from RISAT1 mission can be exploited to identify, map and monitor land cover features in the polar regions, even in the dark winter period. The final results based on the SAR backscattered information will be presented during the conference, which is crucial in discriminating and delineating the land cover features.



**S22 – 9: New Frontiers in Remote Sensing in Antarctic Earth Sciences: Cross-disciplinary advances**

***Explorative NDWI as an Innovative Tool for Semiautomated Extraction of Antarctic Lakes***

Shridhar D. Jawak<sup>1</sup>, Kamana Kulkarni<sup>2</sup>, Alvarinho J. Luis<sup>1</sup>

Earth System Science Organization (ESSO), National Centre for Antarctic and Ocean Research, Govt. of India, Headland Sada, Vasco-da-Gama, Goa, India<sup>1</sup>; School of Electronics, Devi Ahilya University, Indore, Madhya Pradesh, India<sup>2</sup>

The present study deals with numerous normalized difference water index (NDWI) methods to extract lakes from Schirmacher Oasis, Antarctica, by using a very high resolution WorldView-2 (WV-2) satellite imagery. Schirmacher oasis region hosts a number of fresh water as well as saline water lakes, such as, epishelf lakes, open or landlocked lakes, which are completely frozen and semi-frozen. Hence, detecting all these lakes distinctly on satellite imagery was the major challenge as the spectral characteristics of various types of lakes were identical to the other land cover targets. Multiband spectral index pixel-based approach is most experimented and recently growing technique because of its unbeatable advantages such as its simplicity, comparatively lesser amount of processing-time needed than that required by target detection, classification or other feature extraction techniques, easily modifiable as per the requirement of feature to be extracted. In present study, semiautomatic extraction of lakes in cryospheric region was carried out by designing specific NDWI models that would yield the minimum false positives and increase the overall accuracy. The study utilized number of existing spectral indices to extract lakes but none could deliver satisfactory results and hence we explored new NDWI methods that would meet our expectation. The potentials of newly added bands in WV-2 satellite imagery was explored by developing spectral indices comprising of Yellow (585 – 625 nm) band in combination with Blue (450 – 510 nm), Coastal (400 – 450 nm) and Green (510 – 580 nm) bands. In this study, for extraction of frozen lakes by using Yellow (585 – 625 nm) and near-infrared 2 (NIR2) band pair and Yellow and Green band pair worked well, whereas for open lakes extraction, combination of Blue and Coastal band yielded appreciable results which when compared with manually digitized data provided a good match. The spectral characteristics of epishelf lakes were found to be identical to that of white ice, which resulted in misclassification. In a similar manner, the spectral profile of open lakes and land surface resembles each other which often confuse the algorithm, resulting in few inaccuracies. Our work focused on getting a deeper insight into newly added bands in WV-2 and based on that knowledge developing a brand-new index to accurately extract lakes from Antarctica, which might be useful for wide geoscientific applications in cryospheric earth sciences.



**S22 – 10: New Frontiers in Remote Sensing in Antarctic Earth Sciences: Cross-disciplinary advances**

***Exploratory Mapping of Vegetation in the Antarctic Environment using Spatial-Spectral Characteristics of Very High Resolution Remote Sensing Data***

Shridhar D. Jawak<sup>1</sup>; Chayanika Devi<sup>2</sup>; Alvarinho J. Luis<sup>1</sup>

Earth System Science Organization (ESSO), National Centre for Antarctic and Ocean Research (NCAOR), Govt. of India, Headland Sada, Vasco-da-Gama, Goa, India<sup>1</sup>; Institute of Environment Education and Research, Bharati Vidyapeeth University, Pune, Maharashtra, India<sup>2</sup>

Monitoring changes in the distribution and density of plant species often requires accurate and high-resolution baseline maps of vegetation. Detecting such change at the landscape scale is often problematic, particularly in remote areas. Vegetation mapping of plant communities at fine spatial scales is increasingly supported by remote sensing technology. Less frequent imaging with high spatial resolution satellite sensors enable more detailed analyses of vegetation change. This study is the first to use high-resolution WorldView-2 (WV-2) imagery to classify vegetation communities on Antarctic oases and to provide automated means to map vegetation as an important indicator for environmental change. Multispectral imagery (MSI) and panchromatic imagery (PAN) from very high resolution WV-2 have been used for the analysis of vegetation in different forms in Antarctic environment. A range of classification methods have been executed using pansharpened WV-2 data. This study comparatively evaluates vegetation mapping results using supervised and unsupervised classification methods to extract vegetation in Larsemann Hills and Schirmacher oasis, east Antarctica. We also focused on the use of supervised pixel-based classifiers and textural measures, in addition to standard multispectral information, to improve the classification of Antarctic vegetation communities. Classification results were validated with independent reference datasets.



S22 – 11: New Frontiers in Remote Sensing in Antarctic Earth Sciences: Cross-disciplinary advances

***Precise DEM of Schirmacher Oasis by Synergistically Fusing Multitemporal Elevation Datasets***

Shridhar D. Jawak<sup>1</sup>; Neha Sharma<sup>2</sup>; Alvarinho J. Luis<sup>1</sup>

Earth System Science Organization (ESSO), National Centre for Antarctic and Ocean Research (NCAOR), Govt. of India, Headland Sada, Vasco-da-Gama, Goa, India<sup>1</sup>; Indian Institute of Surveying & Mapping, Survey of India, Hyderabad, Andhra Pradesh, India<sup>2</sup>

Digital elevation model (DEM) is indispensable for analysis such as topographic feature extraction, ice sheet melting, slope stability analysis, landscape analysis and so on. Such analysis requires a highly accurate DEM. Available DEMs of Antarctic region compiled by using radar altimetry and the Antarctic digital database indicate elevation variations of up to hundreds of meters, which necessitates the generation of local improved DEM. An improved DEM of the Schirmacher Oasis, East Antarctica is being generated by synergistically fusing satellite derived laser altimetry data from Geoscience Laser Altimetry System (GLAS), Radarsat Antarctic Mapping Project (RAMP) elevation data and Advanced Space-borne Thermal Emission and Reflection Radiometer (ASTER) global elevation data. This is a distinctive attempt to generate a DEM of any part of Antarctica by fusing multiple elevation datasets, which is essential to model the ice elevation change and address the ice mass balance. We analyzed a suite of interpolation techniques for constructing a DEM from GLAS, RAMP and ASTER DEM based point elevation datasets, in order to determine the level of confidence with which the interpolation techniques can generate a better interpolated continuous surface, and eventually improve the elevation accuracy of DEM from synergistically fused RAMP, GLAS and ASTER point elevation datasets. The DEM presented in this work yields a vertical accuracy better than RAMP DEM and ASTER DEM individually. The RAMP DEM and ASTER DEM elevations were corrected using differential GPS elevations as ground reference data, and the accuracy obtained after fusing multitemporal datasets is found to be better than that of existing DEMs by using RAMP or ASTER alone. This is our second attempt of fusing multitemporal, multisensory and multisource elevation data to generate a DEM of Antarctica, in order to address the ice elevation change and address the ice mass balance. Our approach focuses on the strengths of each elevation data source to produce an accurate elevation model.



**S22 – 12: New Frontiers in Remote Sensing in Antarctic Earth Sciences: Cross-disciplinary advances**

***High Resolution Optical Satellite Remote Sensing Data for Mapping Antarctic Lake Bathymetry***

Shridhar D. Jawak<sup>1</sup>; Somashekhar Vadlamani<sup>2</sup>; Alvarinho J. Luis<sup>1</sup>

Earth System Science Organization (ESSO), National Centre for Antarctic and Ocean Research (NCAOR), Govt. of India, Headland Sada, Vasco-da-Gama, Goa, India<sup>1</sup>; Department of Civil Engineering, Symbiosis Institute of Technology (SIT), Symbiosis International University, Lavale, Mulshi, Pune, India<sup>2</sup>

High resolution pansharpened images from WorldView-2 were used for bathymetric mapping around Larsemann Hills and Schirmacher oasis in east Antarctica. We digitized the lake features in which all the lakes from both the study areas were manually extracted. In order to extract the bathymetric values from multispectral imagery we used different models: (a) Stumpf model (b) Lyzenga model and (c) Jupp's model. We tried multiband combinations to improve the results. To test the effect of size and dimension of lake on bathymetry retrieval, we distributed all the lakes on the basis of size and depth (reference data), as some of the lakes were open, some were semi frozen and others were fully frozen. Several tests were performed on open lakes on the basis of size and depth wise distribution. Very shallow lakes provided better correlation ( $\approx 0.8$ ) compared to shallow ( $\approx 0.6$ ) and deep lakes ( $\approx 0.6$ ) for depth wise lake distribution. In case of size wise distribution, large lakes yielded better correlation in comparison to medium and small lakes. The entire comparisons were done on the basis of derived values against the reference values. Both bathymetric map and contour maps are created. We planned to develop the Lyzenga and Jupp's model in IDL programming and compare the results for same lakes with results of Stumpf model in order to check which model yields better results. The results are awaited and will be published during the conference as trial and errors are been carried out.



**S22 – 13: New Frontiers in Remote Sensing in Antarctic Earth Sciences: Cross-disciplinary advances**

***Potential of SAR Imagery for Mapping and Monitoring Iceberg Calving Events in the Antarctic Environment***

Shridhar D. Jawak<sup>1</sup>; Alvarinho J. Luis<sup>1</sup>

Earth System Science Organization (ESSO), National Centre for Antarctic and Ocean Research (NAOR), Govt. of India, Headland Sada, Vasco-da-Gama, Goa, India<sup>1</sup>

Large uncertainties exist in calculating the mass loss of the Antarctic ice sheet due to iceberg calving, as well as in estimating the freshwater input from the inland ice into the Southern Ocean. Antarctica is surrounded by a variety of large, medium and small sized ice shelves, glacier tongues and coastal areas without offshore floating ice masses. In past, two successive austral summer seasons (2010-11) and (2011-12) have witnessed calving of icebergs around the Indian Barrier (cargo unloading site on the shelf ice) in Princess Astrid Coast, East Antarctica. RADARSAT SAR imagery (4<sup>th</sup> May 2012) was processed and analyzed, which showed that a huge portion of the ice shelf measuring nearly 1500 m × 450 m adjacent to the Indian Barrier in Princess Astrid Coast calved and drifted along between 5<sup>th</sup> and 24<sup>th</sup> April 2012 based on seismic data. Spatial analysis of RADARSAT images showed that the calved out portion of the shelf ice disintegrated into 7-10 small icebergs. To monitor such calving events in future, SAR imagery can be used to classify the coastline of Antarctica in terms of surface structure patterns close to the calving front. SAR would also be useful to reveal the time of residence of the ice along a flow path and—associated with it—the healing of surface crevasses can explain the different surface structure distribution close to the grounding line and the calving front on many ice shelves in east Antarctica. Surface structures on ice shelves (e.g., crevasses, rifts, pressure ridges, ice dolines, ogives) can also be mapped using SAR. This information can be used both for scientific studies and expedition logistic applications.



**S22 – 14: New Frontiers in Remote Sensing in Antarctic Earth Sciences: Cross-disciplinary advances**

***Object-Based Image Analysis for Mapping Antarctic Coastal Oasis using High Resolution Satellite Imagery***

Shridhar D. Jawak<sup>1</sup>; Dhiraj A. Raut<sup>2</sup>; Alvarinho J. Luis<sup>1</sup>

Earth System Science Organization (ESSO), National Centre for Antarctic and Ocean Research, Govt. of India, Headland Sada, Vasco-da-Gama, Goa, India<sup>1</sup>; Faculty of Technology (Geomatics), Centre for Environmental Planning & Technology (CEPT) University, Ahmedabad, Gujarat, India<sup>2</sup>

An accurate spatial mapping and characterization of land cover features in cryospheric regions is an essential procedure for many geoscientific studies. A new semiautomated approach by coupling spectral index ratios (SIRs) and object-based image analysis (OBIA) has been introduced to classify very high resolution WorldView-2 (WV-2) satellite image to extract land cover features. This study provides rule sets to be used in object-based classification of WV-2 image to precisely delineate land cover features of Larsemann Hills, east Antarctica. A multilevel segmentation process was applied to WV-2 image in order to generate different sizes of image objects representing different land cover features with respect to scale parameter. Several new SIRs were generated and applied to objects at different segmentation levels to classify land cover classes consisting of landmass, manmade features, snow/ice, and waterbodies. A special care was taken to delineate waterbody class while identifying these areas at image level, considering their different appearance on landmass and ice. The results demonstrate that synergetic usage of newly developed SIRs and image segmentation during the OBIA can provide accurate results with overall classification accuracy of  $\approx 98\%$  for the identification of land cover classes. Results suggest that OBIA can contribute to automatic and semiautomatic analysis for most remote sensing applications in coastal Antarctic areas and synergetic use of pixel-based SIRs could be useful to explore the rich geo-information of the coastal areas.



**S22 – 15: New Frontiers in Remote Sensing in Antarctic Earth Sciences: Cross-disciplinary advances**

***Mapping Supraglacial Debris in the Antarctic Environment Using Very High Resolution Satellite Remote Sensing Data***

Shridhar D. Jawak<sup>1</sup>; Prapti Devliyal<sup>2</sup>; Alvarinho J. Luis<sup>1</sup>

Earth System Science Organization (ESSO), National Centre for Antarctic and Ocean Research, Govt. of India, Headland Sada, Vasco-da-Gama, Goa, India<sup>1</sup>; Department of Civil Engineering, Symbiosis Institute of Technology (SIT), Symbiosis International University, Lavale, Mulshi, Pune, India<sup>2</sup>

Mapping the supraglacial debris and streams in the Schirmacher Oasis, east Antarctica, was undertaken by using WorldView-2 (WV-2) high resolution optical remote sensing data. We used 8band calibrated hyper-spherical color sharpened (HCS) and atmospherically corrected WV-2 imagery. The reference data was generated by manually digitizing debris and supraglacial streams from the satellite imagery. Several trials were performed to extract debris using almost all the existing traditional pixel-based classification techniques over a small domain of our study area. We used supervised classification methods such as Maximum likelihood, parallelepiped, neural network, etc. and several target detection techniques, which indicate that it is practically possible to extract debris from high resolution optical remote sensing data semi-automatically. Presently, we are attempting similar trials for supraglacial stream extraction and then we will attempt to develop new techniques for debris and supraglacial stream extraction, which would be object-based image analysis (OBIA) and spectral index ratio (SIR) approaches. The quantitative analysis of error would be carried out to test the practicability of our approach. The present attempt is expected to provide new and improved methods for semiautomatic feature extraction in supraglacial environment. The comparison of performance between new methods against the existing methods would provide the new direction in this research.



**S22 – 16: New Frontiers in Remote Sensing in Antarctic Earth Sciences: Cross-disciplinary advances**

***Mapping Blue Ice Areas in Antarctic Environment Using Very High Resolution Optical Data***

Shridhar D. Jawak<sup>1</sup>; Tushar Bidawe<sup>2</sup>; Alvarinho J. Luis<sup>1</sup>

Earth System Science Organization (ESSO), National Centre for Antarctic and Ocean Research (NCAOR), Govt. of India, Headland Sada, Vasco-da-Gama, Goa, India<sup>1</sup>; Department of Civil Engineering, Symbiosis Institute of Technology (SIT), Symbiosis International University, Lavale, Mulshi, Pune, India<sup>2</sup>

Blue-ice areas (BIAs) cover 1% of the East Antarctic ice sheet. High resolution PAN-sharpened calibrated images from WorldView-2 (WV-2) were used for extracting blue ice areas in Schirmacher Oasis, east Antarctica. The Schirmacher oasis is located between the edge of the Antarctic ice Sheet and the Novolazarevskaya Nivl Ice Shelf which extends from 70°45' S to 70° 75' S and 11°38' E to 11° 38' E. Blue ice extent may vary because of weather, seasonal effects, and climate change. Blue ice areas are generally visual evidence of long-term ablation. The amplitude of blue ice is lower than that of snow, because the ice surface is smoother than the latter. But difference is not so obvious when applying automatic extraction techniques. Extraction of BIAs in Antarctica deal with the total area of blue ice excluding the other features appearing on or near it. To achieve desirable results and support comparative analysis, multiband image combinations were generated from atmospherically corrected WV-2 data. For feature extraction process, regions of interest (ROI) were considered in which blue ice was used as target and white snow/ice appearing on the blue ice was considered as non-target. Various semiautomatic feature extraction methods, such as, target detection, mapping methods, etc, and many trials were used for extracting blue ice areas. Surface patterns of alternating snow and blue ice bands are found in East Antarctica which becomes obstacle to clearly extract blue ice feature. From the high resolution WV-2 data, reference data (digitized data) were prepared for blue ice area and extracted blue ice area was obtained from feature extraction methods. By comparing reference data and extracted data, bias and root mean square (RMS) error values were calculated. Accuracy assessment was done considering the entire necessary prior results of the blue ice area. Normalized difference spectral index for blue ice is obtained from the spectral profile from maximum and minimum value of band which helped to successfully create and implement the NDBI (normalized difference blue ice index) model. After processing all the 12 test tiles whole image was processed and final blue ice is extracted from the data.



**S22 – 20: New Frontiers in Remote Sensing in Antarctic Earth Sciences: Cross-disciplinary advances**

***Innovative Normalized Difference Snow/Ice Indices for Snow Cover Mapping in the Antarctic Environment Using Very High Resolution Remotely Sensed Data***

Parag S. Khopkar<sup>1</sup>; Shridhar D. Jawak<sup>2</sup>; Alvarinho J. Luis<sup>2</sup>

Department of Geography, University of Pune, Ganeshkhind, Pune, India<sup>1</sup>; Earth System Science Organization (ESSO), National Centre for Antarctic and Ocean Research (NCAOR), Govt. of India, Headland Sada, Vasco-da-Gama, Goa, India<sup>2</sup>

Multispectral (MS) and panchromatic (PAN) images from WorldView-2 (WV-2) satellite were used to develop a set of modified normalized difference snow index (NDSI) ratios for rapid and effective extraction of snow surface area in Antarctic environment. The performance of NDSI is evaluated qualitatively as well as quantitatively against manually digitized reference. Gram-Schmidt (GS) and Wavelet-based principle component analysis (WPC) pan-sharpening methods were used for fusing MS and PAN images. Effectiveness of pan-sharpening algorithms was compared for NDSI-based snow cover extraction to evaluate the consequences of fusion on spectral quality of sharpened images and possible loss in information extraction. The study provides an interactive and rapid method to verify the optimum combination of MS bands that enhances discrimination of snow from the non-snow regions by using the eight spectral bands of WV-2. The error associated with NDSI modification were calculated by using bias in delineated and manually digitized reference snow cover area. Quantitative assessment of extracted snow-covered area using NDSI showed that the WPC (RMSE: 5673.86 m<sup>2</sup>) performed better than the GS (RMSE: 6216 m<sup>2</sup>) pan-sharpening method for extraction of snow covered area. The study also revealed that band 3 (Green), 4 (Yellow), and 7 (nearinfrared1) provided a significant means for generating modified NDSI. The research provides new facets to spectral index ratio research which is expected to contribute to better our understanding of snow-covered regions in near future and potential applications in Antarctic geo-scientific studies.



**S22 – 21: New Frontiers in Remote Sensing in Antarctic Earth Sciences: Cross-disciplinary advances**

***A New Feature Extraction Method for Land Cover Information Mining in the Antarctic Environment Using 8-Band Worldview-2 Satellite Data***

Parag S. Khopkar<sup>1</sup>; Sagar P. Jadhav<sup>1</sup>; Shridhar D. Jawak<sup>2</sup>; Alvarinho J. Luis<sup>2</sup>

Department of Geography, University of Pune, Ganeshkhind, Pune, India<sup>1</sup>; Earth System Science Organization (ESSO), National Centre for Antarctic and Ocean Research, Govt. of India, Headland Sada, Vasco-da-Gama, Goa, India<sup>2</sup>

The multidimensional protocol practiced in this research primarily emphasizes the supremacy of very high spatial as well as spectral resolution Worldview-2 (WV-2) satellite data for Antarctic geoscientific applications. The present attempt has exhausted the available 8band Multispectral (MSI) resolution (2 m) sharpened by Panchromatic (PAN) resolution (0.5 m). A new digital image processing (DIP) methodology enhanced the ability of WV2 resolution to classify water, snow/ice and landmass from one another. Available raw data in the form of 9 tiles was pan-sharpened using Gram-Schmidt (GS) and Principal Component (PC) methods. Along with traditional feature classification methods, an array of customized spectral index ratios (SIR) is developed and implemented on satellite imagery for mapping about 100 km<sup>2</sup> of area nearby Larsemann Hills, east Antarctica. Conventional classification method was implemented by using Mahalanobis classifier and Winner-Takes-All (WTA) classifiers. Pan-sharpening algorithms were compared for SIR-based feature extraction and classification methods to assess the consequent effect of fusion on spectral quality of sharpened images and possible information extraction. PC proved to be the best performing pan-sharpening method than GS (bias: 619.44) for all classification and SIR combinations with bias of -333.47 m. whereas Mahalanobis classifier (bias: -280.21 m) performed better over WTA (bias: 1022.53 m). Root mean square error (RMSE) based assessment for pansharpened classified area showed that, PC method generated less error 1248.89 m<sup>2</sup> than that of GS generating 1983.30 m<sup>2</sup>. WTA classifier delivered better (RMSE: 921.01m<sup>2</sup>) than that of Mahalanobis classifier (RMSE: 2311.18 m<sup>2</sup>). The study also revealed that out of four new bands, Coastal (band 1, 400-450 nm), Yellow (band 4, 585-625 nm), Red Edge (band 6, 705-745 nm), and Near Infrared 2 (band 8, 860-1040 nm) of WV2 imagery provided a decisive tool for mining the polar geospatial information. Despite the availability of the limited data, the research provides new facets to spectral index ratio research which is expected to contribute to our better understanding of cryospheric regions and contribute significantly to the Antarctic geo-scientific applications.



**S22 – 29: New Frontiers in Remote Sensing in Antarctic Earth Sciences: Cross-disciplinary advances**

***A 1:1000 000 Tectonogeological Map of Mac.Robertson Land and Princess Elizabeth Land (East Antarctica)***

Mikhalsky, E.V.<sup>1</sup>; Tkacheva, D.A.<sup>1</sup>; Golynsky, A.V.<sup>1</sup>; Golynsky, D.A.<sup>1</sup>; Laiba, A.A.<sup>2</sup>

Institute for Geology and Mineral Resources of the World Ocean (VNIIOkeangeologia), Russia<sup>1</sup>; Polar Marine GeoSurvey Expedition, St.Petersburg – Lomonosov, Russia<sup>2</sup>

The area of Mac. Robertson Land – Princess Elizabeth Land in East Antarctica is a vast and relatively well exposed terrain which is underlain by geological units and formations with a wide range of age, lithology, and tectonic setting. Thus, both magmatic ages range from Palaeoarchean to Palaeogene, igneous lithologies comprise nearly all known major rock types, as well as many less common but important ones like kimberlites, lamproites and charnockites, and metamorphic assemblages range from greenschist to (high-temperature) granulite facies. The structure of the region is dominated by a giant subglacial late Paleozoic–Mesozoic rift – one of the largest on Earth. The complex geological history and tectonic evolution of this region have resulted in various models to explain the observed geological structure, and these remain the subject of discussion and further investigations. We consider that a new and detailed synthesis of the geology of Mac. Robertson Land – Princess Elizabeth Land is now warranted, even though there are still many outstanding problems to be solved. The main goal of this project is to summarize the available geological and analytical data and produce a comprehensive model of the geological composition and structure of the study area presented in graphical format. The geology of this region has been the subject of investigations since mid1950s. The earliest basic knowledge of the Prince Charles Mountains was acquired by Australian geologists, who went on to carry out medium-scale mapping and more detailed studies in many localities in 1969–1974 and 1987–1993, with investigations in some key areas being carried out subsequently. Soviet and later Russian researchers undertook reconnaissance and medium to large-scale geological mapping of most exposed areas in 1971–1974 and from 1982/83 up to the present. This work was largely performed by the Polar Marine GeoSurvey Expedition, with VNIIOkeangeologia geologists sometimes involved, and provided substantial basic geological information. Altogether geological field data were acquired on many thousands of observation points, with an average 0.05–0.4 points/square km, rising to 2–10 points/square km in certain key areas. Chinese geologists studied some areas in detail, and a joint Australian–German expedition (2002/03) added much to our knowledge of the southern Prince Charles Mountains.

Nearly all exposed areas in the region are underlain by high-grade metamorphic rocks and variously metamorphosed and deformed intrusions. Therefore the observed rock mineral assemblages, and in most cases their structures, reflect the latest tectono-thermal episode in the-geological evolution. Thus the ages of these rocks may be more applicable to a tectonic, rather than a conventional geological, map, considering the latter normally shows protolith formation ages (sedimentation or magmatism). Such information is an important map component helping to understand the geology of the area, so the map includes features of both tectonic and geological maps. As the region is largely composed of metamorphic and plutonic rocks, isotopic ages of these rocks are the key data, and a large number of U–Pb zircon age determinations have recently been published. We accumulated data for more than 270 samples studied for zircon geochronology by means of either bulk TIMS analysis (35 samples) or local SIMS analysis (more than 235 samples, either by LA ICPMS or SHRIMP) in different laboratories.

Our map follows the basic principles of 1:1000 000 geological map compilation standards accepted in Russia. An innovative deviation from these principles is a complex format of indexes applicable to mappable lithotectonic (metamorphic or plutonic/metamorphic) complexes. The basic map units are assigned to two categories: stratigraphic (sedimentary, volcanic, and sedimentary volcanic sequences, including their metamorphosed counterparts) and nonstratigraphic (intrusive bodies, and metamorphic or



plutonic-metamorphic complexes). Metamorphic and plutonic-metamorphic complexes are associations of high grade metamorphic rocks for which the protolith nature, composition and structure can be hard to identify.

Commonly such complexes represent strongly deformed and often migmatitic intercalations of high grade Gneisses (ortho and/ or paragneisses) and crystalline schists. These complexes are shown by ruled color patterns, with the colour indicating both the metamorphic grade and predominant lithology (mafic, salic/psammitic or high-aluminous). However, in many localities either ortho- or paragneisses apparently predominate, so it is possible to distinguish such subcomplexes on the map with vertical (orthogneisses) or horizontal (paragneisses) ruling. An inclined ruling indicates a mixture of strongly varying lithologies. Metamorphic complexes are defined by the age of the thermal/deformational peak responsible for the observed mineral paragenesis and structure. This does not preclude younger overprinting metamorphic events, which are shown with additional specific symbols.

The digital topographic base was created within ESRI ArcGIS (ArcMap 9.3.1) space, using a Polar Stereographic Projection (Pulkovo 1942). Some outcrop areas and localities are show enlarged on the map, as many outcrops are too small to be readable on the scale of the main map. The positions and extent of outcrop areas were sourced from either 18 published 1:200000 topographic maps or the Antarctic Digital Database (ADD) which comprises 1:1000000 data. A large amount of data was utilized in this project, including many isotopic ages, which allows a much more detailed geological history of the region to be established. The new map enables more meaningful regional comparisons and correlations than have hitherto been possible. It reveals a highly complicated geological composition of the area and will help to give a better understanding of its geological structure and evolution. This is needed to improve existing models of Precambrian supercontinent formation and evolution, in particular the assembly and dispersal of Rodinia with subsequent amalgamation of Gondwana: Antarctica is in a key position on many palaeotectonic reconstructions.

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**S22 – 32: New Frontiers in Remote Sensing in Antarctic Earth Sciences: Cross-disciplinary advances**

***Radar Isochronic Dating for the Deep Ice Core Site of Kunlun Station, Antarctica***

Tang Xueyuan<sup>1</sup>; Sun Bo<sup>1</sup>; Cui Xiangbin<sup>1</sup>; Guo Jingxue<sup>1</sup>; Daniel Steinhage<sup>2</sup>; WangTiantian<sup>1</sup>

Polar Research Institute of China, Shanghai, China<sup>1</sup>; Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany<sup>2</sup>

The Chinese First Deep Ice-Core Drilling Project has started at Kunlun station in the Dome A region, East Antarctica. Internal isochronic layers from deep-penetrating radar data collected during the 2004/2005 Chinese National Research Expedition (CHINARE) and the Dome Connection East Antarctica (DoCo) project of the Alfred Wegener Institute (AWI) were linked to compare the new deep ice coring site of Kunlun station and the Vostok ice core site. Six visible layers, upon the depth greater than half the ice thickness at the Kunlun station ice core site, were dated based on the Vostok ice core chronology. At 1640 m depth, an age of ~160,400 yr corresponding to a bright layer at the Kunlun station ice core site was revealed. The age-depth relationship of the ice would be used to correlate the dating of the deep ice core at Kunlun station.



**S22 –128: New Frontiers in Remote Sensing in Antarctic Earth Sciences: Cross-disciplinary advances**

***Antarctic Sea Ice Variability and Trends in the Context to Physical Forcing***

Avinash Kumar<sup>1</sup>; Alvarinho J. Luis<sup>1</sup>

Earth System Science Organization (ESSO), National Centre for Antarctic and Ocean Research, Govt. of India, Headland Sada, Vasco-da-Gama, Goa, India<sup>1</sup>

Using a 34-year long record (1979-2012) of sea ice extent from satellite-based passive-microwave measurements from the Scanning Multichannel Microwave Radiometer (SMMR) and the Special Sensor Microwave/ Imager (SSM/I), analyses on monthly, seasonal, inter-annual and decadal timescales were carried out for five Antarctic sectors - the Weddell Sea, Indian Ocean, western Pacific Ocean, Ross Sea, and Bellingshausen and Amundsen Seas (BAS). The sea ice extent in the Southern Hemisphere (SH) showed positive trend ( $16200 \pm 2208 \text{ km}^2 \text{ yr}^{-1}$ ). Weddell Sea, Indian Ocean and Ross Sea sectors showed positive sea-ice trend and BAS exhibited negative trend. The sea ice trends for the Indian Ocean, Ross Sea, and BAS sectors were statistically significant at 99% confidence level. The SH as a whole exhibited the largest positive trend in the autumn, and lowest in the winter and summer. The study revealed that the trends for Indian Ocean and Ross Sea were positive and consistently progressive from summer to spring seasons, while BAS showed negative trends for all the four seasons. The Weddell Sea and western Pacific Ocean sector showed a statistically insignificant negative trend in winter and spring, and a statistically insignificant and positive trend in summer and autumn. The long-term monthly sea ice trend was negative for BAS, while the SH as a whole exhibited positive trends year round, with low (high) trend in February (May and December). During the decade 2003-2012, the magnitude of yearly-mean sea-ice extent trends for SH was reduced by 68%, but these changes over the last decade were found to be statistically not significant, when compared with the 34-year trends. Over the decades, all the sectors showed positive trends except for the Weddell Sea sector, which exhibited a higher negative trend ( $-5.2 \pm 4.9\% \text{ decade}^{-1}$ ). The Weddell Sea and BAS showed a negative and positive trend, respectively, during 2003-2012. To understand the sea ice dynamics, correlations were explored between sea ice cover and various physical/ climatic parameters. Sea surface and air temperature anomaly data suggested that the Antarctica region has experienced cooling trends in the last two decades. The sea ice increase during 2003-2012 may be linked to the cooling processes after 1993, supplemented by the cumulative effect of ocean currents, winds and other atmospheric parameters. Over the last 34-year period, high positive zonal wind anomalies occurred in the Weddell Sea (especially along the western Antarctic Peninsula) and Ross Sea sectors, whereas the meridional wind showed a significant positive (negative) correlation in the Indian Ocean (Weddell and BAS) sectors. The decadal analysis revealed that the wind-components are changing, mostly cyclic in different decades. During 2003-2012, highest positive zonal wind anomaly occurred in the BAS, whereas highest positive meridional wind anomaly was identified in most of the sectors. The correlation of wind speed with sea ice was positive and significant in most of the sectors; the wind speed intensities gradually enhanced in different decades since 1983-2012. This has one of the strongest links to understand the gradual growth of sea ice, which plays a significant role in ice concentration through both dynamic and thermodynamic effects. The sea level pressure (SLP) anomaly was negative in the Ross Sea and over a part of the Indian Ocean sector, while the sea ice concentration showed negative correlation with SLP for all the sectors, but positive correlation was observed for the Indian Ocean and western Pacific Ocean sectors. The decadal SLP showed a negative correlation with sea ice, suggesting that SLP decreased when the sea ice extent increased. The SLP anomalies are one of the influencing factors of the Weddell Sea and BAS which clearly confirm our sea-ice trend results for 2003-2012. The total column ozone (TCO) showed maximum positive anomaly with a significant positive correlation in the Ross Sea and the BAS, and a negative correlation with sea ice concentration in the Weddell and Indian Ocean sectors. The decadal TCO anomaly indicated depletion of columnar ozone in the last three decades and these depletions have mixed impact on sea ice. The total precipitation around the SH has a negative correlation with sea ice concentration.



**S22 –139: New Frontiers in Remote Sensing in Antarctic Earth Sciences: Cross-disciplinary advances**

***Application of LANDSAT 8 Data for Geological Mapping: Semi-Automated Outcrop Delineation and Lithological Identification***

Alex Burton-Johnson<sup>1</sup>; Martin Black<sup>1</sup>; Peter Fretwell<sup>1</sup>

British Antarctic Survey, United Kingdom<sup>1</sup>

The scale and terrain of Antarctica render it a challenging area for geological mapping. Presented here is a two-step semi-automated methodology for the delineation of snow and ice, and the delineation of sedimentary and plutonic rocks. These methods were then applied to part of the Lassiter Coast area of the Antarctic Peninsula and ground truthed in the 2014/15 field season. The first step in producing a geological map is to identify the areas of outcrop. This can be achieved using remote sensing data, however current techniques are inaccurate at the high latitudes of the Polar Regions where extensive deep shadows are unavoidable. A new method is presented using LANDSAT 8 data to delineate snow and ice despite this issue and its accuracy compared with existing techniques. Once areas of outcrop have been identified, low level lithological determination can be applied to the data. We highlight an example from the 2014/15 field season on the Lassiter Coast of the SE Antarctic Peninsula; a region of plutonic intrusions in to sedimentary sequences with little previous mapping. By exploiting the well known short wave infrared signature of clay minerals the broad distinction can be made between intrusive and sedimentary outcrops via a maximum likelihood classification, aiding mapping and targeted field work. We also show the limitations of this methodology, how thermal bands can improve fidelity, and invite contributions to develop this technique.



**S22 –141: New Frontiers in Remote Sensing in Antarctic Earth Sciences: Cross-disciplinary advances**

***Extracting Outcrop Extents in Antarctica: Current problems, New Solutions and a Complete Dataset for the Antarctic Peninsula***

Alex Burton-Johnson<sup>1</sup>; Martin Black<sup>1</sup>; Peter Fretwell<sup>1</sup>

British Antarctic Survey, United Kingdom<sup>1</sup>

Delineating rock and ice in Antarctica is the first step for any geological geospatial dataset. However current semi-automated techniques developed and widely applied in other glaciated regions (e.g. the Himalayas) are inadequate in their accuracy for the high latitude illumination and low sun angle of the Polar Regions, where resultant deep, extensive shadows pose problems for accurate geological mapping and geospatial research. Presented here is a comparison of the existing datasets and techniques with a new methodology that can be applied to remote sensing data or colour imagery for accurate semi-automated outcrop delineation. To highlight the potential for this methodology we also present its first significant product: a new outcrop dataset for the entire Antarctic Peninsula derived from freely available LANDSAT 8 data.



**S22 –147: New Frontiers in Remote Sensing in Antarctic Earth Sciences: Cross-disciplinary advances**

***Extracting Outcrop Extents in Antarctica: Current Problems, New Solutions and a Complete Dataset for the Antarctic Peninsula***

Leitchenkov German<sup>1</sup>; Mikhalsky E.<sup>1</sup>; Golynsky A.<sup>1</sup>; Aleshkova N.<sup>1</sup>; Masolov V.<sup>2</sup>

Institute for Geology and Mineral Resources of the World Ocean, Russia<sup>1</sup>; Polar Marine Geosurvey Expedition, Russia<sup>2</sup>

Enderby Land is composed of two very distinct tectonic units: the Archaean Napier Complex (Craton) and the Mesoproterozoic Rainer Complex (Mobile Belt) and provides best opportunity to look into both the earliest Archaean and subsequent the Proterozoic processes and their superposition. In this study we summarize the data and present a series of geophysical maps (magnetic anomalies, gravity anomalies, and bedrock topography), crustal cross-sections derived from geophysical data modeling and tectonic sketches based on joint interpretation of all available datasets.

Extensive regional airborne magnetic and radioecho sounding surveys with line-spacing of about 20 km were conducted by Polar Marine GeoSurvey Expedition (PMGE) in 1971/72, 1973/74, 1985/86, 1986/87 and 1987/8 field seasons. Total length of flight lines was about 27000 km. In 1987/88 season airborne geophysical survey also included gravity measurements. In 1970/71 and 1974/75 the western part of Enderby Land was covered with on-land gravity observations and reflection seismic soundings. The total amount of acquired gravity data comprises about 10000 km of airborne lines and about 600 on-land observations (about 20–25 points per 10000 square km). Great amount on-land gravity measurements were also carried out in Australian Expeditions (especially within the central and eastern Enderby Land and Kemp Land) and these data were combined with the Russian data for compilation of Free air and Bouguer anomaly maps.

Magnetic anomalies over the Napier Complex are generally more intensive than those over the adjacent Rayner Complex and the boundary between these tectonic units is well identified by the difference in magnetic pattern. Within the Napier Complex, amplitudes and wavelength of anomalies are thought to reflect lithology of high-grade granulites. Granitic and metasedimentary rocks of the Tula and Napier Mountains correlate with magnetic lows, while orthogneisses in the Scott Mountains correlate with elongated magnetic highs (100–500 nT). Localized banded iron formations can give rise to maximum amplitude of 7500 nT. The ancient Napier Complex is reliably traced under the continental margin and its northern edge actually coincides with continent–ocean boundary recognized from marine geophysical surveys.

The southern Napier Complex is distinguished by a prominent long-wavelength, elongated Bouguer gravity anomaly ranging between 0 mG and 20 mG which crosses this mountainous region (what is absolutely non-typical for isostatically compensated highlands). The density modeling shows that this anomaly is best explained by a high density (2.9 g/cub. cm) gently dipping southward body within the upper crust. This body can be interpreted as lower crust thrusting over upper crust. The overall thickness of continental crust varies here between 35 km and 42 km. The crustal modeling shows that the Napier and Rayner complexes have different structure and the boundary between them is clear and coincides with its geologically proposed surface position (Sheraton et al., 1987). The prominent Bouguer gravity anomaly over the southern Napier Complex which is composed of the Palaeo to Neoproterozoic rocks is thought to be a prominent feature which may reflect the Archaean suturing due to continent collision or other cryptic orogenic processes. This indicates that plate tectonics may have operated on the Earth since the late Archaean. Unfortunately available geological data are somewhat thin to demonstrate what lithologies are responsible for the observed gravity features, and that might be a specific aim of possible investigations in future.



**S22 –185: New Frontiers in Remote Sensing in Antarctic Earth Sciences: Cross-disciplinary advances**

***Extracting Outcrop Extents in Antarctica: Current Problems, New Solutions and a Complete Dataset for the Antarctic Peninsula***

Zhang Shengkai<sup>1</sup>; Xiao Feng<sup>1</sup>; Li Fei<sup>1</sup>; Yuan Lexian<sup>1</sup>

Chinese Antarctic Center of Surveying and Mapping, Wuhan University<sup>1</sup>

The Antarctic ice sheet plays a major role in studies of global climate change and sea-level rise. While the digital elevation model (DEM) of Antarctic is the foundation for the Antarctic ice sheet research. There are four common DEMs of Antarctic, including JLB97 DEM, RAMPV2 DEM, ICE-Sat DEM and Bamber 1km DEM. For lack of large numbers of measured data, the accuracy of the four Antarctic DEMs was assessed by mutual validation. Firstly, the DEMs were processed into same spatial coverage and resolution and elevation datum. Then the elevation difference between each two DEMs was calculated by the raster calculator in ARCGIS. A number of clearly erroneous points were visible in the resulting data, so statistical criterion was applied, and a  $2f$  filter was performed on the elevation difference. As the accuracy of DEM correlates highly with surface slope, statistics (mean difference and standard deviation) of the elevation differences were calculated for a  $0.05^\circ$  slope interval. And the mean difference and standard deviation were plotted as a function of surface slope. It is shown that there exists no obvious trend in the bias with slope. The results show that both of Bamber 1km DEM and ICESat DEM feature high reliability with a bias less than 1.8 m. The elevation difference for RAMPv2 DEM compared to Bamber 1km DEM is bigger than 1.9 m, while in the sloped areas and south of  $81.5^\circ\text{S}$ , the difference is much more obvious, and the reliability for RAMPv2 DEM in those areas is low. The reliability of JLB97 DEM is the lowest among the four DEMs with the bias larger than 10 m.



**S22 – 201: New Frontiers in Remote Sensing in Antarctic Earth Sciences: Cross-disciplinary advances**

***Investigations on Dynamical Coupling Processes in the Antarctica Middle Atmosphere***

Subrahmanyam K V<sup>1</sup>; Kumar K K<sup>1</sup>; Ramkumar G<sup>1</sup>; Babu S S<sup>1</sup>; Sunil Kumar S V<sup>1</sup>; Das S S<sup>1</sup>; Shreedevi P R<sup>1</sup>; Soni V K<sup>2</sup>; Varma A K<sup>3</sup>; Sharad Gurusale<sup>3</sup>; More R S<sup>3</sup>

Space Physics Laboratory, Vikram Sarabhai Space Centre, Trivandrum, India<sup>1</sup>; Environment Monitoring and Research Center (EMRC), India Meteorological Department, New Delhi, India<sup>2</sup>; India Meteorological Department, Pune, India<sup>3</sup>

Antarctica region play a major role in impacting the climate by influencing the sea levels, atmospheric composition and dynamics. During the past few decades, atmospheric research community has become conscious about the Earth's high latitude middle atmosphere as it plays a vital role in the large-scale circulation and momentum exchange processes. Moreover, there are significant variations at polar and low latitudes in the mean wind, temperature structure and large-scale atmospheric tides, planetary waves and gravity waves. The dynamical coupling of the Antarctic troposphere and stratosphere is dominated by gravity and planetary waves. These waves transfer energy and momentum from lower atmosphere to middle atmosphere. It is important to characterize these waves in terms of their frequency, horizontal and vertical wavelengths, propagation characteristics, momentum flux and wave drag. The atmospheric waves also play an important role in dynamically coupling the stratosphere and troposphere. The downward propagating waves can influence the Stratosphere Troposphere Exchange (STE) process. However, the polar middle atmospheric gateway is still poorly understood due the inherent difficult in exploring this region in terms of both technically and logistically. Among others, the role of atmospheric waves is least understood owing to difficulties in characterizing and quantifying them. Thus, there is a compelling need to better understand the role of middle atmospheric dynamics and chemistry at high latitudes. The central objective of the present study is to investigate the dynamical coupling between the stratosphere and troposphere through spectrum of atmospheric waves.

A coordinated GPS balloon borne high vertical resolution observations of winds, temperature and ozone have been carried out at Indian Antarctic station "Bharati" (69.40 S; 76.20 E) during the month of February 2015. From these high resolution profiles the information on gravity and planetary waves over Antarctica region are extracted using standard techniques. Along with the present GPS sonde observations, an attempt is made to investigate the dynamical coupling process using radar observations over the Antarctica region. The preliminary analysis of the vertical profiles of zonal, meridional winds and temperature showed the signatures of upward propagating waves from troposphere to stratosphere. Further, the present study also investigating the exchange processes across the Antarctic tropopause by using the ozone as proxy. It is envisaged that it will lead to the better understanding of the dynamical coupling processes in the Antarctica's middle atmospheric region.



**S22 – 315: New Frontiers in Remote Sensing in Antarctic Earth Sciences: Cross-disciplinary advances**

***Potential Englacial Ice-Flow Variations in the Central East Antarctic Ice Sheet***

Wrona T.<sup>1</sup>; Siebert M.<sup>2</sup>

Basins Research Group (BRG), Department of Earth Science and Engineering, Imperial College, Prince Consort Road, London <sup>1</sup>; Grantham Institute and Department of Earth Science and Engineering, Imperial College London, London <sup>2</sup>

Ice sheet movement is primarily a consequence of basal sliding and internal ice deformation. It is often assumed that ice deformation can be approximated as laminar flow, which decreases exponentially with depth (Glen's flow law). These assumptions are supported by radar data showing laterally-continuous, isochronous layers within ice sheets, which commonly drape over basal topography. Inspection of publicly-available radar data, acquired during Antarctica's Gamburtsev Province (AGAP) expedition, has allowed us to identify examples for where internal layering appears inconsistent with such flow. The data show numerous isochronous layers overlying an up to 1 km thick basal 'echo-free zone', interpreted as being derived from basal freezing. Several of the layers terminate downwards at the top of the refrozen ice, revealing the meteoric ice base to be the lower surface of an unconformity. We suggest two explanations for this unconformity. The first explanation is subglacial melting of the isochronous layers followed by ice advection. The second is englacial erosion produced by flow differences between the meteoric and accreted ice. We investigate the data to identify evidence in support of each of these explanations. Because such a flow velocity difference would challenge the basic assumption of an exponential flow velocity decrease with depth (Glen's flow law), it is important to understand the origin of these layer terminations.



**S22 – 411: New Frontiers in Remote Sensing in Antarctic Earth Sciences: Cross-disciplinary advances**

***Synthetic Aperture Radar (SAR) Data in Mapping and Study of Compacted Snow Dune Complexes and Active Lineament Tectonics in Antarctica***

Misra A<sup>1</sup>; D P Dobhal<sup>1</sup>

Centre for Glaciology, Wadia Institute of Himalayan Geology, Dehradun, India<sup>1</sup>

Mapping and yearlong observation of glacial features in extremely cold regions is rather impossible because of hazardous terrain, hostile weather conditions and lack of logistic and communication support. With the availability of satellite imagery, the study of snow and ice features received new impetus. However, constraints limit the capability of optical remote sensing. Fresh snow blanket conceals the details of glaciers and ice sheets. Secondly, it is not possible to get imagery of appropriate time for details of many ephemeral features, because of inclement weather conditions such as clouds, haze and mist. Synthetic Aperture Radar (SAR) data has capability to overcome most of these difficulties. The uniqueness of SAR data is that it measures surface roughness, enhances relief features to present nearly three dimensional picture of the terrain. It also has fairly good capability to penetrate the snow cover and provides information about underlying solid ice. Furthermore, it measures dielectric constant which is highly sensitive to water content and thus distinctly helped to demarcate various ice facies such as dry, moist and wet. It also enables identification of compactness and together with surface roughness helps in establishing glacial stratigraphy through various stages. Terminal areas of glacier, dominated by rough erratics have also been precisely identified to conclude progression or regression of glaciers. SAR also provides varied viewing angles, such as horizontal-horizontal (hh) and vertical-horizontal (vh) perspectives, which are immensely useful in interpretation of glacial features. Furthermore, SAR interferometry can be utilized in monitoring the sluggish movement of glaciers. Mega snow dunes of Antarctica have been engaging the attention of glaciologists ever since they have been identified on SAR imagery nearly two decades ago. Divergent views regarding their origin have been presented in the past. It was earlier believed that, they have been accumulated by blowing wind, while later studies suggested that they have been carved on ice sheets by katabatic processes. It is believed that directional wind flow is due to intense cooling of lower part of atmosphere at touching distance with the snow. The denser air starts to slide down along the slope resulting in bounce back action creating rippling effect in the snow. The present study covering large parts has shown that these types of dune fields are geographically distributed in various parts of Antarctica. Multi date satellite data has brought out remarkable stability of these dunes. No shifted from one location to the other in last several decades is noticed. Their characteristic shape matches with the sandy fore dunes, which form transverse to the wind direction in coastal regions of all the continents. These dunes have gentle wind ward side and steep lee ward side. Secondly, it has emerged that they represent original snow dunes which have been subsequently compacted during intense cooling and favorable conditions. Similar compacted and lithified Quaternary calcareous dunes are mapped in coastal Saurashtra. Wide interdune areas have very light SAR tones indicating rough surfaces. Wind ward sides, back scatter slightly less energy and are having grey tones, while lee ward sides are smooth and do not reflect any energy thus are completely dark. Dune complexes of several generations are recognized, which seem to be related to alternating glacial and inter glacial cycles. Abrupt termination of innumerable dunes along straight sets of lineament, suggests that the dunes have existed for quite some time, when vertical basement blocks have moved up or down in relation to each other. Subsequent glacial and aeolian processes have accentuated the lineament sets. They can presently be seen as deep transverse depressions. Stabilized sand dunes in Rajasthan are also quite often transected by lineament sets, representing surface expressions of normal faults. The present study thus concludes that the mega dune complexes represent compacted and stabilized form of windblown and accumulated snow. In vast regions of Antarctica they can be utilized for mapping the basement faults. It has also emerged that the Antarctic continent has similar lineament tectonics like all other continents.



**S22 – 444: New Frontiers in Remote Sensing in Antarctic Earth Sciences: Cross-disciplinary advances**

***Ionospheric Response in Antarctica to Large Distant Earthquakes***

C.D. Reddy<sup>1</sup>, Seemala Gopi<sup>1</sup>; Ajay Dhar<sup>1</sup>; K. Jeeva<sup>1</sup>

Indian Institute of Geomagnetism, Navi Mumbai, India<sup>1</sup>

The Antarctica cryospheric and ionospheric systems are sensitive to large distant earthquakes. Following a major earthquake, the surface seismic waves, in particular the Rayleigh waves propagate with velocities 3000 4000 m/s with vertical displacements of few cms as far as at teleseismic distances of ~10000 km. By virtue of the continuity of the vertical displacement, the atmosphere is forced to move concurrently with the Rayleigh waves and propagate almost vertically with a constant kinetic energy with their amplitude increasing exponentially. This energy in the neutral atmosphere is transferred to ionospheric ions and associated electrons by collision processes, which in turn oscillate them almost in phase. The resulting ionosphere electrons oscillating have velocities of a few tens of m/s and are displaced by a few hundred of meters with horizontal velocities imposed by Rayleigh waves.

If the earthquake occurs at ocean bottom, rapid displacement of ocean floor occur, vertically tossing the sea water, Tsunamis are generated, causing surface gravity waves that propagate for great distances in the sea. In the open sea, they have long wavelengths (typically 200 km), long periods (20 minutes) and small amplitudes (a few to 50 cm). It should be noted moreover that, due to their much shorter wavelength and period, the surface noise of ocean swell does not produce significant upward propagating waves in the atmosphere: the atmosphere acts as a filter, enhancing the long wavelength tsunami perturbation over other sources. The atmospheric gravity waves attenuate due to unstable phenomena associated with shear or convection instabilities. Generally, shear instability, which is also known as Kelvin-Helmholtz Instability (KHI), occurs when the Richardson number,  $Ri$ , of the background horizontal wind velocity becomes smaller than 0.25. Note that  $Ri$  is an index of atmospheric stability, which is defined as a ratio of the vertical potential temperature gradient to the square of the wind shear.

It is well established that both the Rayleigh and tsunami waves generated by earthquakes are coupled to the ionosphere through various coupling mechanisms constrained by many parameters e.g. atmospheric viscosity, collision frequencies. The coupling through AGWs is found to be quite effective due to their excitation by the earth surface displacements and their large amplitudes at ionospheric heights. Following a major earthquake, while it is testified that the acoustic shock waves, Rayleigh waves & tsunami waves are the transpicuous sources of ionospheric perturbations, possible excitation of geomagnetic pulsations remain subtle. Understanding the connection between atmospheric and ionospheric perturbations associated with major earthquakes is utmost important for future seismic hazard mitigation. This is facilitated by advances in the monitoring of small-scale perturbations of the ionosphere with both ground and satellite based advanced radio techniques, such as HF Doppler sounding, DEMETER, over the Horizon (OTH) radar, Faraday rotation measurements and GPS. These observations seems complementing the existing seismological observations.

In this study, 30s sampled GPS data from about twenty IGS sites from the SOPAC (<http://sopac.ucsd.edu/>) have been used. The estimated TEC 2 to 8 mHz band pass filtered after removing the receiver biases. And gravity waves are highlighted using a filter with 1 to 5 mHz frequency bandwidth. Though we examined many earthquakes with  $M_w > 6.0$  in the vicinity of Antarctica region, in this paper, we highlight the coseismic induced ionospheric TEC perturbations following the  $M_w 8.8$  Maule earthquake in Chile, occurred on February 27, 2010, causing a vertical uplift and subsidence of ~1.8 m and ~0.5 m respectively, generating a tsunami and triggering icequakes in Antarctica. We attempted to isolate the signal components caused by Rayleigh and/or Tsunami waves. This study essentially addresses the ionosphere response in Antarctica region due to distant large earthquakes.



**S22 – 503: New Frontiers in Remote Sensing in Antarctic Earth Sciences: Cross-disciplinary advances**

***Decadal Variations of Ice-Albedo Feedback Controlling Factors Over Amundsen-Bellinghousen Seas Sector***

Oza, S. R.<sup>1</sup>; Rajak, D. R.<sup>1</sup>; Jayaprasad, P.<sup>1</sup>; Singh, R. K. K.<sup>1</sup>; Suryawanshi, M.<sup>1</sup>; Gupta, M.<sup>1</sup>; Sharma, R.<sup>1</sup>; Raj Kumar<sup>1</sup>

Space Applications Centre, Ahmedabad, India<sup>1</sup>

Cryosphere present in the polar regions play a key role in regulating the Earth’s energy balance through ice-albedo feedback mechanism. Sea ice cover is the largest varying feature in the polar regions, and thereby contributing significantly in Earth’s energy balance. Snow and ice reflectance decreases due to the reduction in sea ice cover induced by increase in surface temperature. Decrease in albedo in turn results into higher absorption of solar radiation that further decreases the ice cover. Hence, understanding of the factors controlling this positive feedback loop is essential to understand the future climate scenario. Recent surface meteorological and ocean observations suggest that Amundsen-Bellinghousen Seas (ABS) sector (130W-60W) is the region sensitive to climate change, showing significant inter-annual changes in the surface temperature and sea ice cover. The variations observed in the ice-albedo feedback controlling factors in ABS sector have been investigated in the present study. The main objective of the study is to investigate the variations in the strength of spring-to-summer ice-albedo feedback controlling factors observed in the ABS sector during recent decade (2004-2013). Sea ice surface (with or without snow cover) is very sensitive to the variation in snow cover. Increase in temperature triggers the surface melting as well as reduces the sea ice cover (SIC). Surface metamorphosis and reduction in snow cover has control over the surface albedo. The change in albedo ( $\Delta\alpha$ ) per 1° change in surface air temperature  $T_s$  ( $\Delta T_s$ ) can be expressed as

$$(\Delta\alpha/\Delta T_s) = k_3 + k_2 (\Delta SIC/ \Delta T_s) \dots\dots\dots (1)$$

The two terms in the right side of the equation indicates the impact of (i) metamorphosis ( $k_3$ ) and (ii) reduction in sea ice cover ( $k_2$ ) over the change in the ice albedo. Here  $\Delta$  represents the change in parameter ( $\alpha$ ,  $T_s$  and SIC) observed in summer month (December) from that observed in the spring month (November). We have used the monthly AVHRR Polar Pathfinder data (at 25km resolution) to generate the derived images of ( $\Delta\alpha/\Delta T_s$ ) and ( $\Delta SIC/ \Delta T_s$ ) for spring-to-summer (November-December) period covering time span from 2004-2013. For each grid cell ( $\Delta\alpha/\Delta T_s$ ) and ( $\Delta SIC/ \Delta T_s$ ) were computed. These computed values for all the grid cells showing sea ice cover in the December month are used to compute the values of  $k_3$  and  $k_2$  using regression approach. The detailed spatio-temporal variations observed in the (i)  $\alpha$ ,  $T_s$ , SIC observed for the spring and summer months and (ii) spring-to-summer changes in ( $\Delta\alpha/\Delta T_s$ ) and ( $\Delta SIC/ \Delta T_s$ ) have been investigated for the study period. Significant inter-annual variations have been observed in the strengths of  $k_3$  (metamorphosis) and  $k_2$  (reduction in ice cover) factors controlling the change in spring-to-summer albedo. Higher impact of  $k_3$  has been observed in the year 2006, whereas  $k_2$  has shown the higher impact in 2011. An important outcome of the study is the statistically significant increasing trend observed in  $k_2$  ( $R^2 = 0.95$ ) and  $k_3$  ( $R^2 = 0.60$ ) during 2006-2011 period. Details on the outcome of the study will be presented in the symposium. Study has demonstrated the use of space-borne data to understand the strength of ice-albedo feedback controlling factors namely surface metamorphosis and reduction in sea ice cover. Statistically significant trend has been observed in these controlling factors for the period from 2006 to 2011. Outcome of the study is very important in the understanding of the role of surface melting induced by increase in air temperature and reduction in sea ice cover in the ice-albedo feedback mechanism in the Antarctic ABS sector.



**S22 – 504: New Frontiers in Remote Sensing in Antarctic Earth Sciences: Cross-disciplinary advances**

***Monitoring Fast Ice Deformation near Indian Research Stations Using Multitemporal / Multimode RISAT-1 Data***

P Jayaprasad<sup>1</sup>; D. Ram Rajak<sup>1</sup>; Rajkumar Kamaljit Singh<sup>1</sup>; Manish Kumar<sup>1</sup>; Maya Suryavanshi<sup>1</sup>; Monica Gupta<sup>1</sup>; Sandip R Oza<sup>1</sup>; Rashmi Sharma<sup>1</sup>; Raj Kumar<sup>1</sup>

Space Applications Centre (SAC) ISRO, Ahmedabad, India<sup>1</sup>

The scientific expedition to Antarctica faces a major threat from Fast Ice near Bharati Peninsula and India Bay. Decanting operations will be highly time consuming and laborious in presence of long stretch of fast ice because of the larger number of sorties required for decanting. Optical remote sensing satellites fail miserably in Antarctic region owing to cloud cover and blizzard. Microwave Synthetic Aperture Radar (SAR) sensors having cloud penetrating capability are unaffected by the above adverse conditions to provide clear images. India's Radar Imaging Satellite1 (RISAT-1) SAR, which provides coarse resolution to high resolution data by operating in various modes, is as an ideal satellite for monitoring the fast ice deformation. RISAT-1 is a state of the art Microwave Remote Sensing Satellite carrying a SAR Payload operating in C band (5.35 GHz), which enables imaging of the surface features during both day and night under all weather conditions. RISAT-1 was successfully launched by PSLVC-19 on April 26, 2012. In the present study the fast ice deformation and other sea ice / Ice shelf conditions were analyzed using multi-temporal multimode RISAT-1 SAR data. The fast ice conditions were taken as one of the component to sea ice advisory. The major objectives of the study are; (1) Assessing sea ice conditions especially fast ice near Bharati Peninsula and India Bay, (2) Monitoring the fast ice deformations and decreasing trends during the ISEA 34 expeditions using RISAT-1 multi temporal data, and (3) Crevasse area detection on the convoy route. RISAT-1 has the following beam modes. Coarse Resolution SCANSAR (CRS), Medium resolution SCANSAR (MRS) and Fine Resolution STRIPMAP1 (FRS1) respectively provide satellite data with 50 m resolution, 240 km swath; 25 m resolution, 120 km swath 3 m resolution, 30 km swath. The ascending and descending sets provide an opportunity view the same area twice a day. Multi-temporal data analysis was carried to monitor the deformation of fast ice and other sea ice conditions. Change analysis was carried out to see the percent change in the pixel values between temporal images of India Bay. An analysis of the backscattering intensity vs. the angle of incidence was also carried out. The data acquisition was planned as per the requirement of the expedition. Initially MRS data were analyzed to assess the fast ice prior to the entry of the ship. FRS-1 data was used to find out fine details of the fast ice especially the leads and deformation of the sea ice for safer ship routing to reach the decanting barrier in case of India bay and fast ice in case of Bharati Peninsula. The optical data with the inherent cloud cover and blizzard cover couldn't be helped much during the sea ice advisory ISEA34. The RISAT-1 SAR data was very effective in providing sea ice advisory by monitoring the fast ice conditions continuously in a desired manner. The ascending and descending data sets from various modes of RISAT-1 proved to be the one which assessed the initial 30km fast ice conditions to that within 3km during the stay of IVAN Papanin (Expedition Ship used for) ISEA34 ship in Indian new barrier. Crevasses are delineated from the image. Ship was spotted on FRS1 and MRS Datasets anchored in the Indian new barrier and sea ice.



## S24 – 34: Frontiers in Antarctic Earth Sciences

### ***Exploration of gamburtsev subglacial mountains, East Antarctica: background and plans for the near future***

Pavel Talalay<sup>1</sup>; Youhong Sun<sup>1</sup>; Zhao Yue<sup>2</sup>; Li Yuansheng<sup>3</sup>; Pinlu Cao<sup>1</sup>; Huiwen Xu<sup>1</sup>; Zhichuan Zheng<sup>1</sup>; Rusheng Wang<sup>1</sup>; Nan Zhang<sup>1</sup>; Xiaopeng Fan<sup>1</sup>

Polar Research Center, Jilin University, China<sup>1</sup>; Institute of Geomechanics, Chinese Academy of Geological Sciences, China<sup>2</sup>; Polar Research Institute of China, China<sup>3</sup>

The Gamburtsev Subglacial Mountains (GSM), located in the central part of East Antarctica, were discovered by the Soviet team of the Third Complex Antarctic Expedition in 1958/59. Exploring the history of the lithospheric structure of GSM was one of the primary goals of the Fourth International Polar Year (2007/08). The multinational and multidisciplinary Antarctica's Gamburtsev Province Project (AGAP) included aerogeophysics, traverse programs, passive seismic experiments and shallow ice core drilling. It was found that GSM has highly dissected Alpine topography reaching maximum elevations of 3000 m and are completely covered by over 600 m of ice and snow.

The range has become the subject of great scientific interest because the mechanism driving uplift of the young shaped GSM in the middle of the old Antarctic Plate is unknown. With only limited constraints available on the topography, geology, and lithospheric structure, the origin of the GSM has been a matter of considerable speculation. The latest interpretation suggested that the GSM were formed during Permian and Cretaceous (roughly 250-100 Ma ago) due to the combination of rift flank uplift, root buoyancy and the isostatic response. Later on, the Antarctic Ice Sheet covered the range and protected it from erosion. However, this theory cannot explain lack of erosion process during many millions years in between uplifting and beginning of glaciation. The next step of the GSM exploration focuses on the direct observation of ice sheet bed by drilling. In order to penetrate into subglacial bedrock in the GSM region the development activity already has been started in China. Drilling operations in Antarctica are complicated by extremely low temperature at the surface and within ice sheet, by ice flow, the absence of roads and infrastructures, storms, winds, snowfalls, etc. All that are the reasons that up to the present moment bedrock cores were never obtained at inland of Antarctica. It is proposed to use cable suspended drilling technology in which an armored cable with a winch is used instead of a pipestring to provide power to the downhole motor system and to retrieve the downhole unit. The use of armored cable allows a significant reduction in power and material consumption, a decrease in the time of roundtrip operations, and a simplification in the cleaning of the hole from the cuttings. It is assumed to choose the drill site with the ice thickness at most of 1000 m and to pierce into the mountain slope to a depth of few meters. Proposed borehole construction includes following steps: (1) dry core drilling of upper permeable snowfirn layer; (2) casing installation; (3) fluid core drilling of glacial ice with bottom fluid reverse circulation; (4) bedrock core drilling. The expected average daily production of ice drilling would be not less than 25 m/day.

All drilling equipment (two 50kW diesel generators, winch, control desk, etc.) will be installed inside a movable sledge-mounted warm-keeping and wind-protecting drilling shelter that has dimensions of 8.8—2.8—3.0 m. Mast has two positions: horizontal for transportation and vertical working position (mast height is 12 m). Drilling shelter is transported to the chosen site with crawler tractor, and all equipment is ready to start drilling in 23 days upon arrival to the site. Total weight of drilling equipment (without drilling fluid) is near 25 tons.

To drill through ice and bedrock a new, modified version of the cable-suspended Ice and Bedrock Electromechanical Drill IBED is designed and tested. IBED drill has modulus construction, and different sections of the drill for different tasks are replaced. The upper part is the same for all variants; it includes four sections: cable termination, slip rings section, antitorque system, electronic pressure chamber. The



motorgear sections are differed by rotation speed of the output shaft of the gear reducer. All modulus contain 3 kW AC3 — 380 V prelubricated submersible motor. Gear reducer for drilling in ice lowers the drill bit rotation speed to 90 rpm; gear reducer for subglacial drilling lowers the drill bit rotation speed to 400 rpm. IBED lower part for ice drilling consists from two parts: chip chamber for filtration of drilling fluid and collecting chips, and core barrel with the drill bit. The outer/inner diameter of the ice core drill bit is 134/110 mm. Length of the core barrel is 2.5 m. Lower part of the bedrock variant is adapted for coring hard rocks using special teeth diamond bit and contains standard 2m length core barrel borrowed from conventional diamond drill string, chip chamber for gravity separation of rock cuttings and dead weights ( $\approx 200$  kg) for increasing of the load on the diamond drill bit. The outer/inner diameters of the diamond bit are 57/41 mm. The preliminary tests showed that teeth diamond drill bit could penetrate into the granite with average rate of 3.18 m/h at low load (3 kN) and torque (28.8 N m).

The new approaches of subglacial bedrock drilling technology are connected with utilization of environmental friendly, low toxic drilling fluids "low molecular dimethyl siloxane oils. They have suitable density viscosity properties, and can be consider as a viable alternative for drilling in glacial ice and subglacial bedrock.

The project is funded by National Science Foundation of China (project No. 41327804) and Geological Survey of China (project No. 3R212W324424). According to approved schedule, the first field tests are planned to carry out just outside Zhongshan Station near Antarctic coast in season 20162017. Next season 20172018 the movable drilling shelter is planned to be transported to the chosen drilling site in the region of GSM, and drilling to the bedrock would be finished during two seasons.

Besides the standard mineralogical, crystallographic, petrographic analysis, radioactive isotope methods ( $^{40}\text{K}$ ,  $^{230}\text{Th}$ ,  $^{234}\text{U}$ ,  $^{238}\text{U}$ ) and magnetostratigraphy are planned to use for dating of rock samples. The borehole magnetometer will be deployed to measure the direction of the magnetic field, and borehole thermometer "to determine geothermal flux..



**S24 – 52: Frontiers in Antarctic Earth Sciences**

***Water-saturated sediments modulate West Antarctic ice sheet stability in the Weddell Sea Sector***

Martin Siegert<sup>1</sup>; Neil Ross<sup>1</sup>

Imperial College London, United Kingdom<sup>1</sup>

The future stability of the Weddell Sea sector of the West Antarctic Ice Sheet is dependent on the Institute Ice Stream, which rests on a major reverse-sloping bed making it sensitive to grounding-line melting. Ice-stream dynamics are also important to stability, as increased flow could lead to thinning-induced flotation and decreased flow could force grounding-line retreat. Here, we show both ice-stream onset and lateral enhanced-flow margin are located at a sharp transition to a newly identified zone of water-saturated basal sediments. We show the sediments receive water from an sub-glacial lake' at the onset, and that water exits the sediment near the grounding line. As the ice-surface is very flat over the sediment, modifications to sub-glacial water-flow could be driven by small ice-thickness changes, leading to alterations in basal conditions and, hence, ice-flow change. Warning signs of such change come from Cryosat2 altimetry showing recent catchment-wide ice-surface lowering.



## S24 – 54: Frontiers in Antarctic Earth Sciences

### *Seismic Subsurface Imaging for Contourites*

Sunjay<sup>1</sup>; Manas Banerjee<sup>1</sup>

Geophysics, BHU, India<sup>1</sup>

Seismic expression of bottom current deposits contourite depositional system (CDS) can be derived from seismic data. Seismic facies are typical of contourites, most of which are equally present in turbidite and/or hemipelagic systems. These are moderate to low amplitude reflectors; regular, migrating wave, moderate to low amplitude reflectors; irregular, wavy to discontinuous, moderate amplitude reflectors; and an irregular, continuous, single high amplitude reflector. In any multidisciplinary study of bottom current influenced sedimentation in the deep sea, geophysical "specifically acoustic surveys play a key role. For simplicity, acoustic surveying is here divided into two main techniques: seafloor mapping (for surface expression and morphology) and seismic reflection profiling (for internal acoustic character, geometry and hence interpretations of the depositional environment). Some inferences can also be made on the relative ages of the sediments (seismostratigraphy). Internal architecture (structure and subunits) and seismic attributes and facies in each subunit marine seismic sources give very deep penetration (km) and are much more suited to deep geological studies of ancient drifts and basement. Seismic reflection profiling provide the basis for a number of classification schemes on the various types of drift morphology and internal configuration. Internal Structure of a Contourite Drift Generated by the Antarctic Circumpolar Current We describe the internal structure and stratigraphy of a well imaged contourite drift from the Southern Ocean. This drift, which we have named the South Falkland Slope Drift, lies on the northern flank of the Falkland Trough due south of the Falkland Islands. Drifts which occur directly in the path of the Antarctic Circumpolar Current (ACC), downstream of the Drake Passage gateway, are of considerable paleoceanographic significance since their detailed stratigraphic record will help to constrain the history of the ACC. Pliocene Holocene contourite deposition under the Antarctic Circumpolar Current, western Falkland Trough, south Atlantic Ocean The eastward flowing Antarctic Circumpolar Current (ACC) has influenced sedimentation on the slope and floor of the western Falkland Trough, where the axis of the current is topographically constrained. Deepwater flow (below 3000 m) has produced a symmetrical sediment drift on the trough floor, with nondepositional margins indicating higher current velocities at the base of slope. To the southeast of the Falkland Islands there is a gap in the North Scotia Ridge, north of which the floor of the trough is swept clean of sediment by the ACC. On the drift, Holocene biogenic sandy contourites overlie Last Glacial Maximum muddy contourites and fine grained diatomaceous hemipelagites. Sedimentation rates here average  $3-4 \text{ cm ka}^{-1}$ . The sandy contourites present in four of the cores from the sediment drift are sharply underlain by the finer grained, diatomaceous hemipelagites. The lack of a coarsening upward sequence, commonly associated with an increase in current velocity may be indicative of high current activity eroding away the finer (negative) sequence. Pliocene and Mid Pleistocene glauconyrich sandy contourites containing radiolarian characterise the Falkland Plateau and the floor of the trough near the gap in the North Scotia Ridge.

Contourites precise imaging is pertinent task before geoscientist for upstream business and to enhance R/P ratio of the nations. Regional seismic reflection profiles can also be used to backstrip or map laterally continuous reflectors or mega sequences and produce models of palaeobathymetry (and hence palaeocurrent pathways) and sediment thicknesses. Estimate of wavelet and corresponding Independent Component : For noise free seismic trace , Independent Component is ,in turn , estimate of the reflectivity with some linear phase shift . For seismic trace corrupted with noise, the recovered Independent Component need not be representative of reflectivity. Geophysical data are analysed by MATLAB, SEISMIC UNIX, etc



## S24 – 64: Frontiers in Antarctic Earth Sciences

### *An extensive basal drainage system in Princess Elizabeth land, Antarctica*

Stewart Jamieson<sup>1</sup>; Neil Ross<sup>2</sup>; Martin Siegert<sup>3</sup>; Jamin Greenbaum<sup>4</sup>; Duncan Young<sup>4</sup>; Alan Aitken<sup>5</sup>; Jason Roberts<sup>6</sup>; Don Blankenship<sup>4</sup>

Durham University, United Kingdom<sup>1</sup>; University Of Newcastle, Australia<sup>2</sup>; Imperial College London, United Kingdom<sup>3</sup>; University of Texas, USA<sup>4</sup>; University Of Western Australia, Australia<sup>5</sup>; Australian Antarctic Division, Australia<sup>6</sup>

The subglacial landscape of Princess Elizabeth Land in East Antarctica is poorly constrained due to a paucity of ice thickness measurements. We analyse a series of satellite imagery datasets, in conjunction with ice penetrating radar data, to reveal ice surface expressions of macroscale landforms beneath the ice sheet. We identify two distinct linear morphologies: a feature that is 140 x 20 km in dimension, and multiple narrow (ca. 10 km) sinuous features up to 545 km long that appear connected. We hypothesise these surface features relate to a large subglacial basin, possibly containing a lake, in the interior of PEL linked to an interconnected canyon system. The canyons bifurcate as they drain northwards to the coast between the Vestfold Hills and the West Ice Shelf, and are more focused as they reach southwards to the head of the Lambert Glacier. The presence of canyons is confirmed at a few localities by radar data from the ICECAP project but no data exist over the proposed subglacial lake. The alignment of our mapped canyons and deep features identified in the radar data inland of the West Ice Shelf indicate that water from the interior of Princess Elizabeth Land may be reaching the grounding line. Smoothing and inverted channels in the base of the West Ice Shelf, just beyond the location of our drainage channels, suggests water may be eroding the ice shelf at a range of scales. We suggest the canyons represent a tectonically controlled valley system subsequently incised by rivers prior to continental scale Antarctic glaciation at 14Ma since which time it has been modified by subglacial water flow. The implication is that the drainage system is a longlived component of the ice shelf. Notwithstanding the scale of the drainage system, it appears to exert little influence upon the ice flow dynamics of PEL, which is in contrast to subglacial drainage systems in other areas



## S24 – 97: Frontiers in Antarctic Earth Sciences

### *Issues and Options for Rapid Access Ice Drilling in Antarctica*

Yang Yang<sup>1</sup>; Pavel Talalay<sup>1</sup>; Cao Pinlu<sup>1</sup>; Wang Rusheng<sup>1</sup>; Zhang Nan<sup>1</sup>; Fan Xiaopeng<sup>1</sup>

Polar Research Center, Jilin University, China<sup>1</sup>

The drill system, called the Rapid Access Ice Drill (RAID), is capable of quickly accessing Antarctic ice sheet bed down to - m of ice and collecting ice intervals of interest and a few tens of meters of core from the subglacial material. Drilling to these depths would be completed within short period of time (two-four weeks) so that several holes could be produced in a single summer field season. The RAID system has been an elusive objective for glaciologists for more than 40 years. Renewed interest comes from geologists seeking subglacial bedrock samples to, for example, validate geotectonic and paleogeographic reconstructions. The approaches to RAID systems can be subdivided into the three following groups: (1) conventional drilling technology used in oil well or mineral exploration industry; (2) hotwater drill systems with subsystem for subglacial sampling; (3) unconventional drilling systems.

For the first time light weight wireline core drilling system was considered as RAID for use within the framework of the International Antarctic Glaciological Project (IAGP), East Antarctica at the beginning of 1970s. Cold air reverse circulation was chosen as cleaning method for the upper 1000 m of the hole. At the depth of about 1000 m arctic grade diesel fuel is proposed as drilling fluid to reduce hole closure and to remove cuttings. The IAGP was not fulfilled due to organizational and financial reasons. The current design of the US drilling community for RAID is based on a modification of a standard rotary diamond coring rig as it was used in the mineral exploration industry, operated in a flooded reverse circulation mode with composite drill rods.

The usage of coiled tubing drill systems for fast access drilling to the subglacial environment and bedrock coring has been proposed decade ago. However, the minimum operating temperature for commercial composite tubing is currently -40°C. At colder temperatures, the tubing liner becomes too brittle. The coiled tubing itself is subject to fatigue every time it is cycled through bending. The usual lifetime of a coil is between 100 and 200 trips, depending upon the axial and pressure loading.

To use conventional drill rigs, many components such as a hydraulic system, casing setup and others will require major developments in order to adapt properly for Polar Region explorations. These drill rigs operate as outdoor machines or use tents or primitive shelters that are not enough at extremely low temperatures and storm winds. In addition, commercial drill rigs are still very heavy and power consuming and require a large logistical load to move and support in Antarctica. A critical area for conventional drilling system development is discovering a way to efficiently separate the chips from the drilling fluid once chips reach the surface. Conventional cleaning systems need serious modification to work properly in a cold polar environment especially with ice chips.

Hotwater drill systems are well known access approaches since 1980s and can be considered as the fastest type of RAIDs. On the way down a hotwater ice coring drill with a ring of water jets as the coring head can be used occasionally to obtain ice cores at targeted depths from hotwater drilled holes. For subglacial bedrock core sampling with a hotwater drill system, it was suggested installing a positive displacement motor (PDM) that rotates core barrel with drill bit instead of the hotwater nozzle. When hotwater passes through the PDM, PDM will convert hydraulic pressure of hotwater flow into rotation and torque in order to drive the core barrel rotating with the drill bit. Then drill bit begins to cut the bedrock at the bottom, and rock chips will be collected by the hotwater flow into the chip chamber which is installed on the upper side of PDM. It just needs to change downhole part of the drill to recover subglacial bedrock samples, however, there are still some problems to solve, e.g. effective removal and collection of solids, reducing of thermal influence on the rock samples, reliable PDM/core barrel/drill bit design.



Another method for subglacial sampling includes two drilling systems: a hotwater drill for fast access drilling and a mechanical drill rig (conventional drill rig or electromechanical drill suspended on armored cable) that should change the hotwater drill system when approaching the ice sheet base. Mechanical drilling in subglacial rocks with hotwater circulation, in principle, is possible but challenging. The problems are associated with clogging of the entrance of the core barrel with fragments of rocks, which then prevented entry of any further material, poor core recovery, and danger of drill string sticking. To avoid such problems it would be possible to replace holewater by low temperature drilling fluid. However, it is necessary to keep in mind that hotwater drill systems produce large diameter holes, and the required amount of the drilling fluid (100-400 m<sup>3</sup>) gives rise to impracticability of this method. Moreover, it needs two independently heavy and power consumed drilling systems: one for predrilling in ice and another one for subglacial sampling. In trying to find methods to drill faster and safely, the new unconventional heating methods (laser, plasma, beam) can be taken into consideration. Perhaps the most promising unconventional drilling system is laser drilling. Proposals for laser drilling in rocks go back almost five decades, but in the past, lasers have been limited by their relatively low power levels and poor efficiency. During the past decade, intensive research has been made into the development of a system that can transmit highpower lasers over long distances via fiber optic cables. The unconventional thermal drills can drill at a high rate but require 10 to 20 times more energy for ice disintegration than conventional rotary rigs. Intensive support is required in the research phase of these technologies.

It is our opinion that hotwater drill systems with interchangeable downhole drill nozzle and mechanical drill with PDM drive can be considered as the most technologically advanced potential RAID, it has good access drilling possibility to get the subglacial samples, even some problems need to be solved.



**S24 – 116: Frontiers in Antarctic Earth Sciences**

***The polarimetric radar wave and its propagating in anisotropic ice sheet***

Bo Sun<sup>1</sup>; Bangbing Wang<sup>2</sup>; Jingxue Guo<sup>1</sup>; Xiangbin Cui<sup>1</sup>; Xueyuan Tang<sup>1</sup>

Polar Research Institute of China, China<sup>1</sup>; Zhejiang University, China<sup>2</sup>

The polar ice sheets play an important role in the global climate system. Its evolution and stability have great impact on climate changing and sea level rising. The huge thick ice sheet (>2000m) are made up of countless micro ice crystals. Single ice crystal shows obvious anisotropy, which own just an exclusive C axis; but the bulk of ice crystals may have the features of C distribution: random or cluster depend on the extent of stress and strain on it. Glen (1955) represented an isotropic ice flow law, which had succeeded explaining the earlier field observations and had been accepted widely. But the later field measurements had showed some discrepancies with the predicted result of Glens flow law when technical progress promotes the precise and extent of detecting, which means the anisotropy of ice cant be neglected when understanding the evolution of ice sheet. Overall, in the past century, the complicated mechanism of EM propagating in anisotropic media impeded the understanding on the propagating feature of radar wave in ice sheet, which had caused more troubles in data processing and data interpretation of polarimetric radar and then limited its application and spread in polar. Here, we employed two methods to clarify the response of EM waves from anisotropic stratified ice. Firstly, we used the method of finite difference in time domain (FDTD) to simulate the response of EM wave in anisotropic stratified ice. The modeling results showed that, the EM wave will split into fast and slow wave, called ordinary and extraordinary wave keeping perpendicular component, while propagating in anisotropic media. In multimedia, the propagating traces of EM waves are more complicated. Secondly we deduced and developed a method to calculate the reflection coefficient matrix directly based on Maxwell equation and the propagation matrix method, and then obtained the Stokes parameters of polarimetric radar. We made different models to simulate the response from polarimetric radar. The modeling results proved that, while relative rotation between survey and media coordinate exist, the echo power will alter with period. The derived formula indicate that, the reflection coefficient is firmly linked to the permittivity of the anisotropic media, and then to the 2nd fabric orientation. So the polarimetric radar can be used for identifying the difference of the permittivity of the anisotropic media, and then identifying the fabric type in ice sheet.



**S24 – 119: Frontiers in Antarctic Earth Sciences**

***Rapid intermediate subice Geological drilling Technology with air Reverse-Circulation Continual Sampling in Antarctica***

Wang Rusheng<sup>1</sup>; Talalay Pavel<sup>1</sup>; Gong Da<sup>1</sup>; Liu Gang<sup>1</sup>

Polar Research Center, Jilin University, China<sup>1</sup>

Although advances in remote geophysical glacier survey are well known, many of the questions could be answered only by drilling. Hereinafter we focused on main problems that require recovering core samples and/or produce boreholes in glaciers.

Ice cores contain an abundance of information about climate. And also, they are allowed to carry out different researches on physical properties and structure of natural ice recovered from different depths that do exert a control on glacier behavior. Rapid access drilling to till and bedrock of glaciers offers unique opportunities for examining processes acting at the bed. Samples of basal and subglacial material contain important paleoclimatic and paleoenvironmental records and provide a unique habitat for life, give significant information on sediment deformation beneath glaciers and its coupling to the subglacial hydraulic system, subglacial geology, and tectonics. In addition, seismic investigation of ice properties and glaciers bedrock topography requires rapid drilling of shallow holes for explosive works.

To answer many of the questions it is not necessary to drill deep holes, which requires expensive powerful heavy drilling equipment. In this case much more lighter and simple shallow drills are preferable for drilling up to the depths of 300-500m. It is very important to rapidly get 300-500m ice core within several days, even one or two days. This will greatly reduce costs and accelerate the research process.

At present, the ice drilling fluid has bad effect on the polar environment, which maybe polluted the air, firn and ice. Specially, the ice is moving, and the drilling fluid remains in the borehole, thousands of years it will eventually flow into the sea, and cause water pollution. So scientists have proposed the air drilling technology in ice sheet. Compressed air as the drilling fluid has many advantages: less environmental pollution, high drilling efficiency, low cost, high penetration rate, etc. At present, air drilling technology is recognized as the contemporary drilling technic that is applied widely and has the most developmental prospective. When drilling with air in the ice, cuttings removing by conventional normal circulation was previously proposed and tested. However, because of loose state of shallow ice near drilling wellhead, the compressed air is leaked and compressed air flow rate dramatically decreases. Thus, the ice cuttings will not be discharged from the borehole bottom, and repeated fragmentation will happen, which results in low drilling efficiency and even in stoppage of penetration. In general, drilling depth can reach only 100 m. Casing of the permeable snowfirn zone can improve penetration process but requires applying of complicated drilling technology with underreaming operations and sealing of casing shoe.

Proposed rapid subice geological drilling with air continually transporting cuttings and cores produces dry hole using air reverse circulation technology. Two options are considered to obtain ice cores without stopping of drilling. When doublewall drill pipe is used, air goes down to the bottom of the hole from the gap between the inner and outer tube, and then carrying ice core and ice chips back to the surface from the drill pipe center channel. When single wall drill pipe and vacuum pump are used, air goes down to the borehole bottom from the circle gap between the borehole wall and the outer of the drill pipe, and then transports the cuttings and cores from the center of pipe with suction function of the vacuum pump. And when rapidly drilling into intermediate subglacier bedrock, there is another method. The hollow through DTH Hammer is needed which can be connected with doublewall drill rod. The rock cuttings and cores will be removed to the surface from the center channel of hammer and drill pipe by rapid air moving flow. Calculations of the air flow rate and pressure drop are presented on the base of flow required for continually transporting the ice core with the most length and diameter.



## S24 – 120: Frontiers in Antarctic Earth Sciences

### *Analysis of Extreme Precipitation Events over the Antarctic Peninsula during the year 2013*

Wayan Suparta<sup>1</sup>; Siti Khalijah Zainudin<sup>1</sup>

Universiti Kebangsaan, Malaysia<sup>1</sup>

Antarctica can be regarded as a desert due to low precipitation. However, near the coastal region, ocean store heats thus create milder temperature and increases chances of higher precipitation. The higher of precipitation rate may produce thunderstorm events and this is very important in improving weather forecasting. This study aimed to analyze the frequency of extreme precipitation event over the Antarctic Peninsula during the year 2013. We collected precipitation data from NASA Tropical Rainfall Measuring Mission (TRMM) for the region of Antarctic Peninsula. From the three selected stations: O'Higgins (63.32°S, 57.90°W), Rothera (67.57°S, 68.13°W) and Palmer (64.78°S, 64.05°W), found three highest precipitation rates which are more than 2.00 mm/hr. The three of highest precipitation is categorized into three cases, which occurred on March 4 (as Case 1), March 31 (as Case 2) and April 14 (as Case 3). To strengthen the investigation, we analyzed the data for three days before and after the cases. We also collect the meteorological data from British Antarctic Survey (BAS) and precipitable water vapor (PWV) map obtained from NCEP/NCAR to support the analysis. The distribution map of PWV is determined for the area, which covers from 60.04°S to 78.34°S and from 53.25°W to 85.80°W. In general, precipitation values were obtained very low before and after of each case. For Case 1, the highest precipitation at the onset days are recorded for O'Higgins (0.12 mm/hr) and Rothera (2.19 mm/hr). This is confirmed by a low pressure at both stations. For Case 2, three stations show the highest precipitation of 0.64 mm/hr (O'Higgins), 3.8 mm/hr (Rothera) and 1.4 mm/hr (Palmer), and PWV maps and meteorological data shows the same condition as in Case 1, a chance for snowfall. For the last case, the highest precipitation on the onset day was recorded at Palmer, which 89% and 52% higher compared to Rothera and O'Higgins, respectively. A less of precipitation at O'Higgins is possibly due to strong wind that blows away the precipitation. For each case, the highest precipitation was in Case 2 (1.95 mm/hr) and the lowest was in Case 1 (1.16 mm/hr), and Rothera is the station with the most precipitation (2.45 mm/hr). The results imply that the precipitation does not distribute evenly throughout the Antarctic Peninsula, where wind direction and geographical landscape as western side of the Antarctic Peninsula have heavier snowfall. With the highest precipitation occurs in a particular place, it would indicate a higher chance of thunderstorms that could produce lightning.

Keywords: Extreme Precipitation, Antarctic Peninsula, Thunderstorms, Forecasting



## S24 – 130: Frontiers in Antarctic Earth Sciences

### *The subglacial lake vostok, East Antarctica: Microbiology of the borehole frozen lake water*

Bulat S.<sup>1</sup>; Khilchenko M.<sup>1</sup>; Karlov D.<sup>1</sup>; Doronin M.<sup>1</sup>; Marie D.<sup>2</sup>

Petersburg Nuclear Physics Institute, NRC "Kurchatov Institute", Russia<sup>1</sup> ; Station Biologique De Roscoff, Roscoff Cedex, France<sup>2</sup>

The objective was to estimate microbial content and diversity in the subglacial Lake Vostok (buried beneath 4km thick East Antarctic ice sheet) by studying the uppermost water layer which entered the borehole upon lake entry (February 5, 2012) and then shortly got frozen within. The samples of so called drillbit water frozen on a drill bit upon lake enter (RAE57) along with redrilled so called borehole frozen water (RAE58) were provided for the study with the ultimate goal to discover the life in this extreme icy environment.

The comprehensive analyses (constrained by Ancient DNA research criteria) of the first lake water samples drillbit (one sample) and borehole frozen (3 different depths 5G21N3425, 3429 et 3450m), are got finished. If the drillbit water sample was heavily polluted with drill fluid (at ratio 1:1), redrilled borehole frozen samples proved to be rather clean but still strongly smelling kerosene and containing numerous microdroplets of drill fluid giving the milky ice colour. The cell concentrations measured by flow cytometry showed 167 cells per ml in the drillbit water sample while in borehole frozen samples ranged from 5.5 (full cylinder 3429m deep frozen water ice core) to 38 cells per ml (freeze centre of 3450m deep moon shape ice core).

DNA analyses came up with total 49 bacterial phylotypes discovered by sequencing of different regions (v3v5, v4v8, v4v6 et fullgene) of 16S rRNA genes. Amongst them all (Alphaproteobacteria (7 phylotypes, mostly Rhizobiaceae), Betaproteobacteria Burkholderiales (7 phylotypes), Gammaproteobacteria (19 phylotypes, mostly Pseudomonadaceae, Moraxellaceae and Enterobacteriaceae), Actinobacteria (6 phylotypes, mostly Micrococcaceae and Microbacteriaceae), Firmicutes Bacilli (7 phylotypes), Bacteroidetes Flavobacteriaceae (1 phylotype)) but two were considered to be contaminants (were present in our contaminant library, including drill fluid findings).

The 1st remaining phylotype successfully passing all contamination criteria proved to be hitherto unknown type of bacterium (group of clones, 3 allelic variants) showing less than 86% similarity with known taxa. Its phylogenetic assignment to bacterial divisions or lineages was also unsuccessful despite of the RDP has classified it belonging to OD1 uncultured Candidate Division. The 2<sup>nd</sup> phylotype was less remarkable and still dubious in terms of contamination. It was presented by just one clone and showed 93% similarity with *Janthinobacterium* sp of Oxalobacteraceae (BetaProteobacteria) " well known "waterloving bacteria. No archaea were detected in lake water frozen samples. Thus, the unidentified and unclassified bacterial w12310 phylotype for the first time discovered in the uppermost water layer in subglacial Lake Vostok might represent ingenious cell populations in the lake, making the life in the lake less elusive. The proof may come (as well as other discoveries) with farther analyses (e.g., sample screening with w12310specific primers) of newly requested moonshape samples of borehole frozen water analyses of which are ongoing. The findings will be discussed in terms of cryoastrobiology.



**S24 – 149: Frontiers in Antarctic Earth Sciences**

***Late glacial subglacial lake sediments recovered and sampled in Pine island bay, Antarctica***

Gerhard Kuhn<sup>1</sup>; Hillenbrand, C. D.<sup>2</sup>; Kasten, S.<sup>1</sup>; Smith, J.<sup>2</sup>; Nitsche, F.<sup>3</sup>; Klages, J.P.<sup>1</sup>

Alfred-Wegener-Institut, Germany<sup>1</sup>; British Antarctic Survey, United Kingdom<sup>2</sup>; Lamont-Doherty Earth Observatory, USA<sup>3</sup>

Subglacial meltwater facilitates rapid ice flow beneath concurrent ice sheets, and there is widespread evidence for a dynamic subglacial water system beneath the Antarctic Ice Sheet. It steers and affects the pattern of ice flow and is a direct result from boundary processes acting at the base of the ice sheet, i.e. pressure induced basal melting. Consequently, the occurrence of subglacial meltwater plays an important role in bedrock erosion, subsequent resedimentation, and in shaping the topography of icesheet beds.

Here we present new geological and geochemical data from sediments recovered on the West Antarctic continental shelf in Pine Island Bay that we interpret as reliable indicators for deposition in a palaeosubglacial lake beneath the formerly expanded West Antarctic Ice Sheet, presumably during or following the Last Glacial Maximum. Characteristic changes of sedimentary facies and geochemical profiles within these cores taken on RV Polarstern expeditions ANTXXIII/ 4 (2006) and ANTXXVI/ 3 (2010) support the presence of an active subglacial lake system during the late stages of the last glacial period. These findings have important implications for palaeo icesheet dynamics, suggesting there was considerable water available to lubricate the bedrock-ice interface and deposit water saturated subglacial sediments (soft tills).

Based on our investigations performed so far, we suggest that the transition from subglacial lake to contact with the ocean took place in the early Holocene. During this time, we speculate, that the ice sheet thinned and successively transformed into an ice shelf with subice cavities flushed by tidal currents. Based on bathymetric maps and relative sea level curves we will aim to estimate ice thickness as the grounding line retreated across the subglacial lake threshold further inland. Our findings may also have implications for ice sheet models, which have to consider the predominantly nonlinear effects related to subglacial hydrology.



## S24 – 158: Frontiers in Antarctic Earth Sciences

### ***Exploring the Recovery Lakes region, East Antarctica, by airborne gravity, magnetics and radar measurements***

Rene Forsberg<sup>1</sup>; Arne V Olesen<sup>1</sup>; Fausto Ferraccioli<sup>2</sup>; Tom Jordan<sup>2</sup>; Kenichi Matsuaka<sup>3</sup>; Andres Zakrajsek<sup>4</sup>; Marta Ghidella<sup>4</sup>

National Space Institute, Technical University of Denmark, Denmark<sup>1</sup>; British Antarctic Survey, United Kingdom<sup>2</sup>; Norwegian Polar Institute, Norway<sup>3</sup>; Instituto Antartico Argentino, Argentina<sup>4</sup>

Longrange airborne geophysics measurements were carried out in the IceGrav2013 campaign in hitherto unexplored parts of interior East Antarctica (Recovery Lakes region), and supplementing the earlier IceGrav2011 campaign over the interior Dronning Maud land region. The airborne measurements provided for the first time a regional coverage of gravity, magnetics and ice penetrating radar for major Dronning Maud land ice stream systems, from the grounding line up to the Recovery Lakes drainage basin, and provide new insight into the geological setting of the area, as well as the nature of the major large active subglacial lakes (Recovery Lakes and A and B). We present the first maps of gravity, magnetics, ice thickness and bedrock topography for the Recovery catchment, and showcase the strong contrasts in bedrock topography and basal reflectivity patterns in the upper and lower reaches of the Recovery Glacier catchment. These new survey results in the Recovery frontier are of major significance for studies of subglacial landscapes and hydrology, and provide new geophysical insights to help study East Antarctic tectonics in relation to supercontinental evolution, unravel the influence of contrasting basal conditions on East Antarctic Ice Sheet dynamics, as well as contributions to completing data coverage in Antarctica for longterm geophysical data compilation projects such as BEDMAP, ADMAP and ANTGP.

The campaign was carried out with a BAS TwinOtter, operating from the alley and Belgrano II stations, as well as a field camp on Recovery Lake B, operated by the Norwegian Polar Institute. Gravity measurements were the primary driver for the survey, with two airborne gravimeters (L&R and Chekan) providing measurements at accuracy level of 2 mGal, supplementing GOCE satellite data, and confirming an excellent submGal agreement between satellite and airborne data at the longer wavelengths. The success of the 2013 airborne geophysics survey, in one of the most inaccessible areas on Antarctica, highlights the possibility of rapidly closing the last gravity data void of Antarctica around the South Pole, and plans are currently being implemented to do this in 2015/16 in an international cooperation. Closing the GOCE data gap south of 83S is especially important for global gravity field modelling, where the Antarctic pole gap remains the last unmapped region on the planet.



**S24 – 181: Frontiers in Antarctic Earth Sciences**

***Research Progress of Debris-Rich Ice drilling technology***

Pinlu Cao<sup>1</sup>; Cheng Yang<sup>1</sup>; Yunwang Chen<sup>1</sup>; Zhichuan Zheng<sup>1</sup>; Rusheng Wang<sup>1</sup>; Nan Zhang<sup>1</sup>; Xiaopeng Fan<sup>1</sup>; Yang Yang<sup>1</sup>; Pavel Talalay<sup>1</sup>

Polar Research Center, Jilin University, China<sup>1</sup>

Drilling into basal ice, till and bedrock has garnered much scientific interest because it offers unique opportunities to research subglacial environments, basal morphology and tectonics and the subglacial hydraulic system. Samples of subglacial material not only contain important records of ice sheet history and climate change but also give significant information about icesheet/ bedrock interaction and how this zone influences the overlying ice sheet dynamics. Moreover, there are may be existing biological activity within the ice sheets or in the basal materials. However, the ice located in this zone is extremely difficult to drill because it is often loaded with debris and rock and may have particles of various sizes in it, ranging from clay and silt to pebbles, cobbles and boulders. The standard steel bits used for ice core drilling are not suitable because the cutters are very easily broken by rock particles because their hardness and abrasiveness are higher than that of the ice. The tool steel and tungsten carbide inserts are easily damaged in intermixed icerock formations. Debris rich ice is also often encountered when drilling into rock glaciers, because of icerock mixtures moving downslope or true glaciers covered by rock debris in polar and mountain regions. Although good progress has been made in the development of special drilling equipment for coring in theses debris rich ice layer, many problems still need to solved, especially in the areas of the production of reliable drill bits and the elimination of heat generated in the hole. This paper reviewed the debris rich ice drilling practices in polar and rock glacier ice, and research progress about the debris rich ice drilling are introduced. In addition, both standard and custom made carbide and polycrystalline diamond compact (PDC) drill bits were test to drill debris rich ice to obtain acceptable penetration rate and torque with minimal load and rotation speed. The results show that both the carbide and the PDC drill bits can drill with high penetration rates in debris rich ice containing very hard and abrasive granite particles at low drill loads of 500-1200 N. When the rock volume content is 30%, the penetration rates are 4.68 m/h, 5.9 m/h and 11.12 m/h for the standard sixtooth carbide drill bit, a PDC bit with a round compact and a PDC bit with a semiround compact, respectively, under a drill load of 500 N with a rotation speed of 100 rpm. Within the range of drill loads of 500 to 1200 N and rotation speeds of 50 to 200 rpm, the maximum torque is no more than 45 Nm, and the power consumption is less than 0.8 kW. In addition, the temperature changes of the bit cutters caused by their cutting action were also measured. Results of the preliminary tests show that temperature variations increase from 3.67 to 5.96 °C when the drill load increases from 450 to 1200 N and from 4.17 to 6.21 °C when the rotation speed increases from 50 to 200 rpm.



## S24 – 358: Frontiers in Antarctic Earth Sciences

### *Radar internal layer stratigraphic constraints on the East Antarctic plateaus old ice*

Cavitte M. G. P.<sup>1</sup>; Blankenship D. D.<sup>1</sup>; Young D. A.<sup>1</sup>; Schroeder D. M.<sup>2</sup>; Siegert M. J.<sup>3</sup>; Parrenin F.<sup>6</sup>; Le Meur E.<sup>5</sup>; Macgregor J. A.<sup>1</sup>

UTIG, UT at Austin, USA<sup>1</sup>; JPL Pasadena, USA<sup>2</sup>; Bristol Glaciology Centre, Bristol, UK<sup>3</sup>; CNRS, Université Joseph Fourier, Grenoble, France<sup>4</sup>; LGGE, Grenoble, France<sup>5</sup>

Our current understanding of ice sheet processes and flow dynamics point to the East Antarctic Plateau as one of the hot spots for finding old ice, yet, much of it remains to be surveyed. In this study, we use airborne radar sounding data collected at 60 MHz over several seasons by the University of Texas Institute for Geophysics (UTIG) to trace internal layering between the Vostok and the EPICA Dome C ice core sites, over a distance of 500 km. Thirteen layers, spanning the last two glacial cycles, between 38 ka and 247 ka, are mapped through the area, encompassing both sides of the divide between Byrd and Totten Glacier catchments. The dates are obtained where the layers intersect the ice core sites, at both the Dome C and Vostok sites. These internal layers are easily traced around Dome Concordia, up to a distance of 250 km, where they exhibit continuous and isochronal geometries. The surveys gridded geometries provide a larger number of crossover points where layer consistency can be ascertained, which further supports the isochronal characteristic of the layers mapped. We independently repeat the analysis using Multichannel Coherent Radar Depth Sounder (MCoRDS) data collected along a single transect between the two ice core sites, and show that the same layers can be traced consistently, with a different radar center frequency and bandwidth. Independent of palaeoclimate signals, radar sounding enables propagation of the Dome C timescale, with a radar depth uncertainty, which represents between a third and a half of the ice core dating uncertainty. Our deepest internal layer belongs to the MIS7e interglacial, and therefore provides a key constraint on potential old ice sites well away from the existing ice core sites and provides accurate age depth bounds for inverse modeling efforts to target spots of old ice. However, as distance from Dome C grows, especially nearing Lake Vostok, internal layer geometries can get very complex because of accumulation and ablation anomalies in the Vostok vicinity. Both of these phenomena, and buried dunes in particular, truncate layer continuity at all levels of the ice column. We show that with an extensive radar grid, such as the UTIG Lake Vostok Survey (LVS) survey, it is possible to circumvent such areas, despite the incoherent nature of the data for that survey. Achieving a direct radar correlation between the two ice cores with a satisfactory uncertainty is certainly possible, and will rely on the community's dedication to acquiring further radar coverage of the divide directly downstream of Vostok, where layer geometries are particularly complicated.



## S25 – 85: Antarctic Meteorite and Micrometeorite

### *The Collection and Studies of Antarctic Micrometeorites from Japanese Antarctic Research Expedition*

Naoya Imae<sup>1</sup>; Takaaki Noguchi<sup>2</sup>; Hideyasu Kojima<sup>3</sup>; Tomoki Nakamura<sup>4</sup>; Toru Yada<sup>5</sup>; Naoyoshi Iwata<sup>6</sup>; Kentaro Terada<sup>7</sup>

National Institute of Polar Research, Japan<sup>1</sup>; Faculty of Arts And Science, Kyusyu University, Japan<sup>2</sup>; Antarctic Meteorite Research Center, National Institute of Polar Research, Japan<sup>3</sup>; Department of Earth Science, Tohoku University, Japan<sup>4</sup>; Japan Aerospace Exploration Agency<sup>5</sup>; Department of Earth And Environmental Sciences, Yamagata University, Japan<sup>6</sup>; Department of Earth And Space Science, Osaka University, Japan<sup>7</sup>

#### 1. Introduction

The extraterrestrial materials depending on their sizes are broadly divided into two, meteorites (more than ~1 mm) and micrometeorites (less than ~1 mm), both of which are effectively collected from Antarctica. However, the collection field is different; the meteorites are concentrated on the surface of the inland ice field around the mountains, and the micrometeorites are recovered from the inside of the Antarctic ice or snow. Micrometeorites include particles from parent bodies different from meteorites, especially from comets. However, most micrometeorites have experienced the atmospheric entry heating, resulting in the partial to complete melting, known as cosmic spherule, and the relict phases survived the melting in cosmic spherules are useful for the study. Small number of micrometeorites has completely survived the atmospheric entry heating, known as unmelted micrometeorites, which are more important for study. The first huge collection was carried out in 1988 by the French team (Maurette et al., 1991). Thereafter, Japanese Antarctic Research Expedition (JARE) started to collect them from various sites, as well as the US team from the South Pole Water Well in 1995 (Taylor et al., 2000). Here we will review the previous collection and the important obtained research results using micrometeorites mainly from the JARE activity.

2. Collection of Antarctic micrometeorites by JARE So far, JAREs have carried out the recovery of Antarctic micrometeorites from the snow of the Dome Fuji Station area, the ice of the Yamato ice field, and the ice of the Tottuki ice field.

2.1. Dome Fuji water tank by JARE37 (1995-1997) A lot of micrometeorites have been discovered precipitates on the water tank sampled by the wintering party (Nakamura et al., 1999; Noguchi et al., 2000).

2.2. Bare Ice Field around the Yamato Mountains by JARE39 (1997-1999) A set of equipment with the icemelting and waterfiltering was newly introduced for the insitu sampling of micrometeorites on the bare ice field around the Yamato Mountains, where is famous for the meteorite concentrated field. As result, they melted ~36 tonice on the ice field, and collected abundant micrometeorites. They also melted ~2 tonice on the Tottuki ice field near the Syowa Station (Yada and Kojima, 2000; Terada et. al., 2001).

2.3. Tottuki ice field by JARE41 (1999-2001) Huge amounts of micrometeorites were collected from the melted water of the Tottuki ice field near the Syowa Station mainly by the new system with the water pump reforming of the previous system. They carried out ~50 ton icemelting and ~40 ton waterfiltering in total (Iwata and Imae, 2002).

2.4. Surface snow near the Dome Fuji Station by JARE-44, -46, -48, -49, -51, -52, and -54. The concentration of micrometeorites in ice and snow only depends on the accumulation rate of snow trapped the micrometeorites. This implies that the best field to collect micrometeorites is the top of the Antarctic ice sheet, where the annual snow accumulation is low (e.g., less than 10 cm around the Dome Fuji



Station). In addition, our previous studies (Nakamura et al., 1999; Noguchi et al., 2000) revealed that the micrometeorites from the surface snow on the Dome area is more fresh, surviving the terrestrial weathering than those from the ice fields, because the micrometeorites in snow are recent fall and those in ice are much old with the age more than 10000 years. Thus, our focus moved to the field, and have requested the snow sampling to the ice core drilling team of these expeditions (in charge of Prof. Motoyama in NIPR) to collect about 10 boxes (0.06 cubic m per a box) per one operation, estimating that the snow weight of ~150 kg per one operation. In order to avoid any contamination, gloves and wears for use in clean room were used for the snow sampling.

### 3. Major research results of Antarctic micrometeorites

3.1. Micrometeorites from comet Micrometeorites from comets have been identified based on the comparison with samples from comet 81P/Wild2 captured by the Stardust spacecraft and chondritic porous interplanetary dust particles (CPIDPs) collected at stratosphere. One of the main research results is micrometeorites including glass with embedded metal and sulfide (GEMS), which are identical with CPIDPs but having larger size (Noguchi et al., 2015). Another is chondrule-like object in unmelted micrometeorites (Imae et al., 2013), which were similar to those of comet 81P/Wild2 (Nakamura et al., 2008). Ultra carbonaceous micrometeorites would have originated possibly from cometary origin (Nakamura et al., 2005). Their features are all different from those from meteorites.

3.2. Other topics High abundances of presolar grains (Yada et al., 2008) are recent remarkable topics. Micrometeorites linked with chondrules from carbonaceous chondrite (CO group) and various chondrite chemical groups have been also identified (e.g. Imae et al., 2013).



**S25 – 115: Antarctic Meteorite and Micrometeorite**

***Reconsideration on the Classification of Brecciated and Highly Metamorphosed Chondrites***

Kimura, M.<sup>1</sup>; Yamaguchi, A.<sup>2</sup>

Ibaraki University, Japan<sup>1</sup>; NIPR, Japan<sup>2</sup>

Collision is one of the most important processes during the evolution of asteroids and planets. Meteorites have the evidence for asteroidal collisions, such as brecciated texture, shock induced vein including high pressure minerals, and the occurrence of exotic clast. These features have been commonly reported from all kinds of meteorite. However, the classification criteria for breccias are not so clear, and many kinds of term for breccia have been proposed. We have started a systematic study on the petrology and classification for breccias and related meteorites. Here we discuss the classification system for such meteorites, especially chondrites. According to the published data for chondrites in NIPR collection (Meteorite Newsletter No.2123), 6.9% and 3% of ordinary chondrites (2319 in total) are breccias and melt breccias, respectively. Among all of them, 9.3% contain shock veins, where an ultrahigh pressure mineral, ringwoodite, is often noticed under optical microscope. In addition, many kinds of high pressure mineral have been discovered from ordinary chondrites by using Raman spectroscopy. These observations indicate that ordinary chondrites were commonly subjected to the asteroidal collision. On the other hand, melt breccias are more abundant (9%) in enstatite chondrites. The high abundance of melt breccias may reflect the lower liquidus temperature of enstatite chondrite than the others. Many carbonaceous chondrites show brecciated texture, and abundantly contain clasts. However, melt breccia is hardly reported, and high pressure minerals have been reported from only a CB chondrite. These features reflect the physical conditions of carbonaceous chondrites, such as high porosity and concentrations of volatile component, in comparison with those of ordinary chondrites. At any rate, breccias are common in chondrites. Here we propose our preliminary classification criteria for the breccias. Fragmental breccias show brecciated texture, consisting of primordial lithology (clast) with interstitial fine-grained mineral fragments. Shock induced features, such as wavy extinction of olivine and pyroxene, are distinctly observed. They do not show any characteristic features for melting. On the other hand, melt breccias experienced partial melting, from the occurrence of glass, euhedral crystals, and spherical grains of opaque minerals. However, they contain clasts with original chondritic texture. Melt rocks are defined to be completely melted rocks without primordial lithology before melting. Some breccias show highly metamorphosed features, such as well developed triple junction and coarse-grained minerals, in spite that they apparently show brecciated texture under optical microscope. They are called recrystallized breccias. The evidence for original shock induced damage, like those in fragmental breccias, was mostly healed during recrystallization. Some highly metamorphosed chondrites have been classified as petrologic type 7. However, many type 7 chondrites are breccias, and experienced partial melting. They must be called melt breccias or recrystallized breccias.



## S25 – 135: Antarctic Meteorite and Micrometeorite

### ***Chemical Group Identification in Ordinary Chondrites by Raman Spectroscopy***

Philippe Claeys<sup>1</sup>; Lidia Pittarello<sup>2</sup>; Kitty Baert<sup>3</sup>; Vinciane Debaille<sup>4</sup>

Vrije Universiteit, Brussel, Belgium<sup>1</sup>; Earth System Science, Vrije Universiteit Brussel, Brussels, Belgium<sup>2</sup>; Materials and Chemistry, SURF, Vrije Universiteit Brussel, Brussels, Belgium<sup>3</sup>; Laboratoire G-Time, Université Libre De Bruxelles, Brussels, Belgium<sup>4</sup>

A large fraction of the meteorites collected worldwide is represented by ordinary chondrites. Most common classification techniques are based on bulk chemistry or on elements ratio of selected minerals and imply destructive or expensive and time consuming analyses. Here we propose to use Raman spectroscopy for identifying the chemical group in ordinary chondrites. The chemical group can be determined by the ratio Mg/Fe in olivine and low Ca-pyroxene, which are common phases in chondrites. The ratio Mg/Fe is generally expressed as fayalite (Fa) and ferrosilite (Fs) content in olivine and low-Ca Pyroxene respectively. The correlation between the position of selected peaks in the Raman spectrum of olivine and pyroxene and the relative content in Fa and Fs allows, therefore, the chemical classification of ordinary chondrites. The existing correlation has been here calibrated for ordinary chondrites, by investigating type 3 ordinary chondrites, which exhibit the largest range of olivine and pyroxene compositions among meteorites.

Antarctic and North-Western Africa ordinary chondrites provided by the Japanese National Institute of Polar Research and by the Royal Belgian Institute of Natural Science were investigated in the form of polished thin section and polished chips. Raman spectroscopy was performed with a confocal Raman microscope LabRAM HR Evolution (HORIBA Scientific), equipped with a multichannel air cooled CCD detector (spectral resolution <1 cm, lateral resolution 0.5  $\mu\text{m}$ , axial resolution 2  $\mu\text{m}$ ), with a solid state laser corresponding to green light (532 nm) at 1.25 mW excitation with 10% filter for preventing any sample damage, available at the Vrije Universiteit Brussel. The precise peak position was evaluated with an Octav/MatLAB script.

Blind tests on samples with different chemical classification, weathering and shock stage confirm the potential of the techniques. However, the reliability of the method depends on the number of analysis, which should be statistically meaningful for the investigated petrologic type. Nonequilibrated chondrites can exhibit a large range of olivine and pyroxene composition and therefore induce difficulties in classification only by means of Fa and Fs content. Highly equilibrated chondrites have a narrow range of olivine and pyroxene composition, so that a small number of analyses suffice for their chemical classification.

Due to the reduced sample preparation (no carbon coating and limited influence of the quality of polishing), the quick instrumental calibration (by checking a silicon wafer, no need of reference materials), and the fast data acquisition (tens of seconds one minute per spectrum), Raman spectroscopy provides an alternative to microprobe for ordinary chondrite chemical classification. The chemical group can be, therefore, determined first by nondestructive Raman spectroscopy, allowing a preliminary fast screening and rough classification of most of ordinary chondrites in large collections.



**S25 – 156: Antarctic Meteorite and Micrometeorite**

***Heterogeneity in the Early Solar System: Constraints from Samarium Neodymium Isotopic Systematics in Antarctic Meteorites and Implications for Silicate Differentiation***

Rosalind Armytage<sup>1</sup>; Vinciane Debaille<sup>1</sup>

Université Libre de Bruxelles, Belgium<sup>1</sup>

The isotopic composition of the Earth's mantle measured today reflects the combined history of differentiation and the initial composition of the material that accreted to form the Earth. In order to study differentiation, it is necessary to first constrain the isotopic composition of the early solar system, and identify the material that may have accreted to form the Earth. High precision measurements of undifferentiated chondritic meteorites provide insight into the isotopic variation (or lack thereof) in the solar system. Antarctic meteorites are a valuable resource for such studies as they are particularly well preserved from the effects of terrestrial alteration.

The short-lived radiometric chronometer  $^{146}\text{Sm}/^{142}\text{Nd}$  ( $t_{1/2} \sim 103$  Myr) is a key system for probing early silicate differentiation on planetary bodies (e.g. Brandon et al. 2009; Debaille et al. 2009; Rizo et al. 2012) as it is coupled to the much longer lived  $^{147}\text{Sm}/^{143}\text{Nd}$  ( $t_{1/2} \sim 106$  Gyr) system. In 2005 Boyet and Carlson found a systematic offset in  $^{142}\text{Nd}/^{144}\text{Nd}$  between chondrites and the modern convecting mantle. Three main hypotheses have been put forward to explain this offset: i) the Earth accreted with a superchondritic Sm/Nd ratio with the larger  $^{142}\text{Nd}/^{144}\text{Nd}$  ratio resulting from the decay of the excess  $^{146}\text{Sm}$  relative to chondrites; ii) The Earth is chondritic but there is a hidden reservoir in the mantle with a subchondritic Sm/Nd ratio that has yet to be sampled; iii) nucleosynthetic anomalies in Nd in the inner solar system are responsible for this difference. Hypothesis iii is the easiest to test, however with the limited data available for meteorites (Boyet and Carlson 2005; Andreasen and Sharma 2006; Carlson et al. 2007; Gannoun et al. 2011), it cannot be currently ruled in or out. Carlson et al. (2007) identified nucleosynthetic anomalies in Nd in carbonaceous chondrites, and anomalies in  $^{144}\text{Sm}$ , a process isotope, have been identified in some carbonaceous and enstatite meteorites, but not in ordinary chondrites (Andreasen and Sharma 2006; Carlson et al. 2007; Gannoun et al. 2011).

Enstatite chondrites (EC) are a natural target when looking for nucleosynthetic heterogeneities and constraining the initial  $^{142}\text{Nd}/^{144}\text{Nd}$  of the Earth. For a number of isotopic systems such as O (Newton et al. 2000), Ni (Regelous et al. 2008), Cr and Ti (Trinquier et al. 2007, 2009), enstatite chondrites provide the closest match to the bulk Earth composition. The current  $^{142}\text{Nd}$  data for enstatite chondrites spans that of terrestrial samples and ordinary chondrites (Gannoun et al. 2011), and as such does not provide a useful test for hypothesis iii.

We will present high precision Nd and Sm isotopic data on a suite of enstatite and ordinary meteorites from the Antarctic collections of both NIPR (National Institute of Polar Research, Japan) and RBINS (Royal Belgian Institute of Natural Sciences) of different petrographic types with a precision on  $^{142}\text{Nd}/^{144}\text{Nd}$  of  $<5$  ppm. By expanding the current chondrite dataset, we will provide constraints on the scale and extent of any nucleosynthetic heterogeneity in  $^{142}\text{Nd}/^{144}\text{Nd}$ , and evaluate the likelihood of the Earth having accreted with a different  $^{142}\text{Nd}/^{144}\text{Nd}$  ratio to chondrites. This will help deconvolve the contribution to this ratio by decay of the short-lived radionuclide  $^{146}\text{Sm}$ .



## S25 – 182 : Antarctic Meteorite and Micrometeorite

### ***Curation of Antarctic Meteorites at the National Institute of Polar Research, Tokyo***

Yamaguchi A.<sup>1</sup>; Imae N.<sup>1</sup>; Kimura M.<sup>2</sup>; Shirai N.<sup>3</sup>; Ebihara M.<sup>3</sup>; Kikuchi M.<sup>1</sup>; Kojima H.<sup>1</sup>

National Institute of Polar Research<sup>1</sup>; Ibaraki University<sup>2</sup>; Tokyo Metropolitan University<sup>3</sup>

Since the discovery of Yamato meteorites in 1969, the number of Antarctic meteorites collected has increased drastically. Now, about 70% of the global collections are from Antarctica. Meteorites are derived from hundreds of asteroids, and Earth's moon and Mars. Thus, along with samples recovered by planetary missions, the research of Antarctic meteorite helps us to understand the origin of solar system and the evolutionary history of planets. The National Institute of Polar Research (NIPR) has one of the largest meteorite collections in the world. Here, we report curation of Antarctic meteorites and future Antarctic expeditions. All Antarctic meteorites recovered by Japanese Antarctic Research Expedition (JARE) are processed at the NIPR curatorial facility. The facility consists of four parts: meteorite storage and processing rooms, an electron microprobe analyzer (EPMA) and a thin section preparation laboratory. The meteorite storage room is a class 10,000 clean room, and is kept at 22 °C for temperature and <50 % for humidity. The meteorite processing room is kept at a positive pressure and has one clean bench for chipping and three diamond wire saws. Meteorites recovered from Antarctica are carefully processed to avoid potential contaminations. Meteorites found on ice sheet are packed in plastic bags. Images and geographical positions are recorded at the same time. The frozen meteorites are shipped and stored at a refrigerator (<20 °C). The meteorites are thawed at room temperatures (~22-24 °C) in a chamber filled with dry nitrogen, or in a low pressure box evacuated using a vacuum pump. After being thawed, meteorites are stored in Teflon bags, further packed in plastic bags, and stored in the meteorite storage room. Meteorites are processed for initial classifications. After macroscopic observations chips of meteorites are separated using diamond wire saws and chisels without fluids for polished thin or thick sections. Classification is conducted using both compositions of minerals obtained by the EPMA and petrographic observations. Some meteorites may require additional analyses (e.g., bulk chemical and oxygen isotopic analyses). We are attempting to analyze siderophile elements in iron meteorites with laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS). Classifications of meteorites are presented as Meteorite Newsletters and the database at NIPR as well as Meteorite Bulletins issued from the Meteorite Society. The database is developed using MySQL, and tree navigation system is used. We plan to conduct meteorite search on the bare ice field around the Yamato Mountains and micrometeorites from fresh snows in other areas (e.g., Dome Fuji) in the Phase IX of JARE planned from 2016 to 2021 (JARE 5863).



**S25 – 188: Antarctic Meteorite and Micrometeorite**

***Eucrite versus Angrite: Micrometeorites as Natural forward Melting Experiments on Chondrites***

McKibbin S<sup>1</sup>; Huber M<sup>1</sup>; Claeys P<sup>1</sup>

Vrije Universiteit Brussel<sup>1</sup>

Early Solar System magmas are represented in meteorite collections by extrusive rocks exhibiting a rather limited number of compositions. The most common are the well-sampled eucrites or other eucrite like meteorites which are basalts consisting of plagioclase and pigeonite, probably sampling several different parent bodies. In contrast, a number of critically silica undersaturated meteorites called Angrites consist of olivine, anorthite, and Al-rich augite and sample a very different type of parent body which appears to be unique. The eucrite Angrite dichotomy is considered to reflect melting of chondritic starting materials under reduced or oxidized conditions respectively. This equates to transfer of Fe from metal to silicate in ordinary chondrite like compositions, or melting of carbonaceous chondrite like bulk compositions which already have a high FeO content. In CaO MgO Al<sub>2</sub>O<sub>3</sub> SiO<sub>2</sub> FeO space (CMAS+FeO), addition of FeO to ordinary chondrite brings the bulk composition away from the melting region which produces eucritic melts on the olivine anorthite pigeonite liquid cotectic, and into a melting region which produces Angritic melts on the olivine anorthite augite liquid cotectic, on the low silica side of a thermal divide (i.e. a tie line) between anorthite and augite. Early Angrite discoveries in Antarctica implicated a high Ca/Al source compared to the eucrite parent body (such as an enrichment of refractory material such as calcium aluminium rich inclusions), but more recent Angrite finds appear to be simple primary melts consistent with the model of melting chondrite with variable additional FeO.

We have investigated the mineralogy and geochemistry of a suite of more than one hundred Antarctic micrometeorite spherules, and have identified several with compositions equivalent to early Solar System extrusive magmas. At least five spherules contain glasses with compositions, which could be regarded as basaltic in a general sense (~50 wt. % SiO<sub>2</sub> and ~612 wt. % each of Al<sub>2</sub>O<sub>3</sub> and CaO), with one very similar to natural eucrite compositions. However, these glasses differ from most eucrites in that they coexist with olivine in the spherule, and can therefore be regarded as more primitive portions of the fractionation sequence. In stark contrast to these objects, we have also identified a single spherule consisting of olivine, Fe<sup>3+</sup> rich spinel, and a glass with an Angrite like composition (~40 wt. % SiO<sub>2</sub> with ~12 wt% Al<sub>2</sub>O<sub>3</sub> and ~16 wt% CaO). The Angritic glass is very similar in terms of major oxide composition to the well studied D'Orbigny and Sahara 99555 Angrites, which are postulated to be near primary melts of an oxidised chondritic source. Genuine Angrites have very low contents of NiO (less than ~100 wt. ppm in these cases), indicating that their parent body separated a Ni(Fe, S) rich core. Our Angritic spherule, on the other hand, contains substantial NiO in both olivine and Fe<sup>3+</sup> rich spinel (~1.5 wt. %). In fact, the presence of Fe<sup>3+</sup> rich spinel as a liquidus phase is enough to indicate that formation for our spherule occurred under even more oxidizing conditions (i.e. in the atmosphere of the Earth) and precludes a genetic relationship with true Angrites.

Nevertheless, complementary eucritic and Angritic melts formed as fusion crust materials in the atmosphere of the Earth parallel the redox control, which various chondritic compositions exert on magma evolution in early Solar System planetesimals. In micrometeorites, bulk composition mostly approximates alkali free carbonaceous chondrite components, or an alkali free ordinary chondrite with or without metal which is prone to oxidation during entry. First melting in such particles therefore occurs near the olivine anorthite pigeonite liquid or olivine anorthite augite liquid cotectics (and importantly in the Angritic case, on the low silica side of the thermal divide, away from eucrites), the difference being whether exposure of Fe metal to air occurred during atmospheric entry. In the event that Fe metal in the micrometeoroid was shielded from air or physically separated, melting should produce a silicate assemblage of olivine and a eucritic liquid which quenches to glass. Exposure of Fe metal to air at high temperature during entry leads to oxidation and repartitioning into the silicate melt, producing an Angritic liquid saturated in olivine and



spinel. As previously noted, the formation of angritic melts may be assisted by incorporation of refractory calcium aluminium rich inclusions.

There exists a small region in CMAS+FeO along the ordinary chondrite+FeO vector which results in melting along the olivine anorthite augite liquid cotectic, but on the high silica side of the thermal divide, nearer the eucrites (i.e. between eucrites and angrites). This region was not explicitly discussed in previous consideration of the phase equilibria of angrites, but high degrees of melting of this composition will result in magmas equivalent to terrestrial mid-ocean ridge basalts (MORB) in terms of major element composition and their sequential saturation of olivine, anorthite, and augite during cooling (spinel which is sensitive to minor trivalent components such as Cr<sup>3+</sup> and Fe<sup>3+</sup>). The absence of MORB like extraterrestrial rocks formed during low pressure melting of planetesimals with intermediate redox states, and probably their absence from our micrometeorite survey as well, indicates that this region is very small. It is bound, on the one side, by a tie line between anorthite and the olivine anorthite augite pigeonite eutectic, and on the other side by a tie line between anorthite and the thermal divide. Thus, despite the complementary nature of eucrites and angrites, it is in fact MORB which is the nearer relation of both, at least in terms of phase equilibrium.



## S25 – 221: Antarctic Meteorite and Micrometeorite

### *Two generations of exsolution in pyroxene, A Thermal story for a mesosiderite*

Seann McKibbin<sup>1</sup>; Lidia Pittarello<sup>1</sup>; Gang Ji<sup>2</sup>; Dominique Schryvers<sup>2</sup>; Vinciane Debaille<sup>3</sup>; Philippe Claeys<sup>1</sup>

Vrije Universiteit Brussel<sup>1</sup>; Electron Microscopy For Material Science (EMAT), University Of Antwerp, Antwerp, Belgium<sup>2</sup>; Laboratoire GTime, Université Libre De Bruxelles, Brussels, Belgium<sup>3</sup>

**Introduction:** Mesosiderites are meteoritic breccias which are stony-iron meteorites consisting of a mixture of metal chemically similar to IIIAB iron meteorites, and silicates which resemble those in Howardite Eucrite Diogenite (basaltic gabbroic) achondrites. The most accredited hypothesis for mesosiderite formation is an impact induced mixture of crustal and core material (with a possible minor mantle contribution) from one or more differentiated bodies. The mesosiderite meteorite Asuka 09545 (A 09545) was found during a joint Belgian-Japanese mission in Antarctica. This mesosiderite is highly equilibrated (B3) and contains large grains of pyroxene exhibiting two generations of exsolution lamellae. The study of these lamellae provides constraints on the thermal evolution of the silicate fraction in the sample.

**Methods:** Preliminary investigations of a polished thin section from A 09545, provided by the Japanese National Institute of Polar Research (NIPR) has been undertaken using scanning electron microscope (SEM) and electron microprobe (EMPA) at the NIPR. Two foils, with size of ca. 5  $\mu\text{m}$  x 5  $\mu\text{m}$  and 8090 nm thickness, were prepared with focus ion beam (FIB) in selected locations: (1) at the boundary between the pyroxene host and the first generation lamellae; and (2) within this lamellae across a set of second generation of lamellae. These foils were investigated with a transmission electron microscope (TEM), equipped with energy dispersive X-ray spectroscopy (EDS) detector and a precession unit, at EMAT, University of Antwerp.

**Results:** A 09545 pyroxene displays two generations of exsolution. The host pyroxene has composition  $\text{Wo}_{3}\text{En}_{59}\text{Fs}_{38}$  and has been identified by TEM as clinoenstatite (Monoclinic, P21/c). Thick (up to 25  $\mu\text{m}$ ) lamellae of augite (Monoclinic, C2/c) are present along a cleavage, with irregular margins and elongated shape, and have composition  $\text{Wo}_{42}\text{En}_{41}\text{Fs}_{17}$ . Within these augite lamellae, a second generation of exsolution appears, with thin (ca. 300 nm) lamellae, parallel to [001], with composition  $\text{Wo}_{1}\text{En}_{56}\text{Fs}_{43}$  and also identified as clinoenstatite (Monoclinic, P21/c), but with very low Ca content (below detection limit).

**Discussion:** Orthopyroxene (a low Ca pyroxene) hosting exsolved augite (a high-Ca pyroxene) is generally referred to as inverted pigeonite (a mid-Ca pyroxene), because it originates during cooling by breakdown of pigeonite crystallized at high temperature. Equilibrium temperatures have been calculated for pyroxene pairs using a multi element geothermobarometer, based on the combined content of Ca, Fe, Al, and Cr, in order to obtain a rough estimate of the exsolution conditions. Both exsolution generations are consistent with a temperature range of ca. 950-1100° C under low pressure conditions. Calculations based on the Fe/Mg ratio show that the second generation exsolution probably formed at slightly lower temperature than the first one. This is consistent with a low cooling rate during thermal metamorphism. Lattice parameters and the orientation of the lamellae also support our rough estimates for temperature and cooling rate. The host pyroxene is in fact monoclinic (i.e. a clinopyroxene), as well as the exsolved pyroxene in the lamellae of augite. Although orthorhombic geometry is expected for inversion of pigeonite at 950-1100°C, and orthorhombic pyroxene should also exsolve from augite, another inversion from orthoenstatite to clinoenstatite occurs at ca. 570°C at low pressure, during slow cooling conditions.

**Conclusion:** In the historical literature, cooling of silicates above 500°C was generally considered to be faster than that of metal, which was extremely slow below 500°C. Metallographic textures indicate that the mesosiderite parent body underwent a uniquely slow cooling process. The presence of low temperature clinoenstatite in mesosiderites supports this history. Low-temperature clinoenstatite has been confirmed in a small number of mesosiderites, and A 09545 can be added to that list.



## S25 – 225: Antarctic Meteorite and Micrometeorite

### ***Successful Joint Field Campaigns for Collecting Meteorites in Antarctica: An efficient Collaboration between Japan and Belgium.***

Debaille V.<sup>1</sup>; Imae N.<sup>2</sup>; Yamaguchi A.<sup>2</sup>; Goderis S.<sup>3</sup>; Mikouchi T.<sup>4</sup>; Pittarello L.<sup>3</sup>; Hublet G.<sup>5</sup>; Van Roosbroek N.<sup>5</sup>; Zekollari H.<sup>3</sup>; Kojima H.<sup>2</sup>; Claeys Ph.<sup>3</sup>

Université Libre de Bruxelles, Brussels, Belgium<sup>1</sup>; National Institute Of Polar Research, Japan<sup>2</sup>; Earth System Science, Vrije Universiteit Brussel, Brussels, Belgium<sup>3</sup>; Department Of Earth And Planetary Science, University of Tokyo<sup>4</sup>; Laboratoire GTime, Université Libre De Bruxelles, Brussels, Belgium<sup>5</sup>

Since 2009, Belgium and Japan have joined forces, logistics and knowledge to organize three successful meteorite expeditions in Antarctica. The first joint JARE 51 mission, in 2009-2010 sampled the Balchen Ice Field, in the eastern Sor Rondane Mountains region, and recovered more than 600 meteorites. Five scientists, including one Belgian, and one field guide, participated to this mission. The second joint BELARE-SAMBA 2010-2011 to the North-West part of the Nansen Ice Field, located to the South of Sor Rondane Mountains, and composed of 2 Belgian and one Japanese scientists, and two field guides (one Belgian, one Japanese), recovered 220 meteorites. Finally, a third JARE 54 BELARE SAMBA 2012-2013 expedition to the Nansen Ice Field was organized during the austral summer 2012-2013. This was the largest recovery party organized, with a total of 10 members (5 Belgian and 3 Japanese scientist, and two field guides) searching for meteorites. During this last expedition, 427 samples were collected on the Nansen Ice field. On the Belgian side, this program is funded by the Belgian Science Policy (BELSPO) and benefits from the logistic support of the International Polar Foundation (IPF). On the Japanese side, the National Institute of Polar Research (NIPR) provides funding and logistic.

In total, more than 1000 meteorites were recovered during those 3 joint expeditions. Notably, the largest sample of those 3 campaigns weighs 18.1 kg, and a dozen of meteorites are over 1 kg. A few achondrites have been collected, such as ureilites, one iron meteorite, and a few HED meteorites as well as a few carbonaceous chondrites.

First, the recovered meteorites are sent to NIPR for careful defreezing. The large samples are cut in two, and shared evenly between Japan and Belgium. After detailed classification made by both NIPR and ULBVUB teams, including the Royal Belgian Institute for Natural Sciences (RBINS), one half comes back to Belgium. All these samples are available for research by the international scientific community. In addition, the most beautiful pieces will be displayed for the public. As such, the unique specimen of 18 kg, an LL-type brecciated ordinary chondrite (A 12389), is already exposed in the permanent exhibit of the RBINS, as a token of the fruitful collaborations between the two countries. Scientific research is currently performed on those samples, in close collaborations between NIPR and ULBVUB teams. As a corollary, Belgium has recently developed a meteorite curation center at the RBINS where the Belgian share of the Antarctic meteorites are stored and curated based on sample requests made by researchers. In this context, a reflection is initiated to promote the fantastic research opportunities offered by these pristine meteorites from Antarctica for understanding the formation of our Solar System and the evolution of planets.



## S25 – 237: Antarctic Meteorite and Micrometeorite

### ***Petrography and Mineral Chemistry of Asuka 12389: An LL3-6 Ordinary Chondrite Breccia from Antarctica.***

Claudio Ventura Bordenca<sup>1</sup>; Steven Goderis<sup>1</sup>; Vinciane Debaille<sup>2</sup>; Philippe Claeys<sup>1</sup>

Vrije Universiteit Brussel<sup>1</sup>; Université Libre de Bruxelles<sup>2</sup>

**Background:** The Asuka 12389 meteorite breccia represents the largest specimen found on the Antarctica continent since 1988. A mass of 18.07 kg was collected during the 2012-2013 Belgian/Japanese expedition. It has been classified as a LL36 regolith genomict breccia at the National Institute of Polar Research of Tokyo (NIPR) and officially approved as of 5 June 2014 (Meteoritical Bulletin Database). This specimen is part of several meteorite samples collected in Antarctica near the Sør Rondane Mountains by three Belgian/Japanese expeditions (2009-2013). The recovered meteorite samples are jointly shared under agreement by the Royal Belgian Institute of Natural Sciences of Brussels (RBINS) and the National Institute of Polar Research of Tokyo (NIPR).

**Objectives:** The main goal of this study is to unravel the complex record of geological processes that affected ordinary chondrite breccias on the basis of a detailed petrographic examination and chemical study of the various lithic components of Asuka 12389. This study contributes to the deciphering of the intricate evolution of the LLchondrite parentbody with the aim of providing useful insights about the collisional evolution of the inner Solar System.

**Methods:** One polished thin section of Asuka 12389 was provided by the National Institute of Polar Research of Tokyo (NIPR) and investigated using optical microscopy to highlight the main silicate components and study opaque phases. The thin section shows a black highly vesicular fusion crust with thickness ranging from 50 to ~300  $\mu\text{m}$ . Chemical compositions of the mineral components were obtained using an Analytical Scanning Electron Microscope (ASEM) JEOL JSM300 equipped with an Energy Dispersive System (EDS). Semi-quantitative analyses were performed at the VUB using an accelerating voltage of 15 kV, a beam current of 60 nA, and counting times of up to 60s. A total of 108 chemical analyses were performed on the clastic components that characterize Asuka 12389. The lithologic inventory of the rock comprises porphyritic and non-porphyritic chondrules, several large angular mm-sized chondritic clasts, fine-grained clastic matrix (including silicate fragments, taenite, kamacite, troilite and chromite grains), a black darkened clast, two impact melt clasts, and a chromite plagioclase assemblage.

**Results:** The petrographic and chemical characterization of the constituents has revealed that Asuka 12389 is a genomict LL chondrite breccia with the clasts and matrix of the same compositional group but different petrologic types (ranging from 3 to 6). Overall texture: The bulk texture is dominated by a variety of light colored clasts embedded in a fine-grained light colored matrix. The overall albedo of the breccia is lighter in color than other ordinary chondrite breccias studied previously. However, it also contains some isolated optically dark clasts with igneous textures. Petrography and mineral chemistry: Four chondrules were identified in thin section, two porphyritic olivine pyroxene chondrules (POP) and two radial pyroxene chondrules (RP). Their longest dimension average is 1.2 mm, which is higher than the mean chondrule diameter of LL chondrite chondrules (0.9 mm). The composition of olivines in POP chondrules falls within the range of LL chondrites, although the pyroxene composition is in the range between Land LLchondrites (Fs<sup>~</sup>22). Mesostasis in these chondrules is oligoclastic in composition.. Also the composition of pyroxenes in RP chondrules (Fs<sup>21</sup>) shows a slightly lower ferrosilite content. Olivine (Fa<sup>27-28</sup>), low Ca pyroxene (Fs<sup>22-23</sup>), high Ca pyroxene (En<sup>49</sup>Fs<sup>8</sup>Wo<sup>43</sup>) and plagioclase (An<sup>18</sup>) outside the chondrules occur as micro-sized anhedral to subhedral grains characterized by the presence of irregular fractures and slightly undulatory extinction (indicating very weakly shock stage S2). The size of the silicates within the LL type clasts is very similar to that of the silicates in the matrix. Generally, the composition of olivine



and low-Ca pyroxene within and outside the chondrules is in range of LL chondrites, although in a few cases the fayalite and ferrosilite contents are slightly lower, typical of L chondrites. Taenite (> 30 wt% Ni) and kamacite (< 5 wt% Ni) occur as monocrystalline grains featured by nonpolygonal, jagged outlines; only very few metal grains have been found in the rock. The Co content in kamacite (3.1 wt%) is in the range of LL chondrites (1.437 wt%). Troilite (64.70 wt% S, 35.30 wt% Fe) occurs as weakly deformed and fizzed textured grains, typical of very weakly shocked ordinary chondrites. Two porphyritic impact melt clasts were identified. The typical texture of these clasts is that of subhedral olivine grains (Fa26-27) enclosed within a fine-grained groundmass rich in Si, Mg and Ca that includes skeletal pyroxenes, interstitial glass and tiny globules of opaque phases. Enrichments in MnO (up to ca. 1 wt%) were observed in olivines within one of the impact melt clasts. A large (up to 2 mm in the longest dimension) black darkened clast with chondritic texture was identified running parallel to the fusion crust. This clast is partly darkened by the intrusion of opaque mineral veining into the cracks and fractures of silicate minerals. The composition of olivine (Fa27) and low-Ca pyroxene (Fs22) in this clast falls in the range between Land LL chondrites. Finally, one rare irregularly shaped lithic clast characterized by tiny chromite droplets (<4  $\mu\text{m}$ ) set in a plagioclase like matrix was found confined to the edge of the thin section with an apparent diameter of approximately 200  $\mu\text{m}$ . Chromite (up to ca. 39 wt% Cr<sub>2</sub>O<sub>3</sub>) is slightly enriched in TiO<sub>2</sub> (<1 wt%). The content of anorthite in the matrix is quite variable (An27-54).

**Conclusion:** Based on the petrographic and chemical examination, Asuka 12389 is an attractive LL chondrite genomict breccia (S2/W1) composed of usual and unusual lithologies embedded in a fine-grained clastic matrix. However, several compositional characteristics are intermediate between Land LL chondrites. Additional EMPA and Raman investigation of the impact melt clasts and the chromite plagioclase assemblage, respectively, are planned to expand the understanding of ordinary chondrite breccia formation.



## S25 – 238: Antarctic Meteorite and Micrometeorite

### *Micrometeorites from the Sør Rondane Mountains.*

Claudio Ventura Bordenca<sup>1</sup>; Matthew Huber<sup>1</sup>; Steven Goderis<sup>1</sup>; Vinciane Debaille<sup>2</sup>; Philippe Claeys<sup>1</sup>

Vrije Universiteit Brussel<sup>1</sup>; Université Libre de Bruxelles, Belgium<sup>2</sup>

**Background:** The Sør Rondane Mountains in the Queen Maud Land of Antarctica represent a new, highly concentrated site for cosmic spherule recovery, compared to other well studied Antarctic accumulation traps (such as the Transantarctic Mountains, the Cap Prudhomme, the South Pole Water Well, and the CONCORDIA collection). The extraterrestrial particles are found within erosion derived debris, most concentrated in cracked and fissured exposures of the wind exposed, granitoid mountain summits. Here, we report an updated statistical summary of the cosmic spherules relative abundances the discovery of several unmelted micrometeorites as well as one potential microtektite. All of these particles are found within the metatonalitic sediment collected at the Wideroefjellet site during the 2012-2013 Belgian/Japanese joint field expedition, after initial study of the region based on satellite imaging and geological maps of the Nansen Ice Field and surroundings.

**Objectives:** The main purpose of this study is to characterize the extracted microparticles from the sediment of the Sør Rondane Mountains and compare these to other micrometeorite/tektite collections and to chemically examine the internal structure of selected polished microparticles to obtain useful insights about their formation mechanisms.

**Methods:** The collected sediment (~1.6 kg in total) was defrosted at the Belgian Antarctic research Station during the field expedition and processed by washing and sieving at the VUB in Brussels to separate the following six size fractions: < 125 µm, 125-200 µm, 200-400 µm, 400-800 µm, 800-2000 µm, and > 2000 µm. A total of 1387 micro particles have been identified so far. Of these, 1377 melted micrometeorites (cosmic spherules) in the 125-800 µm size range and 7 unmelted micrometeorites in the 200-400 µm were handpicked using a Stereo Microscope, 2 unmelted micrometeorites in the < 125 µm size fraction were extracted magnetically, and a single potential microtektite was found and picked by hand in the 800-2000 µm size fraction. Semi-quantitative analyses of scanned areas of variable sizes were carried out on the surfaces of the particles with an Analytical SEM JEOL JSM300 or a FESEM JEOL JSM7000F both equipped with an Electron Dispersive System (EDS) for classification.

**Results:** Melted micrometeorites: In total, 422 melted micrometeorites are identified in the 125-200 µm size fraction, 828 in the 200-400 µm fraction, and 127 in the 400-800 µm fraction. No melted micrometeorites are found in the 800-2000 µm and > 2000 µm fractions. Our results indicate that 43% of these represent barred olivine (BO type) cosmic spherules, 24% is cryptocrystalline (C type), 18% glassy is (V type), 10% is porphyriticolivine (PO type), 4% is iron (I Type), while the final 1% is G Type. A small proportion of the spherules exhibit a FeNi metal bead, at one end almost reaching to the spherule surface, whilst other spherules show one or more subspherical void(s), likely due to the loss of the metal bead during atmospheric entry. The metal beads for the spherules characterized so far are usually 50100 ± 1/4 µm in diameter. Statistically, 8% of the BO type spherules contain a metal bead, 21% for C type, 11% for V type, and 6% for PO type. No metal beads are observed in G type spherules, so far. Unmelted micrometeorites: Only nine unmelted micrometeorites with variable shapes and textures have been found so far. On the basis of SEMEDS observation, all of the seven unmelted micrometeorites found in the 200-400 µm display a subrounded and compact structure, whereas the two magnetically extracted particles show a more irregular, subangular shape. More work is planned on the magnetic fraction. Microtektite: A perfectly rounded and palegreen particle might represent a first potential microtektite. The major element composition of its surface is comparable to that of rare palegreen high-Mg type microtektites found in the Transantarctic Mountains. However, a detailed study is planned to confirm a microtektite origin for this particle.



**Conclusion:** The collection of the Sør Rondane Mountains is highly exciting in terms of the abundance and preservation of extraterrestrial dust particles. A number of representative cosmic spherules and all of the unmelted micrometeorites have been embedded in epoxy to chemically study internal structures. Moreover, the confirmation of the discovery of a microtektite within the Wideroefjellet sediments could significantly extend the Australasian microtektite strewn field.



## S25 – 245: Antarctic Meteorite and Micrometeorite

### ***Bulk Elemental Analyses of Iron Meteorites by Using Instrument Neutron Activation Analysis and Laser Ablation Inductively Coupled Plasma Mass Spectrometry***

Naoki Shirai<sup>1</sup>; Yamaguchi A.<sup>2</sup>; Haba M K<sup>2</sup>; Sekimoto S<sup>3</sup>; Ojima T<sup>2</sup>; Kojima H<sup>2</sup>; Ebihara M<sup>1</sup>

Tokyo Metropolitan University, Japan<sup>1</sup>; National Institute of Polar Research, Japan<sup>2</sup>; Kyoto University Research Reactor Institute<sup>3</sup>

#### Introduction:

Iron meteorites are made of Fe-Ni metal phases with such minor minerals as schreibersite, troilite, cohenite and other Fe-Ni carbides. As most iron meteorites are believed to be samples from the metallic core of differentiated planetesimals, petrological, mineralogical and chemical studies of iron meteorites are fundamental for unraveling the process of planetary differentiation.

Based on the structures, iron meteorites are originally classified into hexahedrites, octahedrites and ataxites. Hexahedrites and ataxites are nearly made of kamacite and taenite, respectively. Octahedrites consist of kamacite and taenite, and they are further divided into six subgroups on the basis of the width of the kamacite from finest (>0.2 mm) to coarsest (>3.3 mm). Almost all iron meteorites are classified into octahedrites. The chemical classification of iron meteorites is based on their trace element compositions (Ni, Ga, Ge and Ir). Bulk elemental abundances for iron meteorites have been obtained by using neutron activation analysis (NAA). Other analytical methods such as laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) have not been very often applied to iron meteorites.

In this study, we present simple and effective procedures for the chemical classification of iron meteorites by using instrumental NAA (INAA) and LA-ICP-MS. Based on the analytical data obtained by two analytical techniques, we discuss the accuracy and the precision of our data and how promisingly our analytical methods can be applied to classification of iron meteorites.

#### Methods:

Canyon Diablo (IAB), Toluca (IAB), Cape York (IIIAB), Muonionalusta (IVA) and Dronino (ungrouped) were analyzed by using two analytical methods (INAA and LA-ICP-MS). In INAA, samples weighing about 150 mg were firstly irradiated for for 10 sec. at a neutron flux of  $4.6 \times 10^{12} \text{ cm}^{-2}\text{s}^{-1}$  at Kyoto University Research Reactor Institute (KURRI) for the determination of Co, Ni, Cu, Ge and Rh. The same samples were reirradiated for 4 hrs at a neutron flux of  $5.6 \times 10^{12} \text{ cm}^{-2}\text{s}^{-1}$  at KURRI for the determination of Cr, Fe, Co, Ni, Ga, As, Mo, Ru, Sb, W, Re, Os, Ir, Pt and Au.

In LA-ICP-MS, analyses in line and/or scanning modes were performed on a representative area of polished chunk samples. A Thermo Element XR coupled to CETAC LSX-213 was operated in low resolution (R=300). The peaks of <sup>57</sup>Fe, <sup>59</sup>Co, <sup>60</sup>Ni, <sup>65</sup>Cu, <sup>69</sup>Ga, <sup>74</sup>Ge, <sup>95</sup>Mo, <sup>99</sup>Ru, <sup>103</sup>Rh, <sup>105</sup>Pd, <sup>182</sup>W, <sup>185</sup>Re, <sup>189</sup>Os, <sup>193</sup>Ir, <sup>194</sup>Pt and <sup>197</sup>Au were monitored. Elemental abundances were obtained using Hoba and North Chile (Filomena) iron meteorites as standard reference samples.

#### Results and discussion:

Seventeen elements (Fe, Co, Ni, Cu, Ga, Ge, As, Mo, Ru, Rh, Sb, W, Re, Os, Ir, Pt and Au) and sixteen elements (Fe, Co, Ni, Cu, Ga, Ge, Mo, Ru, Rh, Pd, W, Re, Os, Ir, Pt and Au) could be determined by using INAA and LA-ICP-MS, respectively. Our analytical results obtained by using two analytical methods were consistent with each other and literature values except for Muonionalusta.

Germanium is one of the key elements for the chemical classification of iron meteorites and has been mainly determined by radiochemical NAA (RNAA), which is time consuming. As both Ni and Ge



abundances could be determined by INAA and LA-ICP-MS. Our two analytical methods are more simple and effective than RNAA.



## S25 – 265: Antarctic Meteorite and Micrometeorite

### *Process of Chinese Antarctic Meteorites Sharing and Research*

Jie Zhang<sup>1</sup>; Bingkui Miao<sup>2</sup>; Wenjun Ni<sup>2</sup>

Polar Research Institute of China, China<sup>1</sup>; Guilin University of Technology, China<sup>2</sup>

**Background:** With rare traces of human presence but rich natural and scientific resources, the polar regions, a scientific book of which scientists devote themselves to the perseverant read, have accumulated huge quantities of exact and detailed records of the evolvement of the Earth's climate, environment and geosphere, human activities, and a good many outer space vents. The scientists collect samples of ice core, biology, sediment, meteorite, rock, and fossil to study in labs.

**Objectives:** Since the first Antarctic research expedition in 1984, China has conducted a lot of polar scientific research expedition activities. Formed by one research ship and three stations: R/V Xuelong Great Wall Station, Zhongshan Station, Arctic Yellow River Station, a polar research expedition system has been set up. Up to now totally 30 Chinese National Antarctic Research Expeditions (CHINARE), 6 Arctic marine science cruises, and ten years of the Arctic Yellow River Station Research Expeditions had been successfully completed. Except research expeditions conducted in the stations and the adjacent areas, four science traverses on the Grove Mountains based on Antarctic meteorite collecting had been accomplished in the important areas of the Antarctica. In 1998 CHINARE found four pieces of different types meteorites in the Grove Mountains Area which is more than 400 km far from the Zhongshan Station for the first time. It was confirmed that the Grove Mountains area is a new area rich in meteorites. In 1999-2013 total four science traverse teams were dispatched and 12,035 pieces of meteorites were found in the middle range of ridge, Harding Mountain, and Zakharoff Mountain in the Grove Mountains area, mainly stony meteorite, stony meteoric iron, and meteoric iron, among which are two Mars meteorites, one Kitchen God Star meteorite, and other rare and unique meteorites.

**Methods:** The meteorite samples collected from the Antarctica by China are state owned and curated in Polar Research Institute of China (PRIC), who builds the Antarctic meteorite repository. To prevent weathering resulting from the thaw of a little of snow and ice on the surface of the meteorite, all of the meteorite samples are kept frozen. At present, several domestic relevant expedition organizations are cooperating in the classification of the samples and will submit all of the information to the Nomenclature Committee of the Meteoritical Society in order to approve the names of the meteorites. According to the Chinese Ordinance on the Administration, Application, and Usage of the Antarctic Meteorite Sample, the meteorite samples are for scientific research, and domestic and international researchers can apply for the Antarctic meteorite samples.

**Results and Conclusion:** Since December 2005, a national polar scientific samples repository has been setup by PRIC in order to integrate, collate and preserve a huge quantity of precious samples such as ice core, biology, sediment, meteorite, rock, and fossils in the polar regions by CHINARE. It has developed a web based management system of Antarctic meteorites samples. It forms an authoritative Antarctic meteorite samples catalog, information publish, application and review platform for sample management and information sharing. It improves the opening degree and utilization for the Antarctic meteorite samples and polar scientific samples resource. In the recently 10 years, the major work following is finished:

1. To make and implement Chinese Antarctic meteorite samples collection, standardization organization, the technology specification and management procedure of storage
2. To build an Antarctic meteorite samples warehouse and a sample analysis lab.



3. To develop and finish the registration of Groove Mountain Antarctic meteorite samples, to make the specification and ruler for meteorite samples information description.
4. To build the web based of tools for meteorite samples management. These tools will be based on a Content Management System (CDM) integrated in the platform of Chinese polar samples website and realize the samples information online registration and sharing, the application and approval, delivery and transportation, utilization, tracing and feedback. All users and curators can access to this CDM.
5. Antarctic meteorite samples public display, education and outreach through the lending to the exhibition or Museum or planetarium. It also runs the topic popularization of science and knowledge sharing online.

**Keywords:** Antarctic meteorite sample Grove Mountains CHINARE



## S25 – 269: Antarctic Meteorite and Micrometeorite

### *The Field Surveys and Concentration Mechanism of Meteorites from Grove Mountains, Antarctica*

B. Miao<sup>1</sup>; Y. Lin<sup>2</sup>; S. Hu<sup>2</sup>; J. Zhang<sup>3</sup>

The College of Earth Sciences, Guilin University of Technology, Guilin, China<sup>1</sup>; The Institute of Geology And Geophysics, Chinese Academy of Sciences, Beijing, China<sup>2</sup>; The Polar Research Institute of China, Shanghai, China<sup>3</sup>

Meteorites are important scientific resources for cosmochemistry and planetary sciences, however they are very rare. Since the discovery of 9 different meteorites in Yamato Mountains in 1969, Antarctica is proved as the treasure of meteorites around all the continents by the efforts of different expeditions of NIPR, ANSMET, EUROMETPNRA, CHINARE and KOREAMET. As of this writing, about 50,000 meteorites have been discovered on the icefields of the east Antarctic ice sheet. Due to the great collection of meteorites provided for scientific research, a lot of great achievements for cosmochemistry and meteoritics have been made, e.g. evidence of life on the martian meteorite ALH 84001, the discovery of some new types of meteorites. In 1998, 4 meteorites were occasionally found in Grove Mountains (GRV) by CHINARE. Until now, 6 meteorite field surveys have been made in the GRV region with 12035 meteorites. So GRV is proved as one of the richest meteorite concentrations in Antarctica. Here the field work and collection of meteorites are introduced and concentration mechanism of GRV meteorites is discussed.

**Field surveys:** The six GRV expeditions are all comprehensive and include surveys on geology, glaciology, geography, mapping, climate, environment, and meteorite. In 1998 a small team of four men was sent by the 15th Chinese Antarctic Research Expedition (CHINARE) first time with a discovery of four meteorites. Another 28 meteorites were found by a special meteorite survey of two weeks in the next field season. In 2002, the third GRV expedition in which the meteorite survey is the main task made a big breakthrough of 4448 meteorites in discovering meteorites during 32 days. Later, three GRV expeditions of the 22<sup>nd</sup>, 25<sup>th</sup>, and 30<sup>th</sup> CHINARE collected 5354, 1618 and 583 meteorites respectively. Except the first GRV expedition of four team members, the other five expeditions consist of eight to ten members. And exception of only one snow tractor in the first GRV expedition, its main equipments for field work included 23 PB240300 snow groomers, 5 sleds with 3 cabins, 2 skidoes and 2 generators.

**Features of GRV Meteorite Collection:** The features of GRV meteorite collection are as follows:

- (1) The GRV meteorites are relative small in mass. The total collection of 12035 meteorites probably including a few earth rocks weigh about 70 kg and range from a fraction of gram to 200 g with an average mass of less than 10 g, the biggest meteorite with mass up to 4360 g, while the ANSET meteorite collection has an average mass of about 240 g.
- (2) 2732 meteorites are classified and named. The majority of the classified meteorites are ordinary chondrites. They also include other rare meteorites of 2 martian meteorites, 3 eucrites, 21 carbonaceous chondrites, 12 mesosiderites, 1 pallasite, 11 ureilites, 2 primitive achondrites and 1 iron.
- (3) GRV meteorites are relatively fresh with lower weathering degree of W2 to W3, also confirmed by the terrestrial ages of 10 GRV meteorites ranging from 0.04~0.23 Ma.

Meteorite concentration mechanism: GRV locates in the Princess Elizabeth Land, about 450 km north to Zhongshan Station. It consists of 64 nunataks and has 500 km<sup>2</sup> of blue ice field. The tendency of topography is from southeast to northwest, i.e. the southeast side is an ice plateau, and the northwest is to the Lambert Valley, so the ice flows zigzag across GRV among the nunataks. Due to obstruction of the ice flows by nunataks and underground mountains, the large areas of blue ice fields are developed with moraines of various sized boulders.



Based on the distribution of meteorites, the characteristics of meteorite concentration mechanism are concluded:

1. GRV has two occurrences of blue ice field and moraine.
2. Almost all patches of blue ice fields were found with meteorites, but they have various densities of meteorites
3. The majority of GRV meteorites are found along the blue ice fields and moraines below the Gale Escarpment. The blue ice fields down stream of ice flows away from the Gale Escarpment have thinner and thinner densities of meteorites gradually.
4. The model of GRV meteorites is behind mountains, in which meteorites are concentrated below the underground mountains and which is different from that of Allan Hills in which the meteorites are concentrated before the mountains where the ice flow is obstructed.

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## S25 – 279: Antarctic Meteorite and Micrometeorite

### *The Field Surveys and Concentration Mechanism of Meteorites from Grove Mountains, Antarctica*

James Karner<sup>1</sup>; Ralph Harvey<sup>1</sup>; John Schutt<sup>1</sup>; Cari Corrigan<sup>2</sup>; Kevin Righter<sup>3</sup>

Case Western Reserve Univ., United States<sup>1</sup>; Smithsonian, United States<sup>2</sup>; NASA (JSC) Johnson Space Center, United States<sup>3</sup>

**INTRODUCTION:** The U.S. Antarctic Search for Meteorites program (ANSMET) has been operating since 1976 and has completed 38 field seasons of collection. Currently the ANSMET meteorite collection contains more than 22,000 recovered individual specimens, roughly 40% of all the meteorites recovered from the Antarctic.

**SEARCH TECHNIQUES:** The first step towards meteorite recovery in Antarctica is locating meteorite stranding surfaces. ANSMET accomplishes this by first examining remotely gathered imagery such as satellite images or aerial photographs. These data are used to locate exposed blue ice whose setting suggests slowed or stagnant flow and an actively deflating surface where meteorite stranding is likely to occur. The second task is ultimately the only way to determine whether a meteorite concentration exists on a blue ice surface go there and look. Over its history ANSMET has found nearly 100 distinct meteorite concentration sites. For many of these sites, detailed reconnaissance has shown that concentrations are high enough to warrant systematic searching. Systematic searching teams typically consist of 8 individuals, but can be higher or lower depending on logistical factors and size of search areas. Search strategies typically follow the transect sampling model. The field team forms a line, each member a few meters to tens of meters apart. The team then proceeds to move across the meteorite stranding surface in a direction perpendicular to this line. After each pass is completed, the team changes direction and a new transect is started, covering new areas of exposed ice. Traverses are adapted to geographical features, hazards, and weather conditions (wind, sun-angle, and snow cover) to maximize coverage and efficiency. The spacing and method of travel (foot or snowmobile) may also vary depending on frequency of meteorite encounter and density of terrestrial rock (if present). The location and path of at least one team member's snowmobile is continuously recorded to establish the geographical location of transects and provide a record of the field team's progress.

ANSMET has chosen to use a simple, inexpensive but very effective meteorite detection system, the human visual system. For areas where the background of terrestrial rock is very low or absent, the innate human ability to rapidly differentiate a scene into key elements and recognize those that are unique or out of place allows field party members to scan enormous areas of blue ice quickly and immediately notice any rocks upon its surface. This ability is limited only by the seeing conditions and the resolution of the human eye, which typically allows a dark, cm sized meteorite to be resolved at distances of up to 100 meters on the light colored ice. Given that ANSMET searches typically involve much shorter distances, we routinely recover meteorite specimens much smaller than this.

The typical procedure for recovery of a meteorite find is as follows. Upon discovering a meteorite, the finder signals the remainder of the team, who mark their current positions within the line and converge on the find site. A GPS equipped snowmobile is brought near the find to record the location while several field party members begin the collection procedure. Each specimen receives a "field number" which is used as a unique sample identifier throughout all subsequent recovery procedures. The specimen is photographed while detailed notes record specimen size, the percentage of fusion crust, the presumed type (e.g., chondrite, iron, etc.), and any further distinguishing characteristics. The sample itself is placed into a clean Teflon(TM) bag and all contact with skin, clothing, or "dirty" implements is avoided. A clean aluminum tag, laser etched with the field number, is then inserted into the bag and arranged to prevent contact with the meteorite. The bag is then securely sealed with freezer tape and put into a larger bag where samples remain during the workday. Upon return to camp, the samples are sorted by sample



number and put into a dedicated storage and shipping container, which is left outdoors to keep the meteorites frozen. These containers are locked, and (still frozen) accompany the field team back to McMurdo, where they remain frozen until late February when they are transported by ship (still frozen) to Port Hueneme, CA. Upon arrival the containers are forwarded by freezer truck to the NASA Johnson Space Center (JSC) in Houston, TX. Note that our protocols are designed to drastically limit anthropogenic contamination of samples and fully document any such contact that may occur inadvertently, such as through serendipitous discovery.

**CURATION:** Disposition of the meteorite samples after recovery is a shared activity by NASA and the Smithsonian Institution. After arrival at JSC, samples are assigned official names and then the bags containing specimens are opened and thawed to room temperature under flowing dry nitrogen. Samples are subsequently stored in glove boxes, either in normal atmosphere (for ordinary chondrites) or nitrogen (for rarer specimens). The field notes prioritize the order of examination and curatorial staff carefully opens each sample in order to prepare a macroscopic description. This description then serves as a guide for the next stage of characterization. For most ordinary chondrite specimens, Fe/Mg ratios are determined on olivine and pyroxene grains to resolve type and petrographic grade. For achondrites or carbonaceous chondrites, thin sections are prepared and a more detailed characterization is performed. In exceptional cases, oxygen isotopes are analyzed to determine planetary parentage; However, efforts are made to limit the characterization of specimens to only data needed for accurate publication of their classification. The initial sample preparation and macroscopic descriptions performed at JSC are then combined with more detailed characterization and classification done at the Smithsonian Institution. These initial classifications are typically published twice yearly in the form of the Antarctic Meteorite Newsletter. Investigators can then request samples in a formal proposal to a panel of scientists known as the meteorite working group (MWG).

**CONCLUSIONS:** Careful systematics during searching, complete characterization of recovered specimens, the preservation of samples in the Antarctic environment, curation at the highest level, and rapid, cost free availability make ANSMET meteorites extremely valuable to the planetary materials research community.



## S25 – 394: Antarctic Meteorite and Micrometeorite

### *Application of Antarctic Meteorites to Grand Performance Test of the near Infrared Spectrometer on board the Hayabusa 2 Spacecraft*

Nakamura T.<sup>1</sup>; Iwata T.<sup>2</sup>; Kitasato K.<sup>3</sup>; Abe M.<sup>2</sup>; Osawa T.<sup>4</sup>; Matsuoka M.<sup>1</sup>; Nakauchi Y.<sup>2</sup>; Arai T.<sup>2</sup>; Komatsu M.<sup>5</sup>; Hiroi T.<sup>6</sup>; Imae N.<sup>5,7</sup>; Yamaguchi A.<sup>5,7</sup>; Kojima H.<sup>5,7</sup>

Tohoku University, Japan<sup>1</sup>; Japan Aerospace Exploration Agency<sup>2</sup>; University Of Aizu, Japan<sup>3</sup>; Japan Atomic Energy Agency<sup>4</sup>; Graduate University for Advanced Studies, Kanagawa, Japan<sup>5</sup>; Brown University, United States<sup>6</sup>; National Institute of Polar Research, Tokyo, Japan<sup>7</sup>

#### **Background:**

Hayabusa 2 mission is a Japanese space mission planned to visit a near-earth C-type asteroid 1999JU3 and recover rocky samples from the asteroid surface. The asteroid is ~1km in diameter and seems to consist of primitive solar-system materials based on reflectance spectra (Vilas, 2008; Abe et al., 2008; Sugita et al., 2013). Sample recovery from C-type asteroid JU3 by the spacecraft is very important to elucidate origin and formation of solar system and life, because the samples are expected to contain volatiles and organics such as pristine water and amino acids that are completely free of terrestrial contaminations. The Hayabusa 2 spacecraft was launched successfully last year, will arrive at the asteroid and collect surface rocks in 2018-2019, and return with the rocks of asteroid to the Earth in 2020.

The Near Infrared Spectrometer (NIRS3) is one of on-board spectroscopic apparatus designated for near infrared spectroscopy to detect absorptions by structural water in phyllosilicates at 2.7 $\mu$ m wavelength and molecular and interlayer water at 2.9-3.0 $\mu$ m (Iwata et al., 2013). During stay near the asteroid JU3, NIRS3 and optical navigation camera, which detects 0.7 $\mu$ m absorption band characteristic of Fe-rich serpentine, will measure reflectance spectra of the JU3 surface and take a leading role to understand distribution of minerals, water, and organics on the asteroid.

Reflectance spectra of JU3 suggest that the asteroid consists of hydrated and dehydrated carbonaceous chondrite materials (e.g., Vilas, 2008). Hydrated carbonaceous chondrites such as CM, CI, and CR chondrites have solar-like elemental abundances and therefore they are very primitive solar system material, although they have experienced extensive aqueous alteration that hydrated asteroids 4.6 billion years ago (e.g., Zolensky et al. 1993). Many hydrated carbonaceous chondrites were later heated up to ~1000°C and dehydrated to variable extents (e.g., Nakamura, 2005). Such dehydrated carbonaceous chondrites are mainly recovered from Antarctica.

#### **Objectives:**

We carried out the ground performance test of NIRS3 flight model for two years prior to the launch of the spacecraft. We have measured reflectance spectra of many carbonaceous chondrites by NIRS3. The purpose of the test is to know the NIRS3 flight model can detect mineralogical and compositional differences between hydrated and dehydrated carbonaceous chondrites and also to understand how precisely water concentrations of the meteorite samples can be estimated based on the 3.0 $\mu$ m feature obtained by NIRS3.

#### **Methods:**

Seven CM, one CI, and one CV carbonaceous chondrite samples, mostly recovered from Antarctica by Japanese Antarctic Expedition Team, were studied. The degree of aqueous alteration and later heating experienced by each meteorite sample was determined based on literature data or the results petrologic observation by electron microscopy and synchrotron X-ray diffraction analysis (e.g., Nakamura et al. 2011). The degree of heating is classified from heating stage I (almost unheated) to IV (heated to high temperature at which secondary olivine and pyroxene form at the expense of phyllosilicates) (Nakamura

et al. 2005). Heating stage of each hydrated carbonaceous chondrite sample is: Murchison CM (Heating stage = stage I), Murray CM (stage I), Y793321 CM (stage II), Jbilet Winselwan CM (stage II), Y982086 (stage II), Y980115 CI (stage II), Y86720 CM (stage IV), and B7904 CM (stage IV). As a reference sample made of anhydrous minerals, Allende CV chondrite is also measured. Water contents of the five meteorites, Murchison, Y793321, Y86720, B7904, and Allende are known to be 8.9, 6.5, 4.8, 2.1, and ~0.1 wt%, respectively (e. g., Antarctic Meteorite Catalog, 1995).

Powdered samples of nine carbonaceous chondrites were measured by the NIRS3 flight model and a FTIR spectrometer at Tohoku University. The wavelength range measurable by the NIRS3 is 1.8 to 3.2 $\mu$ m, while that by the FTIR is 0.4 to 25 $\mu$ m. During measurement by both NIRS3 and FTIR, phase angle is set to 30° and meteorite samples are vacuumed. NIRS3 integration time is 1ms and the stacking number is 1024. Details of the experimental set up of NIRS3 measurement is shown in (Iwata et al., 2014).

### Results and discussion:

Reflectance spectra of nine carbonaceous chondrites were obtained at various grain size (>3350 $\mu$ m, >512 $\mu$ m, >155 $\mu$ m, and >77 $\mu$ m) and some samples were heated to two temperatures (25°C =room temperature, 50°C, and 80°C). All spectra from nine samples show a monotonous increase of reflectance from 1.8 to 2.7 $\mu$ m, a sudden decrease at 2.7 $\mu$ m due to absorption of structural water of serpentine, and a broad absorption due to molecular water at 2.9-3.0 $\mu$ m.

The finer grain-size samples provide higher reflectance and positive slope from 1.9 to 2.7 $\mu$ m in reflectance spectra. Higher-temperature samples show higher reflectance from 2.4 to 3.2 $\mu$ m due to heat radiation. The results indicate that we can estimate approximate grain size and temperature of the surface material of JU3.

The reflectance spectra of meteorite samples indicate that depth of the 3 $\mu$ m absorption band differs greatly depending on the heating stage of the measured samples. A sample of heating stage I (Murchison and Murray) shows the deepest absorption. The four samples belonging to heating stage II show similar depths approximately 40% shallower than stage-I samples. The two stage-IV samples show different absorption features: Y86720 (water content: 4.8%) exhibits a deeper absorption being comparable to stage-II samples, while B7904 (water content: 2.1%) shows a shallower band. Anhydrous sample, Allende, shows shallowest absorption, consistent with the low (~0.1wt %) water content.

The present results indicate that NIRS3 is able to determine the dehydration degree of carbonaceous chondrites and estimate approximate water contents, grain size, and temperature of the JU3 surface material. Therefore it is expected that the NIRS3 obtain valuable information during 1999JU3 observation.



## **S25 – 406: Antarctic Meteorite and Micrometeorite**

### ***Korea Expedition and Curation for Antarctic Meteorites***

Lee, J.I.<sup>1</sup>, Park, C.<sup>1</sup>, Ahn, I.<sup>1</sup>, Lee, M.J.<sup>1</sup>; Kim, T.H.<sup>1</sup>; Yoo, I.S.<sup>1</sup>; Park, S.B.<sup>1</sup>; Moon, J.J.<sup>1</sup>; Baek, J.M.<sup>1</sup>

Division of Polar Earth System Sciences, Korea Polar Research Institute (KOPRI), Incheon, South Korea<sup>1</sup>

Korea Polar Research Institute (KOPRI) has operated Antarctic meteorite recovery program (Korea Expedition for Antarctic Meteorites, KOREAMET) since 2006 with one exception 2009. During the first three seasons (2006-2008), KOREAMET recovered 29 meteorites at the blue ice fields of Thiel Mountains. During 2010 and 2012 seasons, the joint expeditions with Italy were carried out in the Victoria Land with the logistic support of Mario Zucchelli Station. About 150 meteorites were recovered by the joint expeditions. KOREAMET is currently searching for meteorites in the southern Victoria Land with the logistic support of Jang Bogo Station which is the new Korea Antarctic research station established in February 2014. In the last season (2014), 81 Antarctic meteorites were recovered from the blue ice fields in the southern Victoria Land, about 300km south of the Jang Bogo Station. Among them, one ordinary chondrite weighs about 36kg and is the biggest ever in the history of KOREAMET. One LL-group ordinary chondrite contains very primitive textures, thus it is expected to preserve the chemical and isotopic records when the chondrite had formed in the early Solar System. Several carbonaceous chondrites and differentiated meteorites including eucrites were identified. Currently, a total of 320 meteorites were collected during 8 seasons. For the study of Antarctic micrometeorites (AMMs), KOREAMET is collecting clean snow samples in the Victoria Land from 2012 season (52kg in 2012, 408kg in 2013, and 400kg in 2014 season). The melting of snow, separating of dust particles and identification of AMMs are carried out with collaboration of Tohoku University, Japan.

All the meteorites recovered by KOREAMET are stored at vacuum boxes in a clean room (class 1,000) at KOPRI. A curation system of Antarctic meteorites has been renovated since 2012 when the new KOPRI campus was built. A new curator who is responsible for storage, classification, registration and distribution of Antarctic meteorites was invited in 2014. Field-emission electron microprobe, secondary electron microscope, and laser-fluorination oxygen-isotope system at KOPRI are used for classifying Antarctic meteorites. All the meteorites will be registered in the Meteoritical Bulletin Database and distributed to researchers worldwide. KOPRI completely reveals any information about Antarctic meteorites in the website of Korea Curation of Antarctic Meteorites (<http://koreamet.kopri.re.kr>).



**S26 – 22: General Antarctic Earth Science**

***Estimation of Radiative Energy Fluxes in East Antarctica Using Remote Sensing and Meteorological Data During Clear Sky Days***

H S Gusain<sup>1</sup>; V D Mishra<sup>1</sup>; M K Arora<sup>2,3</sup>; Ashwagosh Ganju<sup>1</sup>

Snow & Avalanche Study Estt (SASE) Chandigarh, India<sup>1</sup>; Punjab Engineering College (PEC) University of Technology, Chandigarh, India<sup>2</sup>; IIT Roorkee, India<sup>3</sup>

Energy balance of the cryospheric regions has impact on global climate. Radiative energy fluxes are vital component of the energy balance study. However, these energy fluxes are recorded at very sparse locations using in situ measurements in cryospheric regions. Surface energy fluxes estimated from sparse in situ observations may therefore not characterize spatial variation of energy fluxes over a large snow/ice covered regions. To overcome this problem, remote sensing data can be effectively used in conjunction with sparse ground observations via suitably interpolation or modeling techniques to map energy fluxes at spatial level. In the present paper, incoming shortwave radiation flux, net shortwave radiation flux, net longwave radiation flux and net radiation flux have been estimated at spatial scale for the ice sheet in East Dronning Maud Land, Antarctica. In situ data of the surface energy fluxes and meteorological parameters has been collected using automatic weather stations (AWS) on ice sheet at two locations near Indian Research Station Maitri. Moderate Resolution Imaging Spectroradiometer (MODIS) data on clear sky days of the years 2008, 2009 and 2010 have been used to estimate radiative energy fluxes at spatial scale. Model estimated surface energy fluxes have been evaluated using in situ recorded values of energy fluxes. Air temperature and relative humidity maps of the study area have been generated using AWS data and Shuttle Radar Topographic Mission (SRTM) Digital Elevation Model (DEM). Air temperature maps of the study area have been generated using DEM and in situ recorded air temperature data. Relative humidity maps have been generated using in situ recorded RH and parameterization scheme proposed by Buck (1981). Incoming shortwave radiation flux has been estimated from air temperature and relative humidity maps using parameterization scheme proposed by Zillman (1972). Albedo of the ice sheet has been estimated from MODIS data using narrowband to broadband algorithm. Net shortwave radiation flux maps have been generated from albedo maps and incoming shortwave radiation flux maps. Surface temperature of the ice sheet has been estimated from thermal bands data of MODIS using split window technique. Outgoing longwave radiation flux and incoming longwave radiation flux have been estimated from surface temperature and air temperature maps respectively using Stephan Boltzmann law and parameterization scheme given by Prata (1996). Net radiation flux has been estimated for the study area from net shortwave radiation flux and net longwave radiation flux maps. Absolute errors in estimation of net shortwave radiation flux has been obtained between  $2 \text{ W/m}^2$  to  $129 \text{ W/m}^2$  and absolute error in estimation of net radiation flux has been obtained between  $4 \text{ W/m}^2$  to  $136 \text{ W/m}^2$  during different days while compared with in situ data. Spatial and temporal variation of radiative energy fluxes have also been investigated in the study area. The geospatial maps of the radiative energy fluxes may be quite useful in many snow and hydrological studies, particularly in absence of in situ data from large snow/ice covered area.



**S26 – 24: General Antarctic Earth Science**

***Methodological Consideration for Glacier Mapping in Miyar Basin, Lahaul Himalaya, India***

Sanjay Deswal<sup>1</sup>; Milap Chand Sharma<sup>2</sup>; Rakesh Saini<sup>3</sup>; I.M. Bahuguna<sup>4</sup>; Ajai<sup>4</sup>

Govt. College Dujana<sup>1</sup>; JNU New Delhi<sup>2</sup>; DHSG Central University Sagar, M.P. India<sup>3</sup>; Space Applications Centre (SAC) - Indian Space Research Organisation (ISRO) Ahmedabad, Gujarat, India<sup>4</sup>

This study focuses on the nature of recent behaviour of glaciers in the Miyar basin to assess mechanism of environmental change in recent decades. Glacier fluctuations in the Himalayas have been poorly understood due to inaccessible and jagged terrain and improper interpretation of data sets. The Miyar, one of the largest tributary basins in upper Chenab, contains 16 valley glaciers and 76 other smaller ice bodies. A complex picture emerges out of the analysis. Three categories of glacier behaviour have been noticed; standstill glaciers, slow retreat (59 meters/year) and significant retreat (over 10 meter/year). This study also contributes to the understanding of heightened anthropogenically induced global climate change as proposed by the IPCC (2014). Methodological aspect of glacier mapping has also been addressed in this paper in view of the contentious reporting of glacier recession in recent years arising out of faulty comparison of wrong datasets.



**S26 – 25: General Antarctic Earth Science**

***Estimation of Volume of Eastern Himalayan Glaciers Using Remote Sensing Methods***

Anubha Agrawal<sup>1</sup>; Shresth Tayal<sup>1</sup>

(TERI) The Energy and Resources Institute Delhi, India<sup>1</sup>

The total area of 134 Sikkim glaciers has been estimated to be 547.414 km<sup>2</sup>. Slope dependent method gave the total volume of these glaciers to be 17.762 km<sup>3</sup>. Volume and area estimates of individual glaciers are used to establish a volume-area relationship for Sikkim Himalayan glaciers. The relationship obtained is: The total volume of 134 glaciers estimated using this relationship for Sikkim Himalayan glaciers is 17.515 km<sup>3</sup>. Iceflow velocity method gave the total volume of these glaciers to be 15.3 km<sup>3</sup>. The volume of the ablation (Ab) zone of East Rathong glacier using Global Positioning System (GPS) data is found to be 0.054 km<sup>3</sup>. Volume of Ab zone of the glacier calculated using slope dependent method is ~ 0.037 km<sup>3</sup>. Volume of Ab zone estimated using iceflow velocity method is ~0.038 km<sup>3</sup>. Volumes estimated for East Rathong glacier using field and offfield methods are comparable. The study suggests that Cartosat1 is a suitable Digital Elevation Model (DEM) for glacier studies. Temperature change of Sikkim estimated (+0.7 K) using satellite data from 1979-2011 and temperature change estimated (+0.4 K) using glaciers as proxy for 1976-2013 are comparable, suggesting that glaciers are a good proxy for climate change studies. High rate of volume loss, area loss and rate of retreat along with nearly constant AAR observed in the four glaciers assessed for time period 1976-2009, suggests that AAR is not a robust indicator for the assessment of health of glaciers.



**S26 – 76: General Antarctic Earth Science**

***Chemical Environment of a Lake with Unusual Optical and Thermal Properties on Bharti Island, Larsemann Hills, East Antarctica***

Pawan Kumar Bharti<sup>1</sup>; Enn Kaup<sup>2</sup>; Bhupesh Sharma<sup>3</sup>; U. K. Niyogi<sup>3</sup>

Shriram Institute, Delhi<sup>1</sup>; Department of Isotope Paleo-Climatology, Institute of Geology, Tallinn University of Technology, Tallinn, ESTONIA<sup>2</sup>; Antarctica Laboratory, R & D Division, Shriram Institute for Industrial Research, Delhi, INDIA<sup>3</sup>

The Larsemann Hills is an ice-free area of approximately 50 km<sup>2</sup>, located halfway between the Vestfold Hills and the Amery Ice Shelf on the southeastern coast of Prydz Bay, Princess Elizabeth Land, East Antarctica (69°30'S, 76°19'58" E). The area consists of two major peninsulas Stornes and Broknes, four minor peninsulas, and approximately 130 near shore islands. There are more than 150 lakes on different peninsulas and islands.

The lake L-7 on Bharti Island was studied in order to complete the survey of lakes of Larsemann Hills, made by Australians during 1986/87 summer. Profiling and sampling on that lake was carried out on February 4, 2009 during 28th InSEA for the physical (temperature, dissolved oxygen (DO), pH) and chemical (major ions, several minor and trace elements) plus Chl a at several depths, from ice cover at a midlake station.

Temperature and DO profiles were measured in situ with a calibrated thermistor, DO meter and water samples were taken with a 30 cm long bathometer. Samples were kept at ambient temperature and pH and conductivity were measured a few hours after sampling in the field lab. Samples were subsequently kept frozen and major ions were measured after a few months in Tallinn using HPLC with standard methodology. Trace elements were analyzed using Inductively Coupled Plasma Optical Emission spectroscopy (ICPOES).

Water temperature was 0.7 °C on surface and 9.2 °C in the main water mass, the elevated temperature resulting from solar heating. DO was found low, 4.2 mg/l, under melting ice cover. However, it was oversaturated from 1 m depth downwards, reaching 136% at 5 m and lower depths, except 2.4 mg/l above bottom. Lake water was slightly alkaline (pH from 7.16 to 7.74), and free from any colour, odour and turbidity. Chl a decreased from 0.8 µg/L from under ice cover to zero above bottom. Conductivity of water was 901 µS/cm under ice cover and up to 2690 µS/cm deeper. The major ions were Cl (413-1391 mg/l), SO<sub>4</sub> (45.5 -188 mg/l), Na (144-463 mg/l), Ca (16.9-55.2 mg/l) and Mg (20.4-58.8 mg/l). The sum of these ions under ice cover was observed as minimum (646 mg/l), while it was observed maximum (2173 mg/l) at 6 m depth. Several minor and trace elements were also observed in very low quantity or under detection limits.

The observed data of lake water quality are discussed, also in comparison with data from other lakes on Broknes studied during the 28th InSEA in 2009 and with the data observed by Australian scientists on Broknes and Stornes in 1986/87.

Key words: Water quality monitoring, Antarctic lakes, Larsemann Hills



**S26 – 77: General Antarctic Earth Science**

***ROV Survey of Nearshore Shallow to Deep Carbonate Factories in Terra Nova Bay, Ross Sea***

Marco Taviani<sup>1</sup>; Simonepietro Canese<sup>2</sup>; Claudio Mazzoli<sup>3</sup>; Paolo Montagna<sup>1</sup>; Stefano Schiaparelli<sup>4</sup>

Institute of Marine Science (CNR-ISMAR) Italy<sup>1</sup>; ISPRA<sup>2</sup>, Institute for Environmental Protection and Research, University Of Padova, Italy<sup>3</sup>; University Of Genoa, Italy<sup>4</sup>

Significant carbonate production is largely limited in Antarctica to shallow nearshore and offshore bank habitats. Detailed information about these modern carbonate fabrics is still rather scant and patchy, and there is a growing effort of the scientific community to locate the sites of carbonate production and evaluate their contour habitat conditions. With this aim, a Remotely Operated Vehicle (ROV Pollux III) exploration has been carried out during the Austral summer 2013-2014 in the frame of the Geosmart project, funded by the Italian Antarctic Research Program (PNRA), and focused on geochemical signatures in Antarctic marine carbonate system. Two ROV dives were performed along depth transects, off Adelie Cove and in the Terra Nova Bay Canyon respectively. In both cases, clear patterns in the distribution and type of macroscopic carbonate producers from shallow (ca. 20 m) to deep (ca. 300 m) settings were revealed. Substantial carbonate production is seen off Adelie Cove, where the major calcifier observed is the sea urchin *Sterechinus neumayeri*, an almost ubiquitous species from 20 to 120 m independently from the substrate type. The encrusting coralline alga *Phymatolithon foecundum* is equally abundant along the entire transect down to 120 m, whenever suitable substrates (rocky bedrock, pebbles and cobbles) occur; Indeed, the algae is noticeably absent along the transect between 80-100 m where the bottom is soft and particulate. The pectinid *Adamussium colbecki*, which is a quantitatively conspicuous component at other sites in Terra Nova Bay between ca. 40-80m, was found, with relatively low densities, only between 60-90 m. Minor carbonate macroproducers intercepted by the ROV exploration include occasional serpulids (e.g. *Serpula narconensis*) and gastropods (*Neobuccinum eatoni*). In addition to such living component, locally abundant carbonate shell material is provided by spoils of infaunal bivalves (*Thracia*, *Limopsis*, *Laternula*). The exploration of the Canyon between 220-298 m instead, revealed very low presence of macroscopic carbonate producers which are represented by erect and fenestrate bryozoan colonies of large size. In addition, a number of asteroid, crinoid and ophiuroid echinoderms have been observed in both transects, whose calcareous ossicles will be added postmortem to total carbonate production.

Most carbonate production in this area is, therefore, to be found at shallow depth and, as expected in a low temperature regime as the study area, predominantly represented by calcitic organisms.



## S26 – 82: General Antarctic Earth Science

### *Mineralogy of Antarctic Modern Biogenic Carbonates*

Claudio Mazzoli<sup>1</sup>; Paolo Montagna<sup>2</sup>; John B. Andreson<sup>3</sup>; Marco Taviani<sup>4</sup>; Federico Zorzi<sup>1</sup>

Department of Geosciences, University of Padova, Padova, Italy<sup>1</sup>; Institute of Marine Sciences (ISMAR)-CNR, U.O.S. Bologna, Italy<sup>2</sup>; Department of Earth Science, Rice University, Texas, USA<sup>3</sup>; Institute of Marine Sciences (ISMAR) - CNR, U.O.S. Bologna, Italy; Biology Department, Woods Hole Oceanographic Institution, MA, USA<sup>4</sup>

The increase of atmospheric CO<sub>2</sub> partial pressure (pCO<sub>2</sub>) connected to human activities causes an increase of dissolved inorganic carbon and decrease of pH in surface seawater, potentially frightening calcifying organisms. The response of these organisms to ocean acidification depends on their capacity to upregulate pH in the calcifying sites and on the specific calcium carbonate mineral secreted, determining stress levels that could be fatal. Moreover, the lowering of the saturation state with respect to calcite or aragonite increases the carbonate dissolution, potentially shifting the balance toward a state of net CaCO<sub>3</sub> loss. Surface seawater in the Southern Ocean is already characterized by low carbonate saturation conditions, and represents an ideal target for the study of the effects of ocean acidification on the calcifying organisms. Furthermore, because subfreezing temperatures prevent precipitation of inorganic cements, modern marine carbonates in Antarctica are biogenic in origin resulting from calcifying organisms. Such carbonates formed under the extreme polar conditions only to be found in Antarctica, are important sources of oceanographic and climatic information. A necessary prerequisite for their use as proxies in geochemical studies and for a better understanding of their potential response to ocean acidification is the precise assessment of the skeletal original mineralogy. We have, therefore, started a complete screening of constituents of Antarctic biogenic carbonates in the frame of the Geosmart project, funded by the Italian Antarctic Research Program (PNRA). A variety of modern skeletal parts belonging to dominant benthic and planktic calcifiers (mollusks, scleractinians, octocorals, serpulids, brachiopods, bryozoans, barnacles, echinoderms, foraminifers, ostracods, coralline algae) has been tested at species level using X-ray powder diffraction, microRaman and electron microprobe (EMPA) to recognize the carbonate phases (calcite, low Mg calcite, high Mg calcite, aragonite, laterite) and identify the distribution of major elements. When different carbonates are detected (e.g. calcite and aragonite), their structural location and weight fractions were determined. The systematic determination of the mineralogy of the calcifying organisms along with the knowledge of their relative role in the ecosystems, is the first step towards the understanding of the species specific and ecosystemic vulnerability to increasing CO<sub>2</sub> levels.



## S26 – 99: General Antarctic Earth Science

### ***Constraints on Antarctic Plate Motion and Deformation from GPS Measurements***

Sapna Ghavri<sup>1</sup>; Vineet Kumar Gahalaut<sup>1</sup>; Joshi K.Catherine<sup>1</sup>

National Geophysical Research Institute Hyderabad, India<sup>1</sup>

Antarctic plate comprising the southern polar continent is considered to be stable and seismically quiet yet the crustal deformation studies of this plate are significant as the causative phenomenon are varied, which include plate motion, internal deformation, glacial rebound, seasonal variations, etc. To study these phenomena we have analyzed GPS data from 2008 to 2013 from more than fifty permanent GPS stations from all over the Antarctic continent including one at Indian base station, Maitri. For each day of the analysis, observation files in Receiver-Independent Exchange (RINEX) format are used. Supplementary data required to analyze data from the network, are the GPS data from global reference station from the IGS network (International GNSS Service), broadcast navigation files, and a priori orbits (IGS final solutions). These data were downloaded from the Scripps Orbit and Permanent Array Center (SOPAC) archive for each day. The data processing and analysis were carried out using GAMIT/GLOBK, version 10.40 scientific software package (King and Bock, 2005; Herring et al., 2010a, 2010b). First of all, the daily site coordinates were estimated from the GPS data using GAMIT and then combined to multiepoch velocity solutions estimated by GLOBK. The motion at these sites varies from 4 to 20 mm/year. The Indian site at Maitri moves predominantly towards north at the rate of 7 mm/year. The Euler pole is estimated for east and west Antarctica. We also investigated the role of Trans -Antarctic mountains, a possible rift across the continent. As geologically Antarctica is divided into two major tectonic domains east and west Antarctica, separated by the Trans Antarctic Mountains, so we have estimated the Euler pole for the east and west Antarctica, to understand whether Antarctic plate is a single plate or two plates.

Pole of East Antarctica:

Latitude:  $59.5209 \pm 0.91281$

N Longitude:  $125.2097 \pm 1.0645$  E

Omega:  $0.21988 \pm 0.0064397$  degree/my

Pole of West Antarctica:

Latitude:  $58.5954 \pm 1.306$  N

Longitude:  $131.6768 \pm 0.92716$  E

Omega:  $0.21572 \pm 0.0055304$  degree/my

We found that the relative motion between the eastern and western Antarctica is about 1.3 mm/year but is not well constrained due to the inherent errors of observations and residuals in the velocity estimates (1.5 mm/year). East Antarctica appears to be more stable than the western Antarctica. We also analyzed the seasonal variations in the coordinates. We find that variations are larger at the polar sites. The variation in the total electron content (TEC) is less at pole and increases with decreasing latitude. The seasonal variation in the coordinates appears to be related to the meteorological parameters, namely, temperature and humidity.



**S26 – 105: General Antarctic Earth Science**

***Investigation of Polar Atmospheric Response to the Intense Geo-Space Activities***

Jayanta Kumar Behera<sup>1</sup>; Ashwini K. Sinha<sup>1</sup>; Rahul Rawat<sup>1</sup>; Ajay Dhar<sup>1</sup>

Indian Institute of Geomagnetism, Mumbai, India<sup>1</sup>

Many studies have claimed that energetic particle precipitation (EPP) during high speed solar wind streams (HSS) can cause ionization and subsequent constituent changes in the polar mesosphere and stratosphere (middle atmosphere). Over the last few decades, it has been shown that production of NO<sub>x</sub> and HO<sub>x</sub> in the mesosphere and upper stratosphere region during the precipitation of charged particles (with energy range >30 KeV to 1 MeV) (Meredith et al., 2011) is directly related to the ozone loss in the polar middle atmosphere (Rodger et al., 2007). This study has dealt with the analysis of the interplanetary parameters such as interplanetary magnetic field (IMF), solar wind velocity (Vs), charged particle density (Ns), convection field enhancement (Ec) during such HSS events and their link to the rate of production of NO<sub>x</sub> in the mesosphere. Moreover, the analysis will be used to validate or, to modify the current ion chemistry models (Rusch et al., 1981, Verronen, 2006) which describe the ionization rate and NO<sub>x</sub> production in the polar atmosphere due to EPP.



## S26 – 108: General Antarctic Earth Science

### ***New High Resolution Map 1:5,000 of La Meseta and Submeseta Fms (Late Paleocene-Eocene) of Seymour (Marambio) Island, Weddell Sea***

Manuel Montes<sup>1</sup>; Francisco Nozal<sup>1</sup>; Sergio Santillana<sup>2</sup>

Instituto Geológico y Minero de España, Spain (IGME)<sup>1</sup>; Instituto Antártico Argentino, Buenos Aires, Argentina IAA<sup>2</sup>

Geological mapping in a broad sense is a powerful tool for geological research and usually represents the first and most valuable stage of geologic reconnaissance of a region.

The La Meseta Fm and Submeseta Fm sections of Seymour Island are the only place known in all Antarctica where Late Paleocene and Eocene shelf sediments are exposed in outcrop and in stratigraphic continuity. In that time span occur in Earth History, major geological events: paleoclimatics (PETM, EECO, MECO and Oi) ; Tectonics (opening Drake Passage) or palaeobiologicals (expansion of terrestrial and marine mammals and other vertebrates, etc.). Due to the difficulties of Antarctica shelf drilling through ice and penetrating the overlying mantle of glacial debris, this section remains critical for multidisciplinary geological studies (stratigraphic, paleoclimate, paleontologic, etc.) of high latitude in the Paleocene and Eocene.

The importance for geological science of these formations is clear. Therefore the scale of work for making paleontological and chronostratigraphic samples (magneto, chemo, cyclo) should be more detailed than the published geological map at 1: 20.000 (Montes et al., 2013). This previous map were done by Spain Geological Survey (IGME) with the scientific collaboration and logistic support of the Argentine Antarctic Institute (IAA), in the framework of the collaboration of both institutions, and they are published by IGME with the support of within the new Antarctic Geoscientific Cartography Series as part of the Spanish Polar Research effort.

In this work, we present a new high-resolution map scale 1:5.000 based on the published map 1: 20.000. Fieldwork was conducted during the 2015 season with direct outlet on the ground through GPS Tablet on previous geological contacts, with an approximate working scale 1: 500, and implemented with 3D visualization software (Fledermaus 7.0) on a DEM obtained from the original topographic map 1:10.000, produced by the USGS and IAA. The legends, symbols and map contents, follow the IGME standard for geological and geomorphological maps.

The geological map contains eleven geological units which are part of four formations: La Meseta Fm (late Paleocene to middle Eocene); Submeseta Fm (upper Eocene); Hobbs Glacier Fm (Miocene), and Weddell Fm (Pliocene Quaternary). The map contains too, a legend showing the relationship between units, symbols, geological cross section, stratigraphic columns with a correlation panel, and sketch maps with the geographical and geological context.

The new cartographic data presented are: Mapping Registry most significant levels of bivalve and gastropod coquinas accuracies of +/-5 m. High precision mapping of geological contacts of Formations of La Meseta and Submeseta Fms and their Allomembers. High precision mapping of significant sites of vertebrates. Mapping Position of samplings on standard sections of magneto stratigraphy, clays and Sr isotopes (Ivany, et al, 2008).

The data collection in the field was conducted by ESRI ArcPad 10.0 program and editing the mapping is correct to ArcMap 9. The final edition will be in high resolution PDF.



This map and other of the new Antarctic Geoscientific Cartography Series can be viewed online through a new map service on the web that integer the geothematic cartography (geological and geomorphological).

This browser of geoscientific information, available through the web page of NPDC, allows the visualization and consultation with standard tools from the geological cartography and geomorphological maps and permits managing this information, modifying the order of visualization and the transparence of information layers. The design and the capacity of access to data enable to satisfy needs of scientific community. To reach that objective the geodatabases from different geothematic cartographies have been integrate in the engine of data base, using so the data model developed by IGME for the digital cartography edition as well as SCAR Feature Catalog. The browser is based on ArcGIS Web Mapping, that is a collection of APIs. Web Mapping APIs allow you to develop rich, interactive applications using Silverlight and offers the possibility of add content to the map via online services, add your own tools and widgets, Build standalone applications, add GeoRSS feeds and connect to GIS servers.



**S26 – 122: General Antarctic Earth Science**

***Seasonal and Inter-Hemispheric Differences in the Diurnal Variation of Schumann Resonance Parameters***

Rahul Rawat<sup>1</sup>; S. Manu<sup>1</sup>; A.K.Sinha<sup>1</sup>; S.Gurubaran<sup>1</sup>

Indian Institute of Geomagnetism India<sup>1</sup>

Schumann resonance (SR), a resonant electromagnetic wave in the Earth ionosphere cavity has a fundamental frequency at about 8 Hz with higher order modes being separated by ~6 Hz. SR was first discovered in the middle of the last century (Schumann,1952). In recent years, it has caught the attention of the scientific community as its amplitude can act as a proxy for global temperature changes (William, 1992) and therefore any study on this phenomenon is important from the perspective of climate change. In this paper, the seasonal and inter-hemispheric differences in the diurnal variation of the Schumann resonance key parameters are examined using ground magnetic data obtained from search coil magnetometers operating at a low latitude station Shillong (25°55' N, 91°53'E) in the Northern Hemisphere and the sub-auroral Indian Antarctic station, Maitri (70°45'S, 11°45'E) in the Southern Hemisphere. Signatures of 24 h, 12 h and 8 h components are clearly discernible in the recorded data at both the stations with varying strength. Further, the amplitudes of different harmonics of each SR parameter strongly depict seasonal as well as inter-hemispheric changes at both the stations.



**S26 – 126: General Antarctic Earth Science**

***Investigation of the Effects of Cosmic Ray Input on Clouds and Climate in Antarctica***

Anil Kumar C.P.<sup>1</sup>; Balan N.<sup>2</sup>; Jeni Victor N.<sup>1</sup>; Selvaraj C.<sup>1</sup>; Nair K.U.<sup>1</sup>; Panneerselvam C.<sup>1</sup>; Elango P.<sup>1</sup>; Jeeva K.<sup>1</sup>; Ajay Dhar<sup>1</sup>; Gurubaran S<sup>1</sup>; Venugopal C.<sup>3</sup>

Indian Institute of Geomagnetism, Navi Mumbai, India<sup>1</sup>; Research Institute for Sustainable Humanosphere, Kyoto University, Uji, Kyoto, Japan<sup>2</sup>; School of Pure & Applied Physics, Mahatma Gandhi University, Priyadarshini Hills, Kottayam, Kerala, India<sup>3</sup>

The paper studies the effect of cosmic rays on the clouds and snowfall rates (and hence climate and weather) in Antarctica using nine years of data (2001-2009) covering: the solar maximum phase (2001-2003), declining phase (2004-2006) and long deep minimum phase (2007-2009). The data include solar cosmic flux from ACE (advanced composition explorer) satellite and ground based observations of atmospheric electrical parameters at Maitri ( $70^{\circ}45'S, 110^{\circ}43'E$ , Indian Station) and Vostok ( $78^{\circ} 27'S, 106^{\circ} 52'E$ , Russian Station), Meteorological data at Maitri, Vostok and Scott Base ( $77^{\circ}51'S, 166^{\circ}46'E$ , New Zealand station) and neutron monitors data from McMurdo ( $77^{\circ}51'S, 166^{\circ}40'E$ , American Station). The data are systematically analyzed. The results indicate that the changes in electrical properties of the high latitude atmosphere due to cosmic ray flux affect cloud properties and hence radiative balance of the high latitude climate. The results are discussed in terms of the association of the cosmic ray flux with the production of ions in the atmosphere that leads to cloud condensation nuclei (CCN) and formation of cloud drops which scatter the solar radiation back to space. Depending on the changes in the cosmic ray flux, these processes can enhance/reduce the albedo of the planet and causes cooling/heating of the atmosphere.



**S26 – 134: General Antarctic Earth Science**

***Cosmic Radio Noise (RIO Meter) Observations at Antarctic Stations during Total Solar Eclipse on 23-24 November 2003***

Hanchinal, A<sup>1</sup>

Indian Institute of Geomagnetism, Navi Mumbai, India<sup>1</sup>

30 MHz Riometer (Relative Ionospheric Opacity meter) observations at Indian Antarctic station Maitri (geog. 70°46'S, 110°44'E), during Total Solar Eclipse on 23-24, November 2003 shows reduction in the cosmic radio noise absorption. These observations are compared with observations at Australian stations Casey (geog. 66°17'S, 110°31'E) and Davis(68°35'S, 77°58'E ).Geomagnetic observation at Maitri shows changes in H,Z and D components during eclipse.



**S26 – 178: General Antarctic Earth Science**

***Early Jurassic Silicic Volcanism in the Transantarctic Mountains: Tectonic Setting and Relations to the Gondwana Plate Margin***

Elliot, D.H.<sup>1</sup>; Larsen, D.<sup>2</sup>

School Of Earth Sciences And Byrd Polar Research Center, Ohio State University, USA<sup>1</sup>; Department Of Earth Sciences, University Of Memphis, USA<sup>2</sup>

The record of Early Jurassic silicic volcanism in the Transantarctic Mountains is confined to three areas. The principal region is the Marshall Mountains in the central Transantarctic Mountains (CTM) ; A significant record exists in north Victoria Land (NVL), and just a trace in south Victoria Land (SVL). In the Marshall Mountains the Hanson Formation, radiometrically dated between about 194 Ma and 183 Ma, overlies a disconformity cut across the Triassic Falla Formation and marked by a lag conglomerate. Hanson strata, no more than 240 m thick, consist of laterally extensive, coarse to medium grained quartzose and volcanic sandstone sheets with interbedded silicic tuff, which increases in abundance up section. Hanson beds are overlain by phreatomagmatic deposits of the Prebble Formation, which in turn are overlain by Kirkpatrick Basalt flood lavas, both part of the Ferrar Large Igneous Province.

Hanson quartzose sandstones form multistory fluvial channel units as much as 12 m thick, which are more common lower in the section where they grade upward into greenish gray siliciclastic overbank mudstone but, progressively higher in the section, into fine-grained silicic tuff and reworked tuff.

Quartzose sandstones range from pebbly to medium grained, and includes arkoses with large (2 cm) angular K feldspar grains and common garnet. Volcanic sandstones (litharenites) are coarse to medium grained, with sand sized volcanic clasts having a variety of properties, and grade abruptly into tuffaceous beds. Tuffs, mainly reworked, contain common to abundant fine grained bubble wall shards, probably from Plinian eruptions of distal volcanic centers; However, at least limited more proximal volcanism is suggested by a single occurrence of armored and accretionary lapilli relatively high in the section.

The underlying Falla Formation, the uppermost unit in the Permo-Triassic Victoria Group, which constitutes the fill of a retroarc (foreland ) basin, is approximately 300 m thick at the type section, but elsewhere in the Marshall Mountains is thinner (e.g., 75 m at Mt. Kirkpatrick). The Hanson Formation has a more consistent thickness of 200-235 m, thus pointing to erosion of Falla strata prior to Hanson deposition resulting from uplift and/or tilting. The coarse grain size of the quartzose sandstones and the occurrence of arkoses indicate short transport distances for detrital material and relatively proximal deposition. The depositional setting is interpreted as an axial stream system within a developing rift valley.

The overlying Ferrar rocks provide more direct support for paleotopography and a rift setting, and suggest broad continuity in tectonic setting throughout Early Jurassic time. The phreatomagmatic rocks present in SVL and at the Otway Massif (CTM) document large-scale interaction between Ferrar magmas and abundant groundwater. Pillow basalt ca. 100 m thick at the base of the lava sequence in the Prince Albert Mountains (SVL) indicates confining topography. The lavas in CTM, SVL and NVL include flows more than 100 m thick (and as much as 230 m), suggesting they were ponded. These features demonstrate significant paleotopography during Early Jurassic time.

Evidence in CTM for structural relief during the Early Jurassic is scattered. Monoclines offset Hanson beds at Mt. Falla and at Mt. Lindsay, and also offset Victoria Group strata at the Dominion Range east of the Marshall Mountains. West of the Marshall Mountains, faults with significant throw have uplifted basal Victoria Group strata at least 300 m, and in the same region normal faulting has displaced upper Permian and Lower Triassic beds. A small graben is present in the southern Marshall Mountains. These structural features are within the inferred rift valley. A bounding fault for the inferred rift valley may be present along



the Marsh Glacier; This fault has a throw of at least 2 km. Previous structural studies on faults and Ferrar dikes demonstrated deformation before and during Ferrar time; The principal extension direction was perpendicular to the trend of the Transantarctic Mountains. There are no data indicating structural relief in SVL, although the Mawson Formation includes a massive body interpreted as a landslide and attributed to topographic relief. In both SVL and NVL, phreatomagmatic deposits indicate abundant groundwater and centers of magmatic activity in topographic lows.

Geochemically the fine grained silicic tuffs in the CTM are mainly high silica rhyolites; However, compositions are compromised by reworking and addition of detrital material. Isotopic data suggests they were not derived from Lower Paleozoic Ross Orogen granitoids, nor are they related to the crustal contaminant for Ferrar magmas. Their source region, which must lie outboard of the Ross Orogen belt of the Transantarctic Mountains, is discussed in terms of three scenarios: a plate margin origin related directly to subduction, which is recorded in Lower Jurassic intrusive and extrusive rocks, principally in New Zealand and the Antarctic Peninsula; A region of backarc extension and rifting, now ice covered in West Antarctica; A rift setting related more directly to the Lower Jurassic volcanic and sedimentary rocks in the Transantarctic Mountains. In a broader context, the Transantarctic Mountains rift setting is interpreted to be the inboard margin of extension in a large scale backarc region of the Gondwana plate boundary, initiated in the earliest Jurassic, and generating the pathway for long distance transport of Ferrar magmas.



## S26 – 179: General Antarctic Earth Science

### *A Transantarctic Mountains Digital Geological Map Resource*

Cox, S.C.<sup>1</sup>; Rattenbury M.S.<sup>2</sup>; Martin, A.P.<sup>1</sup>; Morgan F.<sup>3</sup>; Townsend D.<sup>2</sup>; Smith Lyttle B<sup>1</sup>

GNS Science, Private Bag 1930, Dunedin, New Zealand<sup>1</sup>; GNS Science, P O Box 30368, Lower Hutt, Wellington, New Zealand<sup>2</sup>; Landcare Research, Private Bag 92170, Auckland, New Zealand<sup>3</sup>

#### BACKGROUND

There are numerous, hard-copy, regional-scale geological maps of Antarctica that were compiled and published last century. Many have been subsequently scanned and are available in digital image formats, some of these have been geo-referenced, but few are available as more than raster images. Very few GIS-based geological maps have been produced and even fewer are internet-accessible. For the most part the geological maps reliably define bedrock geology ('deep time') but generally contain little representation of glacial geology and lack information on landscape evolution; thus these geological maps are not contributing greatly to identifying Antarctica's role in climate change. The older maps, in particular, have poor spatial reliability compared with modern topographic mapping. To address this, an international effort has been initiated to compile unified geological and geomorphological maps of the Transantarctic Mountains (TAM) that will result in an authoritative GIS dataset to inform studies of glacial dynamics and climate change as well as deep time geology.

#### OBJECTIVES

We have built a prototype geological dataset for the TAM. Its construction embodies a philosophical shift in map compilation dictated by Antarctica's special geological information circumstances, that is, having numerous legacy geological maps but with insufficient opportunity to field verify and infill gaps with new groundwork. Regional-scale mapping in New Zealand and many other countries (and to a lesser extent Antarctica) has typically followed a conventional "bottom-up" construction, whereby information was built up sheet by sheet campaign-style. Increasingly these individual sheets, whether acquired in digital GIS formats or digitally captured from printed copy, are being digitally stitched to provide seamless GIS products (e.g. Rattenbury & Isaac 2012). For Antarctica, however, we are adopting a "top down" construction using GIS technology, whereby work starts from a continent-scale, low density, attribute-poor dataset that is added to and improved through multiple iterations. The philosophy was first introduced to GNS Science through our testing of the Leapfrog® suite of 3D geological modelling software (ARANZ 2015). The top-down approach already has achieved geological map information for the entire TAM, albeit at low spatial resolution and with sparse information, but these will improve significantly as the project progresses. We are utilising very high resolution satellite imagery to assist with mapping geological units and landforms, extending away from well-mapped, field-verified areas into terra incognita.

The aims of this map compilation are to: (1) provide a region-wide modern digital dataset that defines key geological units and a consistent level of information for regional-scale ecological, climatic and environmental analyses; (2) summarise the wealth of work carried out by various Antarctic treaty nations, and provide a bibliographic pointer to the source data; (3) stimulate efforts to update and spatially improve that geological and geomorphological work to meet modern data standards.

#### METHODS



As a starting point we have added geological information to the SCAR Antarctic Digital Database (ADD Version 6) rck01 and mrn01 polygons (SCAR 2015), classifying the outcrops into four simplistic lithostratigraphic units:

- QTms** – mostly Late Cenozoic glacial moraine and scree;
- Czv** – mostly Quaternary-Miocene volcanics;
- DJ** – mostly Jurassic Ferrar Group & Devonian-Permian Beacon Supergroup;
- Pa** – mostly Mesozoic-Paleozoic granitoid & metamorphic rocks.

The original rock polygon data are highly generalised with known and significant spatial inaccuracies in places. They have been derived from source information at widely varying resolution, and for now are suitable for defining geological layers only at small map scales such as 1:1 million and 1:10 million (SCAR 2015). To correct this we are in the process of improving their location through use of satellite imagery orthorectified to decimetre precision, but aim to retain links to the original SCAR dataset so that geological information can still mesh with ecological or biological assessments using the original rock polygons.

The project scale has highlighted a need to develop a continent-scale, high-level stratigraphic nomenclature to describe and classify Antarctica's geological map units. We envisage a scheme similar to that recently established for New Zealand (Mortimer et al. 2014) that classifies the entire continent's rock units in hierarchically organised broad groupings and in a geologically concise manner. Such a classification will provide clearer, more efficient and more effective use of stratigraphic names in an Antarctic digital geological map resource. Other issues arising include the need to: (1) use an internationally recognised markup language such as GeoSciML; (2) have metadata to retain history of changes in successive versions; (3) maintain clear distinction between geological (rock deposit) and geomorphological (landform shape) information.

## RESULTS

The new dataset, termed *geo01* is continental-scale dataset that presently contains geological layer attributes for the TAM. The initial, simple geological attribution provides an immediate overview of the nature and composition of the bedrock, and areas of young volcanic and glacial geology in the TAM. Key glacial sequences and cover deposits are represented by 297 polygons which cover an area of 7300 km<sup>2</sup>.

As work continues to complete attributes across the continent, improve definition of geological information within the polygons, and enhance their spatial reliability, the *geo01* data will be shared freely under web map services (WMS), web feature services (WFS) and their source GIS data on request. Metadata will specifically identify version numbers and history of changes.

## CONCLUSIONS

Adopting a "top down" methodology has already enabled development of unified, continent-scale geological information. This can be provided in a timely manner to end-users with the expectation that the quality and reliability of the product will evolve almost continuously throughout the project. Even after the project conclusion the resource could be curated and improved as a living dataset. This approach also highlights a separate need to develop a high-level stratigraphic nomenclature that classifies the entire continent's rock units in broad groupings in a geologically concise manner. There is now a digital geological map resource available that depicts the general location of principal areas of glacial and surficial deposits in the Transantarctic Mountains.



**S26 – 198: General Antarctic Earth Science**

***Seasonal Variation of Surface Electrical Parameters Measured at Maitri and Vostok, Antarctica***

Jeni Victor N<sup>1</sup>; S. Manu<sup>1</sup>; C. Panneerselvam<sup>1</sup>; C. P. Anil Kumar<sup>1</sup>

Equatorial Geophysical Research Laboratory, Tirunelveli (Tamilnadu), India<sup>1</sup>

Atmospheric electrical parameters have been measured more than a decade at the Indian Antarctica station Maitri. This work deals with the analysis of surface electrical parameters during 2006 & 2009 measured at Maitri (70.45° S, 11.2° E, 117 m AMSL) and Vostok (77.56° S, 106° E, 3,523 m AMSL), Antarctica. Daily, seasonal and annual variation of surface electric field and current density at Maitri station are extensively studied and compared with near pole station, Vostok. In this paper we have reported, the peak values of these parameters are synchronized with global lightning activity, with a minimum at 03 UT and a maximum at 17 01UT. Seasonal curves clearly represent the continental behavior in time (UT) scale along with global signature in day scale. Field measured at Maitri during autumn shows African sector peak at 17 UT and Australian sector peak at 06 07 UT in summer. In the case of Vostok, continental signature is not more distinct; Field has a very close pattern with fair-weather field variation in all seasons. Minimum to maximum ratio estimates the amount of current enhanced throughout a day that varies  $70 \pm 15 \%$  at Maitri and  $70 \pm 6 \%$  at Vostok where 70 % is for Carnegie electric field. The signal strength assessed from amplitude ratio is better at Vostok ( $40 \pm 10 \%$ ) than Maitri ( $40 \pm 15 \%$ ), whereas the poor statistical data set provides the ratio less than 30 %. The calculated conductivity from the electrical parameters at Maitri did not show any seasonal trend, and the average value is around  $\sim 1.9 \text{ to } 2.2 \times 10^{14} \text{ S/m}$ . We suggest that the conductivity calculation performed in this work could be followed in the absence of conductivity measurement and annual pattern is derived from the summer measurement at Maitri under careful examination.



**S26 –210: General Antarctic Earth Science**

***Field Aligned Current Study during the Solar Declining Phase of 23 Solar Cycle***

Jeni Victor N<sup>1</sup>, C. Panneerselvam<sup>1</sup>, C. P. Anil Kumar<sup>1</sup>

Equatorial Geophysical Research Laboratory, Tirunelveli (Tamilnadu), India<sup>1</sup>

Field Aligned Current (FAC) density study has been carried out during the solar declining phase in the year 2004 of 23rd solar cycle with the aid of ambient terrestrial magnetic field of the extended minimum period of 2008 and 2009. We mainly depended on CHAMP satellite data (<http://isdc.gfzpotdams.de/>) for computing the FAC density with backup of IGRF10 model. We have statistically studied three geoeffective storms from the year 2004 and observed the FAC peaks around 5560 Mlat during severe storm whereas quiet time the FAC peaks near  $85 \pm 5$  Mlat. FACs densities during storm are  $5 \pm 4$  times of those during quiet period. This study further indicates that, the FAC is controlled by quasiviscous processes occurring at the flank of the earth's magnetosphere. Detailed analysis will be discussed in the symposium.



**S26 –210: General Antarctic Earth Science**

***Antarctica Online: Communicating Antarctic Science with the Public via an Interactive Online Course***

Atkins, C<sup>1</sup>, Priestley, R<sup>1</sup>, Salmon, R<sup>1</sup>

Victoria University of Wellington, New Zealand<sup>1</sup>

In today's fast-media society, it is challenging to find innovative mechanisms to engage society with critical global issues, such as climate change, loss of biodiversity, ocean acidification and the role of science in society. Issues that are all relevant to, and justifications for Antarctic research. Online platforms such as Massive Open Online courses (MOOCs) are one such opportunity that are increasingly being used to engage a larger and broader audience.

Victoria University of Wellington, (VUW) with the support of Antarctica New Zealand has developed a fully online, interactive course available to university students and members of the public. In this digital poster, we present our preliminary experiences exploring scientific and environmental issues, in particular Earth Science and Paleoclimate via an online course filmed predominantly in Antarctica. It utilizes the latest learning management systems to allow participants to watch prerecorded videos, have access to reading material, and engage in asynchronous dialogue via discussion boards, blogs, and wikis. Given the severely limited opportunities to physically take students to Antarctica, offering lectures filmed in Antarctica provides a virtual fieldtrip experience giving students insight into the unique environment and reality of researchers working in remote locations.

The course examines contemporary Antarctic scientific research, placing it in a wider scientific, historical, political, social and cultural context. Students are encouraged to think critically about the value of Antarctic field research and critically examine the different ways that scientists, policymakers, journalists and artists engage with Antarctic science and the Antarctic continent more broadly.

The course capitalizes on resources and staff from the VUW's Antarctic Research Centre, School of Geography, Environment and Earth Sciences, Science in Context group, and School of Design offering a truly interdisciplinary teaching programme. This modular approach "currently offering modules on history, geology and paleoclimate, science and society and creative arts" is being used as a pilot to potentially profile Antarctic research groups internationally, and cover a wide range of topics and issues.

Using this prototype course as a model, we explore opportunities and challenges involved in engaging different audiences with a wide range of critical issues related to Antarctic research, funding, and politics.



**S26 –234: General Antarctic Earth Science**

***Introduction to the Korean Icebreaker, ARAON***

Kim, H.<sup>1</sup>; Hong, J.K.<sup>1</sup>; Jin, Y.K.<sup>1</sup>

Korea Polar Research Institute, Incheon, Korea<sup>1</sup>

In 2009, Korea Polar Research Institute commissioned the first Korean Icebreaker, Araon. ARAON becomes a milestone of Korea polar research history and for producing superior scientific results. In addition to the logistics to the polar stations, ARAON equips geophysical instruments such as multibeam echosounder, 120 channel multichannel seismic system, marine gravity meter, sub-bottom profiler, marine magnetometer, and 30-m long piston corer. Specifications of Araon are, 7487 GRT, accommodation of up to 85, cruising range of 20,000 nautical miles, endurance of 70 days, 31 TEU of 20 feet container capacity, and operation at the sea state of 6. Every year, she sailed over the Arctic Ocean and the Southern Ocean for scientific surveys and logistics. In the Arctic Sea, we collected geophysical data and core samples in the Chukchi Sea, the Beaufort Sea. In the Southern Ocean, we retrieved data in the Weddell Sea, the Amundsen Sea, the Ross Sea.



**S26 –236: General Antarctic Earth Science**

***Review and Application of Needle Ice Creep Models on Sediment Movement, Marion Island, Sub-Antarctic***

Carl-Johan Borg<sup>1</sup>

Department of Geography, Rhodes University, Grahamstown, South Africa<sup>1</sup>

The amount and rates of material transported by needle ice have been modeled for more than 50 years. Nonetheless, results still only show rough estimates and do not accurately match empirical evidence. The uncertainty derived from assumed responsible physical processes such as rolling, toppling and sliding, under the influence of gravity during melt, by environmental properties like topography and wind. Developing reliable needle ice creep models is important in environments where it results in considerable disturbance to ecosystem functioning. The modeling of sub-Antarctic fellfield biogeomorphic systems, and their responses to climate change, require improved modelling of sediment displacement by needle ice. This paper reviews three existing needle ice models (Higashi and Cortes 1972, Mackay and Mathews 1974, and Matsuoka 1998) that incorporate a variety of environmental parameters. The models' performances are tested on sediment transfer data from sub-Antarctic Marion Island to advance our understanding of slope processes and to develop new models that predict sediment movement. Parameters evaluated are heave, slope angle, frequency, and empirically measured displacement, which were recorded on Marion Island between 2007 and 2008.

The discrepancy between the models' predicted displacements and the actual displacement are used to assess their accuracy. An average accuracy of 0.82% is presented by Higashi and Cortes model, 12.52% for Matsuoka's model and 76.4% of movement was explained by Mackay and Mathew's model when inserting Marion Island data. Model accuracy prediction varied considerably when subgrouping into soil texture and slope angle classes suggesting slope and texture as key environmental controls. However, there are clearly additional controls involved. Noteworthy results show that Mackay and Mathew's model tended to overestimate displacement at low slope angles and underestimate displacement on steep slopes suggesting that displacement mechanisms can have critical thresholds.

The existing slope displacement models, therefore, do not incorporate all variables active in predicting needle ice displacement and other mechanical controls, such as wind and bouncing or sliding which add or retard displacement distance. Currently, research using new methodologies are being employed to advance this knowledge.



**S26 –272: General Antarctic Earth Science**

***Review and Application of Needle Ice Creep Models on Sediment Movement, Marion Island, Sub-Antarctic***

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Amount and rates of material transported by needle ice have been modeled for more than 50 years. Nonetheless, results still only show rough estimates and do not accurately match empirical evidence. This uncertainty derives from proposed physical processes such as rolling, toppling and sliding instigated by gravity and influenced locally during melt by environmental properties like topography and wind. Developing reliable needle ice creep models is important in environments where needle ice performs an important disturbance factor in ecosystem functioning. Specifically, modeling of the sub-Antarctic fellfield biogeomorphic system, and its responses to current climate change, require improved modelling capacities of sediment displacement by needle ice. This paper aims to review three existing needle ice models which incorporate different environmental parameters and test their performance on previously unpublished needle ice induced sediment movement data from sub-Antarctic Marion Island. Model performance will be evaluated in order to further develop understanding of sediment movement mechanisms and the development of new models to predict sediment movement. The parameters needed for evaluation are sediment heave, slope angle, frequency, and empirically measured displacement, which were gathered on Marion Island between 2007 and 2008. Aims are to produce a value of accuracy (discrepancy) between the models' predicted displacement and the actual displacement shown in empirical evidence. The end product will be a percentage where 100% would match the empirical evidence perfectly while lower than 100% shows an underestimation by the model, and over 100% an overestimation of predicted movement. Results from data insertion divided by the empirical measurement and the resulting quota multiplied by 100 produces this percentage of difference between the modeled and measured displacement. Further, results sub-grouped into surface texture and slope angle show how environmental parameters influence displacement. Results show average model accuracy of 0.82% of the first model, 12.52% for the second and 76.4% on the last and most accurate model. Subgrouping by soil texture and slope angle had profound impact on model accuracy where for example Model 3 tended to overestimate displacement at low slope angles and underestimate displacement on steep slopes. Conclusions from data insertion show models are currently not incorporating all mechanisms active in producing needle ice displacement and that models need to be expanded to account for environmental parameters like wind and physical processes which add or retard displacement distance. Incorporation of such mechanisms and their responses to environmental factors is thought to improve predicted displacement by needle ice models.



**S26 –293: General Antarctic Earth Science**

***Weathering and geochemical dispersion in Almirantazgo Bay, Crepin point, Machu Picchu Peruvian Antarctic station: preliminary results.***

Cerpa, L.<sup>1</sup>; Morales, M.<sup>1</sup>; Ng, W.<sup>1</sup>; Ramos, D.<sup>1</sup>; Ramos, D.<sup>1</sup>; Masias, P.<sup>1</sup>

INGEMMET Peru, San Borja, Peru<sup>1</sup>

Global climate changes have a significant impact on the fragile ecosystems of Antarctica. These processes involve significant changes since the last glaciations, one product being exposure of areas with fracturing and weathering of rocks in Antarctica. The melting exposed surfaces of rocks, causing its disintegration due to physical or chemical and even organic processes; This decay involves the decomposition of minerals that are susceptible to these changes and tend to form new compounds. Undergoing environmental disturbances because of human disturbance, Antarctica is a suitable place to conduct a study on the geochemical characteristics of all elements present in the soil, which are closely related to the composition of the original rock.

The preliminary reconnaissance and mapping of geological units were defined by Birkenmajer (1980) and subsequent work. Kraus et al., (2010) define regional geochemical characteristics and they related with paleomagnetism studies in across Almirantazgo Bay. Preliminary reconnaissance map in the Peruvian Antarctic Station was conducted by Palacios (1988) in the Antar II expedition; Geomorphological and stratigraphic units present were defined. Subsequent work performed in Crepin Point and vicinity were aimed at establishing the geotechnical characteristics (Fidel, 1991; Guzman, 1999; Pari & Zavala, 2000), mineralogical (Quispesivana, 1995; Aranda, 1997) and paleontological (Romero 2000; Morales 2002) they established and contributed the geological knowledge of Crepin Point. These studies recognized the presence of volcanic rocks, subvolcanic and intrusive nature that arise and are surrounded by glaciers.

The volcanic rocks outcropping in the area are basaltic andesites and andesites. These are intruded by granodioritic intrusive rocks and subvolcanic dikes; both much younger. This process, where a young rock intrudes to an older, generates a chemical change in the contact zone of both bodies (Barnes, 1997). The changes are reflected when the original minerals, rocks both change their chemical composition and crystallizes under other conditions. Additional to this cooling process and product of magma, which produced both as intrusive volcanic rocks, begin to circulate fluids, high temperature, high salinity and saturated silica known under the name of hydrothermal fluid (Hedenquist and Lowenstern 1994) , staying in host rocks through fractures and minerals precipitate to form associations and are commonly called veins. Both processes produce changes in rocks and alteration zones are called. The correct identification and characterization of alteration zones allows us to delineate areas with different geochemical behavior and having major implications in the formation of soils and in the water system around them.

Studies in sediments in Admiralty Bay and around the permanent scientific stations (Santos et al., 2005; Santos et al., 2007; Ribeiro et al, 2011; Sun et al, 2003) show concentration of As, Cd, Cr, Cu, Ni, Pb and Zn; which are associated, probably permanent human activity in these sectors. However the Antarctic Scientific Machu Picchu station is occupied temporarily during the austral summer, which significantly reduces the influence of human beings on the environment.

During the expedition Antar XXII (2013-2014) and Antar XXIII (2014-2015) geological mapping of a sector Crepin Point were conducted and maps were upgraded, further representative samples of stratigraphic units in the area and some surrounding areas to Machu Picchu Scientific Station were taken; where anomalous values of Cu, Mn, As, etc. detected, however spatial distribution of the elements of this area is yet to be defined, which is included the current work for this year.



**S26 –296: General Antarctic Earth Science**

***TECTONICS APPROACH FROM MASS TRANSPORT DEPOSITS ANALYSIS: THE SCOTIA-ANTARCTIC PLATE BOUNDARY.***

Lara F. Pérez<sup>1</sup>; Fernando Bohoyo<sup>2</sup>; David Casas<sup>2</sup>; F. Javier Hernández-Molina<sup>3</sup>; Jesus Galindo-Zaldívar<sup>4,5</sup>; Andrés Maldonado<sup>5</sup>; Patricia Ruano<sup>5</sup>

Geological Survey of Denmark and Greenland (GEUS), Copenhagen, Denmark<sup>1</sup>; Instituto Geológico y Minero de España (IGME), Madrid, Spain<sup>2</sup>; Royal Holloway University of London (RHUL)<sup>3</sup>; University of Granada, Spain<sup>4</sup>; Instituto Andaluz de Ciencias de la Tierra (CSIC-UGR), Granada, Spain<sup>5</sup>

Global climate changes have a significant impact on the fragile ecosystems of Antarctica. These processes involve significant changes since the last glaciations, one product being exposure of areas with fracturing and weathering of rocks in Antarctica. The melting exposed surfaces of rocks, causing its disintegration due to physical or chemical and even organic processes; This decay involves the decomposition of minerals that are susceptible to these changes and tend to form new compounds. Undergoing environmental disturbances because of human disturbance, Antarctica is a suitable place to conduct a study on the geochemical characteristics of all elements present in the soil, which are closely related to the composition of the original rock.

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## XII International Symposium on Antarctic Earth Sciences

13 - 17 July 2015, Goa, India



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**S26 –303: General Antarctic Earth Science**

***RISAT-1 C-BAND DUAL POLARIMETRIC SAR IMAGERY FOR CLASSIFICATION OF CRYOSPHERIC FEATURES IN ANTARCTIC ENVIRONMENT***

Satej Panditrao<sup>1</sup>; Alvarinho Luis<sup>2</sup>; Shridhar Jawa<sup>2</sup>

Indian National Centre for Ocean Information Services, Hyderabad, India<sup>1</sup>; National Centre for Antarctic and Ocean Research, Goa, India<sup>2</sup>

Land cover classification is one of the widely used applications in the field of remote sensing. Accurate land cover maps derived from remotely sensed data is the major requirement for many geoscientific applications in Polar regions. The present study explores the capabilities of C-band dual polarimetric (HH & HV) level-1 SAR image data from Radar Imaging Satellite (RISAT-1) for land cover feature mapping around Larsemann Hills and Schirmacher oasis, Antarctica. We used RISAT-1 Fine Resolution STRIPMAP (FRS-1) mode data having 3 m spatial resolution. In order to increase the amount of information in dual polarized RISAT SAR data, a band HH+HV was introduced to make use of the original two polarizations. Transformed divergence (TD) procedure for class separability analysis was performed to evaluate the quality of the statistics prior to image classification along with data calibration. For most of the class pairs the TD values were comparative, which indicates that the classes have good separability. Non-parametric classifier Support Vector Machine (SVM) was used to classify RISAT-1 data with optimized polarization combination into three land cover classes consisting of sea ice/snow/ice, rocks/landmass, and lakes/waterbodies. This study demonstrates that C-band FRS-1 image mode data from RISAT-1 mission can be exploited to identify, map and monitor land cover features in the Polar regions, even in dark winter period. The final results will be presented during the conference based on the backscattered information which is crucial in discriminating and delineating the landcover features.



## S26 – 311: General Antarctic Earth Science

### **Study on Aerosol, Solar Radiation Properties and its Influence on Antarctica**

V.E.Nethaji Mariappan<sup>1</sup>; T. Manjunath<sup>2</sup>

Scientist-F, Centre for Remote Sensing and Geoinformatics, Sathyabama University, Chennai, India<sup>1</sup>;  
Scientist-C, Space Technology Cell, Sathyabama University, Chennai, India<sup>2</sup>

Aerosols affect both directly and indirectly the Earth's radiation budget and climate. As direct effect aerosols scatter sunlight directly back into space. An indirect effect, aerosols in the lower atmosphere can modify the size of the cloud particles, changing how the cloud reflect and absorb sunlight and thereby affecting Earth's energy budget. An increase in Solar Radiation under cloudy conditions has also been reported by Tsubo and Walker (2005). Studies revealed that atmospheric parameters such as water vapor and cloud cover have the greatest influence on the Solar Radiation, followed by dust and aerosol effects (Alados *et al.*, 1996. The ratio increases as sky condition changes from clear to overcast and with the increase of water vapor (Jacovides *et al.*, 2003). Similarly SR reached its highest value during sunset and sunrise, and decreased to the lowest value around noon in central Nigeria (Udo and Aro, 1999); in Beijing (Hu *et al.*, 2007), and in Naeba Mountain, Japan (Wang *et al.*, 2007). Solar radiation changes are probably because of increases in anthropogenic aerosols affecting atmospheric and cloud optical properties, and they could have substantial direct effects on plant growth (Stanhill & Cohen, 2001).

Regular monitoring of Solar Radiation, aerosol content, and wind profile for a polar region will give an idea about the spatial-temporal distribution of all the parameters in a polar region. The consequences of the aerosol content along with solar radiation can be studied in details with the available dataset on the flora. Although many studies were conducted in the past on aerosol the Polar Regions none have been linked to wind profile and its ability to disperse them. The following instruments are planned to be used in the study of aerosol in polar region especially in Antarctica.

**Photometer** is used to analyse aerosol content of the atmosphere for a given duration. The parameter such as aerosol is continuously monitored at frequent intervals. Such data set are collected and shall be analysed at a later stage. **Net Radiation Analyser** is used to monitor incoming and diffuse radiation at frequent interval for the day time during study period. This radiation levels such are stored in a temporary storage device. Those data were sorted and analysed for variations for radiation budget. **Sound Detection and Ranging SODAR** : Equipment will be deployed in a given study site, which will measure the wind profile up to a height of 2 km for every six seconds. In addition data on albedo, aerosol could be derived through this data set. Data collected from various instruments shall be assimilated for analysis.

Wind profile is used as a baseline data for our study. This data provides information on temporal and spatial distribution of wind velocity. Coupled with aerosol data derived from photometer may provide dispersion rate of aerosol over the study area. Net Radiation Analyser will provide data on incoming and diffuse radiation over a given time in a given location. This data will also be combined with aerosol data to understand the atmospheric transport phenomenon in polar region. It is anticipated that a proper link can be established with aerosol dispersion rate and solar radiation to growth of flora in the Polar Regions.

Key Words: Aerosol, Solar Radiation, SODAR, wind profile, flora



**S26 –339: General Antarctic Earth Science**

***Tectonocstratigraphic, Palaeogeography and Amalgamation of Sumatra Terranes, Southeast Part of Asian Terranes, Indonesia***

Ipranta<sup>1</sup>; Andi Mangga S.<sup>1</sup>

Geological Survey Center, Jalan Diponegoro nomor 57, Bandung, 40122, Indonesia<sup>1</sup>

The geological, palaeomagnetic, geochemical and geophysical investigation in the Sumatra Region has yielded some new data, has stimulated a re-assessment of stratigraphy, structure, tectonic evolution and which can show a Sumatra geodynamic model. Sumatra Island has in the margin of southwest part of the Eurasia plate in the Sundaland cratonic block and occurred as the amalgamation of allochthonous microplates, continental fragments, Island arc and accretionary by foreland complex which assembled prior to Tertiary. The allochthonous rocks (terrane) are derived from Gondwana land and Cathaysian (Eurasia land), can be divided into four Terranes with Paleozoic to Mesozoic in age, had different origin, lithology and are separated by a suture as main fault with trending NW-SE.

The terranes are: the Bohorok Tigapuluh (East Sumatra/Sibumasu/Sinoburmalaya/West Malaya) terranes, is characterized by the rock types formed Permo-Carboniferous pebbly mudstone/diamictite of marine glacial or fluvio glacial origin, occupied in the Eastern part of Sumatra, the paleomagnetic data should to have lain 41° south, adjacent to or part of NW Australia. Tanjung Karang Gunung Kasih Terrane, is composed of pre-Carboniferous higher metamorphic and sedimentary rocks, occupied in the Southern part of Sumatra, the paleomagnetic data shown 19° North. The KluetKuantan (West Sumatra/East Malaya/Indochina) terranes is occupied by metamorphic, sedimentary and volcanic rocks of Paleozoic-Mesozoic (Carboniferous-Triassic) in age, contains a Cathaysian flora. The terrane occurred in the western part of Sumatra. The major and trace element characteristic indicate that volcanic rocks were related to a subduction process, the paleomagnetic measurement indicate paleo latitude of 30°-24° north, it is shown that during late Paleozoic times Cathaysia was par remove from Gondwana land. In the Late Permian Early Triassic times the Bohorok-Tiga puluh terrane have moved northward nearer to Palaeo equator and collided/amalgamated with the Kluet-Kuantan terrane. They are separated by alone the transcurrent strike-slip fault (the East Sumatra Fault Zones/the Middle Sumatra tectonic Zones) in the Late Triassic to form Palaeo /Proto Sundaland. The SikulehGarba (Woyla) Terrane, consists of the Mesozoic of oceanic island arc, accretionary complex, foreland sequences and plutonic volcanic arc, the paleomagnetic data shown 30°- 31° south (Gondwana land). In the Late Cretaceous-Early Tertiary times Palaeo Sundaland (terrane assemblage) collided with Woyla terrane by West Sumatra/Sumatra Fault Zones). In this time all these terranes have been amalgamated to form Sumatra Island.



**S26 –384: General Antarctic Earth Science**

***A Physical and Chemical Chemical Coupling between the Stratosphere and Troposphere: A Plausible Mechanism to Understand the Solar-Terrestrial Weather Relationship***

K. Jeeva<sup>1</sup>; Tiwari A. K<sup>2</sup>, Behera .J. K<sup>3</sup>; Gurubaran. S<sup>3</sup>; Mala Baggia<sup>3</sup>; Sinha A.K<sup>3</sup>

Equatorial Geophysical Research Laboratory, Indian Institute of Geomagnetism, Krishnapuram, Tirunelveli, Tamilnadu, India<sup>1</sup>; National Centre for Antarctic and Ocean Research, Vasco-de-gama, Goa India<sup>2</sup>; Indian Institute of Geomagnetism, New Panvel, Navi Mumbai, India<sup>3</sup>

The Physics of solar terrestrial and climatological changes and their relations has been a subject of discussion nearly for a couple of centuries. We are not much closer to a resolution of this important issue when we were more than a century ago, and the words of the eminent American astronaut, Charles Young, made in 1881 seems to be applicable even in the present era. The excerpt is “It seems pretty clear that we are not in a position yet to decide the question either way (relationship is there or not), it will take a much longer period of observations, and observations conducted with special reference to subject of inquiry to settle it”. Most of the work done in this area mainly deals with the correlations between the sunspot numbers and the climatological features. To the best of the knowledge of the authors there is no any concrete evidence to link any individual space weather event with atmospheric weather parameters. This implies that there may not be a direct link to cause the changes in the weather parameters but may be an indirect link affecting different regions of the atmosphere causing a cascade effects and this may take considerable amount of time from weeks to months. This invites a serious attention of the scientific community to look into the weather parameters with a unique approach involving multi disciplinary experiments and studies.

Solar activity in the form of energetic particle precipitation, during the geomagnetic storms, is known to impact the chemical balance of the middle atmosphere. In recent years many studies indicated a link from the middle atmosphere to stratosphere and surface of the earth and explained the chemical link from the initial chemical changes to modulation of the polar surface temperature during the northern hemisphere winter months [Rozonov *et al* 2005, Baumgaertner *et. al*; 2011, Seppala *et. al*. 2013]. In the present work we try to link the chemical coupling further downward and its role on the variability of the surface temperature.

In the present work we consider the descending of the Nitrogen Oxides, probably from the stratosphere, and their role in modifying the surface temperature observed over at Maitri, Antarctica. The NO<sub>x</sub> we refer may be produced by the impact of the charged particles from the solar activity or transported to the polar region through the General Circulation of the atmosphere. Besides noticing the change in the temperature at the surface level during the descending of NO<sub>x</sub> enhancement we observed changes in the atmospheric electricity parameters also. This suggests that there are multiple reactions in the atmosphere during the enhancement of NO<sub>x</sub> at the surface level particularly when it descends from the stratosphere. The results are discussed in terms of the reaction of the NO<sub>x</sub> with the Volatile Organic Compounds (VOC) and the possibility of enhancement in the fine aerosols of the atmosphere to reduce the electrical conductivity followed by a raise in the potential gradient and a decrease in the air-Earth current density.

The present work provides a unique approach to understand the relationship incorporating various domains of physical and chemical reactions of the atmosphere and presenting a few results to substantiate the proposed mechanism. The approach is clearly shown in fig 1. The results presented in this work involves various experiments conducted at Maitri, like, atmospheric electricity parameters, Nitrogen Oxides (NO<sub>x</sub>), meteorological parameters obtained from three different locations spread over about 5km<sup>2</sup>. The descending of the Nitrogen oxides from the upper atmosphere is considered here as a source for the enhancement of the surface temperature.



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(Key words: Global Electric Circuit parameters, global circulation pattern, Polar vortex, global thunderstorm activity, Nitrogen Oxides ( $\text{NO}_x$ ), ozone depletion)



**S26 –385: General Antarctic Earth Science**

***Peculiarities in the Diurnal Variation of Air-Earth Current Density and Potential Gradient Observed at Maitri, Antarctica***

K. Jeeva<sup>1</sup>; Gurubaran S<sup>1</sup>; Williams E<sup>2</sup>; Guha A<sup>3</sup>; Sinha A.K<sup>1</sup>; Selvaraj C<sup>4</sup>; Nair K.U<sup>4</sup>; Dhar A<sup>1</sup>

Indian Institute of Geomagnetism<sup>1</sup>, Department Of Civil and Environmental Engineering, Massachusetts Institute of Technology<sup>2</sup>, Department Of Physics, Tripura University<sup>3</sup>, Equatorial Geophysical Research Laboratory, Indian Institute Of Geomagnetism, Krishnapuram<sup>4</sup>

The monitoring of the atmospheric electricity parameters over the ocean, during the Carnegie expedition (1915-1928), proved to be uncontaminated as the ocean surface is nearly free from the meteorological processes, and radioactivity sources [Whipple and Scrase, 1936]. Furthermore aerosol concentrations are markedly reduced in comparison to the situation over land. Suggestions were made to monitor the fair-weather global signature of the electrical parameters from the remote continent, Antarctica, for the reasons i) the weather, for nearly 70% of the time, remains clear ii) high surface winds which generally prevail over other parts of the world generate mechanical turbulence by friction with rough bare ground and can make electrode effect almost nonexistent or very much reduced in comparison with that over sheets of ice iii) deep temperature inversions suppress the local atmospheric convection. Unfortunately the diurnal patterns of the Air-Earth current density (AEC) and potential gradient (PG) observed over Maitri, ever since the first measurement in 1997, have been showing varied diurnal patterns. Many of them are a different pattern to that of the Carnegie curve pattern which serves as de facto standard for ground measurements. While the stations Vostok, Amundsen and Scott, situated over the polar plateau, showed the diurnal variation of PG similar to 'Carnegie curve' the coastal Antarctic stations like Syowa [Davis Burns et al., 1995] and Maitri [Jeeva et al., 2011] displayed quiet varied diurnal characteristics. It appears to us that the fair-weather electrical phenomenon over Maitri or coastal Antarctic regions need to be classified under two broad categories namely large scale phenomena caused by the global thunderstorm activities and small scale activities like perturbation in the electric field and Air-Earth current density probably due to variability in the density of ions and aerosols.

The scope of this work is to provide a convincing mechanism that operates over Maitri (70° 45' 52" S, 11° 44' 03" E, 117m AMSL) to produce peculiar diurnal pattern of the Potential Gradient (PG) and Air-Earth current (AEC). We understand that the authors worked in the atmospheric electricity parameters used data for a very limited and short period. We are using the long term data of air earth current density and potential gradient from the year 2005-2014. The diurnal pattern of the AEC and PG show a peculiar pattern. The peculiar pattern is an ostensible minimum at about the local noon hours and a diminished response to the thunderstorm over Africa. It appears to us that the fair-weather electrical phenomenon over Maitri or coastal Antarctic regions can be classified under two broad categories namely large scale phenomena caused by the global thunderstorm activities and small scale activities like perturbation in the electric field and Air-Earth current density probably due to variability in the density of ions and aerosols. We attempt to explain the causes behind such varied diurnal patterns using the ubiquitous characteristics of the continent like katabatic winds, sublimation and the melting of ice and snow. Emphasis has been given to the thunderstorm activity over the Maritime continent during the austral summer.

**Keywords:** Air-Earth current density, potential gradient, Carnegie curve, Maritime continent, sublimation, katabatic winds, Antarctic polar plateau.



**S26 –427: General Antarctic Earth Science**

***Bathymetry as a Control on Surface Sediment Distribution within Fjords and Implications for Paleoenvironmental Interpretations: An Example from Flandres Bay and Vicinity, Antarctic Peninsula***

Julia Wellner<sup>1</sup>; Yuribia Munoz<sup>1</sup>

University Of Houston, U.S.A<sup>1</sup>

We have analyzed surface sediment and its distribution in Flandres Bay, and Etienne Fjord within the bay, located on the Antarctic Peninsula, in order to understand modern day sediment dispersal patterns in a fjord with a retreating, tidewater glacier. The surface sediment characteristics of 43 cores are included in this study to create a map of sediment distribution in the bay. Sediments within the fjord vary from mud to pebbly mud with varying amounts of biogenic influence. The basins in the inner and outer bay are covered by muddy diatomaceous ooze and diatomaceous mud. Scattered pebbles are present in most samples throughout the bay. In contrast to a simple model of glacial sediment distribution, grain size generally coarsens from the inner to outer portions of Flandres Bay. The finest sediments were found in the proximal portion of Etienne Fjord and are interpreted as fine-grained deposits resulting from meltwater plumes and sediment gravity flows occurring close to the glacier front. The middle of the bay is characterized by a high percentage of silt-sized particles, partially due to a high percentage of diatoms that are included in basic grain size measurements. In the outer bay, sandy to pebbly sediments were found. Because this is a semi-open area, these sediments are likely lag deposits resulting from currents moving from the Bellingshausen Sea into the Gerlache Strait. Paleoenvironmental reconstructions of glacial environments often use grain size as an indicator of proximity to the ice margin. After a detailed analysis of a large number of cores collected in the area, our findings of the most fine-grained deposits in the proximal setting in a modern fjord setting, highlight the variability in sedimentation patterns within a fjord and thus are a reminder of the complexity that may occur downcore and thus in interpretations of past environments. We interpret this pattern to be due to the irregular bathymetry of the fjord, limiting dispersal paths along the sea floor, and to the rapid sedimentation occurring along the margin of currently retreating glaciers.



**S26 –453: General Antarctic Earth Science**

***Multibeam Bathymetry Compilation of the Drake Passage (Antarctica-South America): Batdrake V1.0***

Fernando Bohoyo<sup>1</sup>; R. D. Larter<sup>2</sup>; P. T. Leat<sup>2</sup>; A.J. Tate<sup>2</sup>; E. J. M. Gowland<sup>2</sup>; J. Galindo-Zaldivar<sup>3</sup>; A. Maldonado<sup>4</sup>; M. Flexas<sup>5</sup>; J. E. Arndt<sup>6</sup>; Dr. B. Dorschel<sup>6</sup>; Y.D. Kim<sup>7</sup>; J.K. Hong<sup>7</sup>; J. Lopez-Martinez<sup>8</sup>; A. Maestro<sup>9</sup>; O. Bermudez<sup>9</sup>; F. Nitsche<sup>10</sup>

Instituto Geológico y Minero de España<sup>1</sup>; British Antarctic Survey<sup>2</sup>; Departamento De Geodinámica, Universidad De Granada<sup>3</sup>; A. Maldonado<sup>4</sup>; Oak Grove Drive. Pasadena<sup>5</sup>; Alfred Wegener Institute<sup>6</sup>; Korea Polar Research Institute<sup>7</sup>; Departamento De Geológicas y Geodinámica, Universidad Autónoma De Madrid<sup>8</sup>; Instituto Geológico y Minero De España, Rios Rosas<sup>9</sup>; Lamont-Doherty Earth Observatory, Columbia University<sup>10</sup>

The opening of the main southern oceanic gateways, Drake Passage and Tasman Strait, permitted the modern pattern of global ocean circulation to be established. This allowed extensive exchange of water between the main ocean basins and led to the development of the Antarctic Circumpolar Current (ACC), which caused the thermal isolation of Antarctica, and was partially responsible for global cooling at the Eocene-Oligocene boundary. These gateway openings were important tectonic events involving complex geological process such as continental fragmentation, development of oceanic basins and rifting of continental blocks. As a consequence of this and the subsequent submarine processes, these areas show a varied physiography, in particular the Drake Passage which is the object of this work.

A compilation of precise multibeam bathymetric data obtained on cruises from the period between 1992 and 2014 in the Drake Passage region has been carried out covering the area between parallels 52°S and 63°S and meridians 70°W and 50°W. This first version of the compilation constitutes an international cooperative effort coordinated by the Spanish Geological Survey (IGME), the British Antarctic Survey (BAS), the Alfred Wegener Institute (AWI) and the Korean Polar Research Institute (KOPRI), together with data from the USA available from the Marine Geoscience Data System hosted by Lamont-Doherty Earth Observatory (LDEO).

Contributed data sets were cleaned individually, transformed into a generic ASCII XYZ data format and reprocessed to remove artefacts. The remove-restore IBCSO standard method has been used to retain details of the sea floor morphology where data density and quality is sufficient and this method at the same time prevents the occurrence of artifacts in areas with sparse data. The GEBCO14 dataset, including IBCSO v1.0, was used in order to fill gaps in the coverage. A resolution of 200 m x 200 m has been determined as optimal taking into account depths, acquisition swath systems and final objective of the project.

This new detailed mapping with a 200 m cell resolution of the sea floor in Drake Passage permits identification of the main physiographic features, which are related to the tectonic evolution and the dynamic processes of deep oceanic currents. Seafloor topography in the region is an important boundary condition for high-resolution ocean circulation models and also provides constraints on stress field models for the initiation of Drake Passage opening. Seafloor digital elevation models are also very important in scientific areas such as physical oceanography and marine biology. Next developments of this work will be finishing seafloor feature cartography and digital elevation models and maps, and making the data available from IGME and BAS web servers.

This initiative is part of IBCSO (International Bathymetric Chart of the Southern Ocean), under the SCAR umbrella, which recognizes the importance of regional data compilations in areas of particular scientific interest in the Antarctic, such as the Ross Sea, Drake Passage and the southern margin of the Weddell Sea.



**S26 –487: General Antarctic Earth Science**

***Deriving Sea Ice Parameters using Satellite Data to Support Ship Navigation during Antarctic Expeditions***

Rajak D. Ram<sup>1</sup>; P. Jayaprasad<sup>1</sup>; Singh R.K. Kamaljit<sup>1</sup>; Oza Sandip R.<sup>1</sup>; Beg Javed M<sup>2</sup>; Sharma Rashmi<sup>1</sup>; Raj Kumar<sup>1</sup>

Space Applications Centre, Ahmedabad, Gujarat India<sup>1</sup>; National Centre for Antarctic and Ocean Research (NCAOR) Vasco da Gama, Goa , India<sup>2</sup>

A technique which is developed for monitoring sea ice and deriving sea ice information needed for providing sea ice advisory to Indian Antarctic Expeditions has been described. Safe ship navigation depends on a number of factors related to sea state, weather condition, and ships own characteristics. The ship routing for a scientific expedition may differ a lot than that for a cargo ship and is a little more complicated due to an additional factor of achieving scientific objectives. Navigation in Polar Regions through sea ice being perhaps most tedious task requires complete information on sea ice condition. Continuous processes of sea ice melting, freezing and drifting warrants near real time information on sea ice condition. Sea ice causes retardation in ship speed due to friction. It varies in lateral extent and thickness which depends mainly on geographical position and host of whether parameters. At times, when sea ice thickness is greater than the ships capability to break or cut through results in ships getting stuck and being crushed under the formidable pressure that sea ice can exert because of the ocean currents or volumetric expansion due to cooling temperatures. Conventional ship routing does not provide adequate real time information on sea ice status. The availability of remote sensing data over ocean and polar regions offers opportunities to derive near real time information needed for ship routing. Satellite based remotely sensed data are the only source of monitoring sea ice at synoptic scale with high temporal frequency.

The technique makes use of multi-satellite data and products in optical as well as microwave regions of electromagnetic spectrum. The information is obtained from the analysis of data and products at different spatial resolutions ranging from 5.8 m to 3.125 km (sea ice products). The primary sea ice parameters which affect sailing of ship through sea ice include sea ice concentration, thickness, type, deformations, drift etc. While Resourcesat2 LISSIV data at 5.8m provides the finer details of sea ice during cloud free atmospheric conditions, RISAT1 SAR at 25 / 50 m provides sea ice features unaffected by cloudy atmosphere. Mosaic images prepared from Cloud free Resources at 2 AWiFS and MODIS (Terra and Aqua) data presents panoramic/synoptic coverage of sea ice status over large area. Temporal MODIS / AWiFS data is analyzed to monitor changing sea ice scenario, to estimate sea ice drift, to quantify fast ice near Antarctic Coast, to calculate large icebergs movements etc. Sea ice concentration data product available at 3.125km was used in this study. The information derived from the analysis of different satellites datasets along with predictions about weather parameters are used to provide sea ice advisory.

This technique has been used to provide sea ice advisories to 32nd, 33rd and 34th Indian Scientific Expeditions to Antarctica (ISEA). The Sea Ice Advisories were found useful during voyage ship sailing and were appreciated by the Voyage Leaders and Ship Captains. Overall, the ship routes to sail through sea ice suggested during these expeditions were followed and found safe. Details on techniques of information derivation, integration with predictions and suggested routes to reach/exit to/from Bharati and Maitri regions of Antarctic coast will be presented in the symposium



**S26 –512: General Antarctic Earth Science**

***Taphonomy of Shell Beds from the La Meseta Formation (Eocene, Seymour Island), Antarctica***

Fernanda Quaglio<sup>1</sup>; Warren L<sup>2</sup>; Reguero M<sup>3</sup>; Podesta F<sup>4</sup>; Perinotto JAJ<sup>2</sup>

Universidade Estadual Paulista<sup>1</sup>; Instituto de Geociências e Ciências Exactas, Universidade Estadual Paulista<sup>2</sup>; Instituto Antártico Argentino<sup>3</sup>; Facultad de Ciencias Exactas y Naturales, Universidad De Buenos Aires<sup>4</sup>

Seymour Island (Antarctic Peninsula) is the single place in Antarctica preserving rocks from nearly all Eocene Epoch and represents a critical geological record just before the onset of icehouse conditions in the Paleogene. The northern half of the island exposes the shallow marine deposits of the La Meseta Formation, which is composed of sandstones and secondary mudstones with several shell beds rich in benthic invertebrates and vertebrate remains. Stratigraphic studies interpret the unit as a shallow marine succession deposited in a context of incised valley compound fill in a shelf estuarine and tidal setting with depositional architecture controlled by oscillations in the eustasy or also tectonics. Available ages range from 52 Ma to 33.6348 Ma, indicating that the unit spanned the whole Eocene and reached the very early Oligocene. Despite of some important taxonomic works both on vertebrate and invertebrate groups, the shell beds were never approached taphonomically. Detailed studies of taphonomic signatures are important to access controls external to original living biotic characteristics and permit interpretations on evolutionary, paleoecological and sedimentological data from the last global greenhouse to icehouse transition. A first step of taphonomic analysis is being conducted in order to differentiate in detail depositional settings of the shell beds preserved in the unit. Data available so far include five bivalve rich shell beds in the northwestern portion of the Seymour/Marambio Island, from middle stratigraphic levels of the La Meseta Formation (Campamento, Cucullaea I and II Allomembers, or Telms 36), positioned at the allomembers limits. The shellbeds show erosive base and tabular to lenticular geometry, with lateral extension varying from few to dozens of meters. Each shell bed level is composed of medium to coarse sandstones and gravelly sandstones with clasts ranging from granules to pebbles. Beds are commonly decimeter thick (2570cm), with uppermost shell beds reaching 1.52 meters in thickness (as in the case of Cucullaea II Allomember shell beds), some of them showing fining upward pattern. Taxonomically the studied beds preserve both invertebrate and vertebrate remains (although other shell bed sites preserve apparently monospecific gastropods and bivalves). Molluscs are the most abundant group in the studied sites. Bivalves are represented mainly by arcoids, mytiloids, veneroids and myoids, with cucullaeids and venerids the most abundant families. Gastropod family representatives are mainly trochoids, cerithioids, epitonioids, stromboids, naticoids, buccinoids, conoids and acteonoids. Brachiopod specimens so far identified include terebratulids of the species *Bouchardia Antarctica* Buckman. Although not as frequent as invertebrates, wood fragments and vertebrate remains (including shark teeth and bird bone fragments) were also found. Taphonomic signatures studied so far indicate bioclasts with low to very low fragmentation. In the case of bivalves, which are the most common bioclast, there is no predominance of right or left valves, which are generally convexup orientated. The taxonomic composition show a tendency of richness increase towards the younger shell beds. The high richness in the studied shell beds suggests distinct small scale ecological niches developed during La Meseta deposition times, which is consistent with a transgressive estuarine setting. One of the analyzed shell beds show a different set of taphonomic signatures, as a greater variation of the bioclast sizes, many of them obliquely or perpendicular oriented to the bedding plane, including stacked and nested bivalve shells. This bed occurs in the middle portion of the unit (Cucullaea I Allomember) and includes elongated and rounded intraclasts and concretions. These features suggest that this shell bed was deposited in a distinct sedimentologic context than the other studied beds, with typical signatures of high energy settings, as those related to reworking by currents or storms. The other shell beds, however, exhibit overall patterns of taphonomic signatures, geometries as well as sedimentary facies suggestive of no significant reworking. Also, the presence of unfragmented bioclasts with different size classes and preserved in amalgamated pavement suggests low reworking (by waves or currents). These are similar to residual lag deposits in which clasts



are concentrated by winnowing, which points to paraautochthonous or even autochthonous assemblages. The apparent repeated stratigraphic occurrence of shell bed levels at the base of allomembers reinforces the interpretation of transgressive residual lags. These deposits are often developed during retrograding cycles associated to incised valley filling, when the rate of sea level rise is accelerating at final stages of low stand system tracts. This suggests that the sea level would have exerted a greater role in the basin deposition than tectonics. However, this hypothesis is only tentative and will be confirmed after inclusion of additional taphonomic signatures from other shell bed levels.