The 12th Seoul International Symposium on Polar Sciences

EXPLORATIONS OF THE POLAR SEAS

May 17-19, 2005
KOPRI, Ansan, Korea

Editors: Yeadong Kim
Minkyu Park
Seong-Joong Kim

Organized by Korea Polar Research Institute (KOPRI), KORDI
Sponsored by Ministry of Maritime Affairs and Fisheries
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PREFACE

Dear Participants,

There have been rapid expansion and evolution in polar researches for the past few decades. The polar region is certainly an intriguing place to discover many respects of scientific features. The polar region plays an important role in driving and indicating global change, and undoubtedly they provide a unique opportunity as a test bed of critical hypotheses and theories. Polar sciences do not end in basic aspects but also include the potential from the least explored resources that the polar region harbors. A good science, particularly in the polar region, can be achieved when our research is conducted across various levels and across the border truly in an interdisciplinary fashion. In this respect, I believe our 12th Seoul International Symposium on Polar Sciences is a valuable forum of exchanging information and ideas, and this year’s theme, 'Explorations of the polar seas', is well set and timely.

I sincerely welcome all of you and I urge you to share your knowledge with others via vigorous discussions throughout the Symposium.

Thank you.

May 17, 2005

Dr. Yeadong Kim
Director-General, Korea Polar Research Institute (KOPRI)
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Tectonic and Volcanic Systems

in the Polar Seas:

Explorations and Observations

of Active Seafloor Processes
KEYNOTE LECTURE:
MAPPING AND SAMPLING GAKKEL RIDGE: AMORE AND BEYOND

Peter J. Michael¹, Charles Langmuir², Henry Dick³, David Graham⁴, Steven Goldstein⁵, Jonathan Snow⁶, Jörn Thiede⁷ and Wilfried Jokat⁷

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INTRODUCTION

In the last few years, marine geology in the polar Arctic has blossomed, promoted by international co-operation that has launched expeditions with multiple icebreakers designed or outfitted for scientific research. The Arctic Mid-Ocean Ridge Expedition (AMORE 2001) was a nine week, international voyage involving two icebreakers: the highly accomplished PFS Polarstern, from the Alfred Wegener Institute in Bremerhaven, Germany, and the new U.S. icebreaker, USCGC Healy. It was Healy’s maiden scientific voyage, and she was an excellent icebreaker and scientific platform. AMORE 2001 took place after nearly a decade of planning. At InterRIDGE workshops in 1991, 1994 and 1998, Gakkel Ridge was identified as a spreading center of great interest, scientific goals were outlined and field program needs were described. It was determined that a two ship program would be necessary, but there was a limited number of polar class, scientific icebreakers worldwide. The commissioning of U.S.C.G.C. Healy was one of the driving forces for AMORE 2001. The historic expedition exceeded expectations and went beyond the goals set forth by InterRidge in charting and sampling Gakkel Ridge. The expedition was guided in part by bathymetric charts made by a nuclear-powered submarine during the SCICEX program in 1998 and 1999 (Cochran et al., 2003). Well-navigated aeromagnetic and aerogravity charts (Brozena et al., 2003) also aided in locating the axis.
POLAR OPERATIONS

Bathymetric mapping - Surprisingly, the ships' bottom mapping sonar systems (Seabeam 2112 on Healy and Hydrosweep on Polarstern) were able to generate superb maps of the seafloor even while the ships were breaking ice. The surveyed region covers ~1000 km of the axis from 8°W (Lena Trough) to 88°E, providing the first data for the western Gakkel Ridge. The high resolution of these data reveals geologic detail critical to understanding the segmentation and volcanic and tectonic processes of this ultra-slow spreading MOR. Precise navigation will allow future expeditions to return to targets.

Rock sampling - Rock samples were recovered from > 200 sites along the axis and flanks of Gakkel Ridge, mostly by dredging. After a steep learning curve, the success rate for dredging was high. Flexibility in choosing targets was important because it was necessary to exploit leads through the ice pack, taking into account ice drift velocities. In addition to dredges on both ships, USCGC Healy employed wax cores and PFS Polarstern had a TV-Grab. These methods required less open water. Because the cruise track encompassed a double-pass along most of the ridge, onboard geochemical analysis was used to guide additional sampling on the second pass.

Hydrothermal prospecting - Miniature Autonomous Plume Recorders (MAPRs) were used on most dredges and rock cores to identify and map hydrothermal plumes. Using these data, CTD/rosette deployments were run at six stations. Plume water samples were collected for Mn, methane, and 3He to confirm the hydrothermal nature of the light scattering anomalies and provide some estimate of source strength. Unweathered hydrothermal sulfide chimneys were dredged at one site.

Seismic Reflection and Refraction. To determine the crustal structure of the Eurasian Basin north and south of Gakkel Ridge, two long seismic reflection transects in Amundsen and Nansen basins were acquired. In addition, 36 sonobuoys were deployed to provide sediment and crustal velocities for a depth conversion of seismic data. The excellent data allowed clear imaging of the oceanic basement. The sonobuoys provided signals from deeper levels of the oceanic crust and in a few cases, signals from the Moho are visible. This allowed a minimum estimate of the crustal thickness. Refraction profiles were run to investigate the crustal thickness along the rift valley. In case of reverse shooting at maximum two seismic data acquisition units were deployed on ice floes to record the airgun signals. During profiling, USGCC Healy led the convoy, while RV Polarstern towed an airgun array. Crustal thickness was measured at 18 different locations. Most of the record sections show clear Pn arrivals from the crust/mantle boundaries with velocities between 7.8 and 7.9 km/s.

Additional geophysical experiments. High-quality helicopter-based magnetic data were gathered for prominent bathymetric features with a line spacing of 2 km across the ridge.
Thirty eight heat flow measurements were made at fourteen stations along the rift valley, and seven along an off-axis transect into the Amundsen Basin. Parasound data showed that volcanoes covered most of the seafloor. Seismological and magnetotelluric stations were deployed on the ice at limited distances from the ship. Five MT-experiments, 3-9 days each, were conducted to investigate the conductivity of the earth's crust and the mantle beneath Gakkel Ridge. The ice floes rotation was not strong so the data were reliable. A mobile network consisting of 3-4 RefTek stations was deployed on an ice floe to obtain seismological data that were necessary to probe the upper mantle. Teleseismic as well as local events were recorded.

DISCOVERIES AND FINDINGS

Multibeam bathymetry and dredge lithology show three distinct magmatic-tectonic zones extend from east to west along Gakkel Ridge (Michael et al., 2003). The Western Volcanic Zone (WVZ ; 8°W - 3°E) consists of elongate axial volcanic ridges characterized by abundant volcanism and fresh basalts. Seismic crustal thickness is 1.9-3.3 km (Jokat et al., 2003) confirming gravity studies (Coakley & Cochran., 1998). The Sparsely Magmatic Zone (SMZ) begins at 3°E, where there is a small offset. Axial depth abruptly deepens by 1100 m (Michael et al., 2003), magnetic intensity dramatically decreases and free air gravity abruptly increases (Vogt et al., 1979; Brozena, et al., 2003). From 3°-13°E, there are large exposures of mantle peridotite while basalts are nearly absent. From 13°-29°E, there are widely spaced volcanic centers and basalts cover a small portion of the axial valley. The eastern Volcanic Zone (EVZ) extends east of 29°E and is characterized by widely spaced magmatic centers and basalts that cover most of the axial valley. Volcanism is highly focused without offsets, showing that magmatic segmentation can arise by mantle processes alone.

Hydrothermal activity was surprisingly abundant along Gakkel Ridge (Edmonds et al., 2003). 80% of MAPR deployments recorded hydrothermal plumes, in contrast to expectations for an ultraslow-ridge. This high frequency is related in part to the water column density structure and the ridge bathymetry that favor plume dispersal. Nevertheless, there are 9-11 vent sites over 1100 km of the axis (Edmonds et al., 2003), 2-3X higher than expected. Almost all of them are associated with volcanic summits. Focusing of mantle melts may lead to large volcanic centers where the heat necessary to fuel hydrothermal systems is concentrated. Ultraslow spreading rates may foster deep, long-lived faulting that permits access to the heat, especially when there are heat sources within older, fractured lithosphere (Michael, 2003).

Mid-ocean ridge basalt (MORB) chemistry (Langmuir et al., 2004 and in prep; Michael et al, 2003b) reveals a remarkable transition in the composition of the Arctic mantle that coincides closely with the bathymetric boundary of the SMZ. MORB from the WVZ are enriched in Ba and H2O at a given level of mantle enrichment. There is a sharp gradient in H2O/Ce and Ba/La
at 3°-14°E. To the east, basalts resemble Pacific MORB. To the west, H2O/Ce and Ba/La remain high along Knipovich and Jan Mayen Ridge, suggesting a large anomaly. Sr-Nd-Pb-He isotope ratios are also distinctive (Soffer et al., 2004 and in prep.). WVZ lavas have high Sr and low Nd isotope ratios, like Indian Ocean MORB. They have high 206Pb/204Pb. Their isotope ratios are similar to alkali basalts from nearby Spitzbergen Island that formed by melting of continental lithosphere, suggesting that continental material is entrained in Gakkel ridge’s source. This is also supported by the occurrence of the boundary between Morris Jesup Rise to the west and Yermak Plateau. MORB from the WVZ also have lower values of Na8.0 suggesting a larger extent of melting compared to SMZ and EVZ. At first glance, the increase in Na8.0 and the transition from WVZ to SMZ appears to reflect the expected a signal of progressively decreasing magmatism and extents of melting eastwards as spreading rate declines. But such a trend does not continue to the east, since the SMZ is placed between zones of higher volcanic output on both sides. Hence factors in addition to spreading rate must play a role in determining magmatic vigor. The fact that the SMZ has the same strike as the WVZ also shows that ridge obliquity is not an important controlling factor in this region. Most likely the source chemistry, especially the additional H2O in the WVZ, is the major factor.

REFERENCES


SEISMICITY, TECTONICS, AND UPPER MANTLE FLOW IN THE ANTARCTIC PENINSULA REGION

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INTRODUCTION

The western Scotia sea region represents a natural tectonic laboratory for exploring the processes by which plate tectonic processes change through time, as the plate motions and the plate configuration have undergone significant changes during the past 4 Ma., and the rapid evolution of plate boundaries in this region may be continuing.

Until recently there had been no available seismological data from locally deployed seismographs, and thus very little was known about the seismicity and upper mantle structure in the region. From 1997-1999, we conducted the Seismic Experiment in Patagonia and Antarctica (SEPA), which installed 10 broadband seismographs and 14 ocean bottom seismographs in the region. The purposes of this deployment were to determine:

1) What seismological evidence exists for current subduction beneath the Antarctic Peninsula?
2) What is the seismological structure and earthquake activity of the active back-arc spreading center in the Bransfield Strait?
3) Is there evidence from seismic anisotropy for large scale mantle flow around S. America into the South Atlantic?

THE SEPA DEPLOYMENT

The Antarctic portion of the SEPA project included seven land stations and fourteen ocean bottom seismometers (OBSs). Each land station consisted of a Streckeisen STS-2 seismometer and a Reftek 24 bit digital acquisition system with GPS timing, and data were recorded continuously at 25 or 40 samples/second. Three sensors were deployed at Chilean Antarctic
military bases; these stations were outfitted with ARGOS state of health satellite transmitters to help maintain reliable operation despite their limited access. These transmitters allowed remote monitoring of the status of the instrument, and therefore possible correction of problems at the Antarctic bases through communication with local operators. Four other sites were located in the field, with no attendants or electric power available. Logistics permitted visits to these sites only once or twice a year during the Antarctic summer. These sites were equipped with power supplies which use solar power during most of the year, but rely on banks of Carbonaire batteries during the winter months. Some stations operated throughout the entire winter unattended, and the majority of the Antarctic stations recorded data for about nine months each year. Most of the land stations were installed during February, 1997 and were removed in May, 1999.

During December of 1998 through May of 1999 we also deployed 14 ocean bottom seismometers (OBSs) of the Office of Naval Research (ONR). The primary OBS line is perpendicular to the SEPA array, so the OBS data allowed for more accurate locations of events. Seven of the OBSs were equipped with broadband Precision Mechanical Device (PMD) sensors and the other seven used 1 Hz L4 sensors, and all OBSs were also equipped with differential pressure gauges.

SEISMICITY AND CURRENT SUBDUCTION IN THE SOUTH SHETLAND TRENCH

The data we obtained indicates a high level of local seismicity \( (m_b \ 2-4) \), and we accurately located more than 150 earthquakes \cite{Maurice et al., 2003}. Many of the earthquakes occur at locations and depths indicative of ongoing subduction in the South Shetland trench. A focal mechanism determined by waveform inversion for the largest event in the forearc shows a shallow angle thrust mechanism. The maximum depth of seismicity is approximately 60 km, but the majority of the events are shallower than 30 km. The deepest events occur just seaward of the South Shetland Islands. These seismic results are consistent with recent magnetic and GPS data that suggest continued subduction at a very slow rate. The South Shetland trench thus represents an extreme end member of hot subduction resulting from slow convergence of young lithosphere, and the absence of intermediate depth earthquakes is consistent with thermal assimilation of the slab at shallow depths.

STRUCTURE AND EARTHQUAKE ACTIVITY OF THE BRANSFIELD RIFT

Surface wave phase and group velocity measurements provide constraints on the upper mantle structure of the Bransfield Strait. The crust thickens from east to west within the Bransfield Rift \cite{Vuan et al., 2005}. Upper mantle velocities are low compared to global
models at least to depths of 100 km, but are higher than active backarc basins such as the Lau and Mariana regions, suggesting that the upper mantle temperature anomaly is not as strong in Bransfield as in backarcs showing established sea floor spreading.

The SEPA array also located many earthquakes associated with volcanism and rifting in Bransfield Strait. A swarm of events located on a submarine volcano suggests the possibility of current eruptive activity. Earthquakes associated with rifting in the northeastern portion of the strait are clustered along well-established rifts that are visible in bathymetric profiles, but the seismicity is much more diffuse to the southwest [Maurice et al., 2003]. This observation is consistent with other evidence that extension at the southwestern end of the Bransfield strait is less well organized, and that extension has propagated from northeast to southwest.

SEISMIC ANISOTROPY AND MANTLE FLOW

Mantle flow around South America through Drake Passage is predicted by several previous studies based on the geological history and morphology of the Scotia and Caribbean regions and shear wave splitting observations from South America, which show mantle flow beneath the subducting Nazca plate along the strike of the South America trench. Preliminary results from shear wave splitting analysis of teleseismic SKS and SKKS arrivals from the SEPA experiment provide constraints on the pattern of upper mantle flow directions [Helffrich et al., 2002]. The fast polarization directions in the Antarctic Peninsula region are oriented in a NE-SW direction, consistent with flow along the strike of the arc. In contrast, fast splitting directions in Patagonia are small and oriented perpendicular to the strike of the arc. Taken together with splitting measurements at permanent seismographs at Palmer station, the Falklands, and South Georgia, these measurements do not suggest a pattern of mantle flow from the Pacific region into the Atlantic through the Drake Passage region.

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SEISMICITY OF THE POLAR SEAS: THE POTENTIAL FOR HYDROACOUSTIC MONITORING OF TECTONIC AND VOLCANIC PROCESSES

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MAJOR SOURCES OF SUBMARINE SEISMICITY AND VOLCANISM

Within the Arctic Basin, the Eurasian-North American Plate boundary is defined by the ultra-slow spreading Gakkel Ridge system. Full spreading rates range from 14 mm/yr in the west, where the Gakkel Ridge connects with the Spitsbergen Transform Complex, and 6 mm/yr in the east, where extension transitions toward a broader zone of continental rifting across the Laptev Shelf.

Global seismic networks provide good azimuthal coverage throughout the Arctic Basin, with present day seismic catalogs being complete for events as small as \(~4.5\, m_b\) [Tolstoy et al., 2001]. Event detection is aided by the location of sensitive seismic arrays within Alaska, northern Canada and Europe. These arrays belong to the International Monitoring System; and, although waveform data is not openly available, phase picks and amplitude data are contributed to the International Seismological Centre.

Seismicity along the Gakkel Ridge is characterized by spatial and temporal event clusters that tend to be associated with discrete volcanic centers. The largest recorded swarm occurred between January and September of 1999, with more than 250 earthquakes located by land-based seismometers. This activity was co-located with a region of anomalous high-backscatter seafloor imaged by the SCAMP sidescan sonar system and has been interpreted as having a likely volcanic origin [Edwards et al., 2001; Tolstoy et al., 2001].

In contrast to the Arctic Basin, the Southern Ocean surrounds the comparatively stable Antarctic continent. The South Shetland Trench, located just seaward of the South Shetland Islands, is the last surviving segment of a subduction zone that once extended along the entire western margin of the Antarctic Peninsula. Global seismic catalogs show very low levels of
seismicity, in part reflecting the poor station coverage within this part of the world and dearth of array stations within the southern hemisphere. Temporary deployments of local seismic networks, however, have recorded numerous earthquakes (2-5 m<sub>s</sub>) that delineate a shallow Wadati-Benioff zone beneath the Antarctic Peninsula and show evidence of fore-arc thrusting [Robertson-Maurice et al., 2003].

Sources of shallow submarine volcanism, many of which are unexplored, exist throughout the Bransfield region, within the transtensional sections of the South Scotia Ridge and along the South Sandwich Backarc. Elsewhere, within the Ross Sea, potential sources are associated with a volcanic system that includes the well-instrumented Mt. Erebus.

UNDERWATER SOUND PROPAGATION

The speed of sound in the ocean is influenced primarily by pressure and temperature. At mid-to-low latitudes, thermal stratification creates a negative velocity gradient within the upper water column that causes sound to be refracted downward as the velocity decreases with decreasing water temperature at depth. Below the thermocline, where temperature varies little, the pressure effect dominates, with a positive sound speed gradient that bends sound waves upward. These sound speed gradients create a velocity minimum, often referred to as the SOund Fixing And Ranging (SOFAR) channel. Acoustic energy trapped within this low-velocity waveguide propagates through a series of upward and downward refractions, spreading cylindrically (r<sup>-1</sup>), rather than spherically (r<sup>-2</sup>) as it would in the solid Earth (Figure 1a). The efficiency of the SOFAR channel allows many natural and anthropogenic noises to be detected over distances of thousands of kilometers.

![Figure 1](image.png)

**Figure 1.** Ray-tracing comparison of sound propagation from in-water sources within (a) sound channel and (b) half-channel environments.
The axis of the SOFAR waveguide is deepest in the subtropics and comes to the surface in high latitudes, where it creates a half channel (Figure 1b). Half-channels exist where the water is approximately isothermal from the sea surface to the seafloor, resulting in a continuous increase in sound speed with depth. In such an environment, acoustic energy will propagate through a series of sea surface or sea ice reflections (Figure 1b). Due to the efficiency of these (low frequency) reflections, half-channel propagation mimics a surface duct, allowing for long range propagation and coupling into the sound channel at lower latitudes (as shown in Figure 2).

Figure 2. Transmission loss model for the long-range propagation of sound from a shallow 40-Hz source near the Antarctic coastline, across the Antarctic convergence zone and coupling into the mid-latitude SOFAR channel.

POTENTIAL FOR HYDROACOUSTIC EXPLORATION IN THE POLAR SEAS

The efficient nature of sound propagation within the oceanic water column can be exploited to detect and locate small-to-moderate magnitude earthquakes that would otherwise go unnoticed by the global seismic networks. This is accomplished using the water-borne Tertiary (T-) waves generated by these undersea quakes. The analysis of seismic patterns and the potential identification of submarine harmonic tremor also provide a mechanism for identifying regions of active submarine volcanism.

Previous observations have highlighted the utility of hydroacoustic observations for seismotectonic studies in the Arctic. Blackman et al. [2000], for example, have demonstrated that the processing of U.S. Navy hydrophone recordings from the northern Atlantic reduced the detection threshold by 2-3 orders of magnitude along portions of the Mohns Ridge (73°N, 4°E) during a 1995 spreading episode. Although academic monitoring capabilities within the Arctic Ocean are extremely limited at the present time, ocean observatory initiatives in the U.S. and
elsewhere have the potential to facilitate basin-wide efforts in the future.

In November of 2005, using a network of six autonomous instruments, we expect to begin long-term hydroacoustic monitoring of the Drake Passage Region (Antarctic Peninsula). To accommodate the extremely cold water and strong currents within this region, modifications have been made to the OSU/NOAA hydrophone design used in previous projects at mid-latitudes. Specifically, the strength of the mooring line was doubled and the standard spinning mechanical hard-drives were replaced with oil-filled drives that are rated to -20°C. A test hydrophone mooring (complete with current meter) was deployed in the Bransfield Strait from a Russian Icebreaker on 20 November 2004 and recovered on 14 December 2004. This test deployment went exceptionally well, and the T-waves of dozens of earthquakes from throughout the Bransfield Strait were recorded clearly during the four-week deployment (Figure 3).

![Figure 3. a) Time series and b) spectrogram of an earthquake-generated T-wave recorded during the test-deployment of the OSU/NOAA cold-water hydrophone. Broad-band pulses are airguns from an active source seismic survey.](image)

REFERENCES


RIFTING AND VOLCANISM IN THE BRANSFIELD STRAIT BACK-ARC BASIN, ANTARCTICA

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INTRODUCTION

Studies of oceanic back-arc basins (BABs) in the western Pacific produced a generalized model for back-arc basin formation wherein arc crust is rifted into a series of sub-basins that are then taken over by a propagating seafloor spreading center (e.g., Hawkins, 1995). Little is known, however, about how BABs form in continental crust, perhaps because such BABs are rare (Bransfield Strait and Okinawa Trough may be the only active continental BABs that are opening without a large strike-slip component). A propagating rift model (from NE to SW) has been proposed for the opening of the Bransfield Strait based upon aspects of its geophysics and geochemistry (Barker and Austin, 1998; Christeson et al., 2003; Robertson Maurice et al., 2003; Fretzdorff et al., 2004). The rift in Bransfield Strait does not have a well-developed spreading center, but the similarity of some of its axial neovolcanic ridges to those in western Pacific BABs such as the Mariana Trough suggest that the Bransfield rift may be at or near the transition from rifting to seafloor spreading. This presentation will summarize the geologic history of Bransfield Strait, and the current evidence for subduction, rifting, volcanism, and hydrothermal activity there. There are many remaining questions about the development of continental back-arc basins that could be addressed by future studies in Bransfield Strait.

GEOLOGY AND GEOPHYSICS

The northern Antarctic Peninsula is a dynamic region of volcanic and tectonic activity. The former Phoenix Plate (now part of the Antarctic Plate) is subducting toward the southeast beneath the South Shetland Island Arc (Figure 1). A remnant of the Phoenix-Antarctic spreading ridge northwest of the South Shetland Trench ceased spreading at about 3 Ma, and subduction into the trench slowed considerably at that time, leading to a change in subduction zone stresses and the initiation of rifting in the back-arc (Barker, 1982). In response to
continued trench rollback, the South Shetland Islands are currently rift ing away from the Antarctic Peninsula at ~1 cm/yr (Bevis et al., 1999), creating the 100-km wide Bransfield Strait back-arc basin. Most of the earthquake activity in the area is shallow (<30 km), and is related to subduction in the South Shetland Trench or rifting and volcanism in Bransfield Strait, although a few well-located earthquakes as deep as 65 km may be in the downgoing slab (Robertson Maurice et al., 2003). Additional evidence for continuing subduction includes ongoing deformation of the trench sediments (Maldonado et al., 1994). Arc volcanism on the South Shetland Islands appears to have ceased at ~20 Ma, but extension-related Quaternary volcanic rocks are found throughout the area, including on islands and seamounts in Bransfield Strait, and in a few places on the South Shetland Island Arc. The only subaerial volcano in the region confirmed to have been historically active is Deception Island (in the SW corner of Figure 2; most recent eruption in 1970).

Figure 1. Tectonic sketch map of South Shetland Islands/Bransfield Strait area. The South Shetland Islands are rift ing away from the northern Antarctic Peninsula, opening the Bransfield Strait back-arc basin.

With few exceptions, dredging the numerous volcanic features in Bransfield Strait recovered glassy, vesicular pieces of basaltic pillows and sheet flows. Rock compositions have an almost perfectly bimodal distribution, with strong frequency peaks at basaltic andesite and rhyolite. The rhyolites were found on four different axial volcanic features in two different areas, two features near 57°W and two near 59°W (Figure 2). These are the same two areas where seafloor and water column studies found evidence for hydrothermal activity (Klinkhammer et al.
2001). Trace element and radiogenic isotopic compositions of the volcanic rocks range from similar to rocks from the nearby South Shetland Island Arc to virtually indistinguishable from mid-ocean ridge basalts (Keller et al., 2002).

![Multibeam bathymetry map of Bransfield Strait area showing volcanic rock types sampled from the submarine features. Approximate locations of known hydrothermal activity are also shown.](image)

Hydrothermal signatures were observed in the water column during RVIB Nathaniel B. Palmer cruises in 1995 and 1999 (Klinkhammer et al., 2001). Seafloor sampling near the inferred source of one of the main hydrothermal plumes yielded a sulfide chimney fragment with texture and mineralogy indicative of venting temperatures in excess of 250°C; and warm (42-49°C) sediment containing native sulfur and Fe-sulfides, overlain by hard, siliceous crusts and underlain by a layer of rhyolitic tephra. Sampling at the other main plume location yielded fresh basalt and rhyolite, and several chunks of hydrothermal barite with sulfides. No diagnostic vent fauna were observed at either location, although there did appear to be higher abundances of epifauna in the areas near the plumes. We either missed observing and sampling the exact vent areas, or typical mid-ocean ridge vent fauna are absent at these sites, perhaps because the Southern Ocean represents a significant barrier to the global dispersal of vent organisms.
CONCLUSION

Many opportunities remain in geology and geophysics in and around Bransfield Strait:
-- Locating and determining focal mechanisms for earthquakes associated with rifting in the Bransfield Basin and slab motion beneath the South Shetland Islands. Does the mechanics of rifting vary along the axis of Bransfield Strait in accordance with the propagating rift model?
-- Monitoring for volcanic seismicity, especially at Deception Island and along the submarine neovolcanic ridge.
-- Searching for the missing volcanism. There is a time gap in known volcanic activity between the last known arc volcanism at ~20 Ma and the first known rift volcanism at <0.7 Ma. This is despite the fact that the unique plate configuration requires that subduction continued during this time interval.
-- Continued search for hydrothermal vent locations and potentially unique chemosynthetic ecosystems, especially if the vents are rhyolite-hosted.

REFERENCES


[Session II]

Polar Climate:

Glacial and Atmospheric Sciences,

Oceanography
THE OZONE LAYER AND UV-B RADIATION IN THE AMERICAN SOUTH CONE AND ANTARCTIC OZONE HOLE 1992-2004

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INTRODUCTION

During the recent decades there has been an increasing concern related to ozone layer and solar ultraviolet radiation, UV-B (280-320 nm), reaching the surface of the earth (WMO, 2003). The Antarctic Ozone Hole (AOH) is a phenomenon of strong ozone depletion in the Antarctic stratosphere, this is a consequence of heterogeneous chemical reactions and dynamical processes that enhance ozone losses by reactions with chlorine, (Solomon, 1990). Punta Arenas (53.0°S, 70.9°W) is the southernmost city in Chile with a population of approximately 120000. Due to its location, well within the area affected by the Antarctic Ozone Hole, this population may well be the first group to show health problems from environmental effects of severe ozone depletion. A considerable increase in the number of sunburns was reported during periods of low ozone and high ultraviolet radiation during the mid to late Austral spring of 1999 (Abarca and Casiccia, 2002). Systematic observation of ozone and UV-B with a Brewer spectrophotometer have been made in order study during the ozone hole conditions (Casiccia et al., 2003). In addition, the vertical distribution has been investigated during campaigns in spring time. Since 2002 we are doing measurements of the vertical distribution using Umkehr technique. Here we present measurements of column ozone, vertical distribution of ozone and ultraviolet radiation UV-B made in Punta Arenas and Magallanes region to period 1992-2004.

SOME RESULTS

In Fig1(a) shows a time series of daily total ozone values for Punta Arenas obtained from the Brewer Spectrophotometers from may 1992 to December 2003. The red solid line represents the running average (n=30) for the same period. Fig1(b) shows a comparison between the Punta Arenas Brewer and the TOMS of the ozone data.
Fig. 1.- Total ozone observed at Punta Arenas measured by Brewer (a) instrument during 1992-2003. (b) Comparison of Brewer and TOMS data.

Fig. 2(a) shows monthly mean Brewer spectrophotometer measurements compared with the reference values plus and minus one standard deviation as indicated with the hatched areas (Casiccia, et.al., 2003). Fig. 2(b) shows monthly mean Brewer spectrophotometer measurements to 2000, 2002 and 2003 compared with the reference values plus and minus one standard deviation, the reference values was calculated from TOMs data 1978-1987 a non-AOH period. Here is possible to see that ozone values during the spring and summer are lower than reference values and that standard deviations are larger during the months of September and October due to the perturbations generated by the AOH.

Fig. 2.- Ozone monthly averages and standard deviations for (a) 1992-2000 period (b) 2000, 2002 and 2003 years.
Ozone profiles obtained from ECC soundings and Umkehr (Brewer 180) at Punta Arenas in 2001 and 2003 respectively. In each case it is possible to see the destruction of the ozone concentration between 12 and 25 km.

![Graph](image)

Fig. 3.- Vertical profile of ozone concentration obtained from ECC and Umkehr.

The consequence of the lower ozone concentrations in the stratosphere during perturbed days is a larger UV-B intensity at ground level. Fig. 4 shows a comparison of two spectra weighted of the action spectrum of CIE, during two events in 2000. One refers to a day with normal ozone and the other a day with ozone depletion.

![Graph](image)

Fig. 4.- Comparison of two spectra weighted for the spectrum of CIE, for 12 October and 18 October, using the spectra for 15 October for reference.
SUMMARY AND CONCLUSIONS

The Antarctic ozone hole has been observed over Punta Arenas, Chile, a populated region of 120000 inhabitants across the Antarctic Peninsula. Measurements of total ozone column, vertical profile (Umkehr) and UV-B radiation were made with a Brewer spectrophotometer. On several occasions vertical distribution ozone was measured by using ECC ozonesondes launched on balloons. The data indicate that this region is regularly subject to the influence of the Antarctic Ozone Hole, during the spring and summer time. The total ozone, vertical distribution and UV-B radiation observations are being carried out by the Laboratory of Ozone and RUV of the University of Magallanes at several locations in Magallanes region and it is hoped that these observations will be important for investigation related to long-term trends and impact on the population.

REFERENCES


CLIMATE CHARACTERISTICS RELATED WITH THE BASIN SEDIMENTS IN BRANSFIELD STRAIT, ANTARCTICA

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INTRODUCTION

In recent years several sediment cores have been collected from the eastern Bransfield Basin, Antarctic Peninsula region by the Korean Antarctic Research Program (Yoon et al., 2003; Bahk et al., 2003). The analysis results of the sample cores revealed that some sedimentation records may be useful as palaeoclimate and palaeoceanography proxies. Among these results, Bahk et al. (2003) reported that the samples in the EB-2 and GC00-13 cores showed the laminated sediment fabric with potential seasonal signatures including the diatom ooze laminae organized by different diatom species and the laminated sequence consisting of terrigenous laminae and diatom laminae. Therefore, laminated seasonal sedimentation records like the above core samples will be useful to reconstruct regional palaeoclimate and palaeoceanography (Anderson et al., 1991; Grobe and Mackensen 1992; Pudsey et al., 1994).

DATA AND METHODS

This study used monthly mean surface air temperature, much of it obtained from the internet web site [http://www.cerc-bas.ac.uk/iced/gima](http://www.cerc-bas.ac.uk/iced/gima), 6-hour wind data for the period of 40 years from NCEP/NCAR reanalysis data, Sea Surface Temperature (SST) from NOAA/AHRR weekly high resolution data, and sea ice concentration estimated from the combined various satellite measurements. This study examines the relationships among sea ice concentration, surface air temperature, surface wind, and SST (Sea Surface Temperature) to understand the climate characteristics related with the basin sedimentation process in Bransfield strait.
RESULTS

In Fig. 1, even though Esperanza and Orcadas are further north in 4 degrees of latitude than Rothera and Faraday, the annual temperature distributions are comparable. It is also found that Esperanza and Orcadas are much colder particularly in autumn and winter than Rothera and Faraday. These results are in a good agreement with the well known climatic characteristics in the Antarctic Peninsula: milder conditions in the west side of the Peninsula and colder conditions in the east side. And these results are also consistent with the prevailing southerly and southwesterly surface winds in autumn and winter.

The variability of surface air temperature in this region is compared with that of the regional atmospheric circulation. The surface air temperature is positively correlated with frequency of northwesterlies and negatively correlated with frequency of southeasterlies (Fig. 2). This relation is more evident in the northern tip of the Peninsula for autumn and winter. The trend analysis of wind frequency in the study area shows that increasing and decreasing trends in the frequency of northwesterlies and southeasterlies, respectively, in the northwestern part of the Weddell sea for autumn and winter. And also it is found that these winds are closely related with decreasing of sea level pressure in the southeastern region of Antarctic Peninsula.

Fig. 1. Annual temperature variations in Antarctic peninsula for the period 1962-2001.

Fig. 2. Correlation coefficient between surface air temperature (°C) and frequency of wind direction (%) at Esperanza for the period of 1961-2001.

Fig. 3 shows the results of correlation analysis for the surface wind and the sea ice concentration nearby Esperanza. During the autumn (Mar., Apr., May), the sea ice concentration is correlated positively ($r=0.67$) with the frequency of southeasterlies and negatively ($r=-0.45$)
with the frequency of northwesterlies. Near Esperanza the sea ice concentration is also compared with the surface air temperature on seasonal means (Fig. 4). It is evident that the air temperature is negatively correlated with the sea ice concentration. This relation is more robust during the autumn.

Fig. 3. Relation between frequency of wind direction (%) at 65°S, 55°W and ice concentration at 62°04'S, 56°23'W for autumn time (SON): (a) NE, (b) SE, (c) SW and (d) NW.

Fig. 4. Relation between surface air temperature (°C) at 63°24'S, 56°59'W and sea ice concentration at 62°04'S, 56°23'W.

SUMMARY AND CONCLUSIONS

In the monthly data analysis in the vicinity of the Bransfield strait, during the autumn (Mar., Apr., May), the frequency of southeasterlies is correlated positively with the sea ice concentration and negatively with the surface air temperature, and the frequency of northwesterlies is reverse. These relationships are explained by the process that the
southeasterlies of the cold air from the Antarctic Continent affect the ocean current around Bransfield strait, and then the ocean current makes the sea ice generated in the Weddell sea drift into the strait. During the spring (Sep., Oct., Nov.), sea ice concentration and surface air temperature are closely correlated with the frequency of northwesterlies with warm air mass. Also, the sea ice concentration in Bransfield strait shows the positive correlation with the SST in the some parts of the northern boundary region during the autumn and spring. And these relationship may rather propel the sea ice melting in proportion to the sea ice concentration during the autumn.

REFERENCES


THE NORTHERN HEMISPHERE ANNULAR MODE: IMPACTS ON THE EXTRATROPICS AND RELATIONSHIPS WITH THE TROPICS

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INTRODUCTION

The Northern Hemisphere Annular Mode (NAM) also known as the Arctic Oscillation (AO) recognized by Thompson and Wallace (1998, 2000) is a dominant mode of boreal winter extratropical atmospheric variability. Time series of the NAM index characterize intensity of the middle and high latitude westerlies and cyclone activity. So that, the NAM strongly impacts wintertime temperature and precipitation in middle and high latitudes on the time scales from synoptic to, at least, decadal. In particular, the abrupt high latitude temperature rise from the 1960s to 1990s is associated with the abrupt transition of the NAM from negative to positive polarity (Hartman et al., 2000). Furthermore, in high latitudes, the impact of the wintertime NAM is sensible throughout the rest of year due to its strong dynamical and thermodynamical impact on the Arctic sea ice and land snow cover which keep the memory about wintertime conditions at least till the next autumn (Kryjov, 2002, 2004; Rigor et al., 2002). The basic structure of the mode can be simulated with climatological mean sea surface temperature distribution that means that the NAM is an internal mode of atmospheric variability (Shindell et al., 2001). However, empirical evidences of the middle troposphere NAM-like response to the ENSO were documented by Horel and Wallace (1981, Fig. 9) when the NAM mode was not recognized yet. Nowadays, impacts of tropical SST, particularly SST variations associated with the ENSO, on the NAM are widely discussed. The studies are mainly focused on the relationships between the wintertime NAM and concurrent ENSO cycle, i.e. the ENSO indices lead the NAM by not more than several months. In this study we focus on the relationships between the wintertime NAM and SST anomalies associated with the previous ENSO cycle, with the lags exceeding a year.

DATA AND METHODS

We have studied linear dependencies applying simple and partial correlation and multiple regression analysis. All correlation/regression coefficients were obtained on the detrended series. Significance level was assessed accounting for serial correlation.

RESULTS

The wintertime NAM in year 0 strongly correlates (r=0.5) with autumn(-2 yr.) SST in the Bengal Bay and maritime continent (BB SST), with correlation being quite stable and exceeding correlation with autumn(-1 yr.) – winter(0 yr.) SST in the Eastern Equatorial Pacific. The autumn BB SST anomaly in turn is correlated with preceding Indian summer monsoon rainfall (r=0.3 - -0.4) and preceding winter-spring Nino SST indices (r=0.4 - 0.6). So that we consider it to represent the state of the tropical climate system as a result from in the preceding winter-summer processes. Due to cyclicity in tropical SST, it also correlates with autumn(-1 yr) – winter(0 yr.) Nino SST indices (r=-0.4 - -0.5).

Correlation between JF SLP and SON(-2) BB SST, with SON (-1) Nino3 SST influence being eliminated, bears resemblance with that of the NAM and NAO (Figs. 1a). Correlations with the tropospheric and stratospheric NAM indices (Fig. 1b) yield mainly tropospheric response to the variations in tropical SST (-2 yr.) which exceeds response to the almost simultaneous tropical SST variations.

![Figure 1. Partial correlations. Contour interval is 0.1, absolute values below 0.3 are omitted.](image-url)
Such lag correlations may be explained with cyclicity in tropical SST variations, however, only partly since simultaneous response is much weaker. Ice/snow extent predictors of the NAM (NAO) suggested by Saunders et al. (2003) and Saito et al. (2001) do not correlate with the SON(-2) BB SST. Areas of the overlapping of significant correlations of the JF NAM and SON(-2) BB SST with SST in year (-1) cover only the Western Pacific. They may provide some persistence, however, the signal decays within several months.

The air chemical composition is also a persistent characteristic of the climate system and it may keep the memory about conditions of its formation. Radiatively active components of the air such as CO₂, water vapor, etc., affect circulation through the changes in atmosphere temperature distribution (e.g., Shindell, 2001). Correlations between the series of adjacent differences of SON(-2) BB SST, spring-summer(-1) CO₂, and JF NAM are about 0.4. The vertical profile of the CO₂:NAM correlation has local maximum between 100 and 300 mb surfaces that matches theoretical scheme of the CO₂ impact on the circumpolar vortex: increase (decrease) in CO₂ concentration leads to enhancement (weakening) of the meridional temperature gradient between the tropical upper troposphere and polar lower stratosphere. Regression map (Fig. 2) confirms that interannual changes in the 100-300 mb layer thickness are consistent with theoretical impact of CO₂. However, the detrended series of adjacent differences represent only interannual changes in the gas concentration, with accumulation being left beyond analysis. Absence of the significant trends in the NAM and H100-H300 mb layer thickness also implies that it is rather non- or weaker accumulated component.

![Figure 2. AMJ(-1) CO₂ regression coefficients (m/ppm) when 100-300 mb layer thickness (H100_300) is regressed on AMJ(-1) CO₂ and SON(-1) Nino 3 SST. Results were obtained on the detrended series of adjacent differences.](image)

CONCLUSION

We have shown that response of the wintertime NAM to SST variations associated with the previous ENSO cycle is stronger than to those of the concurrent ENSO cycle. Preliminary study
yields that the signal may (partly) come through the associated changes in the chemical composition of the atmosphere.

REFERENCES


THE STABILITY OF THERMOHALINE CIRCULATION IN A TWO-BOX MODEL

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INTRODUCTION

The sea surface thermal forcing, which acts in the direction of the present thermohaline circulation in the North Atlantic, is opposite to the haline forcing from the freshwater flux. The strong negative feedback between the sea surface temperature and the surface heat flux removes changes in the sea surface temperature rapidly. However, the freshwater flux, which arises from the local imbalance between precipitation and evaporation, is independent of the sea surface salinity. The difference in the boundary conditions for temperature and salinity may give rise to multiple equilibria of the thermohaline circulation under identical boundary conditions (see Weaver and Hughes 1992; Marotzke 1994; Whitehead 1995 for reviews). Therefore, the thermohaline circulation can switch from one equilibrium to another rapidly (thermohaline catastrophe) if the thermal or haline forcing is perturbed. Studies ranging from simple box models to fully developed primitive-equation numerical models have demonstrated the thermohaline catastrophe.

It has been suggested that the mechanism behind the thermohaline catastrophe is a large-scale advective process (Walin 1985), but the effect this advective process has on stability of the thermohaline circulation has been neglected. Instead, many studies have been focused on boundary conditions for salinity, that is, the parameterization of the air–sea freshwater exchanges and their effects. In Stommel’s (1961) two-box model, a linear mass transport relation was assumed, and the strength of the circulation $\Psi$ through a capillary pipe connecting two boxes, $\Psi \sim \Delta \rho$, where $\Delta \rho$ is the density difference between the two adjacent boxes. This linear relation has been used in most box models, which suggest that if freshwater flux to the Northern North Atlantic increases by a small amount, the present thermohaline circulation of North Atlantic would be reversed (Huang et al. 1992). A simple scaling analysis based on geostrophy and advective–diffusive buoyancy balance in the thermocline (Bryan and Cox 1967; Welander 1971) suggests a nonlinear mass transport relation, $\Psi \sim \Delta \rho^{1/3}$, for the oceanic
thermohaline circulation. In this study the effects of different mass transport relation on the stability of Stommel’s classical two-box model have been explored.

A TWO-BOX MODEL

The classical model, based on Stommel (1961), consists of a polar box and an equatorial box as shown in Fig. 1. The equations of temperature and salinity in each box are

\[
\begin{align*}
\dot{T}_P &= C_{TP}(T_P - T_E) + |\Psi|(T_E - T_P) \\
\dot{S}_P &= V_p H_{SP} + |\Psi|(S_E - S_P) \\
\dot{T}_E &= C_{TE}(T_E - T_P) + |\Psi|(T_P - T_E) \\
\dot{S}_E &= V_E H_{SE} + |\Psi|(S_P - S_E)
\end{align*}
\]

The subscripts \(P\) and \(E\) denote quantities for the polar and equatorial boxes, respectively. The restoring condition is used for temperature boundary condition and the quantities with a caret denote reference temperature. The restoring timescale for temperature \(\tau_T = V_T/C_{T0}\), where the volume of a box is \(V_T\). Virtual salt flux \(H_{SI}\), where \(i=E\) or \(P\), is from the commonly used restoring condition or the interactive condition by Nakamura et al. (1994). The volume transport \(\Psi\) in this study is either on of the following:

\[
\Psi = \begin{cases} 
\Psi_G = C_G[\alpha(T_E - T_P) - \beta(S_E - S_P)]^{1/3} & \text{nonlinear} \\
\Psi_F = C_F[\alpha(T_E - T_P) - \beta(S_E - S_P)] & \text{linear},
\end{cases}
\]

where \(\alpha\) is the thermal expansion coefficient, \(\beta\) is the salt expansion coefficient, and \(C_G\) and \(C_F\) are constants whose values are set to yield \(\Psi = 10\ \text{Sv} \ (\text{Sv}=10^6\text{m}^3\text{s}^{-1})\) when \(\Delta\rho = \Delta\rho_p\) (\(\Delta T = 20^\circ\text{C}\) and \(\Delta S = 2\text{ppt}\)), which represents the meridional sea surface density gradient of the present North Atlantic.

Figure 1. A two-box model
RESULTS

In Fig. 2, hysteresis diagrams from models with the restoring salinity boundary condition are presented. In the linear model, the present thermal-model circulation (point $P$) becomes unstable and switches to a haline mode circulation if the haline forcing increases by 20%. This is similar to earlier box models using the linear mass transport relation such as Huang et al. (1992), in which $H_S$ is from $(E-P)$. In contrast, in the nonlinear model 60% increase in the haline forcing is required for the instability of the present thermal-model circulation. In this model it is less likely that a small increase in the haline forcing (or freshwater flux) would cause the catastrophic transition. Results with different thermal forcing show the same tendency.

![Figure 2. Hysteresis diagrams from models with the restoring salinity boundary condition.](image)

The models with the nonlinear mass transport law show greater stability than those with the linear law when the same salinity boundary conditions are used. The largest contribution to stability is from advection related quantities so that the change in the mass transport law makes the largest change in stability. The faster circulation in the nonlinear model weakens the meridional salinity gradient and removes the salinity anomalies more effectively. The faster circulation, furthermore, prevents the water in the polar (equatorial) box from obtaining (losing) enough freshwater to build up a strong salinity gradient. Stronger haline forcing is required to reverse the thermal-mode circulation.

SUMMARY AND CONCLUSIONS

The Using a two-box model, the effect of mass transport on the stability of a thermal mode (high latitude sinking) circulation has been studied. The equilibrium circulation tries to remove temperature and salinity (or density) anomalies and stabilize the circulation. On the other hand,
salinity anomalies try to weaken the circulation and intensify the meridional salinity gradient; this is the strongest destabilizing process. In a model with nonlinear transport, the circulation becomes relatively stronger than that in the linear model as density anomalies intensify. The stronger circulation in the nonlinear model reduces the meridional salinity gradient and removes the anomalies effectively. Thus, nonlinear models show significantly greater stability, irrespective of the freshwater flux parameterization.

REFERENCES


A COUPLED MODEL SIMULATION OF OCEAN THERMOHALINE PROPERTIES OF THE LAST GLACIAL MAXIMUM

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INTRODUCTION

Earlier estimates suggested that the deep ocean was about 2°C cooler than modern during the last glacial maximum (LGM), but more recent estimates suggest that glacial deep ocean temperatures were within the error range of the freezing point of sea water in all ocean basins (e.g., Boyle, 2002). At present, North Atlantic Deep Water (NADW) is saltier than Antarctic Bottom Water (AABW), as a result of higher sea surface salinities in the North Atlantic compared to the Antarctic continental margin. In contrast to the modern ocean, the saltiest water appears to have been in the Southern Ocean during the LGM (Adkins et al., 2002). The objective of this study is to investigate the response of oceanic thermohaline properties to glacial boundary conditions using a coupled atmosphere-ocean-sea ice climate system model.

MODEL AND EXPERIMENTS

The model employed in the current study is the Canadian Centre for Climate Modelling and Analysis (CCCma) coupled general circulation model. The atmospheric component of the coupled model is a primitive equation model characterized by T32 horizontal resolution corresponding to a 3.75°Gaussian grid, and 10 vertical levels. The oceanic component is a modified version of the GFDL MOM version 1.1. The horizontal and vertical resolutions are 1.875° x 1.875° and 29 vertical layers. The coupled model includes a representation of sea ice thermodynamics and sea ice dynamics. The atmosphere and ocean components interact once per day exchanging heat, fresh water, and momentum. A fixed annual cycle of heat and freshwater flux adjustment fields are applied over both ice-covered and open-ocean, and do not change as the climate evolves. A detailed description of the atmosphere, ocean, sea ice, and land surface components of the coupled model is given in other papers (Kim et al., 2002, 2003).
The reference simulation (REF) has a specified CO$_2$ concentration of 330 ppm, and a contemporary land mask and topography. The LGM simulation features a decreased CO$_2$ concentration of 235 ppm, and ice sheet topography using the ICE-4G reconstruction of Peltier (1994). The ice sheet volume requires an estimated LGM sea level drop of 120 m. This is equivalent to about 3% of the total ocean volume and results in an increased global mean salinity of about 1 psu. The ocean volume (thus the global salinity) is not modified.

RESULTS

Meridional sections of observed potential temperature and salinity in the global domain are shown in Fig. 1 and are presented to show as a reference for the modern conditions. The data are from Levitus and Boyer (1994) for the potential temperature and Levitus et al. (1994) for the salinity. The most distinctive feature in the meridional sections is the southward extension of the warm and saline tongue associated with NADW (Lower Circumpolar Deep Water (LCDW) in the Southern Ocean). Another salient feature shown in the observed meridional section is the low salinity tongue deepening northward to about 1000 m associated with Antarctic Intermediate Water (AAIW) (Fig. 1b). Lying below CDW, the cold and relatively fresh AABW tongue is also visible.

![Fig. 1 Zonally averaged annual-mean meridional sections of the observed (a) potential temperature and (b) salinity for global domain.](image)

Fig. 2 presents the simulated potential temperature and salinity, zonally-averaged in the global domain, for the REF and LGM simulations and their changes. The features found in the observed sections are reproduced reasonably well in the REF simulation. First, the propagation of the fresh AAIW tongue to the north is clearly reproduced. Second, the southward intrusion of the relatively warm and saline NADW tongue is well represented. Third, the relatively cold and fresh AABW tongue is present in the Southern Ocean. Overall, the simulated deep water in the REF simulation is warmer by about 1°C and saltier by about 0.1 psu than the observed values. The warmer and saltier biases in the REF deep water in comparison to the observed seems to be
associated with a too weak convection in the Southern Ocean and the associated formation of relatively colder and fresher AABW.

Fig. 2 Zonally averaged annual-mean meridional section of the simulated (a) potential temperature and (b) salinity for the REF, (c) potential temperature and (d) salinity for the LGM, and (e) potential temperature change and (f) salinity change.

With the imposition of glacial boundary conditions, polar oceans becomes close to the freezing point in the LGM (Fig. 2c), yielding deep ocean cooling of about 4°C (Fig. 2e). Although this amount of LGM cooling compared to modern is too large because of a warm bias in the REF deep water, the resultant near freezing LGM deep ocean temperature in the LGM simulation is supported by the recent paleoceanographic estimate using sediment core pore fluids of benthic fossils (Schrag et al., 1996; Adkins et al., 2002).

The simulated LGM salinity section shows qualitatively different features from that of present (Fig. 2b and 2d). The high salinity tongue found in the REF northern mid-latitudes, that are associated with the Mediterranean and NADW outflow in the present ocean, is absent in the LGM section and the northern hemisphere oceans become overall fresh. The deep ocean freshening in the northern hemisphere is originated in the northern North Atlantic where surface salinity is substantially reduced in the LGM simulation (Fig. 4a). As described in Kim et al. (2003), the North Atlantic freshening in the LGM is associated with an increase in local precipitation over evaporation and increased fresh water supply to the North Atlantic from the Mississippi and Amazon rivers. In the Southern Ocean, the deep ocean becomes saltier in the LGM simulation and the AAIW tongue is almost absent (Fig. 2d). That the Southern Ocean deep water is saltier than the northern hemisphere deep ocean in the LGM simulation is consistent with observational proxy estimates by Adkins et al. (2002).
CONCLUSIONS

The imposition of glacial boundary conditions leads to heat loss to the atmosphere from the deep ocean through enhanced vertical mixing and active turbulent heat fluxes. At a near-equilibrium LGM state, the deepwater temperature becomes close to the freezing point, a result supported by several recent proxy estimates. The LGM boundary conditions also result in a marked modification in the sea surface salinity. Sea surface salinity is decreased in the northern hemisphere, largely due to freshening of the northern North Atlantic, and is increased over the Southern Ocean in part due to an increase in sea ice formation and a drier climate in the southern high latitudes. In conclusion, deep ocean conditions simulated by the coupled model are in reasonable qualitative agreement with observational proxy evidence. The coupled model results largely illustrate mechanisms responsible for the LGM deep ocean change. In particular, the redistribution of surface freshwater budget leads to a weaker and shallower North Atlantic overturning circulation and rather different deep ocean thermohaline properties during the LGM.

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THE INFLUENCE OF ENSO ON THE GENERATION OF DECADAL VARIABILITY IN THE NORTH PACIFIC

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INTRODUCTION

The pattern of the Pacific Decadal Oscillation (PDO) has both tropical and extratropical loadings. Still unresolved is the debate whether this mode of Pacific climate variability originates from the tropical Pacific or whether it is created by atmosphere-ocean instabilities in the extratropics.

Based on a Coupled General Circulation Model (CGCM) simulation, Latif and Barnett (1996) proposed that positive air-sea interactions in conjunction with the propagation of Rossby waves in midlatitude may give rise to North Pacific decadal climate variability. The simulated decadal mode of extratropical variability bears some similarity with the observed PDO. In the later modeling studies (Schneider), the importance of coupled air-sea interactions for this mode was relaxed and the importance of stochastic forcing and spatial resonance (Saravanan) was highlighted. Several possibilities exist to communicate the extratropical decadal signals into the tropics. Among them the Gu and Philander (1997) hypothesis of advecting extratropical temperature anomalies on isopycnal surfaces into the tropical Pacific has received a lot of attention. However, further quantitative estimates (Schneider et al. 1999; Nonaka et al. 2000) revealed that this pathway is rather inefficient for the generation of decadal variability in the tropical Pacific. The footprinting mechanism (Vimont 2003) may also help to communicate extratropical signals into the tropical Pacific as well as decadal transport changes of the subtropical cells (Kleeman 1999, Nonaka). Alternatively, Bratcher and Giese (2002), Giese et al. (2002) and Luo et al. (2003) suggested that the decadal signals in the tropical Pacific originate from the South Pacific.

In addition to the extratropical forcing mechanisms several tropical mechanisms have been suggested which may explain the presence of decadal variability in the tropical and extratropical Pacific. Neglecting ocean dynamics, even the mixed layer has the ability to integrate the stochastic momentum and heat fluxes, yielding a red-noise spectrum (Hasselmann 1976).
Another source for ENSO irregularity (chaos) and hence decadal variability in the tropical Pacific is the nonlinear interaction between ENSO and the annual cycle (Jin et al. 1994, Tziperman et al. 1994). For certain coupling strengths the annually varying background state in the tropical Pacific can trigger low-dimensional ENSO chaos as a result of nonlinear resonances and the devil staircase. Timmermann and Jin (2002) and Timmermann et al. (2002) and Timmermann (2003) hypothesize that ENSO chaos as well as the emergence of decadal El Nino bursting can be generated without invoking neither extratropical processes nor annual cycle and stochastic forcing.

Timmermann et al. (2002) argue that a heteroclinic connection in phase-space between a saddle node (weak La Nina state) and the saddle point (radiative convective equilibrium) organizes ENSO dynamics in a particular way: ENSO variations grow until they reach the maximum intensity El Nino, then a quick reset takes place and the small ENSO variations grow again. Due to the skewness of El Nino and La Nina in this model, the decadal growth of the ENSO amplitude is immediately translated into decadal background state changes. Hence decadal tropical variability is a residuum of skewed ENSO amplitude modulations. This idea had been supported by Timmermann (2003) using a CGCM simulation and by Rodgers et al. (2003). Given the strong atmospheric teleconnection from the tropical Pacific to the extratropical North and South Pacific, decadal variability in the extratropical Pacific can be easily triggered from decadal changes of ENSO and the associated changes of the climate background condition. This scenario may also explain why the PDO exhibits such a strong equatorial symmetry. Furthermore additional persistence of the teleconnections and extratropical SST anomalies may originate from extratropical ocean dynamical changes or the re-emergence mechanism.

To be more specific we aim to address the following questions: Is the PDO just the residuum of very strong El Nino events? How much of the decadal North Pacific SST variability can be explained in terms of decadal modulations of ENSO and atmospheric teleconnections?

ASYMMETRIC INTERANNUAL SSTA VARIATION IN THE NORTH PACIFIC

The asymmetric interannual SSTA variation in NP for a certain decadal period can be rectified into the decadal variation of NP SST. In particular, ENSO might induce the asymmetric interannual NP SSTA through its asymmetrical variation (e.g., El Nino and La Nina are not symmetric) and the asymmetric midlatitude teleconnection with respect to ENSO forcing. These two effects will be discussed in this section.

The anomalous tropical heating associated with ENSO perturbs the atmospheric circulation field that propagates onto the North Pacific sector. Through this atmospheric teleconnection, the ENSO influences the North Pacific climate variability. Interestingly, this teleconnection is not
simply linear; the La Nina is more influential
than El Nino (Hoerling et al. 1997). This
nonlinear teleconnection also has been
extracted by the nonlinear projection (Wu
and Hsieh 2004), and this objective sta-
tistical method provided the consistent result with that
shown by a simple composite method in
Horeling et al. (1997, 2001). Here, we obtain
the nonlinear regression map of 500hPa
giopotential height and SST anomalies with
respect to ENSO index. Both data sets, which
covers about recent 53 years are obtained from
NCEP reanalysis (Kalnay et al. 1996) and
ERSST.v2 (Smith and Reynolds 2004),
respectively.

Figure 1 shows the response of 500hPa
giopotential height (GPH) and SST over the
North Pacific during the boreal winter time to a specified Nino-3 index value obtained from the
nonlinear response function. The nonlinear response function is defined as following;

$$ \chi(\vec{x}, Nino) = \sum_{i=1}^{N} E_i(\vec{x}) \cdot C_i(Nino) $$

(1)

Where $\vec{x}$ is the state vector, $E_i$ is the eigenvector obtained by EOF of GPH or SST over the
North Pacific, and $C_i$ is the nonlinear regression function, which represents the nonlinear fitting
curve between the EOF PC time series and Nino-3 index. We use the five leading EOF modes,
thus $N=5$. The nonlinear function ($C$) has been obtained by using the artificial neural network
(NN). In the present NN, we use only one input variable (NINO3 SST) and five output variables
(EOF PCs). This approach is basically same as that of Wu and Hsieh (2004). The input variable
is first nonlinearly mapped to two intermediate variables (i.e. Hidden Neurons), which are
linearly mapped to five output variables. The NN model parameters are optimized in order that
the mean square error between the output variables and the observed EOF PCs is minimized.
We repeated above calculation with a bootstrap approach by randomly selecting data sample, so
they show the present results are not sensitive to the data sampling (not shown).

As shown in Fig. 1, to the weak ENSO ($\pm 1$ °C of Nino-3), both GPH and SST in the North
Pacific respond quite symmetrically – almost same pattern and comparable amplitude with an
opposite sign. As the ENSO forcing becomes larger (for example, $\pm 2$ °C and up of Nino-3),
however, two patterns show strong asymmetry. The maximum SSTAs in North Pacific
associated with El Nino and La Nina are commonly located east of the date line around 40 °N,
but the amplitude by La Nina (-2 °C) is almost twice larger than that by El Nino (+2 °C). Hoerling et al. (1997) also showed that SST pattern associated with La Nina is stronger than that associated with El Nino in their composite analysis. In GPH response to ENSO, not only the amplitude but also the location shows asymmetric feature. The GPH pattern associated with El Nino is shifted to the southeasternward (around 150°W, 40°N), while that associated with La Nina shifts to the northwesternward (around dateline, 50°N), compared with the weak forcing response pattern. This zonal shift of GPH pattern may be related to the difference in the location of the tropical heat source between El Nino and La Nina (Hoerling et al. 1997; Kang and Kug 2002). The anomalous atmospheric circulation might induce the anomalous latent heat flux and the anomalous oceanic vertical mixing, which obviously modify the SST anomaly. Since the anomalous atmosphere circulation should be incorporated with the established mean circulation in order to generate anomalous surface heat flux and oceanic vertical mixing, the different spatial distribution of the atmospheric circulation anomaly, even though the amplitude associated with El Nino is comparable to that associated with La Nina, may result in a relatively big difference in SST response. As expected, the nonlinear regression pattern of the latent heat flux to the Nino-3 SSTA (not shown here), shows asymmetric feature with respect to Nino-3 SSTA. The warming (cooling) by the latent heat flux during La Nina is well matched to the positive (negative) SSTA in the Fig. 1.

In addition to the nonlinear response of the North Pacific SSTA to the ENSO as shown in Fig. 1, the asymmetry of ENSO (Burgers and Stephenson 1999; An 2004) also directly cause the asymmetric behaviors of North Pacific SST variation. The El Nino is in general stronger than La Nina, and this El Nino-La Nina asymmetry especially becomes dominant since the late 1970s (e.g., An 2004; An et al. 2005). The difference between two panels in Fig. 2 shows that the El Nino-La Nina asymmetry is underwent the interdecadal changes as also mentioned in An (2004). In the following section, we will show how this decadal changes in the El Nino-La Nina asymmetry is linked to the decadal change in North Pacific SST.

Figure 2 shows the observed and simulated decadal change in North Pacific SSTA obtained from the hindcast experiment. Although our calculation is Fig. 2. Decadal change of observed (upper panel) and the simulated (lower panel) North Pacific SSTA. The simulated SST has been obtained from the nonlinear statistical model for a given observed Nino-3 index.
done by a simply way so that rather than the comparison in the quantity, the comparison in quality is reasonable. In general, two patterns are quite similar. Particularly, the hindcast well simulates the SST anomaly in the east of the dateline where the ENSO strongly influences, while the SST anomaly over the west of the dateline including the Kuroshio extenstion is less matched to the observation.

SUMMARY AND DISCUSSION

The midlatitude atmospheric circulation pattern is mainly determined by the intrinsic atmospheric waves such as midlatitude storms and by the large-scale atmospheric waves originated from the tropics, mostly by ENSO (An and Wang 2005). While the intrinsic atmosphere waves are considered as stochastic process in the seasonal timescale, thus the seasonal prediction point of view, the pattern generated by the ENSO mainly reminds as a signal. As shown in the previous sections, even the symmetric ENSO forcing can generate the asymmetric response in the North Pacific SST through the nonlinear teleconnection. Thus, the long term accumulation of this asymmetric interannual fluctuation of the North Pacific SSTA could manifest itself as a change in the mean state, particularly decadal-to-interdecadal variation through a rectifier effect.

The nonlinear rectification due to the asymmetric ENSO forcing and the nonlinear teleconnection may not be limited over the North Pacific, because ENSO influences all over the globe. For example, the ENSO is known to influence the tropical Indian Ocean (Klein et al. 1999; Xie et al. 2002) and Atlantic Ocean (??) and to interact with the local climate. The relationship between Indian Ocean (also Asian Monsoon) and Pacific Ocean underwent the interdecadal change. The interannual SST fluctuation over the Indian Ocean, referring the basin-wide and dipole modes (a.k.a. zonal mode), is modulated in the decadal timescale. In this sense, the decadal modulation of ENSO can be rectified into not only the tropical background state (Rodgers et al. 2004) but also the extratropical background state. The exploration regarding the global climate change rectified by ENSO will be in our next study.

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TEMPORAL VARIABILITY OF TOTAL OZONE, WATER VAPOUR, AOD, UV RADIATION (305, 312 & 320 NM), CO₂, CH₄, CO AND O₃ REVEALED BY GROUND BASED OBSERVATION IN CHANGING CLIMATIC CONDITION OF ANTARCTICA

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ABSTRACT

A synopsis of the temporal characteristics of total ozone column, total water vapour, aerosol optical depth (AOD), UV radiation at 305nm, 312nm and 320nm, carbon dioxide methane and carbon monoxide measurements revealed by ground based instrument over the Maitri, an Indian research station in Antarctica is presented. While, the study of temporal characteristics of surface ozone (2000) was made using data available from nearby station Syowa (Japan). The total column ozone (1997, 2002-04), water vapour (1997, 2002-04) AOD (2002, 2004) and UV (2002, 2004) radiation measurements were done using Microtops-II Sunphotometer. The CO₂ (2002-2004) and CH₄ (2003-2005) measurements were made during 21st – 23rd Indian Antarctic Scientific Expedition (IASE) using online Gas Chromatograph. While, gas filter correlation non-depressive IR absorption (NDIR) CO analyzer was used for continuous measurement of surface air CO concentration during 22nd IASE (Feb-March 2003).

A comparative study of total ozone showed direct relationship between the stratospheric temperature anomaly and year-to-year variation in total column ozone. A strong positive relationship is observed between day-to-day variability of UV radiation at 305 nm, 312 nm and 320 nm and total ozone. The observation showed signature of increasing total water vapour column at Maitri, Antarctica. A strong positive correlation has also been between surface
temperature and water vapour, and showed a signature of increase in the surface temperature. A low aerosol optical depth of about 0.03 is found for this anthropogenically least-affected continent on the earth. During the observational period, CO₂ surface air concentration showed mean yearly value of 368.43 ppm in the year 2002 and 369.72 ppm in the year 2003 indicating an increase by 1.3 ppm. This corresponds to a growth rate of 0.35% per year. Mean CH₄ concentration for sixteen-month period has been observed to be 1.699 ppm with standard error of ±0.0025. Unlike CO₂ the CH₄ do not show any evidence for an increase in the observation period. Particular attention is given to identifying diurnal variability of surface CO and O₃ over polar region. Diurnal changes in CO concentration were systematically observed in Antarctica during clear sky conditions, with higher CO concentrations in daytime sunlight period, indicating that the solar induced CO production processes are active in surface snow layers. The mean CO production rate (007h-14h) during observational period is 3.4ppb/h. The seasonal behavior of surface ozone revealed the photochemical loss rate of 56% with respect to the maximum and minimum concentration observed during observational period. A linear regression analysis applied to the data set showed photochemical loss rate decreased at a rate of 0.12 (±0.002) ppb/day from summer minimum to winter maximum (before mid-winter day). While the negative slope from winter maximum to summer minimum after mid-winter day suggest a photochemical loss rate of 0.08 (±0.003) ppb/day. The diurnal variability of surface O₃ shows an increase in ozone in night (until 7h) and a decline between 7-19h. in the present communication a detailed analysis and results obtained in presented.

Key Words: Ozone, UV radiation, AOD, carbon dioxide, methane carbon monoxide, water vapour
MODELLING OF KATABATIC WINDS OVER ANTARCTICA

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ABSTRACT

A one-layered mathematical model is developed for flow of katabatic winds over Schirmacher region of East Antarctica. The model stands on momentum and sensible heat transport to the ice slope surface under calm conditions. The estimation of model parameters have been made using high-resolution maps of pressure contours and the measurements of surface based meteorological parameters. The wind velocities have been computed using the model with actual slope of 130°, the ratio of mean bulk coefficient ($C_B/C_M$) and over a large variations in slope angle ($\alpha$), potential temperature gradient between air parcel and slope surface ($\theta$), slope length (l). The model results suggest that it is the inclination angle or terrain slope and the distance at which inversion forms control the speed of katabatic winds. It further indicates that the slope on the icy terrain controls the direction of katabatic wind.

Key Words: Antarctica, Katabatic winds, cold air parcel, momentum and sensible heat, cold air parcel and ice surface
[Session III]

Geophysics
INTRA-PLATE SEISMICITY AND RECENT LITHOSPHERIC DYNAMICS IN THE ANTARCTIC AND SURROUNDING OCEAN: ESTIMATION OF THE OCCURRENCE OF BALLENY EARTHQUAKE 1998

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The Antarctic continent and surrounding ocean were 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 increased. In this presentation, seismicity in the Antarctic and surrounding ocean is evaluated based on the compiled data in 1964-2002 by International Seismological Centre. The total of 13 seismicity areas were classified into the Antarctic Continent (three areas) and oceanic regions within Antarctic Plate (the other 10 areas). Generally seismicity in the continent is very low. Wilks Land is the most active area in the Antarctic Continent; several small earthquakes detected during four decades. In the ocean area, seismic activity in the area of 120⁰W sector is three times larger than the other areas. This is considered to be involved a stress concentration toward the Easter Island Triple Junction among Antarctic Plate, Pacific Plate and Nazua micro-Plate. Three volcanic areas, Deception Island, Mt. Erebus and Mt. Melbourn, are high seismic activity areas.

Recently some intra-plate earthquakes became to be located in the southern ocean. Most intraplate earthquakes in the surrounding ocean are not caused by stress after deglaciation. A large Mw=8.1 earthquake occurred off the northeast coast of Antarctica near the Balleny Island region on March 25, 1998; which was one of the largest intraplate earthquakes ever recorded. It was argued that the subevents aligned along the nodal plane trending east-west direction, which indicates that the earthquake occurred along this east-west, left-lateral, strike-slip fault. Tsuboi et al. (2000) showed this fault mechanism is consistent with crustal motion of the Antarctica derived from the Earth's response to present-day and past ice mass changes in Antarctica (James and Ivins, 1998). It was quantitatively examined the regional earthquake potential associated with postglacial rebound of the lithosphere. The stress variations caused by the ice mass change were calculated in the same manner as those in James and Ivins (1998)
with the viscosity $10^{21}$ Pa sec, and 120 km thick elastic lithosphere. The stress changes occur in a background tectonic stress orientation at 75 degrees east.

The results show that the Coulomb stress change becomes significantly negative (promoting seismicity) around the 1998 earthquake region, which indicates that the ice mass change can be a possible cause of the earthquake. The results also imply that the thickness of the lithosphere can be an important parameter to the quantification of the stress change caused by the ice mass change. Time variations in seismicity around the Balleny Earthquake Region have drastically changed before / after the main shock occurred in 1988 March. The most recent distribution of the hypocenters around this area seems to extend toward inland of Wilks Land, followed by the excitation of local events beneath the continental ice sheet.
CHARACTERISTIC SEISMIC WAVES RECORDED BY THE EXPLORATION ON THE MIZUHO PLATEAU, EAST ANATRCTICA: RESPONSES FROM VALLEY STRUCTURE OF THE BEDROCK AND BACKGROUND SEISMICITY

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Characteristic seismic waves from natural sources were recorded in seismic exploration experiments on the Mizuho Plateau, East Antarctica. The teleseismic waves show high signal-to-noise ratio in spite of a small magnitude of the event. These waves were classified into the following three kinds: (1) a teleseismic events; e.g., occurred at Kermadec Is. region, (2) local ice-quakes around the Lützow-Holm Bay Region, and (3) an unidentified event around Antarctic (X-phases). The seismic recordings of natural sources obtained by seismic exploration provide us interesting features of the seismic wavefield. We can find the discordances of the frequency contents and of the arrival times in the traces. The following anomalous features are seen in the waveforms of the stations just above the valley structure of the boundary between the ice sheet and the upper crust. (1) The frequency contents of 1.5, 3.0 and 5.0 Hz are large compared with those in other stations and those of 2.0 Hz are small. (2) A difference of the response generated from the valley structure might exist according as the kind of incident waves such as of P and S waves: P-wave incidence to this valley structure might result in the normal arrival, on the other hand, S-wave arrival might be delayed.

A significant feature of the X-phases is successive arrivals of seismic energies with almost zero slowness for about 100 s after the onset. The candidate of the event might be the Rat Is. (Aleutians) earthquake. However, we will show that it would not be the event to produce the X-phases. An epicentral distance from the event to the center of the observation line is about 152°. Since this event has a small magnitude (4.8 mb), it is uncertain that such a small earthquake could be recorded by seismographs at a large epicentral distance. Therefore, we cannot expect that different responses would be generated by the complex topography of the boundary between the Rat Is. event and the Kermadec Is. event. However, there is a difference between the waves of the X-phases and the Kermadec Is. event. The gap of 2.0 Hz in the middle part of
seismic line is found in these two cases. The peak of 1.5 Hz with the time delay of about a second after the gap is seen only in the X-phases and that of 3.0 Hz without time delay is only in the Kermadec Is. event.

Features of the X-phases are clearly different from those of the local icequakes. A possibility of the origin of the X-phases may be regional intraplate earthquakes. Such regional events around Antarctica from 1900 to 1999 are compiled by Reading (2002). East Antarctica from 90°E to 180°E, particular in Wilkes Land, Transantarctic Mountains and Ross Sea areas, is the region showing highest seismicity in the Antarctica. From the comparison with the arrival data at Syowa Station, the maximum amplitudes of seismic phases appear to arrive at Syowa with the delay of several seconds. Therefore the X-phases may be considered to come to the exploration observation line and then Syowa Station from the relatively active seismogenic region in Wilkes Land – Ross Sea area.
MAGNETIC FABRIC OF PSEUDOTACHYLYTE IN THE MT. RIISER-LARSEN AREA, EAST ANTARCTICA

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INTRODUCTION

A fault related pseudotachylyte is an aphanitic rock attributed to frictional melting associated with co-seismic faulting. Pseudotachylyte is generally regarded as unfoliated, i.e. it has no planar/linear fabric elements that may enable us to estimate the direction and sense of slip. We studied the magnetic anisotropy of pseudotachylyte in the Mt. Riiser-Larsen area to assess the possibility of magnetic approach as a method of structural analyses.

Magnetic fabric analysis often offers precise and non-destructive way to quantify the average alignments of minerals in a small rock sample. Anisotropy of magnetic susceptibility (AMS) usually reflects alignments of Fe-bearing minerals or anisotropic distribution of magnetite grains. It is widely recognized that AMS has a potential to provide valuable information of strain history in fault rocks and igneous rocks. On the other hand, anisotropy of isothermal remanent magnetization (AIRM) reflects only magnetic minerals. We employed AIRM to study the alignment of newly crystallized magnetic minerals. This idea is based on Nakamura et al. (2002) in which they confirmed that submicron magnetite is formed in experimentally generated pseudotachylites.

This study reports the AMS and AIRM fabrics of pseudotachylyte from the Mt. Riiser-Larsen area, Enderby Land, East Antarctica. The main object is to demonstrate the orientations of the magnetic fabrics and to identify the source minerals that control the magnetic fabrics.

SAMPLES AND EXPERIMENTS

The pseudotachylites is located in the western part of the Mt. Riiser-Larsen area in NE-SW strike. The fault vein occurs in a nearly vertical zone in granulite-facies felsic gneiss of the Archean Napier Complex. The main minerals in the wall rocks are quartz, feldspar, orthopyroxene and ilmenite. The fault vein of maximum 10 cm width and 220 cm long consist
of dark matrices with closely spaced joints, and inclusions of variable size of lithic fragments. Presence of several injection veins is an evidence for melt origin of the rock. Amplitude and sense of the slip are unknown owing to the lack of definitive indicators. Microscopic observations showed some typical textures of pseudotachylyte, such as embayments in lithic clasts, acicular microlites of orthopyroxene, and flow structures. Powder X-ray diffraction analysis showed the strong diffraction peaks corresponding to quartz and feldspars, along with smaller peaks for orthopyroxene.

Nine core samples were collected from the fault vein using a portable drill. AMS measurements were carried out for eight specimens (10.8 cm³) using a Kappabridge magnetometer. AIRM were measured for five specimens using a pulse magnetizer and a cryogenic magneometer. The nine-position measurement scheme of Girdler (1960) was applied. After the IRM acquisition, the specimens were each time demagnetized in a maximum alternating field of 100 mT to isolate the high-coercivity component. In order to identify the magnetic carriers, we performed the following rock magnetic measurements: hysteresis measurements, stepwise acquisition experiment of IRM and stepwise thermal demagnetization of a composite IRM (Lowrie, 1990). The composite IRM was orthogonally acquired at 2.5 T, 0.4 T and 0.12 T. To estimate the ferromagnetic contributions to AMS, mean high-field magnetic susceptibility was obtained from 5 rock tips using an alternating gradient force magnetometer. The gradient in hysteresis loops between 1.0 and 1.2 T were used for the calculation.

RESULTS AND DISCUSSION

The results of AMS and AIRM measurements can be described in terms of an ellipsoid with three orthogonal principal axes, designated the maximum, intermediate and minimum susceptibility axes (Fig. 1). AMS principal axes of the pseudotachylyte are largely scattered, while those of AIRM shows well defined, tri-axial distributions. However, the orientation of their magnetic foliations defined by the plane through the maximum and intermediate principal axes are close to each other. It is noted that the magnetic foliations are not exactly parallel to the fault strike.

The results of the rock magnetic experiments showed that the mean low-field magnetic susceptibility is as low as $7.5 \times 10^{-8} \text{ m}^3/\text{kg}$, close to the high-field magnetic susceptibility of $7.7 \times 10^{-8} \text{ m}^3/\text{kg}$ obtained from the hysteresis loops (Fig. 2a). The result of the stepwise acquisition of IRM showed the relatively high saturation field of more than 1 T (Fig. 2b). Presence of at least 2 magnetic minerals was indicated by the result of the demagnetization experiments (Fig. 2c). The relatively high coercivity mineral has the maximum unblocking temperature ($T_u$)
between 280 and 320 °C, and small fraction of the lower coercivity mineral has \( T_u \) between 580 and 600 °C.

![AMS and AIRM projections](image)

**Figure 1.** Equal area projections of the AMS and AIRM principal axes. Open symbols are raw data for each specimen. Solid symbols and shaded areas are mean directions and 95% confidence ellipses, respectively.

![Hysteresis loop, stepwise IRM acquisition, and thermal demagnetization](image)

**Figure 2.** Representative results of rock magnetic measurements: (a) hysteresis loop, (b) stepwise IRM acquisition and (c) thermal demagnetization of the composite IRM.

The results of low- and high-field susceptibility infer that AMS is mainly carried by paramagnetic minerals, probably by acicular microlites of orthopyroxene and/or orthopyroxene in host rock fragments. Because maximum susceptibility axis of orthopyroxene should correspond to its c-axis, the acicular crystals should tend to lie on the magnetic foliation. It is, however, uncertain the scatter in the maximum axes reflects their actual orientation distributions because AMS may be largely disordered by the alignments of pyroxene in gneissic fragments.

The microscopic observations revealed that ferrimagnetic pyrrhotite (Fe\(_7\)S\(_8\)) of smaller than a few micrometers are localized in fracture planes of some quartz and orthopyroxene clasts. This is consistent with \( T_u \) of 320 °C. AIRM is probably controlled by the lattice preferred
orientation of pyrrhotite. The mode of occurrence also infers that the production of pyrrhotite is associated with the formation of the pseudotachylite, rather than secondary products due to fluid migrations. Brandl and Reimold (1990) and Camacho et al. (1995) also reported similar inclusions of opaque minerals in pseudotachylite from the other areas, indicating it is a common phenomenon. Pyrrhotite was observed in the host rocks as accessory minerals, and this could be the source for the inclusions.

The orientation of the magnetic foliation appears to correspond to the microscopic flow structures defined by the elongate lithic clasts and flow streak. The flow structures are, however, absent in some of the specimens. Although the cause for the crystallographic orientation of the magnetic carriers is beyond the scope of this study, we suggest that magnetic fabric analysis, especially AIRM, may be a good detector for subtle foliation or lineation in pseudotachylite.

SUMMARY

Magnetic fabric of the pseudotachylite in the Mt. Riiser-Larsen area, East Antarctica were studied. Through the rock magnetic analyses including anisotropy of magnetic susceptibility (AMS) and anisotropy of isothermal remanent magnetization (AIRM), the following conclusions can be drawn.

The AMS and AIRM of the pseudotachylite in the Mt. Riiser-Larsen area are mainly controlled by alignment of orthopyroxene and pyrrhotite, respectively. Only AIRM fabrics show well defined tri-axial distributions of the principal axes. Their magnetic foliations are, however, consistent to each other and oblique to the fault strike. The magnetic foliations are consistent to microscopic flow structures, suggesting that the AMS and AIRM fabrics reflect the primary structures associated with the generation of the pseudotachylite.

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THE STRUCTURE OF THE TRANS-ANTARCTIC MOUNTAINS AND EAST ANTARCTICA FROM BROADBAND SEISMOLOGY - THE TAMSEIS EXPERIMENT

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The 2000-2003 TAMSEIS experiment is the largest deployment of broadband seismographs in Antarctica and demonstrates the potential of seismology in imaging the structure of the Antarctic continent. This experiment deployed 44 broadband seismic stations extending from the Ross Sea (RS) to the East Antarctic Plateau in order to investigate the lithospheric structure beneath the Trans-Antarctic Mountains (TAM) and East Antarctica (EA). The experiment consisted of three components: 1) A 1400 km linear array of 17 seismic stations extending from the central regions of the East Antarctic craton to the TAM  2) an intersecting 400 km dense linear array of 16 stations extending from the coast across the TAM in the Dry Valleys region. 3) 11 stations in coastal regions within 300 km of Ross Island. Stations were installed using helicopter and twin otter aircraft operating out of McMurdo station and a remote field camp.

Combined receiver function and Rayleigh wave phase velocity inversion, as well as P and S wave tomography constrain models for the development of the TAM. The crustal thickness increases rapidly from 20 ± 2 km in the Ross Sea to 40 ± 2 km beneath the TAM, achieving the maximum thickness immediately beneath the TAM crest. Farther inland, the crust of EA is uniformly 35 ± 3 km thick over a lateral distance greater than 1300 km. The phase velocities and body wave tomography indicate high velocity cratonic upper mantle beneath EA, low velocity beneath WA, and a transition beneath the TAM crest. These results are in agreement with models suggesting that warm buoyant Ross Sea upper mantle extends beneath the edge of the TAM, inducing flexural uplift of the mountains. Both Rayleigh wave phase velocities and SKS splitting results show a large uniform region of azimuthal anisotropy within the uppermost mantle of EA, with fast axes oriented about N55E. The shallow depth of the anisotropy indicated by the surface waves suggest it results from remnant upper mantle lattice preferred orientation from past deformational episodes, rather than the current upper mantle flow pattern.
The mapping of upper mantle anisotropic directions offers a possible method for delineating geologic terrains in ice covered East Antarctica.
3D AEROMAGNETIC MODELLING IN THE GRUBERGEBIRGE AREA, 
CENTRAL DRONNING MAUD LAND, EAST ANTARCTICA

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SUMMARY

The aeromagnetic field in the Grubergebirge area in the central Dronning Maud Land, East Antarctica is interpreted using 3D aeromagnetic modelling. The prominent magnetic minimum in this area is associated with the extended anorthosite. The volume of anorthosite values about 30,000 km³. The intruded granites explain the magnetic maximum flanking the Grubergebirge. The most negative magnetic anomaly of the Grubergebirge, particularly in the area of the lake Untersee between the Ritschergipfel and the Mentzelberg is fitted only by modifying the model structure with an opposite magnetic direction, which might be related to the impact structure.

INTRODUCTION AND GEOLOGIC, PETROMAGNETIC SETTING

In 1995/96 the Federal Institute for Geosciences and Natural Resources (BGR) carried out the GeoMaud expedition, which focused on investigations of the structure and geological history of the Earth's crust in central Dronning Maud Land (cDML) from 7° to 16°E and from 69° to 73°S.

As an important tool for solving structural questions in ice-covered areas and for interpretation of deep-seated crustal features, a detailed aeromagnetic survey covered a major part of cDML. That survey discovered a prominent magnetic low in the Otto-von-Grubergebirge (hereafter referred to as Grubergebirge) with highest elevations above see level of 2810 meter (Ritschergipfel), 2320 meter (Zimmermann-Berg), and 2330 meter (Mentzelberg). Towards the north, the Grubergebirge opens in form of a deep glacial valley with the lake Untersee in its deepest part (563 m) (Damasek et. al., 1999).

The Grubergebirge, as a area of this investigation (Fig. 1) is in the central Dronning Maud Land (cDML in Fig. 1) from 12° to 14°E and from 71° to 71°30'S (77x77 km).
In the northern part of the investigation area the magnetic field anomaly pattern is characterised by linearly arranged magnetic anomalies of moderate amplitude (on the order of 100 nT; 1 nT = 10^{-9} Tesla). The southern part of the study area is dominated by elongated anomalies of higher amplitude than in the north. As seen Figure 1, a prominent magnetic low of about −600 nT extends northeast and covers the entire Grübergebirge. To the northwest, the magnetic low is flanked by a wide transition zone which forms the transition to a magnetic high in the Skaly Gubkina area reaching more than +350 nT. To the southeast of the Grübergebirge magnetic minima and maxima occur in a more irregular pattern (Damasek et al. 1999).

![Aeromagnetic field map](image)

**Fig. 1:** Aeromagnetic field in the study area and the locations of exposed rocks. Contour lines are at 5 nT and in the high-gradient zone at greater intervals. The locations of the N–S cross sections from north and south in Figure 2 and the E–W cross section in Figure 3 are also shown.

The geometry and rock parameters of 3D modelling were estimated using geological information and magnetic susceptibility data obtained from samples collected during the GeoMaud expedition (Damasek et al. 1999). The geological structure of the investigation area is characterised by upper mesoproterozoic metamorphic rocks with a susceptibility value of 200×10^{-5} (SI) that are intruded by voluminous igneous rocks of differing composition. The metamorphic rocks crop out in the Mittlere and Westliche Petermannkette, at the northern tip of the Oestliche Petermannkette, at the northern flank of Mount Schneide and in the Skaly Gubkina area (Fig. 1). They are represented by high-medium-grade
metasedimentary and metavolcanic sequence, which were intruded by syn-tectonic orthogneisses of silicic to intermediate composition (Damaske et. al. 1999).

The Grubergebirge is characterised by an elongated anorthosite body with a susceptibility of $20 \times 10^5$ (SI), which mainly composed of typical massif type anorthosite containing > 90% plagioclase (Ashwal, 1993). In the central part of the Grubergebirge, these anorhositic are completely undeformed and unmetamorphosed. In contrast, the peripheral parts of the Grubergebirge anorthosite were intensively foliated and transformed to meta-anorthosite under high-grade conditions. In the Grubergebirge was intruded by the granitoid with a susceptibility of $800 \times 10^5$ (SI) which contains abundant rafts of the older meta-anorthosite. The other rock types occurring within the Grubergebirge have higher susceptibility values than anorthosite. For example, the susceptibility values of both the granites (more than $4000 \times 10^5$) and gabbros (more than $3500 \times 10^5$) in that area are extremely high. A very small biotite granites body with susceptibility of $4000 \times 10^5$ (SI) exposed in the Skaly Gubkina (Damaske et. al. 2002).

In this paper, I present the geological structure of the Grubergebirge with respect to the results of a 3D modelling of the aeromagnetic anomalies. The magnetic susceptibilities of the rocks as the most important constraints for the modelling are summarised in Table 1 (Damaske et. al. 2002).

<table>
<thead>
<tr>
<th>Rock</th>
<th>susceptibility ($10^5$ SI units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>metamorphic rocks</td>
<td>200</td>
</tr>
<tr>
<td>granites</td>
<td>4500</td>
</tr>
<tr>
<td>anorthosite</td>
<td>20</td>
</tr>
<tr>
<td>gabbro</td>
<td>2500</td>
</tr>
<tr>
<td>granitoid</td>
<td>800</td>
</tr>
</tbody>
</table>

THREE-DIMENSIONAL AEROMAGNETIC MODELLING

Modern techniques of computer-based modelling (e.g., Goetze, H-J. & Lahmeyer, B. 1999) take advantage of the 3D geoinformation systems (GIS) functionality that makes it possible to incorporate estimations derived from geological information and magnetic

Sections across the study area from north to south are shown in Figure 2; they were constructed from geological and petromagnetic data in Table 1. The positive magnetic anomalies of about 300 nT in the Skaly Gubkina area are caused by the intruded granites with a magnetic susceptibility of 4500×10^-5 (SI) (between profile-km 1010 and 1020 in Fig. 2A). The local negative anomalies in the area of Ritschergipfel (from profile-km 1000 to 1020 in Fig. 2D) and Mentzelberg (from profile-km 1010 to 1020 in Fig. 4E) can be explained by an elongated body of anorthosite flanked by granites and gabbros with high susceptibilities of about 4000×10^-5 (SI).

![Diagram](image)

**Fig. 2:** N-S cross sections in the study area; the anomaly minimum in the Gruber-gebirge can be mainly explained by the elongated anorthosite. The maximum in the Skaly Gubkina area is caused by the intruded granites.

As shown in Figure 2D, however, the extreme minimum of the Ritschergipfel in the Grubergebirge of less than -600 nT (profile-km 1020) could not be modelled by the anorthosite only (the differences between measured and calculated magnetic anomalies are more than 200 nT). To better fit both amplitudes,
we need an unknown body of lower susceptibility than the anorthosite (20×10⁻⁵). In the computer modelling, we placed a model body within the anorthosite (polygon 1 in Fig. 2D) with a susceptibility of -2500×10⁻⁵ (SI) and a average thickness of about 4 km. This allowed the minimum of the Ritschergipfel and the lake Untersee to be fitted. A volume of the modified body values about 200 km³.

To verify the local anomaly in the northern part of the Mentzelberg (profile-km 1000 in Fig. 2E), a polygon with a susceptibility of -2500×10⁻⁵ (SI) in the metamorphic rocks and an average thickness of about 2 km is also included (polygon 2 in Fig. 2E). A volume of the polygon 2 values about 600 km³.

![Diagram](image)

**Fig. 3:** An E–W cross section clearly shows that the difference of about 900 nT between the anomalies coincides with the prominent susceptibility variation (more than 4000×10⁻⁵ (SI) between the Oestliche Petermannkette and the Grubergebirge.

These bodies with an opposite magnetic direction, modified nearing the lake Untersee between the Ritschergipfel and the Mentzelberg may be related to large impact structure, E.g. meteorite. The E-W cross section in Figure 3 clearly reveals that the magnetic maximum in the Oestliche Petermannkette is associated with the intruded granites. In contrast, the minimum in the Grubergebirge coincides with the anorthosite, which volume is assumed about 30 000 km³ (Fig. 4). The difference of about 950 nT between the high in the Oestliche Petermannkette and the low anomaly in the Grubergebirge can be explained by a magnetic susceptibility difference of about 4500×10⁻⁵ (SI) between the granites and the anorthosite. The local anomaly in the Grubergebirge, particularly in the area of Mentzelberg (between profile-km 40 and 50 in Fig. 3), is explained by the addition of a further body with a negative susceptibility.

**CONCLUSION**

3D modelling of the aeromagnetic field, geological and petromagnetic data leads to the following conclusions: (1) The magnetic high in the Skaly Gubkina area is due to granites,
which often show high susceptibilities of about $4500 \times 10^{-3}$ (SI) here. (2) The prominent magnetic minimum in the Grubergebirge coincides with the elongated anorthosite. (3) However, the extreme magnitude of $-600 \times 10^{-5}$ nT near the lake Untersee between the Ritschergipfel and the Mentzelberg can only be modelled by including a additional rock with a negative susceptibility of about $-2500 \times 10^{-5}$ (SI). Therefore, the low can be explained by the combined effect of the elongated anorthosite and the modified rock, which is speculated to be related to impact structure.

(4) A model geometry of the extended anorthosite body (Fig. 4) is characterised by an anticline structure that strikes East-West. The volume of this anorthosite in the investigation area is about 30 000 km$^3$.

![Model geometry of the extended anorthosite body](image)

**Fig. 4**: Model geometry of the extended anorthosite body, which characterised by an anticline structure and causes the prominent magnetic minimum anomaly in the Grubergebirge. The volume of this anorthosite values about 30 000 km$^3$.

**DISCUSSION**

Magnetic minerals responsible for magnetic anomalies can be classified in two groups according to whether their magnetic susceptibility is negative or positive: The negative susceptibility means that the magnetisation induced in the mineral by a magnetic field is in the opposite direction as the field, which generally due to a impact structure (R.W. Girdler et. al., 1992). On the basis of the negative susceptibility of the rocks analyzed for this study, I hypothesise that the unknown impact structures are enclosed by the anorthosite in the area of the Grubergebirge and cause the prominent minimum of about -600 nT. What kind of material these rocks are, and the geological interpretation of the negative magnetization in this area, however, remains uncertain.

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WHAT HAPPENS IN GAS HYDRATE-BEARING SEDIMENTS DURING/AFTER MASSIVE GAS EMISSION INTO WATER COLUMN IN THE SEA OF OKHOTSK?

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INTRODUCTION

Gas hydrates are an ice-like crystal in which gases, mainly methane, are held within rigid case of water molecules. As vast quantities of gas hydrates stored beneath the seafloor in the world have been reported, gas hydrates become a major target in marine research because of their potential as a future energy resource and their role on climate and environments (Kvenvolden, 1993).

Many active gas and fluid venting sites at the seafloor and gas flares in the water column have been detected in the Sea of Okhotsk where massive gas hydrate deposits have been found (Ginsburg et al., 1993; Matveeva et al. 2003, Biebow et al. 2003). In the N.E continental margin off Sakhalin Island, we simultaneously collected both high-resolution seismic and hydroacoustic data along the survey lines to examine fine-scale seismic structures of gas hydrate-bearing sediments and ongoing gas-emission features in the water column, respectively. Correlation of those two data sets enables us uniquely to investigate migration paths of methane in gas hydrate-bearing sediments directly associated with ongoing methane releases into the water column. We present here a model of the evolution of the gas chimney during and after large-scale gas release occurs in the water column.

METHOD AND DATA

In the framework of the 2003 CHAOS (hydro-Carbon Hydrate Accumulations in the Okhotsk Sea) Project, high-resolution seismic and hydro-acoustic surveys were carried out
simultaneously on the same survey tracks (Fig. 1). A total 83 km of high-resolution seismic data were collected to examine detailed subsurface features associated with gas/fluid emanations in gas hydrate-bearing sediments. The data were obtained using a sparker system "SONIC-4" made in Russia. A sparker source was operated at the frequency of 200-1200 Hz and the energy of 500-2000 J. Single channel streamer was used as a receiver. The system provides a resolution of 2-5 m for sediment strata and a bottom penetration of 50-300 m. To detect and investigate acoustic indications of gas emission sources into water column, the level of acoustic backscattering was collected using mainly 12 kHz hydroacoustic system "ELAC".

RESULTS

During the CHAOS cruise, 75 gas flares were newly detected during hydro-acoustic survey that was simultaneously conducted with high-resolution seismic survey. Some flares rise up to several hundreds meters from the seafloor near sea surface. In case of Flare F34a, its height is about 800 m (Fig. 2a). The widths of the flares at the seafloor are obviously less than 100 m. Flare F36 is well associated with topographic elevation (Fig. 2a). A cluster consisting of Flares F41-F43 is floating, not extending from the seafloor (Fig. 2b). It is indicated that gas emanation occurs intermittent.

High-resolution seismic profiles show many narrow near-vertical structures (gas chimney) which seem to extend from the HARs around the BHSZ toward the seafloor, occasionally reaching to the seafloor (Fig. 3). On seismic profiles, we can see two kinds of chimneys showing different seismic characteristics; (1) narrow and confined white-colored wipeout (little or no coherently reflected seismic energy) chimneys, (2) wide and diffuse dark-colored (enhanced reflection) chimneys. Occasionally, some wipeout (WO) chimneys are converted to the enhanced reflection (ER) chimneys near the seafloor.

In this study, high-resolution seismic and hydroacoustic profiles obtained on the same survey tracks show a remarkable relationship between acoustic chimneys in subsurface and gas flares in water column. Flares F34b and F35 on profile LV31-21-2 also seem to take place over the ER chimneys or enhanced reflections near seafloor. On profile LV31-22, three flares (F36a, F36b, and F37) are well associated with topographic mounds developed at the slope break, beneath which strong, wide and diffuse enhanced reflections appears at the interval of about 100 ms in depth. We can not see any flares above a distinct WO chimney at about 1 km landward of the mounds. As shown on seismic profile LV31-32 (Fig. 3), gas flares F46a, F47 and F48 rise from topographic expressions just above the ER chimneys, whereas no flares occur above the WO chimneys. Among them, flare F46a is called 'Kitami flare' associated with a major pockmark in the study area.
CONCLUSIONS

We propose a scenario to explain occurrence of two kinds of chimneys in gas hydrate-bearing sediments: (1) As warm fluid with gas is migrating upward into seafloor along the fault, the area around the fault become non-gas hydrate stability condition around the fault. Gas/fluid migrating along the fault saturates diffusely into adjacent sedimentary layers, which forms relatively wide ER chimney with enhanced reflection along the fault. (2) After stoppage of warm fluid supply, the ER chimney comes back under gas hydrate stability condition as inner temperature decreases. Thus gas in the chimney is converted into gas hydrates. Focused saturation of gas hydrates along the fault makes the narrow WO chimney. (3) New ER chimney is formed at the sites where gas/fluid is migrating upward along other path.

The Sea of Okhotsk is a unique area to study how methane migrates from subsurface to the atmosphere through the ocean. The high-resolution subsurface and hydroacoustic water-column images presented here give us better understanding to what happens in the gas-hydrate bearing sediments during and after methane releases into the ocean. One implication from this study is that methane released into the water column could come from the depths below BGHS. It means that we need to expand methane cycle related to gas hydrates into the deeper depths.

ACKNOWLEDGEMENT

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Fig. 1. Study area and locations of high-resolution seismic lines and gas flares.

Fig. 2. Features of gas flares newly detected during 2003 CHAOS Leg 1 cruise.
Fig. 3. High-resolution seismic profile of LV31-32. F46a, F47, and F48 (color insets) are gas flares. BSR: bottom simulating reflector, ER: enhanced reflection, HAR: high-amplitude reflectors, WO: wipe-out.
[Session IV]

Geology
SO178-KOMEX: MASS EXCHANGE PROCESSES AND BALANCES IN THE OKHOSTK SEA – BACKGROUND AND FIRST RESULTS

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Cruise SO178-KOMEX (Kurile Okhotsk Sea Marine EXperiment) focussed on detailed structural geological, geochemical, paleoceanographical and petrological investigations in the Okhotsk Sea. The expedition aboard RV SONNE was based on previous cruises conducted in the framework of the KOMEX project and is part of the German-Russian Cooperation. The major objective of this cruise was the use of technologically sophisticated video-guided instruments, the excellent coring facilities of RV SONNE together with its high-precision navigation system in order to enable detailed hydroacoustic mapping, detailed sampling of vent systems, associated ecosystems, and mineralizations as well as the recovery of long piston cores (25 m) with a high resolution of the stratigraphic column.

The Okhotsk Sea as a semi-enclosed "ocean" provides the unique opportunity to study the distributional patterns of materials, flux rates, and water mass formation, as well as circulation and climate dynamics because of the close spatial relationship and interaction of the geosphere, biosphere, cryosphere, hydrosphere, and atmosphere. Within the global ocean system, the marginal Okhotsk Sea plays a major key role as it provides the highest methane production rate of the northern hemisphere. Due to long-term sea-ice cover, the globally important release of methane into the atmosphere is extremely seasonally regulated. Methane is released into the Okhotsk Sea and the atmosphere from different sources. Volcanic systems, seeps of hydrocarbon accumulations, as well as gas hydrates and microbially diagenetically produced fluxes are known. We focussed on the near-surface gas hydrates and vent-related mineralization patterns on the northern Sakhalin Slope and in the Derugin Basin. The TV-guided sampling and observation systems provided spectacular views and samples of distinct sites. Detailed sampling of vent biota, for the first time including bacterial mats, pore water analysis, cores through the gas hydrate layer, barites and carbonates as well as a very detailed CTD sampling of methane flares enlarged our knowledge of these systems and provided a dataset for further improved quantification of methane fluxes.
SHRIMP U-Pb DETRITAL ZIRCON AGES AND GEOCHEMICAL PROVENANCE ANALYSES FROM LIBERTY HILLS AND LIPTAK FORMATIONS, ELLSWORTH MOUNTAINS, ANTARCTICA

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INTRODUCTION

The Ellsworth Mountains (EM), are located inland south of the Weddell sea, forming part of the Ellsworth - Whitmore Mountains (EWM) crustal block, one of five allochthonous terranes recognized in West Antarctica (Dalziel & Elliot, 1982). They are 350 km long and 80 km wide, and include the Sentinel and the Heritage ranges, respectively towards the north and south of the Minnesota Glacier. Last palaeogeographic reconstructions suggest that the EWM crustal block originated from a position adjacent to southern Africa and the Coats Land coast of Antarctica along palaeo-Pacific margin of Gondwana, however much uncertainty exists about its precise palaeo-latitude and palaeo-orientation (Curtis & Storey, 1996; Curtis, 1998; Curtis & Lomas, 1999; Curtis, 2001; Randall et al., 2004).

In this study, we present the first results of a broad geological study, that was carried out at Patriot Hills on the Middle to Late Cambrian Liberty Hills and Minaret Formations (LHF and MF respectively). We also present the results of the petrographical and geochemical analysis of LHF samples collected at the Union Glacier valley, and of samples of the Howard Nunatak Formation (HNF; Linder Peak Member) collected at the Tyree Mountain, north of the Vinson Massif (Sentinel range).

SEDIMENTARY PROVENANCE ANALYSIS

Seven Heritage Group (HG) and six Crashsite Group (CG) sandstones were selected for petrographic and geochemical analysis due to their low deformation and recrystallisation. Following Dickinson et al. (1983), sand-sized grains and lithic clasts were mineralogically identified for plotting in QFL and QmFLt diagrams, with between 120 and 210 points per slide
for five HG sandstones and about 200 points per slide for the CG sandstones (Fig. 1a). The HG samples were collected from the LHF, at the Patriot Hills area located at the southern tip of the Ellsworth Mountains. The CG samples were collected in six points at the Sentinel range and central Heritage Range. Discriminant functions were calculated as described by Roser and Korsch (1988). The data were normalised for that purpose on a 100% loss-on-ignition (LOI) free basis.

The results of point-count analysis are shown in a QFL diagram (Dickinson et al., 1983) (Fig. 1a) in which all the HG and CG sandstones plot in the continental block field. Specifically HG samples plot in the transitional continental subfield and CG samples plot in the craton interior subfield. In the Roser and Korsch (1988) diagram (Fig. 1b), all the HG and CG samples plot in the P4 field that corresponds to quartzose sediments of mature continental or recycled provenance. This provenance is commonly interpreted as representing clastic compositions typical of passive margin tectonic settings (Roser & Korsch 1988). The ratios of some elements are used in Fig. 1c (McLennan et al. 1993) to study the provenance of the samples. In this plot the Th/Sc ratio is used taking as a reference the upper continental crust Th/Sc ratio of >1. In this diagram all the samples, the HG and the CG sandstones, display Th/Sc values greater than 1, characteristic of differentiated sources. There is a good correlation between the Th/Sc ratio and the Zr/Sc ratio. The high values of the later are indicative of zircon concentration due to transportation and sorting from the source to the basin.

SHRIMP U-Pb AGE DETERMINATIONS

We analyzes three samples coming from: Liberty Hills Formation at Patriot Hills (sample EA1) and Union Glacier valley (sample EA2), and from Linder Peak member of Howard Nunatak Formation (sample EA3, Sentinel Range). Most of the 123 grains analyzed in these samples (23, 50, 50, respectively) plot on the concordia line in a 207Pb/235U vs. 206/Pb238U diagram with the exception of which give ages under 950 My (6 grains) in the sample EA1, over 2200 My (5 grains) in the sample EA2 and over 1400 My (4 grains) in the sample EA3. The preferred ages of the rest of the analysed zircon grains vary between 420 and 1931 My. In an age vs probability plot, the data set shows: in sample EA1, ca. 90% of the data form a large peak at ca. 1080 My, which can be resolved into two peaks at 1041 ± 12 My (2σ) Ma and 1090 ± 9.5 (2σ); the sample EA2, shows three sharped peaks, at ca. 460 My, 500 My and 530 My, seven grains with ages ranging between 560 and 610 My., and the rest of the grains (14) with ages ranging between 820 and 1120 My.; in the sample EA3, four large peaks are observed, at 520, 550, 570, and 600 My, while the rest of the grains show ages ranging between 720 and 1180 My.

CONCLUSIONS

The pattern of detrital zircon ages has the following implications: a) The source area was composed of Middle Ordovician to Ediacaranian (460-600 My) and Stenian (1000-1150 My) age rocks or their sedimentary derivatives, without evidence of 600-1000 My age sediments; b) The age of Liptak formation at the analyzed site, is younger than Middle Ordovician Epoch (<460 My), implying the possibility of an Ordovician age for the upper part of Howard Nunatak Fm.

The petrographic and geochemical features of the HG and the CG sandstones characterize them as being derived from similar sources of cratonic affinities, and suggest that these units represent a long time span of deposition (about 100 Ma) in a basin located on a rifted continental margin. This is in good agreement with the new tectonic scenario proposed by Curtis (2001), which account for the presence of rifting along a margin otherwise dominated by active subduction by Middle to Late Cambrian.
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PAN-AFRICAN EVENT IN DRONNING MAUD LAND, EAST ANTARCTICA

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The Dronning Maud Land (DML) which is the Indian Ocean sector of East Antarctica has been considered to be the southern continuation of the Mozambique belt in continental plate reconstructions. Japanese geologists have been investigating the eastern part of DML (approx. 20E – 50E) since IGY. In the eastern DML, there are several discrete, isolated high-grade plutono-metamorphic terranes. These are, from west to east, the Sør Rondane Mountains (SRM), Yamato-Belgica Complex (YBC), Lützow-Holm Complex (LHC), Rayner Complex (RAC) and Napier Complex (NAC). A key to the understanding of this area in a Gondwana context one must necessarily distinguish between Pan African and Grenville aged plutonic and metamorphic events. The SHRIMP U-Pb zircon ages, together with previous petrological, geochemical and Sm-Nd isotopic studies for metamorphic and plutonic rocks from eastern DML suggest the constraints for the tectonic history in the eastern DML, although the age data are still insufficient. The present talk focuses on the SRM which is considered to be one of the targets of the field geology during IPY.
GEOCHEMISTRY OF SUBMARINE VOLCANIC ROCKS AT THE PHOENIX RIDGE, ANTARCTICA: IMPLICATIONS FOR THE EXTINCTION OF SPREADING

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ABSTRACT

The K-Ar ages, whole-rock geochemistry and Sr-Nd-Pb isotopes have been determined for the submarine basalts dredged from the P2 and P3 segments of the Phoenix Ridge, Drake Passage, Antarctica, for better understanding on the extinction of seafloor spreading. At the P3 segment, the K-Ar ages of the rifted ridge basalts are 3.5-6.4 Ma, and those for axial seamount basalts are 1.5-3.1 Ma. The K-Ar ages for the basalts at the rifted ridge in the P2 segment are 1.4-2.1 Ma. We suggest that the extinction of seafloor spreading at the P3 and P2 segments occurred at 3.3 and 1.5 Ma, respectively, on the basis of ridge structure and formation time of basalts. This result favors a stepwise extinction model rather than a simultaneous one on the extinction of the Phoenix Ridge. The volcanic lavas from the P3 segment (older than 3.3 Ma) are low-K tholeiitic basalts, and geochemically similar to N-type MORB, whereas those from the P2 segment and P3 axial seamount (younger than 3.3 Ma) are medium-K, mildly alkaline basalts with E-type MORB geochemistry, suggesting that the melting degree decreased and the melting depth deepened after 3.3 Ma, regardless of the different extinction time between P3 and P2 segments. The younger basalts (P2 segment and P3 seamount) with E-type MORB geochemistry are isotopically less depleted than the older basalts (P3 segment), indicating the isotopic heterogeneity of the uppermost mantle sources responsible for the formation of primary magmas beneath the Phoenix Ridge.

INTRODUCTION

Understanding the sequence of events leading to the cessation of spreading at ridge segments approaching subduction zones is of great interest. In the Drake Passage, between South America and Antarctica, the last remnant of the once-extensive Phoenix-Antarctic spreading center, the Phoenix Ridge, appears to have become extinct at some time during the Pliocene (Larter and Barker, 1991). As a result, a small remnant of the former Phoenix plate, confined between the Shackleton and Hero Fracture Zones, has become welded to the Antarctic
plate. Larter and Barker (1991) indicated that three inactive segments of the Phoenix Ridge survive, which called (northeast to southwest) as P1, P2, and P3 (Fig. 1). On the basis of new bathymetric and magnetic anomaly data, Livermore et al. (2000) suggested that extinction of all three remaining segments occurred at the time of magnetic chron C2A (3.3+0.2 Ma), synchronous with a ridge-trench collision south of the Hero Fracture Zone.

During the 1999-2000 austral summer season, a half of P3 segment was mapped using a multibeam echo sounder fitted to the Korean research vessel R/V *Onuri* (Fig. 2), and an anomalously big seamount at the spreading axis was found. During the 2000-2001 and 2002-2003 summer cruises with R/V *Yashmorgeologiya*, submarine fresh lavas from the P2 and P3 segments have been intensively dredged, and geochemically investigated.

We present new results of K-Ar ages, whole-rock geochemistry and Sr-Nd-Pb isotopes for the submarine basalts from the P2 and P3 segments, and will discuss about the time-dependent geochemical variation and the exact extinction time of the Phoenix Ridge.

![Fig. 1. Tectonic boundary map over the bathymetry predicted using satellite altimetry in Drake Passage (Smith and Sandwell, 1994). Dark gray area shows below 4000 m depth and light gray above 3000 m. Solid lines are active boundaries, dotted lines represent the fracture zones and the thick dotted lines represent inactive spreading axis. BS, Bransfield Strait; HFZ, Hero Fracture Zone; P1, P2, P3, Phoenix Ridges; SFZ, Shackleton Fracture Zone; SST, South Shetland Trench; WSR, West Scotia Ridge.](image)

**MORPHOLOGY**

P3 segment (Fig. 2): The near-axis spreading center morphology of the P3 segment shows high relief and has a nodal basin, at depth of 4500-5500 m. This segment is ~200 km long and ~40 km wide. It is extending to southwest Hero Fracture Zone. At the segment center, a prominent seamount is present, which rises to 750 m depth and has a mean diameter of ~30 km. The southwestern region of the axial seamount is flanked by two great ridges which rise to ~2500 m depth. The northwest flank is broader and further away from the ridge axis than the southeast flank. It is supposed that both of flanks may be rifted parts of a former axial topographic high, and the different depth of the ridges may be caused by asymmetric lithospheric stretching during the last extension stage. The axial valley is interrupted by fossil transform, Hero Fracture Zone. It is associated with deep valley and flanked the steep scarp with
a trend of N135°E parallel to the spreading axis.

P2 segment (Fig. 3): Off-axis morphology of the P2 segment is generally comparable to that of fast or intermediate spreading ridges, such as the East Pacific Rise or Pacific-Antarctic Ridge, dominated by linear, axis-parallel magmatic ridges and straight, sharply defined fracture zones. Abyssal hills strike perpendicular to fracture zones, except near transforms, where fabric as much as 10 km from the transform appears to be rotated in a clockwise sense (Livermore et al., 2000).

The near-axis spreading center morphology of P2 shows very high relief, and is anomalous when compared to either fast or slow spreading ridges elsewhere. Well-developed nodal basins occur at both ends of P2, at depths of 4000–4500 m, and are the only areas in which any significant accumulation of sediment has occurred. Between them, the ridge crest rises to a depth of ~2000 m near the segment center, forming a saddle-like structure. The axial region is flanked by two great ridges; that on the northwest flank rises to an unexpectedly shallow 570 m depth near the segment center, and that on the southeast flank is deeper than 1500 m. The ridges are equidistant from the ridge axis, and have similar trends, suggesting that they are rifted parts of a former axial topographic high.
RESULT AND CONCLUSIONS

Though some of the volcanic glasses occurred at the surface of pillow lavas show abnormally old ages (older than 70 Ma) due to excess radiogenic Ar, most of lavas have K-Ar ages ranging from 1.4 to 6.4 Ma. At the P3 segment, the K-Ar ages of the southeastern rifted ridge basalts (PR3) are 3.5-6.4 Ma, and those for axial seamount basalts (SPR) are 1.5-3.1 Ma. The K-Ar ages for the basalts at the northwestern rifted ridge in the P2 segment (PR2) are 1.4-2.1 Ma. Considering that the rifted ridge basalts were formed at a former axial topographic high, it is likely that the extinction of seafloor spreading at the P3 and P2 segments occurred at 3.3 and 1.5 Ma, respectively. This result favors a stepwise extinction model rather than a simultaneous one on the extinction of the Phoenix Ridge.

Volcanic rocks are mostly basaltic lavas with glassy surfaces, and have SiO$_2$ contents ranging from 49 to 52, MgO from 4 to 9 and Al$_2$O$_3$ from 15 to 18 wt.%. The volcanic lavas from the P3 segment (PR3, older than 3.3 Ma) are low-K tholeiitic basalts, and geochemically similar to N-type MORB, except some higher concentrations of alkali elements (Cs, Rb and K). The lavas from the P2 segment (PR2) and P3 axial seamount (SPR) with younger ages than 3.3 Ma are medium-K, mildly alkaline basalts. They show similar enriched trace element patterns (E-type MORB geochemistry) except Pb concentration (Fig. 4). This temporal variation suggests that the melting degree decreased and the melting depth deepened after 3.3 Ma, following that the melting zone became cool down to a depth of garnet peridotite field.

![Fig. 4. N-MORB normalized diagrams of the Phoenix Ridge (Sun and McDonough, 1989).](image)

The younger basalts (PR2 and SPR with E-type MORB geochemistry) generating from deeper mantle are isotopically less depleted than the older basalts (PR3), indicating the isotopic heterogeneity of the uppermost mantle sources responsible for the formation of primary magmas beneath the Phoenix Ridge (Fig. 5). The shallower upper mantle related to the generation of PR3 magma would have been more depleted due to time-integrated, voluminous output of magmas since late Mesozoic.
Fig. 5. Plots of $^{87}\text{Sr}/^{86}\text{Sr}$ versus $^{143}\text{Nd}/^{144}\text{Nd}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ for samples from the Phoenix Ridge.

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NEW EVIDENCES OF PAST ICE SHEET FLUCTUATION IN INTERIOR EAST ANTARCTICA

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INTRODUCTION

The fluctuations of the East Antarctic Ice Sheet (EAIS) in relation with global climate change is subject to much debate. The use of different methods, such as land-based geological and geomorphic observations, marine sediment and geophysical investigations, ice-core isotopes inversion analyses, and numerical modeling, has led to disparate results. What was the behaviour of the inland ice sheet accompanying large expansion and thickening in peripheral areas during climatic cooling events? Was there any large-scale ice sheet collapse occurred during the warm climatic episode of the Pliocene? Land-based data concerning the past ice surface elevation of the interior EAIS are very scarce because of extreme difficulty of access.

We focused our research on the Grove Mountains (GMs), an unknown region located in the interior East Antarctica. A multidisciplinary investigation in the GMs has firstly been undertaken by the Chinese Antarctic Research Expedition (CHINARE) during 1998—2003. Here we present the results of this endeavour, which include glacial geology, cold desert soils, sedimentary boulders, spore-pollen assemblages from both of soil and sedimentary boulders, and bedrock surface exposure ages in the GMs.

GEOGRAPHIC SETTING

The GMs are a group of isolated nunataks exposed inland of the EAIS (72°20'S to 73°10'S, and 73°50'E to 75°40'E). A total of 64 nunataks is distributed on the blue ice-snow field over an area of ~3 200 km², ~450 km south of the Chinese Zhongshan Station. The regional ice flow direction is northwestwards, away from the central part of the EAIS (e.g. Dome Argus), where the ice surface exceeds 4,050 m asl.

The nunatak ridges extend along the regional equilibrium line separating the zone of net ablation from the inland zone of net accumulation. Because of their impediments of ice flow,
they are responsible for the existence of neighbouring blue ice regions where wind-induced ablation is more rapid than snow accumulation. The blue ice surface elevation in the GMs is \(-2,000\) m, and the most height of the main nunataks is \(800\) m above the ice surface (Fig. 1).

The GMs expose mainly upper amphibolite to granulite facies metamorphic rocks, syn-orogenic to late orogenic granite, and post tectonic granodioritic aplite and pegmatite. The ages of deformation (\(-550\) Ma) indicate that the GMs belong to a Pan-African orogenic belt connecting with the Prizn Bay zone\(^4\). The absence of active structures and earthquakes, nor Cenozoic volcanism implies that the region has been geologically stable since the Late Mesozoic Epoch.

![Legend](image)

**Fig. 1.** The sketch map showing locality, landscape feature and ice flow lines in central part of GMs.

**GLACIAL GEOLoGY**

The ice surface lines on the stoss slopes of the rocky nunataks are asymmetrically higher. The stoss slopes show smoothly abraded bedrock, with a surface sparsely littered with erratic till patches. The lee and lateral sides of the nunataks show up generally as sharp bluffs, resulting from both ice flow scraping and erosive normal faulting.
The upper parts of the high nunataks show generally jagged ridge-crests. The lower parts, less than ~100 m above the recent ice surface display landforms attesting to glacial erosion, as do most of the low nunataks. Trimlines on bedrock, drift boulders and till patches are common. Some of the low nunataks show typical "roches moutonnées". The scarcity of erosive imprints in the upper areas of the nunataks signals an important limit, indicating that the last rises of the ice sheet did not exceed this elevation.

Mount Harding, located in the central part of the GMs, shows a peculiar topography. Both the ends of this hill crescent are steeper crests, with heights of 200 m above the ice surface. The central segment of the arc-shaped ridge-line descends progressively until it reaches the altitude of recent ice surface. A stagnant pond of blue ice, tens of km² wide, lies inside ridge-crescent, because regional ice flow could not override it since the end of the last cold event.

An arc-shaped, stadial ice-cored moraine extends along the western outskirt of the stagnant blue ice pond. It was abandoned by the paleo-ice tongue as it retreated behind the ridgeline during regional ice surface descent. This moraine consists of supraglacial debris mainly derived from Mount Harding, but there are also a few exotic boulders coming from the far southeastern part of the inland ice sheet. A till layer only a few cm thick is present at the base of the rocky clast covers. The thick gravel cover has well kept the underneath blue ice out of air-induced ablation since the last retreat of the ice sheet, which accounts for its present elevation, ~25 m above this surface.

DESSERT SOILS

Several cold-desert soil-patches were found on the southern slope of Mount Harding. They stand ~100 m above recent ice surface. Widespread surface desert pavement is common, with some waterlaid structures in the soil layers. The soils have generally abundant water-soluble salts, with slightly acid component and negligible organic matter content. Because of weathering of iron-bearing minerals, the upper horizons of most soil profiles are strongly stained. As melt-water is absolute condition for the formation of soil, the highest temperature we recorded during field work (austral summer) is -10 °C, thus the presence of desert soil indicates a relatively warmer climatic environment once existed in the area.

Based on the standard of weathering characteristics of soils, the age of soil formation is between 0.5 and 3.5 Ma. The preservation of soil patches suggests that the regional fluctuations of the ice surface never reached this altitude, because any higher rise of the ice would have scraped all soils away.
SEDIMENTARY BOULDERS

Except bulk of "in situ" local metamorphic debris, many "foreign" sedimentary boulders have also been sampled from the terminal ice cored moraine of Mount Harding. They range from breccia to sandstone, with sandy clay or calcareous cement. Their states of consolidation show typical glaciogenic lithified and unliethified diamicts. The shapes of quartz grains show typical surface mechanical textures. The grain size distribution of the sandstone is indicative of post-depositional modifications by melt-water action. These diamicts should be formed in a frontal environment of large ice sheet.

Cenozoic spore-pollen assemblages have been recognized from both the soils and the outwash sedimentary boulders. The floras include Nothofagus, also Artemisia and Chenopodiaceae, which are the typical pollen lived in the Pliocene. Most of the species of this spore pollen assemblage only survive in mild climatic conditions. This indicates that there was a warmer climatic period in this region, and that the margin of the EAIS once stood some distance upstream from the GMs.

EXPOSURE AGES

We sampled bedrock profiles for surface exposure dating with in situ cosmogenic nuclide $^{10}$Be and $^{26}$Al, and the results show good relationship between cosmogenic nuclide exposure ages and altitudes of all samples. Preliminary results show that ages range between middle-late Pliocene to early Quaternary. The good relationship between nuclide concentrations and the altitudes with simple exposure histories suggests that the $^{10}$Be and $^{26}$Al concentrations have not reached secular equilibrium, and indicates a monotonous decrease of ice surface level of the interior EAIS in the GMs from middle to late Pliocene. The simple exposure histories of top samples would require a thick ice cover, at least 200 m thicker than today in this region before the Middle Pliocene. 5 samples at lower altitudes till to present ice surface must have been shielded from cosmic ray after initial exposure. Therefore the ice sheet must have gone up covering these samples after Pliocene. Considering the altitudes of samples with complex exposure histories, the EAIS in the GMs could reach a level less than ~100 m higher than present ice level during the later fluctuate.

CONCLUSION AND DISCUSSION

Based on geomorphic evidence, inferred ages of formation of desert soils, lithologic analyses of sedimentary boulders, spore pollen assemblages, coupled with in-situ cosmogenic nuclide exposure ages, we suggest that:
1. The margin of the EAIS has once been beyond of the GMs region, some 450 km southeast of the recent coastal zone before the Middle Pliocene.

2. The ice sheet has subsequently been re-advanced till to more than 200 m higher than today, then the EAIS suffered a stable long processes of descend from more than 2.3 Ma to 1.6 Ma.

3. The ice surface turned into a drastic turbulence period with acutely fluctuation since the Early Pleistocene, but the highest level it again raised has never exceeded \( \sim 100 \) m higher than today, even during the LGM.

Our results support a dynamic fluctuation model of the interior EAIS since the climatic warm event of the Pliocene. It is possible that the highest ice surface level in the GMs has been much higher than 200 m than today, with the time of starting to a stable descend. Our scenario consorts in time with climatic events in global scale. The stable descend of interior ice sheet of the East Antarctica occurred during the same period with the formation of extensive ice sheet in the northern hemisphere, also with the abrupt change of sedimentary rate around the Tibetan Plateau. The acute fluctuation of ice sheet (complex exposure history) during the Quaternary is consistent with frequent glacial cycles in the northern hemisphere.

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[Session V]

Paleoenvironments
RADIOCARBON AGES OF SORTED PATTERNED GROUNDS IN KING GEORGE ISLAND, SOUTH SHETLAND ISLANDS, WEST ANTARCTICA

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Lichen and moss colonize the surfaces of glacial debris left after deglaciation. Transformation of unsorted debris into sorted patterned ground causes early plant remains to be preserved in the fine-grained center, which are encircled by a coarse clastic border. Radiocarbon ages of the plant remains from the sorted stone circles/polygons in King George Island, South Shetland Islands, West Antarctica, were dated as 290–4710 ¹⁴C yr B.P. Later addition of younger plant remains by means of convective motion of the soil particles within stone circles/polygons of different sizes results in a wide range of underestimated ages for deglaciation. There is a positive correlation between ¹⁴C age and the size of the circles/polygons. The oldest age determined for a large stone circle coincides well with the regional deglaciation age recorded in marine and lacustrine sediment cores, suggesting the possibility that patterned ground is a useful terrestrial proxy for paleoclimatic events in periglacial environments.
LATE QUATERNARY SEDIMENTARY PROCESSES IN THE NORTHERN CONTINENTAL MARGIN OF THE SOUTH SHETLAND ISLANDS, WEST ANTARCTICA

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INTRODUCTION

The western margin of the Antarctic Peninsula (AP) has responded sensitively to the past climatic change due to its polar to subpolar climatic setting and broad continental shelf. Previous studies in this region demonstrate that a grounded ice sheet extended across the continental shelf to the shelf break during the Last Glacial Maximum (LGM), and the main deglaciation in the shelf area began at about 11,000 yr BP (Sugden and Clapperton, 1986; Pudsey et al., 1994; Larter and Vanneste, 1995; Yoon et al., 2002). Because the action of grounded ice sheets largely controls sediment transport and deposition as well as paleoceanographic condition, the sedimentological study of marine sediments plays an important role in understanding the paleoceanography and the glacial/deglacial history. In this study, we present a reconstruction of the changes in sedimentary processes and depositional environments based on analyses of sedimentary and echo facies of marine sediments taken from the northern continental margin of the South Shetland Islands.

MATERIALS AND METHODS

Gravity cores (80-580 cm long) at 5 stations were collected from the study area during the expedition of the Korea Antarctic Research Program 2001/2002. X-radiographs of sediment slabs were taken from the lengthwise-cut split cores to observe sedimentary structures. Grain size of core sediment was analyzed using standard sieves and a Micrometrics Sedigraph 5000D. High-resolution (3.5 kHz) seismic profiling (ca. 1,400 line km) and deep-camera survey were also deployed during this cruise to obtain information on seafloor topography and acoustic characteristics of subsurface sedimentary sequences.
SEDIMENTARY FACIES

Six sedimentary facies are classified, based on grain texture and sedimentary structures of
the core sediments: (1) bioturbated mud, (2) indistinctly-layered mud, (3) thinly-laminated
mud/sand, (4) homogeneous mud, (5) wispy-laminated mud, (6) deformed mud. Bioturbated
mud, the most predominant facies recognized in all cores, is attributed to hemipelagic
deposition and/or weak and slow bottom (contour) currents (Stanley and Maldonado, 1981;
Chough and Hesse, 1985). Thinly-laminated mud/sand and homogeneous mud commonly occur
as couplets in the trench and incised valleys, and are generally accepted as deposits of low-
density fine-grained turbidity currents. Indistinctly-laminated mud observed in the trench,
incised valleys and the mid slope was most likely emplaced by contour current, tail of turbidity
current or meltwater heavily laden with fine-suspended sediments. Wispy-laminated mud facies
in cores from continental shelf and slope areas was probably deposited from downslope bottom
current with high sediment fallout rate (Yoon, et al., 1991; Yoon, 1995). Deformed mud is
interpreted to represent gravity-induced slumping and sliding on steep continental slope.

ECHO FACIES

The high-resolution echo characters were classified into 6 echo facies on the basis of clarity,
continuity, and shape of bottom and subbottom echoes together with seafloor topography. Echo
facies IA is mainly recorded from the upper continental slope and trench walls, where it is
characterized by relatively distinct, sharp bottom echoes without subbottom reflectors. This
echo is interpreted to represent semi-consolidated sediments reworked by bottom-hugging
currents. The floor of incised valleys in the continental shelf are dominated by echo facies IIA
which shows semi-prolonged bottom and several parallel subbottom echoes. This echo facies
suggests a combined effect of hemipelagic settling and turbidity currents or meltwater turbid
plumes (Damuth 1978; Yoon et al., 1991). Echo facies IIB-1 recorded from the floor of trench
and slope canyons is associated with very prolonged bottom echoes showing smooth and
undulatory surface topography. The transparent acoustic character is generally accepted
characteristics of thick beds of turbidites or contourites (Damuth, 1978; Pratson and Laine,
1989). In the shelf and the upper continental slope, echo facies IIB-2 is characterized by very
prolonged bottom echoes with no discrete subbottom reflectors, showing hummocky seafloor
topography less than a few meters high. The origin of this echo facies is interpreted as coarse-
grained tills deposited directly from glaciers coming from the South Shetland Islands. In some places of the continental slope and trench, echo facies II A is characterized by irregular, overlapping hyperbolae with significantly varying vertex elevations (tens to hundreds of meters). This echo indicates structurally-deformed or irregularly-eroded hard rock basement or semi-consolidated sediment (Embley and Jacobi, 1977; Yoon et al., 1991). Echo facies II C, mainly recorded from the restricted area of the upper to mid continental slope, is characterized by regular, overlapping hyperbolae with slightly varying vertex elevations (tens of meters) and slightly prolonged subbottom reflection. This echo facies is interpreted to indicate deposits of slump/slide and debris flow (Embley and Jacobi, 1977; Yoon et al., 1991).

CONCLUSIONS: SEDIMENTARY PROCESSES

Distribution of the echo and sedimentary facies suggests that sedimentary processes in the northern continental margin of the South Shetland Islands were significantly affected by grounded ice sheet during the LGM and subsequent glacier-retreating period. When the grounded glaciers extended to the present shelfbreak during LGM, coarse-grained subglacial tills were widespread in the shelf area, and deep troughs in the shelf were carved beneath the fast-flowing ice steam (Fig. 1A). As the glacial margin retreated landward after LGM, dense meltwater plumes released from the retreating ice-front were funneled along the glacier-carved troughs, and accumulated channel- or canyon-fill deposits in the shelf and the upper to mid slope (Fig. 1B). At this time, some upper slope sediments seem to have been rarely reworked by

Figure 1. Reconstruction model of glacial-marine sedimentation in the northern continental margin of the South Shetland Islands.
slope failures and contour currents. After the glacial retreat, sediments in the shelf and slope areas have been mainly introduced by persistent (hemi) pelagic settling, and fine-grained turbidity currents frequently occur along the axis of the South Shetland Trench (Fig. 1C).

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COMPARISON BETWEEN THE MARINE ISOTOPE RECORDS AND ICE CORE RECORDS IN THE SOUTHERN HEMISPHERE

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High-resolution δ^{13}C and δ^{15}N records of diatom-bound organic matter (δ^{13}C_D, δ^{15}N_D) from ODP site 1094, South of the Polar Front, are combined with reconstructions of summer sea surface temperature and winter sea-ice to establish changes in surface water characteristics associated with the main climatic events of the past 640 ka. The six glacial-interglacial δ^{13}C_D cycles show excellent agreement with SPECMAP δ^{18}O and Vostok CO₂ content, suggesting that global physical processes rather than local biological factors were the main influences on δ^{13}C_D. By contrast, there is weak correspondence between the Vostok dust record and the δ^{13}C_D and δ^{15}N_D records. The data do not support the hypothesis that glacial iron fertilization of the Southern Ocean was the main factor lowering atmospheric CO₂, if dust accumulation represents iron input. The records indicate that sea ice cover, water column stratification and iron addition from deep water mixing are more likely to explain our observations.
PROVENANCE OF SEDIMENTS IN THE BRANSFIELD STRAIT, WEST ANANTARCTICA

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The Bransfield Basin is a Quaternary marginal basin separating the South Shetland Islands from the Antarctic Peninsula. To determine provenance and factors controlling the composition of sediments in the Bransfield Basin, we analyzed major, trace and rare earth element composition and Nd, Sr and Pb isotopic composition for six piston core sediments from the western and eastern Bransfield basins (Fig. 1).

Figure 1. Bathymetric map of the Bransfield Strait with location of piston core samples. Bathymetric contour units are in meters. Strong surface currents in Bransfield Strait (open arrows; Zhou et al., 2002) and flow paths of the Weddell waters (Gordon et al., 2000) are also shown. CBB=Central Bransfield Basin; WBB=Western Bransfield Basin; GS=Gerlache Strait.

Bransfield sediments have chemical characteristics similar to sediments deposited in a tectonically active setting where the source rocks are predominated by igneous rocks of intermediate to mafic composition: low K and high CN in the A-CN-K diagram, low La/Sc, low
Th/Sc, and lower LREE/HREE than average shale. Low chemical alteration index of the sediments, about 45 in average, suggests minimal effect of weathering on the sediment composition. Source rocks of the Bransfield sediments have been composed of Mesozoic to Tertiary arc volcanic and plutonic rocks from the Antarctic Peninsula and South Shetland Islands mostly. Meanwhile, contribution from other rock types in the northern Antarctic Peninsula region, such as Trinity Peninsula Group or Scotia Metamorphic Complex, seems to be negligible.

Bransfield sediments can be divided into three distinct compositional groups. Group I (S3 and S15) sediments have lower La/Yb and less prominent negative Eu anomaly than Group II (S4, S7 and S9) sediments (Fig. 2). They are also characterized by negative Ce anomalies. Group I sediments have been mainly derived from igneous rocks of the South Shetland Islands, and more widespread Group II sediments from the Antarctic Peninsula. Group III sediments, very low in La/Yb (Fig. 2) with the lowest $^{87}$Sr/$^{86}$Sr and the highest $^{143}$Nd/$^{144}$Nd values, have been derived from the Deception Island. Composition of Bransfield sediments is largely controlled by source rock compositions, and distribution of sediments is further modified by current and topography of the basin.

Figure 2. (La/Yb)$_{CN}$ vs. (Eu/Eu$^*$)$_{CN}$ for the sediment of the Bransfield Basin. Subscript CN denotes chondrite-normalization (Sun and McDonough, 1989). Values of NASC (Gromet et al., 1984), NMORB and OIB (Sun and McDonough, 1989) are shown for comparison. Background data for the field of Trinity Peninsula Group of Antarctic Peninsula (AP) are from Willan (2003), mafic rocks of the Scotia Metamorphic Complex of the South Shetland Islands (SSI) from Valeriano et al. (1997), eastern and western coast of the northern Antarctic Peninsula from Saunders et al. (1980), Cretaceous volcanic rocks of Livingston Island from Tarney et al. (1982), Tertiary volcanic rocks of King George Island from Jin and Jwa (1990), Jwa (1991), and Yeo et al. (2004), and Quaternary volcanic rocks of Deception Island from Jwa and Kim (1991) and Keller et al. (1992). Symbols are the same as in Figure 1.
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Poster
SEISMICITY RATES OF SLOW-, INTERMEDIATE-, AND FAST-SPREADING RIDGES: INSIGHTS FROM LONG-TERM HYDROACOUSTIC MONITORING

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INTRODUCTION

Ocean basin earthquakes recorded on National Oceanic Atmospheric Administration/Oregon State University and U.S. Navy hydrophone arrays are used to evaluate long-term volcano-tectonic seismicity levels from segments of the fast-spreading rate East Pacific Rise (EPR) from 20° S-20° N, intermediate-spreading rate Juan de Fuca Ridge (JdFR) from 39°-52° N and Galapagos Rift (GR) from 90°-103° W, and the slow-spreading northern Mid-Atlantic Ridge (MAR) from 5°-60° N. Ocean hydrophones record the acoustic energy of seafloor earthquakes that propagates along the ocean sound channel with little attenuation over large distances. Frequency-magnitude relationships (Bohnenstiehl et al., 2002; Dziak et al., 2004) indicate the hydrophone catalogs are complete to body-wave magnitudes of ~2.5 (EPR and GR), 2.5 (JdFR), and ~3.0 (MAR), an improvement of 1.5 to 2 units over the land-based seismic catalogs for mid-ocean ridge systems. Using the hydrophone earthquake catalog, we evaluated the basic statistics of earthquakes from the JdFR (12 years of data), and compared that to the seismicity statistics along the GR (6 years), EPR (6 years) and MAR (4 years of data from 5°-39°N; 16 months from 39°-60°N). During these monitoring periods, five confirmed seafloor spreading events (four of which were associated with magmatic activity) were recorded on discrete JdFR segments, while 6 possible magmatic events were observed on the EPR, one on the GR, and one on the MAR. Empirical orthogonal functions are also used to elucidate the space-time patterns of seismicity and compare between the various spreading rates ridges, as well as to investigate the recurrence rate of seafloor spreading events.
EARTHQUAKE DATA

Small- to moderate-sized earthquakes occurring on mid-ocean ridges (MOR), transform faults, and subduction zones in the east Pacific and north Atlantic Oceans have been located and catalogued by a series of hydrophone arrays maintained by NOAA/OSU since the early 1990s. Global and regional seismic networks offer critical information on the spatial patterns and source mechanisms of seismicity in the ocean basins. However, the low magnitude of earthquakes associated with MOR volcanic activity, at least at fast- and medium-spreading ridges [Dziak et al., 2004], and the relatively high detection thresholds of land-based seismic networks (M > 4) for the majority of the global MOR system, often results in an incomplete picture of the seismic activity or a failure to detect it altogether. In the last decade, hydroacoustic methods have been developed further to provide improved monitoring of the tertiary phase or T-wave of MOR seismic activity [Fox et al., 1995]. Since acoustic T-waves propagating in the ocean sound-channel obey cylindrical spreading (r^2) energy loss as opposed to the spherical spreading (r^3) of solid-earth seismic P-waves, sound channel hydrophones can often detect smaller (M<4) and therefore more numerous earthquakes than land-based seismic networks [Dziak et al., 2004].

Figure 1 (left) shows 21,934 earthquakes located using the U.S. Navy SOSUS-NOAA hydroacoustic monitoring system along the Juan de Fuca Ridge from September 1991 through January 2002. Figure 1 (middle) shows the earthquakes located recorded by a NOAA-NSF network of autonomous hydrophones (white stars) along the East Pacific Rise (EPR) and Galapagos Rift from May 1996 through December 2002. A total of 12,184 earthquakes were located along the EPR and transforms, while 4,967 were located along the Galapagos Rift. Figure 1 (right) show T-wave earthquake locations (red dots) recorded by a NSF-NOAA autonomous hydrophone network (white stars) along the northern Mid-Atlantic Ridge south of the Azores from February 1999 to December 2002. A total of 9,436 earthquakes were located during this time period. A French-American (SIRENA) network of hydrophones was deployed north of the Azores from May 2002 to September 2003. A total of 1,185 earthquakes have been located from the 6 months of data analyzed.

ANALYSIS METHODS

Empirical Orthogonal Function (EOF) analysis is used to objectively decompose the hydroacoustic earthquake catalogs of the Juan de Fuca Ridge, East Pacific Rise, and Atlantic Oceans into spatial and temporal patterns of observed seismicity. Eigenfunctions transform and quantify the data into orthonormal, independent modes of variability. Our analysis is modeled around the eigenstructure of the covariance matrix achieved through a mean matrix
Figure 1: Earthquakes (red dots) detected and located by NOAA/OSU hydrophone arrays along mid-ocean ridge systems in the north and east Pacific and north Atlantic Oceans.

product transformation of the original data (Preisendorfer, 1988). Our data set \( D \) is an \( n \times m \) matrix of \( m \) grid cells with \( n \) observations (events/month). \( D \) must be transformed to \( X \) by removing the mean value at each location from its seismicity time series.

\[
X_{ij} = D_{ij} - \mu_j
\]

From this data matrix we obtain the covariance matrix \( C \) as:

\[
C = X'X
\]

Using the matrix \( C \) we are able to compute the orthogonal set of eigenvectors that are treated as columns to form the matrix \( E \). Each eigenvector within \( E \) gives the spatial pattern of each mode of variability contained in the data set. The first eigenvector axis points in the direction of maximum variance, the second eigenvector axis point in the direction of the second largest amount of variance and so on. The time series history of each mode of variance, \( B \), represented in the eigenvectors of \( E \) is calculated as:

\[
B = XE
\]

Each column in \( B \) gives the time series history of its associated spatial pattern of variance described by the eigenvector in \( E \). Therefore using this technique we are able to quantify spatial and temporal modes of variability within the T-phase earthquake catalog.

**DISCUSSION**

Overall, the EOF analysis is a robust method to elucidate and quantify space-time variability in seismicity rate changes in the Juan de Fuca Ridge-SOSUS and MAR-EPR
autonomous hydrophone earthquake databases. The largest earthquake sequences (dominant modes of variability) on intermediate- and slow-spreading ridges occur on ridge segments, whereas on the fast-spreading ridge they occur on transform faults. Similarly, the vast majority of seismicity on the slow-spreading ridge occurs on the ridge segments, but on the fastspreading ridge seismicity is concentrated on the transform faults. The intermediate-spreading JdFR exhibits both a high level of seismicity (during brief periods of intense activity) on the ridge segments and a steady overall level of seismicity on the transforms. MAR transform faults are conspicuous for their paucity of earthquakes, exhibiting infrequent seismicity that represents less than 5% of the mode of variability. This is in stark contrast to fast and intermediate transforms that exhibit high seismicity rates. Aseismic slip occurring in the presence of serpentinite has been proposed to explain the lack of MAR transform seismicity (Reinen et al., 1994).

<table>
<thead>
<tr>
<th></th>
<th>NE Pacific (GOSUS)</th>
<th>EPR</th>
<th>Galapagos Rift</th>
<th>MAR</th>
<th>SIRENA</th>
</tr>
</thead>
<tbody>
<tr>
<td>μ (events/month)</td>
<td>151.7 ± 15.9</td>
<td>151.5 ± 11.2</td>
<td>63.2 ± 6.2</td>
<td>153.4 ± 9.3</td>
<td>74.4 ± 8.2</td>
</tr>
<tr>
<td>ρ skewness</td>
<td>4.9</td>
<td>3.0</td>
<td>2.8</td>
<td>1.8</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Table I summarizes the overall mean and skewness of the four ridge systems. Seismicity from both transforms and ridge segments are included. Mean earthquakes per month are strikingly similar for the JdFR, EPR and MAR despite significant differences in spreading rates, whereas skewness varies significantly. This indicates that although fast-, intermediate-, and slow-spreading ridges have similar overall event rates, the intermediate-rate ridge has many large, short duration earthquake swarms, while fast- and slow-spreading ridges tend toward a more steady level of seismicity. The higher skewness of fast (transform dominated) versus slow (ridge dominated) seismicity again indicates the relative impulsive versus steady-state character of fast- and slow-spreading ridge seismicity. The intermediate-rate JdFR and Galapagos Rift differ by twice the mean event count and half the skewness. These differences could be due to the lack of large transforms and/or the low event count, long duration earthquake swarms (similar to the slow-spreading ridges) exhibited by the Galapagos Rift.

REFERENCES


A RECORD OF ATMOSPHERIC CO$_2$ FROM THE SIPLE DOME, ANTARCTICA ICE CORE

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INTRODUCTION

Understanding how the atmospheric concentration of CO$_2$ changed in the past in response to other changes in the climate system provides us with a better understanding of how current and future changes in the carbon cycle will influence our future climate. CO$_2$ records from Antarctic ice cores (e.g., Petit et al., [1999]; Fischer et al., [1999]) are considered to be representative of the paleoatmosphere concentrations because low dust content prevents significant in situ production of CO$_2$ by carbonate-acid reaction as found in Greenland ice cores. The Siple Dome ice core from West Antarctica was drilled from 1997 to 1999 (Fig. 1). The site is at 81.66° S, 148.82° W, at an altitude of 621 meters asl, with an annual mean temperature of -25.4 °C and an accumulation rate of 12.4 g cm$^{-2}$ yr$^{-1}$ as water equivalent. The high accumulation rate at Siple Dome allows rapid climate changes to be more accurately preserved and permits more accurate assessment of the relative timing between ice-isotopic variations (e.g., surface temperature) and of variations in included gases (e.g., atmospheric CO$_2$) compared to the low accumulation rate sites like Vostok or EPICA Dome C. In this study, we compare the CO$_2$ record from the Siple Dome ice core with those from other Antarctic ice cores using common time scales based on the GISP2 (Greenland Ice Sheet Project 2) gas age and correlation to
Antarctica using CH$_4$ concentrations variations. We also examine the relative timing of the CO$_2$ increase and temperature change.

METHODS

Included air in ice is dry extracted by mechanical crushing of samples of ~4 to 6 cm$^3$ at -50

Figure 2. Comparison of Antarctic ice core CO$_2$ records (Modified from Ahn et al. [2004]). (a) Siple Dome $\delta$D$_{ice}$. (b) Antarctic ice core CO$_2$ records. Error bars represent one standard error deviation of replicate measurements at the same depth interval. The brackets indicate averages of two anomalously high values of six samples from the same depth interval. (c) Difference in CO$_2$ records. (d) Melt layers [Das, 2003]. The lengths of bars indicate the confidence level. 1, sure; 0.75, probable; 0.5, possible. (e) Potential excess CO$_2$ from acid-carbonate reaction. The dashed horizontal line represents 0. Non-sea-salt Ca (nssCa) was assumed to have been in the form of CaCO$_3$ and has totally reacted with excess H$^+$. YD, Younger Dryas; ACR, Antarctic Cold Reversal.
°C. The total liberated air is then frozen into mini cold traps at temperatures of 32 K achieved with closed cycle He refrigerators. Three aliquots of standard air with CO₂ concentrations bracketing the samples are introduced over the crushed ice for every six samples. Measurements are performed with tunable diode laser spectrometry by scanning a single vibrational-rotational CO₂ absorption line (at Doppler resolution) several times. The daily internal precision is better than 2 ppm.

RESULTS

In general, Siple Dome CO₂ record (solid circles and solid squares in Figure 2b) follows temperature as indicated by δD (Figure 2a) which is the proxy temperature indicator. The results can be compared to other Antarctic ice cores as shown in Figure 2b. Siple Dome CO₂ concentration decreases from 214 ppm at 38 kyrBP to 186 ppm at Last Glacial Maximum (~ 18 kyrBP) and then rapidly increases up to 247 ppm during the early last Termination. After a decrease during the ACR (Antarctic Cold Reversal), 15 to 13 kyrBP, reaching a local minimum of 239 ppm, Siple Dome CO₂ rapidly increases again reaching up to 284 ppm at the end of the last Termination (11.5 kyrBP). During the Holocene, CO₂ decreases to a local minimum of 261 ppm at about 8 kyrBP and then continuously increases up to 285 during the late Holocene. It is interesting to note that the CO₂ increase rate slows down during the ACR. This confirms EPICA Dome C records [Monnin et al., 2001].

![Figure 3. Time lag analysis of (dCO₂/dt) after (d(δD)/dt) in the Siple Dome ice core during the last deglaciation (Modified from Ahn et al. [2004]). Histograms of the time lags are obtained by Monte Carlo simulation for CO₂ concentrations.]

The correlation coefficient between the dCO₂/dt and d(δD)/dt was calculated (Fig. 3). The maximum correlation coefficients were obtained with a 369 ± 23 years lag (mean ± 1σ) for maximum Δage (= ice age – gas age) and 196 ± 25 (mean ± 1σ) for minimum Δage. Therefore, a lag of CO₂ versus Siple Dome temperature is likely, and our results provide strong support for previous suggestions of a close link between Antarctic temperature and CO₂ change during the deglaciation.

Despite similarities in general time series of CO₂ records with other Antarctic ice cores, at some age intervals, the Siple Dome ice shows higher CO₂ concentrations by up to 20 ppm (mol CO₂ / mol air) than those in other Antarctic ice cores (Fig. 2). In order to examine the possible
mechanisms for the excess CO$_2$ in the Siple Dome ice core, we check the CO$_2$ difference between Siple Dome and Taylor Dome or Dome C (Fig. 2c). The most likely mechanism is the snow melting/refreezing [Neftel et al., 1983]. CO$_2$ can be considerably enriched in frozen melt layers due to the high solubility of CO$_2$ in meltwater. Around the melt layers in the Siple Dome ice, the CO$_2$ reaches up to $\sim$ 740 ppm (excess CO$_2$ $\sim$ 460 ppm) compared to the normal value of $\sim$ 280 ppm (Fig. 4). Thus, it is likely that small melt layers, which are not detected visually, can exhibit the excess CO$_2$ up to 20 ppm. The excess CO$_2$ (Fig. 2c) is weakly associated with the occurrence of visual melt layers (Fig. 2d).

![Diagram of CO$_2$ levels in Siple Dome ice core]

**Figure 4.** High-resolution study on a sample with melt layers. Sample length = 30 cm, Gas age = 2740 years.

**SUMMARY AND CONCLUSIONS**

We present the CO$_2$ record of air included in the Siple Dome ice core, Antarctica. The general time series of Siple Dome CO$_2$ concentration is similar to previous studies in other Antarctic ice core CO$_2$ records. Siple Dome ice also shows that surface temperature inferred from $\delta$D$_{ice}$ correlates well with CO$_2$ concentration as shown in other Antarctic ice cores. During the last termination, it is likely that the change of the Siple Dome CO$_2$ concentrations lags the Siple Dome temperature change. Our results provide strong support for previous suggestions of a close link between Antarctic temperature and CO$_2$ change during the deglaciation. Despite similarities with other Antarctic ice cores, the Siple Dome ice shows higher CO$_2$ concentrations than those in other Antarctic ice cores at some depth intervals. The most likely cause of these elevated concentrations is excess CO$_2$ due to surface melting.

**REFERENCES**


State University, 2003.
ON RELATIONSHIP BETWEEN ATMOSPHERIC TELECONNECTIONS AND ICE EXTENT OF ARCTIC SEAS

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INTRODUCTION

Climate model projections of a future climate change due to increased greenhouse gas concentrations show a maximum annual mean warming near the surface in the high northern latitudes. This warming is aligned with a retreat of sea ice. Numerical experiments, which were performed by Hilmer and Lemke (2000), show that a net reduction of Arctic sea ice volume amounts to the 4% per decade for the period starting with the 1961, the decrease within the 1987-1998 was three to six times larger than within the previous periods.

Some sensitivity experiments with a sophisticated sea ice model have revealed that the sea ice cover is most strongly affected by the surface air temperature and the surface wind field whereas other forcing parameters play a minor role. On the other hand, both aforementioned parameters are strongly affected by the atmospheric teleconnection patterns. The Arctic Oscillation, the North Atlantic Oscillation (NAO), and the Pacific/North American (PNA) can be considered as the dominant atmospheric modes of variability in the Arctic.

The joint analysis for the variability of atmospheric circulation and sea ice extent (SI) in the Arctic seems as attractive but for the case of observational time series there are some difficulties. First from theirs consists in the comparatively short monthly time series of ice conditions for most seas in the Arctic basin since reliable data appeared at the satellite era. Other difficulty lies in the fact that the SI is characterized by pronounced annual variations with the summer minima and the winter maxima. Against these variations the low-frequency atmospheric influence is hard evolved.

In this paper, to reveal the atmospheric forcing of the SI in some Arctic seas we use approach based on the wavelet decomposition which allows to solve some questions by extracting the common characteristics of variability in the time frequency space. This method was successfully applied to many geophysical signals, including the time series of atmospheric
teleconnection patterns and sea ice (see Grinsted et al., 2004; Jevrejeva et al., 2003; Khokhlov et al., 2004).

METHODS AND DATA

Main approach used in the current study is cross wavelet transform which was in detail described by Grinsted et al. (2004). Only key features are provided here.

Wavelets are the fundamental building block functions, analogous to the trigonometric sine and cosine functions. The particular wavelet can be characterized by how it is localized in time and frequency (for details see Daubechies, 1992). When using wavelets for feature extraction purposes the Morlet wavelet is a good choice, since it provides a good balance between time and frequency localization.

The idea behind the continuous wavelet transform (CWT) is to apply the wavelet as a bandpass filter to the time series. The wavelet is stretched in time by varying its scale and normalizing it to have unit energy. The CWT of a time series with uniform time step is defined as the convolution of this series with the scaled and normalized wavelet. The cross wavelet transform of two time series is defined as complex conjugation of two particular CWT. This approach allows to define the cross wavelet power (CWP) and the local relative phase (LRP) between two time series in time frequency domain.

Here, we consider monthly indices for the NAO and the PNA as well as the monthly ice extents in the Bering Sea, the Baffin Bay, the Greenland Sea, and the Kara-Barents seas from November 1978 to December 2002. The sea ice extent dataset is derived from brightness temperatures by the bootstrap algorithm (Comiso, 2002). Except for the Bering Sea, which is ice-free during August, other seas are ice-covered during all seasons. It is naturally that sea ice conditions in the Bering Sea are affected by the PNA rather than the NAO whereas for other three seas the influence of the NAO should be dominant. The choice for the three seas in the Atlantic sector is conditioned by the different trends in the ice thickness during the last decades of twenty century (Hilmer and Lemke, 2000). We standardize all time series and, since the monthly sea ice extent is far from normally distributed, transform indices for the SIs into a record of percentiles (in terms of its cumulative distribution function).

RESULTS

It is naturally that for the case of two particular seas the cross wavelet power with the 5% significance level (SL5) has maxima in the 8-16 month band which are caused by the annual variations of the SI. On the other hand, in such time band the local relative phases of sea ice extent in the Atlantic basin lead slightly that in the Bering Sea. Figure 1 showing the CWP and
LRP of SIs in the Bering Sea and the Greenland Sea can be considered as the example of such behaviour. Also, the comparatively large CWP outside the SL5 is registered for these seas only.

**Figure 1.** The CWP of the SIs time series in the Bering Sea (BSI) and the Greenland Sea (GSI). The SL5 against red noise is shown as a thick contour and cone of influence where edge effects might distort the picture is shown as a lighter shade. The LRP is shown as arrows (with in-phase pointing right, anti-phase pointing left, and GSI leading BSI by 90° pointing straight down).

Other interesting feature of cross wavelet relationship in Fig. 1 is the fact that on the time scale with the 3-4-year period the LRP is anti-phase. Moreover, the 3-4 year band is characterized by the significant wavelet coherence calculated as proposed by Torrence and Compo (1998). To a certain extent, this behaviour can be analogous to the Antarctic Dipole in the Southern Ocean (Simmonds and Jacka, 1995; Yuan and Martinson, 2001) though the CWP is not significant.

Consider the CWP of the teleconnection patterns and sea ice extents (Fig. 2). As for the previous case, one can be noted that there almost always is significant common wavelet power in the 8-16 month band for whole period under consideration. However, the NAO and the GSI are in-phase, whereas the PNA and the BSI are anti-phase. At the same time, less significant, but comparatively large, CWP is registered in the case of the NAO and GSI with the 3-5-year period (with leading NAO). The last finding is also confirmed by the experiments of Hilmer and Jung (2000).

**SUMMARY**

We use wavelet analysis to reveal coherence in the variability of atmospheric circulation and ice conditions in the Arctic seas. This analysis allows decomposing time series as well as estimating common wavelet power. Using the CWP we uncovered that there is the significant
anti-phase relationship between the ice extent in the Bering and the Greenland seas. To a certain extent, this relationship can be analogous to the Antarctic Dipole in the Southern Ocean.

Figure 2. The CWP of the NAO and GSI (left), and the PNA and BSI (right) time series. All parameters are the same as in Figure 1.

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SEASONAL VARIATION OF WATER MASS STRUCTURES OF MARIAN COVE, THE SOUTHERN SOUTH SHETLAND ISLANDS, WEST ANTARCTICA

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INTRODUCTION

Along with a global mean surface temperature increase by 0.6°C during the 20th century, the AP is one of the rapid warmings. The mean annual temperature around the AP has risen by more than 2.5°C in the last 50 years that is more than twice the average for other Antarctic areas [Jacka and Budd, 1998]. The AP’s warming has caused several notable changes in the distribution of plants and animals, snow elevation and the extent of surface snow cover [Jacobs and Comiso, 1997; Smith et al., 1999]. The most important change is glaciers and ice shelves vulnerable to climate change. Recently, like their retreat and collapse of the western AP [Shepherd et al., 2003; Skvarca et al., 1998; Vaughan and Doake, 1996], the tidewater/valley glaciers in the South Shetland Islands lying on the line of the AP has rapidly retreated [Park et al., 1998; Birkenmajer, 2001].

The two important mechanisms for explaining recent rapid warming on the AP [Vaughan et al., 2001] are (1) change of large-scale atmospheric circulation over the AP since the 1970s and (2) change of oceanographic circulation. Thompson and Solomon [2002] suggested the influence by the first mechanism accounts for only ~50% of the warming. It suggests to the importance of another climate change mechanism. Of a powerful influence on the climate of much earth as well as the AP is the ACC, the band of water flowing eastward around the Southern Ocean. The Antarctic cruises of R/V Yuzhmogeologiya (Russia) were conducted in the southern Drake Passage between 61~54°W (November 23~26, 2003) and annual CTD (Conductivity/Temperature/Depth) data for 2000 (16 times) and 2004 (12 times) at Marian Cove, one of Antarctic fjords, were obtained to investigate annual water column structures associated with the fronts of the ACC in the northern AP. The objective of this study is to examine seasonal changes of water masses related to the ACC regime within the southern South Shetland Islands.
showing the regional warming trends.

MATERIALS AND METHODS

Hydrographic data were obtained using a CTD (conductivity-temperature-depth) water column profiler at Marian Cove of King George Island and in Drake Passage. CTD profiles were obtained through SEABIRD model SBE 911 (24 Hz sampling rate) with model 11 deck unit and SBE 19plus profiler (4 Hz sampling rate). The conductivity cell was flushed by a pumping system so that no artificial spikes were generated. Salinity was derived from temperature and conductivity data and after using calibration measurements made before the cruise. For SBE 911 profiler, salinities are accurate to within ±0.001 psu. The salinity, temperature, and depth data acquired using IBM PC connected to the Sea-Bird deck unit were averaged over a 1.0 m depth interval. A SBE 19plus profiler/rosette unit was used at all stations for vertical profiles of the physical, optical, and biological characteristics of the water column and to collect water samples. Additional sensors attached to the CTD included an irradianc sensor (QSP 2300, Biospherical Instruments) for Photosynthetic Available Radiation (PAR), a 25-cm pathlength transmissometer (Sea-Tech), dissolved oxygen sensor (SBE 43) and a pulsed fluorometer (WETLabs-WETStar).

RESULTS

Due to the deep submarine sill (~60 m), water exchanges are active and make Marian cove easily connected with the open ocean conditions. Hence, water column characteristics at Marian Cove vary seasonally. For 2000 and 2004, potential temperature ranges from −1.5 to 1.8°C, salinity from 27.60 to 34.17 and density from 20.45 to 27.49 kg m⁻³ (Figs. 1 and 2). Based on the vertical profiles of these water column characteristics, we identified three distinct water masses: fresh ice-melt surface water, warm/fresh summer water, and cold/saline winter water.

Through CTD measurements during the short term of austral summer (December to February), ice-melt surface water and warm water of the mid depth were found even at the head of tidewater glacier. In austral summer, predominant supraglacial discharges from melt of termini of glaciers and small meltwater streams are reflected in the formation of low-salinity water. At the mid depth between the mid February and the early March, temperature maximum (>1.6°C) and density minimum (<27.20 kg m⁻³) indicates warm/fresh summer water (Fig. 1 and 2). After April when glacial discharges and intrusion of the warm water disappeared, cold/saline winter water gradually occupied the northward extension of sea ice from Weddell Sea. The winter water shows temperature minimum (<−1.3°C) and density maximum (>27.45 kg m⁻³) from the mid August to the late October. More importantly, the difference between warm/fresh
summer water and cold/saline winter water indicates the prominent transition of two water masses and the change of seasonal circulation clearly recognizable in Antarctic fjord system.

![Figure 1. Seasonal variation of (a) potential temperature (°C), (b) salinity (psu) and (c) sigma-Θ (kg m⁻³) at Marian Cove sampled in the year 2000.](image1)

![Figure 2. Seasonal variation of (a) potential temperature (°C), (b) salinity (psu) and (c) sigma-Θ (kg m⁻³) at Marian Cove sampled in the year 2004.](image2)

To identify the annual circulation pattern connected to the water column variability, we portrayed the connection between the ACC and the poleward regime through water column characteristics of Marian Cove (Figs. 1 and 2). The intrusion of warm water suggests the possibility of southward extension of the ACC regime. More explicitly, the SPF of the ACC matches well with warm/fresh summer water, implying that the source region of the warm water is part of the ACC regime. The reliability of correspondence for two water masses is extensive front features of the SPF traced from the eastern Bellingshausen Sea to Drake Passage, a
passage of 400 m deep in the southwest between Smith and Snow islands (Figure 1), and the strongest NE current (~40 cm s⁻¹) along the south flanks of the South Shetland Islands. In summary, we conclude that the ACC regime advances poleward in the mid summer when the ASW gradually weakens and disappears.

One of the questions related to the poleward movement of the ACC is its influence over the AP. Indeed, the ice shelves in the western AP are affected by the southward extension of the ACC regime. UCDW shoals dramatically southward across the ACC, so that the warm deep water originated in the far north are able to meet with the grounded ice shelves in the western AP. Although we cannot evaluate how much the prevalence of the ACC is during the warm period, the recent retreat of the grounded ice shelves is due to high basal melting with southward movement of 0.0°C January isotherm. For example of the southern South Shetland Islands, as another evidence of the extensive influence of the ACC regime, the seasonal temperature maximum (>1.5°C) at Marian Cove during the mid summer indicates the recent prevalence of the ACC regime since the first CTD measurements of 1988 at the cove).

For the interpretation of the temporal effect of water column properties using change of oceanic circulation, the glaciological setting and the surrounding ocean is important. In the South Shetland Islands, where there are no ice shelves, the valley/tidewater glaciers are critical for global climate research. At Marian Cove of Maxwell Bay, the retreat rate of tidewater glacier is rapid up to ~81 m yr⁻¹ in more recent years (1988–2001) than the past (1957–1988) (~12.5 m yr⁻¹). In addition, Ecology Glacier at Admiralty Bay has been in a state of continuous retreat at least since 1956. The retreat was slow from 1956 to 1989, amounting to 4.0–4.5 m yr⁻¹; it rapidly accelerated in the past decade (1989–1999) up to 30 m yr⁻¹. Summer poleward movement of the ACC has been associated with warm water intrusion to the South Shetland Islands lying on the extension of the western AP. Eventually, the recent warming trends may be caused by the intense intrusion of warm water along with the recent change of atmospheric circulation showing the trend toward stronger circumpolar vortex during the summer-fall season.

CONCLUSION

Antarctic fjord system provides useful information on the regional environmental change, though it is limited and inaccessible. In view of the water column properties for Drake Passage and one of Antarctic fjords out of the southern South Shetland Islands, the seasonal change of water masses was found at Marian Cove, King George Island of the northern AP. While in the mid summer temperature maximum (>1.6°C) and density minimum (<27.20 kg m⁻³) existed, from the mid August to the late October the temperature minimum (<1.3°C) and density maximum (>27.45 kg m⁻³) characteristics were prominent. Particularly, the existence of warm/fresh summer water indicates poleward progression of the ACC regime, causing the
recent rapid warming trend over the southern South Shetland Islands. Investigation of seasonally varied Antarctic fjord water masses may allow to evaluate poleward movement from the warm ocean of the ACC regime. Accordingly, the long-term monitoring of the water column characteristics on the boundary between the ACC and the polar regimes in the northern AP will provide the important archive of the ocean dynamics as well as the key of illustrating the regional warming.

REFERENCES


GLACIO MARINE SEDIMENTATION AND ITS PALEOClimATIC IMPLICATIONS ON THE WEST SPITSBERGEN FJORD (ISFJORDEN) OVER THE LAST 15000 YRS

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INTRODUCTION

The West Spitsbergen fjords and bays are climatically sensitive. This is mainly due to the present oceanographic regime characterized by north-flowing warm Atlantic Water in the West Spitsbergen Current along the continental margin with sharp gradients to cool, partly sea-ice covered Polar Water. The Spitsbergen fjords are influenced by relatively warm Atlantic Water transported from south with the West Spitsbergen Current and cold Polar Water from north. The sea-ice varies seasonally (Dowdeswell and Dowdeswell, 1989). Fast ice forms in coastal areas by about late November and is usually retained until late May or June (Wadhams, 1981). Pack ice us usually present around northern Spitsbergen throughout the year (Vinje, 1985). Geographical shift of the ocean front may cause large climatic changes affecting the life habitat and glaciomarine processes in the area. We have investigated multi-proxy records from the West Spitsbergen area, one from a middle fjord, Isfjorden and the other from the ice-proximal zone of Isfjorden. The purpose of the present paper is to (1) present well-dated paleoclimate data for the West Spitsbergen area during the Holocene and (2) investigate millennial-scale climate change and variability.

MATERIALS AND METHODS

Sediment sampling

Two sediment cores (JM98-818-PC and JM98-845-PC) from Isfjorden were obtained using gravity corer. Two cores were analyzed sedimentologically, geochemically and micropaleontologically to reconstruct paleoenvironmental changes.

Laboratory analyses
Volume magnetic susceptibility (MS) of the two cores was determined at 2 cm intervals using a Bartington MS-2B core sensor. Values of MS are expressed as 10-6 in cgs unit. The cores were cut lengthwise in the laboratory; one half was visually described and sliced for X-radiographs, and the other was used for subsampling. Subsamples were taken every 2 cm down the length of the cores to determine grain size, total organic carbon (TOC), and calcium carbonate (CaCO₃) contents. Physical sedimentary and biogenic structures were revealed through X-radiographs of 1-cm-thick sediment slabs. Microfossil assemblages, i.e., diatoms and benthic foraminifers, were examined in each sample. Total and carbonate carbons were determined by a Carlo Erba NA-1500 Elemental Analyzer by measuring the CO₂ content formed by combustion at 1100 °C and treated by hot 10% HCl, respectively (Heath et al., 1977). TOC content was obtained by measuring and calculating the difference between the total carbon and the carbonate carbon. Intact shell or shell fragment from the cores were used for AMS (Accelerator Mass Spectrometer) radiocarbon dates. The dating was performed by Nuclear and Geoscience Laboratory of New Zealand.

Chronology

The chronology of JM98-845-PC is based on 9 AMS radiocarbon dates performed on mollusk shells (Figure 1). A reservoir correction of 464 years was subtracted from the original dates (Mangerud and Gulliksen, 1975). A carbonate date near the surface material (6 cm in core depth) in the JM98-845 is ~440 (uncorrected), which indicates that 464 years correction is reasonable. The C-14 data yielded an average sedimentation rate of about 66 cm per 1,000 years for the core.

Figure 1. Down-core variation in corrected C-14 age and sedimentation rate.
RESULTS

Figure 2. Lithology of the cores JM98-818-PC and JM98-845-PC. Two cores are composed of four distinct sediment facies.
Figure 3. Vertical distribution of TN (%), TOC (%), C/N ratio and CaCO₃ (%) of the cores JM98-818-PC and JM98-845-PC.

CONCLUSION

1) Overconsolidated diamicton at the base of JM98-845-PC is supposed to be a basal till deposited during the LGM
2) Deglaciation of the fjord commenced since the glacial maximum, marked by the deposition of interlaminated sand and mud in the ice-proximal zone, and lasted for about 4,000 years with decreasing C/N ratio
3) Colder condition and following increased terrigenous input due to the glacial advance occurred at around 10,800 yrs BP with a drop in TOC content as well as a decrease in C/N ratio, which is probably coincident with the YD event in the North Atlantic region.
4) A climatic optimum occurred between 7,800 and 2,400 yrs BP, coinciding with a mid-Holocene climatic warm from the Laurentide Ice Sheet. At this time primary productivity enhanced in open marine condition, resulting in the deposition of organic-enriched pebbly mud with evidence of TOC maxima and C/N ratio minima, and causing post-depositional dissolution
of calcium carbonate component in sediments.
5) Around 2,400 yrs BP (the onset of Neoglacial), pebbly mud characterized by a decrease in TOC content as well as an increase in sand content, reflect the formation of more extensive and seasonally persistent sea ice, which might cause increased terrigenous input, as evidenced by an increase in C/N ratio.

REFERENCES


REVISED LITHO- AND CHRONOSTRATIGRAPHY OF THE VOLCANIC ROCKS IN BARTON PENINSULA, KING GEORGE ISLAND, ANTARCTICA

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INTRODUCTION

Despite the intense studies on the geology of Barton Peninsula, King George Island over the last two decades, there have been considerable differences on the lithologic and stratigraphic classifications between published maps. Recent compilation and synthesis made by Lee et al. (2002) and Willan and Armstrong (2002) considerably resolved these problems; however, there still remain uncertainties on the stratigraphic subdivisions of the volcanic rocks. Furthermore, the reinterpretation of the isolated massive basaltic andesite units as the intact-preserved earliest-stage spatter/cinder cones, contrary to the previous conjectures viewing as the lastest-stage hypabyssal intrusions, proposed by Kim et al. (2005), demands a more precise age constraints for the volcanic rocks. This study attempts to refine the litho- and chronosratigraphy of the Barton volcanic rocks, based on lithofacies analysis, field mapping and Ar/Ar age datings.

LITHOSTRATIGRAPHY

Barton Peninsula consists largely of stratified volcanic succession that has been pierced by plutonic and hypabyssal intrusions (Fig. 1; Davies 1982; Tokarski 1988; Park 1989; Birkenmajer 1998; Lee et al 2002; Willan and Armstrong 2002). The volcanic succession (300–500 m thick) characteristically shows a progressive lithologic change from the lower volcaniclastic-rich deposits to the upper lava-flow-dominant deposits. Because of the transitional lithologic change, there have been considerable mismatches on the boundary of the lower volcaniclastic and the upper volcanic deposits among the previously published maps. To resolve this problem, this study suggests tripartite subdivision of the volcanic succession, following Willan and Armstrong (2002): lower volcaniclastic deposits with subordinate sedimentary rocks (Sejong Formation, 100–200 m thick), the middle wedge (0–100 m thick) of tuff/lava alternations with sparse sedimentary layers and the upper volcanic sequence (200–300 m thick) dominated by basaltic andesite lavas with subordinate tuffs (Fig. 1).
Figure 2. Geologic map of Barton Peninsula. Locations of age-dated rock samples are denoted.

The Sejong Formation is represented by very thick, tabular beds of basaltic to andesitic, welded to non-welded, tuff breccias and lapilli tuffs, emplaced by pyroclastic flows (largely block-and-ash flows), resulting from Vulcanian explosions associated with volcanic dome extrusions and/or collapses (Kim et al., 2005). The rare intervening andesite lava flows suggest occasional effusions and the associated fluvial red sandstone/siltstone couplets and mass-flow conglomerates indicate active hydrologic remobilizations during inter-eruptive periods. At the base of the Sejong Formation, distinctive edifices of massive basaltic andesite occur as irregular to semi-circular patches in map view (Fig. 1). These rocks were formerly regarded as late-stage intrusions (dikes or plugs) (Tokarski 1988, Birkenmajer 1998, Lee et al. 2002, Willan and Armstrong 2002). The lack of distinctive discordant contacts and thermal metamorphism affecting the adjacent volcaniclastic rocks however does not support a late-stage origin. Furthermore, our new findings of the fringing basaltic agglomerates or agglutinates around the massive basaltic andesites through a transitional zone of fractured basaltic lava flows strongly indicate fire-fountaining (Hawaiian) to Strombolian eruptions through an open vent eruptions and subsequent emplacement of “ponded” lavas filling the vents at small-scale spatter/cinder cones. These cone complexes are there designated as a new stratigraphic unit (Chottae member) that occupies the base of the Sejong Formation, since they are draped, either unconformably or conformably, by the volcaniclastic rocks.
CHRONOSTRATIGRAPHY

A lot of K–Ar datings have been made for the basaltic andesites or andesites in the Upper Sequence (Park 1989; Kim et al. 2000; Hur et al. 2001), whereas only one sample was dated from the lower Sejong Formation (Table 1). We have analyzed two basaltic andesites (SA1 and O5) of Chottae member, one andesite lava (SA 3) of Sejong Formation, and one basaltic andesite (SA 4) of the Upper Sequence for the $^{40}$Ar/$^{39}$Ar age determination. One basaltic andesite (SA 2) of Chottae member was also analyzed for the K–Ar age determination. The results are shown in Fig. 2 and Table 1 and well support the revised lithostratigraphic classification of the Chottae member rocks as the lowest stratigraphic unit. Combined with the previous data, our new data suggests volcanic activities at 50–45, 45–44 and 44–42 Ma for Chottae member, Sejong Formation and the Upper Sequence, respectively, although the K–Ar ages are very dispersive because of excess argon effect by the postdated hydrothermal alterations (cf. Willan and Armstrong 2002).

![Figure 3. Ar-Ar isotope correlation diagrams of basaltic andesites (SA 1, SA 4 and O5) and andesite (SA 3) from Barton Peninsula. $T_1 =$ isochron age. For sample locations, see Fig. 1.]

CONCLUSIONS

Based on lithofacies analysis, field mapping, and radiometric age datings, the volcanic succession of Barton Peninsula, King George Island, can be divided into three formations: the lower pyroclastic deposits with subordinate sedimentary rocks (Sejong Formation), the middle wedge of tuff/lava alternations, and the upper sequence of basaltic andesite lavas with minor tuffs. The Sejong Formation comprises isolated, massive basaltic andesite flows with fringing basaltic agglomerates and agglutinates (Chottae member) at the base. The Chottae member represents the precursory fire-fountaining to Strombolian eruptions at cinder/spatter cones
during the 50–45 Ma, whereas the Sejong Formation indicates the volcanic climax with explosive Vulcanian eruptions at a large volcanic center (stratovolcano) at about 45–44 Ma. The middle wedge and the upper sequence suggest the lingering sporadic explosive and effusive eruptions, and the late-stage effusions and reworked deposition during the 44–42 Ma, respectively.

REFERENCES


Park, B.-K., Potassium-argon radiometric ages of volcanic and plutonic rocks from the Barton Peninsula, King George Island, Antarctica. J. Geol. Soc. Korea, 25, 495-497, 1989. (in Korean)


Table 1. Whole-rock radiometric ages of volcanic rocks of Barton Peninsula.

<table>
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<tr>
<th>Stratigraphy</th>
<th>Symbol*</th>
<th>Lithology</th>
<th>Method</th>
<th>Age (Ma)</th>
<th>Reference</th>
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<td>Tuff wall-rock at Qtz</td>
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<td>57.17±1.98</td>
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* For sample locations, see Fig. 1.

Abbreviations: Seq.=Sequence, Frm.=Formation, mbr.=member, Qtz=quartz.
SEDIMENTARY FACIES AND ARCHITECTURE OF A GIGANTIC GRAVELLY SUBMARINE CHANNEL SYSTEM IN A CRETACEOUS FOREDEEP TROUGH (THE MAGALLANES BASIN, SOUTHERN CHILE)

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INTRODUCTION

The Lago Sofia conglomerate (LSC) in the Cretaceous Cerro Toro Formation, southern Chile (Fig. 1), is deep-marine gravelly deposits, which are hundreds of meters thick, kilometers wide, and extend laterally for more than 100 km (Winn and Dott, 1979). The LSC has been formerly interpreted as deposits of submarine-fan channels. Recent study by the authors suggests, however, that the conglomerate represents more likely a gigantic submarine channel system, which consisted of a series of basin-marginal tributaries and a downstream trunk channel along the basin axis. The channel deposits provide an unusual opportunity to study microscopic to macroscopic characteristics of submarine channels. This study documents the characteristics of the tributaries and the axial trunk channel that have distinctive sets of lithofacies and architectures, and infers the evolution of the LSC channel system.

![Map of study area](image1)

**Fig. 1.** a) Location map of the study area. b) Depositional setting of the Magallanes Basin during the Cretaceous.
GEOLOGICAL SETTING

The Magallanes Basin consists of a deep, NS-trending foredeep trough in the west and a gently sloping foreland ramp in the east (Wilson, 1991)(Fig. 1b). Throughout the late Cretaceous, arc- and cordillera-derived elastic sediments were dispersed along the foredeep trough, resulting in deposition of a thick (6.5–7.5 km), deep-marine strata, including the Cerro Toro Formation (Scott, 1966; Wilson, 1991; Winn and Dott, 1979). The geometry and depositional regime of the basin persisted for about 30 Ma until the latest Cretaceous. During the Maastrichtian, deformation in the Patagonian fold-thrust belt began to migrate eastward, producing substantial changes in basin geometry and sediment dispersal patterns (Biddle et al., 1986; Wilson, 1991). Clastic material was shed eastward from the rising cordillera, and the basin depocenter shifted eastward and widened to encompass the former foreland ramp.

SEDIMENTARY CHARACTERISTICS, DEPOSITIONAL SETTING, AND ARCHITECTURAL ELEMENTS

Conglomerate bodies in the northern study area (Lago Pehoe and Lago Goic areas) are several tens to more than 100 m thick and separated by hundreds of meter thick hemipelagic mudstones (Fig. 2a). They consist of ungraded, inverse-to-normally graded conglomerates with thin lenses of massive or stratified sandstones. The conglomerates are generally clast-supported, well imbricated, and contain sedimentary intraclasts. They are interpreted to have been deposited by composite mass-flow events, comprising a turbidity current, a gravelly hyperconcentrated flow, and a mud-rich debris flow (Sohn et al., 2002).

In the southern study area (Lago Sofia area), the LSC occurs as about 400-m-thick conglomerates with rare intervening fine-grained facies (Fig. 2b). The conglomerates are mainly composed of crudely to thinly stratified and low- to high-angle cross-stratified conglomerates with rare intercalations of disorganized to inverse-to-normally graded conglomerates, suggestive of deposition mainly from highly competent turbidity currents.

Previous studies interpreted that the LSC was deposited in submarine channels developed upon a submarine fan (Winn and Dott, 1977; 1979), but a number of sedimentary features contradict with this interpretation. For example, the LSC is encased in a thick hemipelagic mudstone, and the paleoflows are far from radial, negating the possibility of a depositional system with a diverging sediment dispersal pattern. Instead, the LSC suggests a submarine channel system, which developed along the NS-trending foredeep axis of the Magallanes Basin.

A number of sedimentary features in the LSC are similar to those of terrestrial fluvial deposits. An architectural element analysis for the LSC in the Lago Sofia area shows that five architectural elements can be classified on the basis of large-scale bed geometry and
sedimentary facies (Fig. 3): (1) stacked sheets, (2) laterally-inclined strata, (3) foreset strata, (4) hollow fills, and (5) dianitic. The LSC here consists of eight channel complexes bounded by major erosional surfaces. In general, turbidite conglomerates dominate and form stacked sheets. The stacked sheets, laterally inclined strata, and hollow fills are laterally transitional to one another, reflecting juxtaposed geomorphic units of deep-sea channel systems.

![Diagram of Lago Pehoe and Lago Goic areas](image)

Fig. 2. Distribution of the LSC and Paleoflow patterns in the Lago Pehoe and Lago Goic area (left) and Lago Sofia area (right).

<table>
<thead>
<tr>
<th>Elements</th>
<th>Geometry</th>
<th>Description</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stacked sheets (Element S)</td>
<td>Sheet-like</td>
<td>Sheet-like, hundreds of meters in lateral extent</td>
<td>Stacking of fine-grained beds by turbidity flows</td>
</tr>
<tr>
<td>Laminae (Element L)</td>
<td>Sheet-like or lenticular</td>
<td>Laminae-like, 1-2 mm thick, several meters in lateral extent</td>
<td>Laminated sediments formed by turbidity currents</td>
</tr>
<tr>
<td>Flow units (Element F)</td>
<td>Lenticular</td>
<td>Lenticular, several meters in lateral extent</td>
<td>Downcurrent migration of debris flows</td>
</tr>
<tr>
<td>Hollow fills (Element H)</td>
<td>Lenticular</td>
<td>Lenticular, several meters in lateral extent</td>
<td>Filling of channels, minor channel forms, and failures</td>
</tr>
<tr>
<td>Dianitite (Element D)</td>
<td>Sheath-like</td>
<td>Sheath-like, several meters in lateral extent</td>
<td>Sheath-like deposits of mud-rich conglomerates forming on concave-up, foreset strata, and foreset surfaces</td>
</tr>
</tbody>
</table>

Fig. 3. Characteristics of architectural elements in the LSC.
CONCLUSIONS: EVOLUTION OF THE LSC SUBMARINE CHANNEL

The LSC is similar to terrestrial river deposits in sedimentary facies and architecture, as pointed out by Winn and Dott (1979). The stratified conglomerate common in the Lago Sofia deposits is nearly identical to those of gravel-bed rivers. The architectural elements of stacked sheets, laterally-inclined strata, foreset strata, and hollow fills are also similar to the deposits of gravelly braided rivers (Jo et al., 1997). These suggest that the Lago Sofia submarine channels were similar in geomorphology to terrestrial, gravelly braided rivers.

The main sedimentary processes in the LSC are the formation of various gravel bars and the filling of hollows by turbidity currents. The architectural elements of stacked sheets, laterally-inclined strata, foreset strata, and hollow fills represent a range of morphologic units constituting the submarine channels. The gravels might have been transported downstream by a number of turbidity currents over long period, forming various morphologic units, rather than by single turbidity-current events. Debris flows forming the mud-rich diamicrite beds are also the principal process operative in the submarine channels. The diamicite beds are relatively abundant in the lower part of the channel conglomerate body, suggesting that the sediment failures occurred more frequently in the early stage of channel filling.

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VARIABILITY OF GLOBAL THERMOHALINE CIRCULATION DUE TO THE DRAKE PASSAGE

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Global thermohaline circulation in an idealized ocean was simulated to verify its variabilities due to the bottom topography of the Drake Passage in the Antarctic Ocean. It was represented by NOAA/GFDL Modular Ocean Model, MOM, 3. Grids consist of latitudinal and longitudinal 2° and vertical 20 layers. We simplified the oceans as three rectangular oceans linked together by the Antarctic Ocean. All of the bottom topography was ignored as a flat bottom except that of the Drake Passage. Wind over the surface layer has no zonal variation but only meridional one and restoring temperature and salinity were symmetric distribution across the equator. There were no zonal variations in all surface boundary conditions. Due to the variation of bottom topography of the Drake Passage, most changes of thermohaline circulation occurred in the North Atlantic but for the changes of the Antarctic Circumpolar Current directly affected by it. And especially in the cases with the shallow Drake Passage, the thermohaline circulations were strengthened in global ocean areas. In this study, we would explain how the effect of bottom topography in the Drake Passage on the thermohaline circulation propagated to the northern hemisphere and the reason why circulation changes were emphasized in specific areas.
Figure 1. Stream function: 1. No significant changes appear in the stream function in the Pacific Ocean due to the bottom topography in the Drake Passage. 2. Overturning of deep layer in the Atlantic Ocean is strengthened slightly. 3. But the overturning of intermediate layer in the Atlantic Ocean is weakened, especially in the northern part.
HYDROACOUSTIC MONITORING OF SUBMARINE VOLCANO-TECTONIC ACTIVITY, ICEBERG NOISE, AND MARINE MAMMAL VOCALIZATIONS WITHIN THE BRANSFIELD STRAIT AND WESTERN SCOTIA SEA, ANTARCTICA

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INTRODUCTION

During the last decade, the value of hydroacoustic studies in monitoring ocean floor seismicity has been demonstrated through work using the U.S. Navy’s Sound Surveillance System (SOSUS) [e.g., Fox et al., 1994] and arrays of moored autonomous underwater hydrophones (AUHs) [e.g., Bohnenstiehl et al., 2002a; Dziak et al., 2004a]. As a result, the analysis of hydroacoustic data has revolutionized our understanding of mid-ocean ridge eruptive processes, illuminated the complex structure of subduction zones and transform faults [Okal and Talandier, 1997; Dziak et al., 1996] and has shown great promise as a tool in addressing a variety of tectonic problems [e.g., Bohnenstiehl et al., 2002].

In anticipation of the International Polar Year in 2007-2008, NOAA/OSU, collaborating with KORDI and LDEO, will deploy an Autonomous Underwater Hydrophones (AUH) array for a period of one year to record seismicity along the Antarctic Peninsula and western Scotia Sea. This array will take advantage of the efficient propagation of sound in the oceans to detect, locate and analyze the distribution of small and moderate-size earthquakes along the South Shetland Islands (SSI), Bransfield Strait, and South Shetland Trench (SST). We anticipate this research will identify first-order correlations between the spatio-temporal distribution of earthquakes and major geologic features in the region. Such observations will provide insights into the dynamics of subduction and back-arc spreading, as well as the levels of otherwise unobserved submarine volcanic activity in the region. A result from a preliminary test deployment in 2004 near the proposed study site (62°S-58°W) is discussed.
The South Shetland Islands are located along the western Antarctic Peninsula between 60° and 63°S. Our hydrophone geometry is designed to optimize coverage along the Antarctic Peninsula (within the Bransfield Strait), but will also provide coverage across the entire western Scotia Sea covering the Shackleton Fracture Zone and the north and south Scotia Ridges. In addition, the array geometry will allow us to detect and locate tectono-volcanic earthquakes from the South Sandwich Island volcanic arc and back-arc, and the South Sandwich Trench. Our primary objectives in monitoring the western Scotia Sea is to produce a catalog of (>2.5-3.0 m/s) shallow-hypocenter earthquakes, ice-motion source locations, as well as a catalog of marine mammal calls. This database, to be made available via the World-Wide Web as the data are processed, will include estimates of origin time, locations, acoustic-source magnitudes and associated errors. These data will allow us to:

1. **Examine the overall temporal and spatial pattern of earthquake production along the Antarctic Peninsula and western Scotia Sea**

2. **Evaluate the occurrence and distribution of submarine volcanic activity (via detection of earthquake activity and volcanic tremor) along the Antarctic Peninsula, Scotia Sea, and Bransfield Strait back-arc basin.**

3. **Use acoustic records to investigate the movement and breakup of ice within the region.**

4. **Assess the type and distribution of baleen whale populations in the region.**

Six hydrophones will make up an array; and each hydrophone package consists of a single ceramic hydrophone, a pre-amp filter to whiten the ambient noise, an accurate Q-tech clock (< 1 s/yr drift) that is GPS synchronized before and after deployment, and logging computer. A standard alkaline D-cell battery packs supplies the power, and the electronics and battery pack are housed within a titanium pressure case which minimizes corrosion. The Antarctic instruments will record continuously at a sample rate of 100 Hz (1-40 Hz band pass) and with a 16-bit A/D resolution. The extreme cold water (-2° C) and strong currents of the Drake Passage required modifications to the AUH design adopted in previous mid-latitude monitoring projects. Specifically, we doubled the strength of the mooring line and replaced the standard laptop hard-drives with a hermetically sealed drive which is rated to -20°C. KOPRI deployed a test NOAA hydrophone mooring (complete with current meter) in the Bransfield Strait from the R/V *Yuzhmorgeologiya* during the transit leg from Punta Arenas to King George Island on 20 November 2004 and recovered the hydrophone on 14 December 2004. The test went exceptionally well and acoustic data were collected flawlessly. Figure 2 is a representative record of the Antarctic hydrophone data showing the time series (bottom) and spectrogram (top) of an earthquake T-wave as well as airguns from a seismic survey. To our great satisfaction the T-waves of dozens of earthquakes from throughout the Bransfield Strait were clearly recorded by the hydrophone during the 4-week deployment.
Our long-term deployment, funded by Ocean Exploration, will begin in November 2005. After the scheduled recovery in 2006, data will be fully processed for T-wave epicenters within six months of instrument recovery. In keeping with the spirit of data sharing, a catalog of locatable T-wave events will be made available as the data are processed. It should be noted that all of our data will be analyzed by early 2007, allowing us to have results available for public and scientific presentations in observance of the International Polar Year in 2007-2008.

**Figure 1.** Boundaries (heavy colored lines) of the Shetland (SL), Scotia (SC), and Sandwich (SW) plates. Surrounding plates are Antarctica (AN) and South America (SA). The former Phoenix plate ([Ph]; dashed black line) has now merged with AN. Oblique Mercator projection with great circle passing E-W through (32° W, 58° S). Boundary types are: CCB continental convergent boundary, CTF continental transform fault, CRB continental rift boundary, OSR oceanic spreading ridge, OTF oceanic transform fault, OCB oceanic convergent boundary, SUB subduction zone. Cross-hatched regions are orogens. Color shows topography from ETOPOS. Solid dots are shallow (< 70 km) hypocenters from ISC catalog, 1964-1991; beachballs are lower-hemisphere projections of double-couple parts of moment tensors of shallow centroids from Harvard CMT catalog, 1977-1998. White triangles are subaerial Recent volcanoes from Simkin and Siebert [1995]. Black vectors give model velocities (with numbers in mm/yr) relative to plate whose identifier is underlined. From Bird [2003].

**Figure 2.** Time series and spectrogram showing 200 seconds of data from hydrophone deployed in Bransfield Strait. Diagram shows clear T-wave arrival from nearby earthquake (range of -45-60 km) as well as impulsive arrivals from an airgun survey.

RESULTS

The 2004 hydrophone test deployment in the Bransfield Strait indicates a low attenuation environment for acoustic wave propagation with the clear recording of T-waves from several regional Antarctic Peninsula earthquakes. For hydrophones deployed in the western Scotia Sea,
the Transmission Loss (Collins, 1993) for acoustic wave propagation was estimated from the volcanic arc and trench at the South Shetland Islands for a 5 Hz signal. There is generally little loss (~95 dB) in signal strength for propagation from both source locations to a hydrophone 500 m deep moored 600 km away in the abyssal plain (60°S-70°W), indicating earthquakes from these locations will be easily detected acoustically. The sound speed profiles for the region are surface limited throughout the year, signifying that acoustic waves will interact with the sea-surface. The propagation models suggest, however, that this will not adversely affect the earthquake detection capability for this hydrophone array geometry.

SUMMARY AND CONCLUSIONS

Based on the successful test monitoring in the Antarctica, we will proceed a one-year deployment of six autonomous underwater hydrophones to monitor seismicity along the Antarctic Peninsula and western Scotia Sea. This array will take advantage of the efficient propagation of sound in the oceans to detect and locate the acoustic (T-wave) signals of (>2.5-3.0 m/s) earthquakes, volcanoes, ice movement, and marine mammals throughout the region. Preliminary results indicate that in the remote Antarctic waters, a long-term hydroacoustic monitoring is promising in achieving number of goals, including: a) Examine the overall temporal and spatial pattern of earthquake production along the Antarctic Peninsula and western Scotia Sea; b) Evaluate the occurrence and distribution of submarine volcanic activity (using earthquake activity and volcanic tremor) along the Antarctic Peninsula and throughout the Scotia Sea; c) Monitor the volcanic arc and back-arc for volcanic tremor and constrain those factors controlling its generation in the submarine environment; d) Monitor the acoustic signature of ice breakup and movement within the Antarctic Peninsula region, and e) Assess the type and distribution of baleen whale populations in the region where little information exits.

REFERENCES


THERMAL DYNAMICS OF ACTIVE LAYER AT THE DASAN STATION, SVALBARD

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INTRODUCTION

Quantitative analysis of the processes underlying the thermal and hydraulic dynamics of permafrost soils is important to predict the meteorological phenomena on the permafrost area or to parameterize the interaction between soil and atmosphere in the global climate model (Han, 1991; Han and Jung, 1994; Harrison, 1991). In this study, the borehole temperature measurements at the Dasan station were made by Baroo-Diver geothermal datalogger. The thermal dynamics of active layer at the Dasan Korea Arctic Research Station, Svalbard (78° 55.5' N, 11° 56.0' E) is represented in the soil temperature that can be measured with high accuracy and high temporal resolution.

TEMPORAL VARIATION OF THERMAL PROPERTIES

During September 28, 2002 - August 12, 2003, three temperature data were obtained by Environ Mon every thirty minutes. Fig. 1 shows the temperature variations at the depth of 0.25m, 0.5m, and 0.75m. We can determine the thermal diffusivity using the estimation of the phase shift between the temperature projected from the ground surface with the measured temperature. At the Dasan station, the average thermal diffusivity indicates the range of thermal diffusivity $4\times10^{-7}$ to $6\times10^{-7} \text{m}^2\text{s}^{-1}$.

In order to describe the more precise thermal processes of active layer, it is necessary to analyze the temporal variation of thermal quantities: conductive heat flux and heat generation (latent heat). Obviously, the thermal dynamics of permafrost soils cannot be understood from conductive heat transport alone. Further dominating processes are the
transitions of water between the solid, liquid and vapor phase and the convective transport of heat either in the liquid or in the vapor phase.

Fig. 1 Temperature variations from September 28, 2002 to August 12, 2003. The rectangle indicates an period with dominating heat conduction.

The conductive heat flux can be calculated from the finite difference approximation of subsurface temperatures. In addition, we can define the mean production of latent heat by the integral of the rate of heat production in the depth and time elements(Roth and Boike, 2001).

Fig. 2 Four periods during the annual freeze-thaw cycle: isothermal period (0-75 days), cold period (75-225 days), warming period (225-275 days) and thawing period (275-318 days). Cold period can be subdivided into four short period (A, B, C, D) and thawed per
Fig. 3 Relationship between the production of latent heat and the conductive heat flux estimated in the layer of 50 cm - 75 cm. Four plots show the result of (a) mixed period, (b) cold period, (c) warming period and (d) thawed period. 6-hour averaged value is

We may distinguish four periods in the view of the thermal dynamics: the cold, warming, thawing and isothermal period(Fig. 2). In cold period with sufficiently low temperature, we can find the strong consumption of latent heat and strong negative heat flux. As would be expected, the water evaporating and upward migration play an important role of heat transporting from subsurface layer to surface and cooling the subsurface soil. The conductive heat flux and latent heat turn positive throughout the soil profile in warming period. This process indicates melting snow cover that cause an increasing downward vapor flux toward the colder layers. In thawing period in which the thawing front passes the active layer, the vapor migrates toward the colder layer under the thawing front and the migration of vapor accelerates the thawing process of thawing front. In the period that the temperatures stay near 0°C in isothermal period, conductive heat fluxes are very small. This means that the macroscopic phase boundary prevents temperature fluctuations from the surface to reach greater depths.

The relationship between the heat flow and heat generation can be a good criterion for the classification of geothermal characteristics(Fig.3). In the case of cold period that has the positive correlation between the heat flux and heat generation, especially, the freezing and thawing of water and migration of water vapor are highly dependent on the geothermal gradient(Fig. 4). However, the relation patterns of the temperature decreasing stages(A, C) and the temperature increasing stages(B, D) are slightly different. It is thought that this differences are correlated with the activities of water evaporation and vapor migration.
Fig. 4 Relationship between the latent heat and the conductive heat flux in the short intervals of the cold period.

SUMMARY

Using the continuous data over a period of 318 days at the Dasan site, Svalbard, we deduce and quantify the processes which constitute the thermal dynamics. Conductive heat flow, migration of water vapor, and heat generation from phase transition are analyzed. Average thermal diffusivity indicates the range of thermal diffusivity $4 \times 10^{-7} \sim 6 \times 10^{-7} \text{m}^2 \text{s}^{-1}$. We distinguished four periods in the view of the thermal dynamics: the cold, warming, thawing and isothermal period. The relationship between the heat flow and heat generation can be a good criterion for the classification of geothermal characteristics. The Dasan experiment is a good test of the geothermal method of climate reconstruction because the permafrost is a valuable recorder of climate change.

REFERENCES

INTERPRETATION OF LATE QUATERNARY PALEOENVIRONMENT FROM A SEDIMENT CORE OF THE DRAKE PASSAGE IN THE ANTARCTIC OCEAN

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The water flow pattern of the Drake passage is characterized by the Antarctic Circumpolar Current (ACC) including three major fronts which are SAF(Subantarctic Front), PF(Polar Front) and SACC(Southern ACC Front). The latitudinal fluctuations of these fronts are strongly influenced by glacial-interglacial climate change and those records thus are well imprinted on the marine sediments.

The major purpose of this study is to reconstruct paleoproductivity and water fronts fluctuations related to paleoclimate change of Southern Ocean. In the present study, several biogeochemical indicators such as organic carbon and nitrogen contents, their stable isotopes ($\delta^{13}C$, $\delta^{15}N$) and Biogenic Opal contents are determined with the core sediments (GC89-06), which was collected in the deep basin of the Drake Passage, Antarctic. The stable carbon isotope values in sediment ranges from -24.4% to -25.4% (average value: -24%), suggesting that the origin of organic matter is mostly marine production. Although organic carbon contents are very low(average: 0.25%) because core located in deep water(4500m), organic carbon and nitrogen contents increased during the LGM period because of the enlarged marine production and decreased during the Deglaciation period, and also showed periodical changes in the Holocene. It seems to be affected by the SACC that moved southward from LGM to Holocene.

Biogenic opal which is produced by marine diatom was measured by using Mortlock's Method (Richard A. Mortlock, Philip N. Froelich, 1989). Biogenic opal contents are from 12% to 24%, indicating similar changes to those of organic carbon and nitrogen contents. But in some periods, biogenic opal contents was low, even though organic carbon contents was high, demonstrating that other phytoplankton instead of diatom was dominant species in this region.
Fig. 1. Distribution of total organic carbon content(%), total nitrogen content (%), $\delta^{13}C(\%)$ and $\delta^{15}N(\%)$ in core of GC98-06.

Fig. 2. Fluctuation of the SACCF during the LGM & Holocene
3-D GPR IMAGING AND RESISTIVITY STRUCTURE BY MT
NEAR KING SEJONG STATION

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INTRODUCTION

In this study, a new high-frequency magnetotelluric (MT) technique has been used to analyze the deep subsurface architecture without the costly burden of a seismic-reflection survey. Profile of high-resolution magnetotelluric data was acquired near King Sejong Station in the Antarctic interprets the data in terms of resistivity structures including faults. In addition to MT Survey, GPR (Ground Penetrating RADAR) method, which is one of the geophysical techniques used in polar regions, was applied to get the 3D subsurface imaging by 3D slicing across the crevasse developed in the glacier.

DATA ACQUISITION

1. Magnetotellurics

The MT method, a depth-sounding technique measuring Earth's natural time-varying electromagnetic fields, probes subsurface structure of electrical resistivity at depth (Vozoff, 1991). The simultaneous electrical and magnetic measurements are made throughout a band of frequencies that translates to a section of investigation depths. In this study, the high-frequency MT data were collected along 4 Km near King Sejong Station with 50 - 200 m intervals. For profile stations, Eₓ (x-component of electric field) and Hₓ (x-component of magnetic field) are lined up with the profile line, and Eᵧ and Hᵧ are orthogonal to the profile direction. The high-frequency MT fields were recorded using the IMAGEM system (Nichols et al., 1994) in the frequency range of 10 to 10,000 Hz; this range is higher than conventional MT and probes the structure down to the upper crust, approximately a depth of a few kilometers depending on the effective penetration of electromagnetic energy, \( d \approx 500\sqrt{\rho/f} \), where \( d \), \( \rho \), and \( f \) represent skin depth, electrical resistivity, and frequency, respectively.

Impedance tensor was calculated from \( Eₓ \), \( Eᵧ \), \( Hₓ \), \( Hᵧ \) cross powers (Swift, 1985; Vozoff, 1991; Shon et. al., 2000). E-polarization (\( Eₓ \), \( Hᵧ \)) and B-polarization (\( Eᵧ \), \( Hₓ \)) were differentiated by crossing the possible fault or geologic structure lines with \( Eₓ \). There is no control for cultural
biased data since the IMAGEM system – MT system which was used in this study - uses local self-references. The basement of study area is very resistive (>5,000 ohm-m), so frequency above 10 Hz was used. For static shift EMAP (Electromagnetic Array Profiling; Bostick, 1986) filtering was used. Individual station was examined by 1D inversion and, and 2D sections (line ES1 and line ES2, Fig. 2) were examined by EMAP filtering and 1D Bostick inversion. Figure 1 is an example of high-frequency MT data obtained by IMAGEM system. Top window shows an apparent resistivity, second is a phase and third is a coherence diagram. The fourth window shows a true resistivity sounding acquired by Bostick inversion.

Fig. 1 MT Survey Line

Fig. 2 Apparent resistivity (top window), impedance Phase (second) coherency (third) recorded. True resistivity soundings is in the bottom window. TM data are shown with solid square symbol, while TE are shown with open symbol.

2. Ground Penetrating RADAR

A GPR antenna transmits high frequency electromagnetic pulse wave into the subsurface. If the transmitted energy encounters a boundary with sufficient contrast in dielectric permittivity, some of energy will be reflected. These reflections are recorded by the receiving antenna and the amplitude of the reflection depends on how large the change in dielectric permittivity across the boundary is, and how close the boundary is to the surface (Pettersson and Nobes, 2003). A Sensors and Software pulseEKKO 1000 unit with 225 MHz antennas was used for the GPR surveying. Due to diffractions – one of the phenomena of traveling waves, which is considers as a noise in GPR – it is not easy to get the true subsurface configurations from GPR profile. Subsurface interpretation is possible from experience and signal processing which is time-taking procedure and sometimes brings image distortion by processing itself.

To overcome and detour diffractions in 2D GPR profiles, the concept of 3D slicing from lots
of 2D GPR profiles was adopted as shown in Fig. 3. GPR survey was performed on the crevasse developed in the glacier near King Sejong Station covered by snow.

Fig. 3 Example of GPR Profile. It shows a diffraction due to object(s) in the subsurface.

Fig. 4 GPR Slicing (horizontal profile) from 2D GPR Profiles (vertical sections)

RESULTS AND CONCLUSIONS

1. Magnetotellurics

Fig. 5 Subsurface Resistivity structure by MT survey. Faults are indicated by black lines.

From 2D MT profile, it is possible to configure the resistivity distribution in the subsurface. Also faults can be interpreted from the section. The interpreted from MT resistivity profile are almost coincides geological field study. It shows that MT will be a powerful promising tool for the geological and geophysical study of deep subsurface structure.
2. 3D GPR Slicing

From the study performed on the crevasse in the glacier, 3D slicing shows exact size and dimensions of crevasse on the corresponding depth (Fig. 6), which was not possible and/or very difficult by conventional method and techniques. A new technique using the concept of GPR Slicing shows a successful 3D imaging of (seismic) reflection data including GPR.

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PETROLOGY AND MINERALOGY OF THE SALMAGORA ULTRAMAFIC-ALKALINE-CARBONATITE-COMPLEX, KOLA PANINSULA, NW RUSSIA

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ABSTRACT

The Salmagora complex consists of the sequence of ultramafic-alkaline-carbonatite rocks (dunite - wehlrite - ultrameliilitolite - turjaite - pyroxenite - melteigite - ijolite - urtite - carbonatite). Dunite, wehlrite, ultramelilitolite, pyroxenite are cumulate facies, whereas foidolites seem to have been derived from the residual magma after crystallization of cumulate of pyroxenite. Chemical compositions and mineral assemblages of dunite and wehlrite show a simple evolution trend, whereas pyroxenite-foidolite series branched into two types. Phlogopite and perovskite occur as dominant accessory phases in the first type pyroxenite-foidolites, whereas garnet and sphene as typical accessory phases in the second type. The second type pyroxenite-foidolites show HREE enrichment relative to the first one due to these mineral assemblages, and their major mineral compositions are also clearly distinguished from those of the first series rocks. These differences suggest that the two type series rocks evolved from different magmas. Whole rock compositions of melilitolites are distinct; they have extremely fractionated chondrite-normalized REE patterns (more than 1000 times enriched LREE). Whole rock and mineral compositions of the cumulate facies (dunite and wehlrite) and the first type pyroxenite-foidolite series show a continuous variation, whereas those of melilitolites and the second type pyroxenite-foidolite series show different evolitional trends. Thus the cumulate facies and the first type pyroxenite-foidolite series are considered to represent a continuum from a common magma. However, in order to explain the typical geochemical and mineralogical features of the melilitolites and the second pyroxenite-foidolite series, it is necessary to consider at least three batches of magma responsible for the formation of the whole Salmagora ultramafic-alkaline-carbonatite complex.

Keywords: Salmagora, Kola Peninsula, Ultramafic-alkaline-carbonatite-complex
INTRODUCTION

The poorly exposed Salmagora complex (26 km² at the surface) located in the southern part of the Kola Peninsula is hosted by Archean gneiss, and consists of a series of concentric ultramafic, alkaline and carbonatitic rocks. It was discovered in 1949 and subsequently studied for 15 years (Kukharenko et al., 1965). The age of the Salmagora intrusion was estimated to be 375 Ma using the U-He method for garnet from ijolite (Kukharenko et al., 1965). This is consistent with the ages (360-380 Ma) obtained by Kramm et al. (1993) for other Paleozoic alkaline complexes in the KAP. Geology of the intrusion and associated mineralization have been reported based on the recent drilling to explore the apatite and perovskite ores (Korobeinikov et al., 1998). However, their work was mainly concentrated on the copper-sulphide mineralization, and the occurrence and genetic relation among the rock facies are still poorly understood. In this paper, we present systematic mineralogical and whole-rock geochemical data to understand the characteristics and genesis of the Salmagora complex.

![Geological map and cross-section of the Salmagora complex](image)

**Fig. 1** Geological map and cross-section of the Salmagora complex (Korobeinikov et al., 1998).

WHOLE ROCK AND MINERAL CHEMISTRY

The Salmagora complex consists of ultramafic cumulate facies (dunite, wehrlite, pyroxenite,
ultramelilitolite and turjaite), and foidolite series rocks with subordinate carbonatite. Pyroxenite and foidolite series rocks are divided into two types based on their mineral assemblages and geochemical properties.

Compositional variations of the Salmagora ultramafic cumulate facies such as dunite, wehrlite and pyroxenite are within the range of those from other Kola ultramafic rocks (Arzamastsev, 1994). MgO contents of dunite and wehrlite show a quite large variation from 30 to 42 wt%, whereas MgO contents in the other silicate rocks ranges from 3 to 12 wt%. All the rocks of the complex show enriched chondrite-normalized REE patterns. Especially, melilitolites have extremely high LREE/HREE ratios. Except for the melilitolites, total REE content increases more or less regularly through the rock sequences. Wehrlite has slightly higher HREE contents compared with those of dunite. The type I pyroxenite-ijolite-melteigite series rocks, which share same mineral assemblage with the former ultramafic cumulate facies and are considered to be a member of earlier sequence, have similar REE patterns to those of dunite. The type II pyroxenite-foidoelite series rocks have slightly lower LREE contents but remarkably higher HREE contents compared to the type I rocks, and thus show upward concave patterns. This feature more intensively appears in the type II pyroxenite and melteigite, which is probably due to an extensive crystallization of sphene and garnet in these rocks.

Clinopyroxene from the type I pyroxenite mostly covers all compositional ranges of Al and Ti of which contents largely decrease with the rock sequences. Fe and Na contents progressively increase with evolution. Although early crystallized clinopyroxenes from the type I pyroxenite have higher Al and Ti contents compared to those of wehrlite and melilitolites, Mg numbers and Na contents are mostly overlapped. Compositions of phlogopite from melilitolites are distinguished from the other populations; they are more enriched in Al₂O₃ and depleted in Na₂O. The evolutional trend of mica from the type I series is different from that of the type II series. A part of micas from the type II series evolves up to biotite composition. Na content of phlogopite systematically decreases toward late stage rocks, except for phlogopite from melilitolites, which is a reflection of the change of interstitial melt compositions. Spinel group minerals occur in all the rock constituents of the Salmagora complex and their chemical compositions vary from spinel (sensu stricto) to the pure magnetite. The variety containing the highest spinel component in dunite evolves toward pure magnetite in foidolites. Al and Mg contents decrease with evolving rock sequences.

CONCLUSIONS

The Salmagora ultramafic-alkaline rocks seem to have been produced by several intrusions from successive batches of magmas. The continuous and systematic compositional variation in minerals and bulk rocks from dunite to the type I pyroxenite-foidoelitic rock series suggest that
they were derived from a common magma. However, the type II pyroxenite-foeldolitic rock series with distinctly different mineral paragenesis and geochemistry are likely to have been formed from another batch of magma. And, finally, to explain the significantly different geochemical and mineralogical characteristics of melilitolites, which have extremely high LREE/HREE ratios and particularly different mineral compositions, it is necessary to consider an involvement from an additional source to their parental magma.

REFERENCES

HOLOCENE TEPHRA IN SEDIMENTS OF HOTEL AND RUDY LAKES ON KING GEORGE ISLAND, SOUTH SHETLAND ISLANDS, WEST ANTARCTICA

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Several tephra layers are present in lacustrine core sediments collected from Hotel and Rudy lakes on King George Island, South Shetland Island, W. Antarctica. The tephra layers are more abundant in a long Hotel Lake core. This study uses volcanic glass samples from five tephra layers of Hotel Lake and from one tephra layer of Rudy Lake. Volcanic glasses are mostly brown with some transparent ones. Morphologically, tephra are classified into pumice shards, blocky glasses and bubble wall glasses and their relative proportions are different from samples to samples. Also, volcanic glasses contain a few to abundant small bubbles and lath-like microcrystal inclusions. Major element analyses of glass shards reveal that the majority of the glasses range from basalt to low-silica andesite and are subalkaline series medium-K tholeiites. Although minor, some glasses with rhyolite compositons are observed in A, B, D and E tephra layers of Hotel Lake. Based on chemical fingerprints the majority of tephra in these lake sediments are interpreted to have blown from Deception Island located 130 km southwest of King George Island. But, some tephra in A layer of Hotel Lake were derived from Penguin Island located east of King George Island closely. The result of this study show that C layer of Hotel Lake core and R-120 layer of Rudy Lake core, which are conventionally thought to be correlatable, do not share similar geochemical characteristics. Rather, this study suggest that the R-120 layer of Rudy Lake is more correlatable with B layer of Hotel Lake. This study implies that more chemical criterion is needed to study tephrachronology and correlation and to understand paleoenvironmental evolution.