EUG XI

Symposium CC02

High Latitude Cenozoic-Quaternary Ice Sheets and Climate – Records of their Role in Global Climate Change

Convenors

Gary Wilson
Ralph Schneider
Andrew Kerr
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MondayAM Session

CC02 : MOam01 : G3
Sedimentary Facies and Landforms Associated with Valley Glaciers in Svalbard: Evidence for Changing Dynamic and Thermal Regimes

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Sedimentary facies and landforms associated with glaciers and ice sheets bear the imprint of a wide range of processes, especially those linked to glacier dynamics and thermal regime (which in turn depends largely upon climate). Discrimination of the glaciogenic facies associated with different climatic regimes in the geological record is still at an early stage of development, but is vital if we are to model former ice masses. One factor that has previously been largely overlooked is how a glacier might respond dynamically to a changing climate, and how this is reflected in the sediments. Here, we present the results of a structural and sedimentological investigation of four valley glaciers in Svalbard (Norwegian High-Arctic) that addresses this issue.

The main focus of the paper is midtre Lovénbreen and austre Lovénbreen, two typical land-based polythermal valley glaciers. Additional observations were made at austre Brøggerbreen and vestre Lovénbreen Midtre Lovénbreen has a long record documenting its response to 20th century climatic warming. Structural mapping of the glacier and analysis of sediments in the proglacial area of midtre Lovénbreen indicate that the thermal structure and dynamic regime of the glacier have changed through time. Dynamically, midtre Lovénbreen was once heavily crevassed and relatively fast-flowing, but now is slow-moving and virtually crevasse-free. The sedimentary record indicates that the glacier was wet-based and sliding on its bed when it was in a more advanced state, probably at its Neoglacial maximum (late 19th/early 20th centuries). During this advance, a thin deforming layer of diamicton, commonly fluted, was draped over the existing morphology in the presently exposed proglacial area. This morphology consisted of large streamlined sandy gravel ridges aligned parallel to ice flow. Erosion of the underlying bedrock appears to have been limited. Radio-echo soundings of the glacier show that at present it is part-frozen to the bed (polythermal). Modification of the bed is inhibited under this thermal regime and as a result the supraglacial environment dominates modern sedimentation. Comparative studies on austre Lovénbreen, which probably is also polythermal, indicate similar sedimentary characteristics and facies associations although here there are much more extensive areas of striated bedrock,. In contrast, both austre Brøggerbreen and vestre Lovénbreen are predominantly cold-based. Collectively, these four glaciers suggest a regional trend of glacier recession and thinning accompanied by a change in thermal regime from predominantly wet-based, through partly frozen, to completely frozen. This study suggests that Svalbard valley glaciers have several dynamic modes and that glaciers switch between these dynamic modes largely as a reaction to changes in mass balance. Similar investigations of facies associations and glacier structures are required at other modern glaciers to improve our ability to infer climates associated with former ice masses.

CC02 : MOam02 : G3
Geophysical Investigations of Ice-Influenced Sedimentation on Arctic Continental Margins

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During the Late Cenozoic, ice sheets have grown and decayed a number of times around the margins of the Norwegian-Greenland Sea. Under full-glacial conditions, fast-flowing outlet glaciers reaching to the shelf break have delivered large quantities of sediments to the upper continental slope. This diamictic material has been redistributed by large debris flows to build major submarine fan systems on both the Norwegian-Barents-Svalbard margin, and off East Greenland south of about 70 degrees North. The North-East Greenland margin has a quite different pattern of large-scale sedimentation, however. Here, the Greenland Basin is dominated by several submarine channel systems, up to 70 m deep and 300 km long, together with extensive fields of regular sediment waves. By contrast with the rest of the margin, large submarine fans are not present. This downslope-flow dominated sedimentation is suggested to be related to the formation of cold, dense water related to sea-ice freezing and brine rejection. The dense water flows down the slope in both channelled and unchannelled form and presumably contributes to the bottom-water component of the thermohaline circulation.

CC02 : MOam03 : G3
Two New Mechanisms of Sediment Erosion/Deposition beneath Fast Moving Ice Streams

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Geologic evidence such as deep erosional troughs and submarine 'till deltas' indicate that fast ice streams and outlet glaciers are capable of eroding, transporting and depositing large volumes of debris at high rates (up to ~100 m^3/yr per meter width, where '~' denotes 'the order of'). To sustain such high sediment fluxes, erosion of glacial substrata must be occuring at a rate of up to ~1 mm/yr. Since there is a considerable current interest in the dynamics of the ice streams and the geologic products of their activity, it is important to understand the physical mechanisms that control the rate of sub-ice-stream sediment generation and transport. Previously, a viscous model of deforming sub-ice-stream till beds was used to quantify these processes. In this model, debris-transport rates are scaled with: (1) the thickness of the till layer squared, (2) the shear stress being applied to the till by the ice base, and (3) the inverse of the till viscosity. However, results of laboratory and field tests indicate that till rheology is nearly Coulomb-plastic rather than viscous. We propose two new mechanisms that may be responsible for high rates of debris transport in weak subglacial till beds. The first mechanism, till dragging by plowing ice bumps, dominates the debris transport in a steady-state and is capable of producing transport rates of ~100 m^3/year per meter width. In our numerical ice-stream model, the till dragging is scaled with: (1) average amplitude of ice bumps,and (2) the ice velocity. These steady-state transport rates are equivalent to spatially-averaged erosion rates of ~1 mm/yr, over long time periods (> ~1000 years). The second mechanism of till transport, 'till plug flow', is more efficient, at ~100-1000 m^3/yr per meter width. However it operates only over short time periods, during freeze-on triggered ice stream stoppage (~100 years). When the basal thermal regime changes from melting to freezing, the upper part of the till quickly consolidates and moves with the ice. In our numerical ice stream model we scale the till plug flow with:(1) the thickness of the consolidated till, and (2) ice velocity. These two mechanisms produce rates of erosion and debris transport by ice streams that are broadly consistent with evidence from the geologic record. It is also advantageous that they can be parameterized and incorporated into numerical ice stream models. Hence it allows for such models to be constrained by geological observations.

CC02 : MOam04 : G3
Carbonate Diagenesis of the Cenozoic Sedimentary Sequence from the CRP-3 Core, Ross Sea, Antarctica

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The diagenetic features of the Cenozoic glacigenic sedimentary sequence recovered at the CRP-3 drillhole were first described and logged in the stratigraphic description of the Initial Report. Sixtyseven samples from the 790 m of core were selected in order to study the main fabric, texture, ultratexture, mineralogy and stable isotope composition. Authigenic calcite is the most abundant precipitate throughout the CRP-3 core. Fossiliferous concretions/ nodules occuring in the upper 350 m of the sedimentary sequence exhibit an early marine, shallow burial cementation by fringing/sparry low-Mg calcite, related to dissolution of the calcareous biogenic tests. Their isotopic signature ($\delta^{18}O$ = -7.3 to -10.1 ‰ PDB; $\delta^{13}C$ = -6.2 to -14.3‰ PDB) suggests a moderate influence of glacial melting waters (25-40%). Extensive carbonate cementation occurs below 350 mbsf in sandstone lithologies and is represented by an early stage of fringing Fe-rich calcite or siderite and a subsequent stage of blocky crystals of no-Mg calcite, thought to be partially formed during over pressuring and compaction, as suggested by pressure solution patterns along the framework grains. ^{18}O depletion ($\delta^{18}O$ = -12.6 to -18.2 ‰ PDB) of these cements indicate a stronger influence of glacial meltwaters (>60%) over the CRP-3 drillsite, which is consistent with the climatic changes inferred from the interpretations of the sedimentary facies. Associated with carbonate cementation are authigenic zeolite minerals and authigenic smectites, representing early precipitates. Pyrite is commonly recorded either as a discrete cement phase fringing coal particles or as framboids dispersed within the matrix, and within biogenic tests.

CC02 : MOam05 : G3
Landscape Evolution of the Convoy Range and Mackay Glacier, Transantarctic Mountains

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We analyse the geomorphology and landscape evolution of the Transantarctic Mountains inland of McMurdo Sound and Cape Roberts. It is possible to distinguish a preglacial assemblage of landforms related to fluvial activity and a set of glacial landforms related to an expanded ice cover. The preglacial landscape is represented by a series of flattish erosion surfaces and escarpments that culminate in the Convoy Range at an altitude of over 2400 m. The surfaces are dissected by often sinuous valleys bounded by valley benches and/or rectilinear slopes. Landforms of glacial erosion comprise (a)glacial troughs, especially near the coast, (b) landforms of areal scouring on the flanks of Mackay Glacier and along the coast up to altitudes of 1450 m and (c) a remarkable suite of subglacial meltwater landforms including scablands, meltwater channels, plunge pools and pot holes, the latter reflecting the sudden outburst(s) of a massive subglacial lake. The meltwater activity has modified all landscape assemblages, including the highest land surfaces of the Allen Hills and the Coombs Hills, as well as escarpment fronts and valleys dissecting the surfaces. Comparable meltwater landforms extend to the adjacent Dry Valleys block where they have been dated to the mid-Miocene. We conclude that, as in the Dry Valleys and the Royal Society Range, the landscape was eroded first by rivers and subsequently by overriding ice and had achieved essentially its present form by the mid-Miocene. Subsequent erosion is restricted mainly to the Mackay outlet glacier. The presence of drowned river valleys with rectilinear slopes extending below present sea level implies that there has been little, if any, tectonic uplift since the mid-Miocene. It will be interesting to compare these findings with those derived from the Cape Roberts core immediately offshore.

CC02 : MOam06 : G3
The Application of Cosmogenic Exposure Dating to Glacial Deposits of the Last Deglaciation in the Southern Andes of Chile

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The region of Feugo Patagonia in the southern most Andes supports glaciers that are sensitive to climate and hold an excellent record of change during the last glaciation. Recent field investigations have identified complex sequences of glacial sediments and landforms that record the advance and retreat of ice lobes of the extensive Late Glacial Southern Andes Ice sheet. It has been suggested that glacial dynamics in this region are controlled by the location, moisture content and intensity of the westerlies (Hubbard, 1997; Denton et al, 1999), which are themselves controlled by global pressure systems. Knowledge of the timing of glaciation therefore, indicates both precipitation and temperature regimes at varying latitudes throughout Patagonia. Through the construction of an accurate chronology the nature of interhemispheric climate change

during the last glacial termination could be elucidated. This is currently a contentious topic which continues to be widely debated (Bluner et al, 1998;. Lowell et al, 1995; Denton et al, 1999).

This project applies cosmogenic exposure dating to a variety of glacial landforms, which are a product of advancing glaciers during the last glacial cycle. Two localities were selected in southern-most South America, Torres del Paine (51°S) and The Strait of Magellan (53°S). Surface rock samples have been taken from mapped geomorphological limits for analysis of the terrestrial in situ cosmogenic isotopes ^{10}Be and ^{26}Al. The samples are under preparation at Edinburgh, in a new dedicated cosmogenic nuclide laboratory, and the isotope ratios are being measured with AMS at the ETH/PSI tandem facility at ETH Zurich.

To date, attempts to produce a reliable radiocarbon chronology for the Paine and Magellan Regions have yielded few useful bracketing dates due to the lack of preserved organic material. However the preliminary chronology obtained from this work (McCulloch et al., 2000), provides an ideal testing ground for cosmogenic surface exposure dating. This poster presentation aims to demonstrate the results of the first analyses, and the implications and interpretations of this chronology for this climatically important region.

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CC02 : MOam07 : G3
New Evidence for Stable Pliocene Climate in Antarctica from In Situ Cosmogenic Noble Gases

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The Dry Valleys region, Antarctica, is a key area for paleoclimatic and paleoglaciological investigations in Antarctica. Two surface exposure data sets from this region give evidence for a stable climate in Antarctica since early Pliocene. Beacon Valley acts as an overflow basin of Taylor Glacier, a large outlet glacier of the East Antarctic Ice Sheet (EAIS). Thus, it records every increase in EAIS volume due to warmer and/or more humid climatic conditions. On the other hand, large remnants of glacier ice under the valley floor, overlain by till, represent a sensitive indicator of climate warming (Sugden et al., 1995). We present here a surface exposure dating study of eleven rock samples, some from the surface of the till, others buried by till and ice. Surface boulders yield minimum ages of 3 Ma. All buried samples show significantly lower cosmogenic noble gas concentrations than expected from the present shielding by overlying ice and till. This implies a stronger shielding in the past which can be best explained with a higher ice level in Beacon Valley since the Mid-Pliocene. These results confirm the findings of Sugden et al. (1995) and Schäfer et al. (2000) that the ice has been deposited many million years ago and imply exceedingly low sublimation rates. The second data set was taken at Pivot Peak , a nunatak in Ferrar Glacier near Beacon Valley. This is another outlet glacier of the EAIS and therefore responds to EAIS volume changes. Pivot Peak is close to Mt. Feather where diatom-bearing Sirius Group sediments are found (Webb et al. 1984). Webb et al. (1984) used these sediments to argue for a widely deglaciated interior Antarctica in the Pliocene with a subsequent overriding of the Transantarctic Mountains by the EAIS. We analysed samples from a moraine only 150 metres above the present ice surface. Boulders from the top of the moraine give minimum ^{3}He and ^{21}Ne exposure ages of 4.5 Ma. This implies that Ferrar Glacier has never been considerably thicker than at present since early Pliocene. Our results both from the remnant ice in Beacon Valley as well as from the Pivot Peak moraine suggest that the EAIS volume did not change significantly since at least early Pliocene. According to the age of the remnant ice, no ice collapse occurred, contradicting Webb et al. (1984) who propose a deglaciation of the area during the Pliocene. The results from Pivot Peak moraine (1500 m a.s.l.) are in contrast to the suggested Pliocene overriding of the Transantarctic Mountains to an altitude of nearly 3000 m a.s.l. in this area (Webb et al. 1984). Thus, both data sets strongly argue for a stable climate in Antarctica since at least 4.5 Ma.

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CC02 : MOam10 : G3
Millennial-Scale Climate in the Labrador Sea: Linkages between Atmosphere, Surface-Water, and Deep-Water

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Records of surface-water isotopic composition in the Labrador Sea (IMAGES cruises MD101 and MD99) show high-frequency climate change signals during the last glacial cycle as well as all Heinrich events and several major Dansgaard-Oeschger cycles. The same high-frequency climate change is documented for physical and optical sediment properties that mainly varying deep-water processes. Heinrich events are marked by light δ^{18}O values of *N. pachyderma* and highs in density, velocity, and magnetic susceptibility. Thus, the variation of surface-δ^{18}O values can be either predicted from core logging using the procedure developed for reference site 2024, or it can be derived site-specifically by incorporating δ^{18}O measurements of individual cores. Both prediction and derivation provide a paleoclimate proxy record at unprecedented resolution. Further studies will have to establish the boundary conditions for the prediction for the Labrador Sea.

Physical property logs of Labrador Sea sediments represent deep-water processes rather than reflecting variable input of IRD or biogenic components. Deep-water origin of log signals is inferred from grain-size analysis, benthic δ^{18}O, the relation of density and velocity, and magnetic susceptibility considerations. As for grain-size distribution, for example, highs in physical properties correspond to larger amount of sortable silt, a clear indication of faster deep-water currents during times of light surface-water δ^{18}O values. These times also correspond to higher air temperature over Greenland. The close correlation of δ^{18}O in ice, surface-water δ^{18}O, and core logs implies a strong link and common forcing of atmosphere, sea surface, and deep water; yet the nature of this forcing is unknown.

Variations in current strength along the west coast of the Labrador Sea are ultimately related to the production of NADW. Variable strength of bottom currents are also reconstructed from changes in the relative amount of magnetic material. Times of non-correlation between core log and surface-water δ^{18}O contain a climate signal of decoupling of forcing factors; e.g., during times of substantial sea-level rise, surface-water δ^{18}O values changed dramatically, whereas deep-water properties did not. The varying extent to which core logs from different locations correlate to surface-water δ^{18}O values, describes differences in deep-water processes among sites; e.g., the current velocity at site 2025 was apparently higher than at site 2024, an interpretation that is substantiated by the observation that site 2025 is presently located closer to the water depth of the high-velocity core of NADW.

CC02 : MOam11 : G3
Ice Sheet Response to Moisture Supply and Orbital Forcing from a Late Pliocene Arctic Ocean Record

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A multiproxy analyses of Hole 911A (Ocean Drilling Program (ODP) Leg 151) drilled on the Yermak Plateau (eastern Arctic Ocean) is used to investigate the behaviour of the Svalbard/Barents Sea ice-sheet (SBIS) during late Pliocene (~3.0-1.7 Ma) climate changes. Contemporary with the “Mid-Pliocene global warmth” (~3 Ma), a warmer period lasting ~300 kyr with extended ice-free conditions in summer in the marginal eastern Arctic Ocean is assumed to be an important regional moisture source, and possibly one decisive trigger for intensification of the Northern Hemisphere glaciation in the Svalbard/Barents Sea area at ~2.7 Ma. An abrupt pulse of ice-rafted debris (IRD) to the Yermak Plateau at ~2.7 Ma reflects distinct melting of sediment-laden icebergs derived from the SBIS and may indicate the protruding advance of the ice sheet onto the outer shelf.

Spectral analysis of the total organic carbon (TOC) record being predominantly of terrigenous/fossil-reworked origin indicates SBIS and possibly Scandinavian ice sheet response to incoming solar radiation at obliquity and precession periodicities. The strong variance in frequencies near the 41 kyr obliquity cycle between 2.7 and 1.7 Ma indicates, for the first time in the Arctic Ocean, a close relationship of SBIS growth and decay patterns to the Earth’s orbital obliquity amplitudes, which dominated global ice volume variations during late Pliocene climate changes.

CC02 : MOam12 : G3
Oligocene and Miocene Antarctic Paleoglacial History from Cape Roberts Cores Compared with Global Proxy Records

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Three Cape Roberts Project (CRP) drill cores were obtained from Roberts Ridge, a sea-floor high at 77° S,12-16 km offshore from Cape Roberts, McMurdo Sound, Antarctica. The cores, respectively ca 147 m, 624 m and 939 m long, were designed to recover successively older sediment from a dipping section; recovery in each was in the mid-90% range. (?)Eocene/ Oligocene through Quaternary age sediment was recovered; the Oligocene and Miocene sections are of interest here. Those intervals include 12 facies occur in associations in repeated in sequences throughout the cores and which represent different depositional environments through time. Inferred depositional systems include: outer shelf with minor iceberg influence, outer shelf-inner shelf-nearshore to shoreface under iceberg influence, deltaic and/or grounding-line fan, and ice proximal-ice marginal-subglacial (mass flow/rainout diamictite/subglacial till) singly or in combination. Sediment accumulation rates through the Oligocene and Miocene appear to have been very high based on sedimentary structures and well-controlled dating of some intervals. Facies associations indicate high volumes of glacial meltwater and if the glaciers were not fully temperate, they certainly were at the “warm” end of the polythermal range. The amount of meltwater appears to have decreased gradually with time

through the Oligocene but Miocene glaciers remained polythermal. The Oligocene section is very thick and represents repeated glacial fluctuations through time near to and across the site; the older Miocene section is glacially dominated whereas the younger section is much less so. Different time intervals are preserved in the CRP succession than recovered previously at CIROS-1, 70 km to the south, however, the whole time span represented in both cores is similar and inferred paleoglacial regimes are comparable. Changes in paleoenvironmental interpretations up the CRP cores are used to estimate relative glacial proximity to the site through time. These inferred glacial fluctuations are compared with global eustatic sea level and $\delta^{18}O$ curves to evaluate the potential of glacial fluctuations on Antarctica influencing these records of global change. Although there are dating concerns over some intervals, in general, the high sediment accumulation rates provide a moderate resolution on the timing of glacial fluctuations. The interpreted glacial fluctuation records do have similarities to the global proxy records; however, some significant differences occur, especially in number and magnitude of Antarctic glacial fluctuations.

CC02 : MOam13 : G3
Environmental Magnetic Record of Cenozoic Climate Change from the Victoria Land Basin, Ross Sea, Antarctica

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The CIROS Program (1986) and the Cape Roberts Drilling Project (1997-1999) resulted in the recovery of about 1800 m of discontinuous Early Miocene to the Late Eocene glaciomarine sediments from the Victoria Land Basin of the Ross Sea, Antarctica. The CIROS and Cape Roberts Project (CRP) sedimentary sequences were studied by international teams of scientists with the aim of understanding Cenozoic climate change in Antarctica and the processes that led to the development of continent-wide glaciation. Our group used an environmental magnetic approach, for which we determined various rock magnetic parameters on samples taken at an average spacing of 0.5-1 m. Our data indicate that variations in the concentration, grain-size and composition of the magnetic grains in the CIROS and CRP sequences took place on time scales of tens of thousands of years to a few million years. Magnetite is the main magnetic mineral, and its delivery to the Victoria Land Basin appears to be controlled by climatic changes of regional significance. In particular, prior to onset of the McMurdo Group volcanism, we believe that intervals of low magnetite concentrations correspond to periods of widespread glaciation on the continent and that intervals of high magnetite concentrations correspond to episodes of relatively warmer climate. Using this framework, we infer that climatic deterioration began in the middle to late Eocene and that the marked increase in glaciation at the Eocene/Oligocene boundary was preceded by several periods of cold climate in the late Eocene. Our data also indicate that there may have been significant fluctuations in the extent of glaciation during the Late Oligocene and Early Miocene. However, beginning in the uppermost Late Oligocene, the environmental magnetic signal is also affected by the influx of detritus from local McMurdo Group volcanism.

CC02 : MOam14 : G3
A New High-Resolution Magnetostratigraphy from Eocene-Oligocene Sediments, Maud Rise, Antarctica

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Changes in the plate tectonic configuration and in the intensity of glaciation at high southern latitudes have had a major impact on the development of global climate. With the aim of developing a more complete picture of continent-wide glaciation in Antarctica, we have developed a new high-resolution Eocene-Oligocene magnetostratigraphy and environmental magnetic study from sediments cored near the crest of Maud Rise (Weddell Sea) during ODP Leg 113. We have analysed u-channel samples from ODP Holes 689B (cores 14H-20H), 689D (6H-12H), 690B (10H-16H), and 690C (7H-9H) using a pass-through cryogenic magnetometer with measurements at 1-cm intervals (4-cm spatial resolution). These results provide a clear magnetostratigraphy at least for much of the Eocene and Oligocene, from chron C18 to C7 (c. 40 - 25 Ma). The two cores can be tied together via magnetostratigraphy and, with greater resolution, via sediment magnetic properties. For intervals with well-constrained continuous deposition, spectral analysis techniques were applied to environmental magnetic parameters to test the possibility of the existence of a cyclic signature. This investigation reveal a strong and regular cyclic pattern and frequency analyses indicate climatic control of fluxes of magnetic particles to Maud Rise. The environmental magnetic record is also being analyzed to determine whether it provides information about changes in weathering regimes on the Antarctic continent by comparison with clay mineralogy data.

Monday PM Session

CC02 : MOpm21 : G3
Cyclic Sedimentation Offshore East Antarctica during the Late Miocene: Results from ODP Site 1165, Prydz Bay

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ODP Site 1165 is situated in a water depth of 3357 m on the continental rise offshore from Prydz Bay and lies in front of the outlet for the Lambert glacier-Amery Ice Shelf system that today drains 22% of East Antarctica. The site was drilled mixed pelagic and hemipelagic sediments from the southwestern side of the Wild Drift. The drift is an elongate sediment body formed by the interaction of sediment supplied from continental shelf and slope with westward-flowing bottom currents.

We analysed colour spectra, multi sensor core logs, and XRF-scans from Cores 8 to 15 (ca. 5 to 9 Ma) measured at a resolution of 1 to 5 cm. These records show cyclic amplitude changes with depth at cm to m scale and reflect variations in the amount of terrigenous and siliceous biogenic material. Opal measurements on selected samples indicate a range of 5 to 30% for the biogenic component. A multiple linear regression approach combining discrete opal data and continuous core logging records was used to estimate percent biogenic silica at a high resolution. Maximum silica values are typical for greenish sediments indicating biogenic hemipelagic sedimentation under warmer climate conditions.

Compared to opal rich layers terrigenous dominated intervals display much lower green/gray colour ratios and are characterized by higher densities, magnetic susceptibilities and iron contents. These darker sediments were interpreted as contouritic facies deposited during maximum ice advances.

Spectral analyses in the depth domain together with shipboard bio- and magnetostratigraphic data demonstrate that the cyclic sedimentation in this interval occurs at Milankovitch periodicities, and hence is controlled by earth's orbital variations. In other intervals with less constrained shipboard age control Milankovitch cyclicities were identified using periodicity ratios of the spectral peaks. The detected obliquity and precession cycles are in turn used to improve the shipboard sedimentation rates. Refined sedimentation rates together with the opal estimations allow the calculation of biogenous and terrigenous accumulation rates.

CC02 : MOpm22 : G3
Future Antarctic Margin Drilling – The ANDRILL Initiative and McMurdo Sound Portfolio

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Deep-sea sediment records together with global climate models predict that Antarctic ice sheets have played an important role in the global climate and ocean system. However, the role of the Antarctic cryosphere in long- and short-order variations and major transitions is poorly understood and remains largely unproven. Due to the long-term existence of immense ice sheets and major erosional episodes during ice sheet expansion, stratigraphic records exposed on the Antarctic continent are rare and incomplete. Stratigraphic records from the Antarctic margin are comparatively more complete and their locations are ideally suited for recording and dating ice sheet oscillations and associated oceanic variations. In McMurdo Sound, these records are also key to deciphering the development of the West Antarctic Rift. ANDRILL is a multinational initiative to recover Antarctic margin stratigraphic records in a series of portfolios around the Antarctic continent using Cape Roberts Project technology. The McMurdo Sound Portfolio proposes a 7-8 year program of acquisition of new geophysical data and drilling with the following major aims: 1) To obtain high-resolution (1-100 k.y.), seismically linked, chronologically well-constrained, stratigraphic records from the Victoria Land Basin. 2) To document the fundamental behaviour of ancient ice sheets, and to better understand the factors driving ice growth and decay. 3) To investigate the role of Antarctic ice sheets on long- and short-order Cenozoic - Recent global climate, sea-level elevation and ocean circulation. 4) To decipher long and short-term evolution and timing of the development of the West Antarctic Rift system, associated volcanism, uplift of the adjacent rift-shoulder - the Transantarctic Mountains, associated tectonic stress regimes, and tectonic forcing of climate.

CC02 : MOpm23 : G3
Orbitally Induced Oscillations in the East Antarctic Ice Sheet: Direct Evidence from Cape Roberts Project Drilling

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Oxygen isotope records from deep-sea sediment cores imply that continental ice volume and global temperatures during latest Eocene to Miocene (34 to 15-myr) time were influenced by high-latitude, 100-kyr and 40-kyr, astronomical cycles. Here, we present the first direct evidence of orbital control on cycles of glacial advance and retreat of the Ross Sea margin of the East Antarctic Ice Sheet (EAIS) within that distant time period. The evidence comes from CRP-2/2A, a hole drilled through shallow marine strata 12 km off Cape Roberts near the edge of the Victoria Land Basin. The CRP-2/2A cores comprise 23 unconformity-bound, glacimarine sedimentary cycles, deposited 29 to 21 million years ago, that record oscillations in the ice margin across the continental shelf. Age data from $^{40}Ar/^{39}Ar$ geochronology of volcanic ash beds, microfossil biostratigraphy, $^{87}Sr/^{86}Sr$ analyses of molluscs, and magnetostratigraphy constrain the time period for three of the cycles (9, 10 and 11) to less than 450,000 years (correlation A) or 120,000 years (correlation B). This is the first proximal sedimentary evidence of orbitally-induced fluctuations in the margin of the ancient East Antarctic Ice Sheet, reflecting a fundamentally different type of behaviour in a time when planetary temperature was around 3°C warmer than the present day.

CC02 : MOpm24 : G3
Mid Pleistocene Antarctic Ice Sheet and Southern Ocean Climate Instabilities

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Until recently, the collection of Southern Ocean cores available to the paleoceanographic community was assembled some twenty years ago and few cores remained suitable for high-resolution work. ODP Leg 177 recently recovered high-sedimentation rate cores along a North-South transect across the Antarctic Circumpolar Current (Gersonde et al., 1999). Each of these sites has sedimentation rates exceeding 13 cm/kyr during the Pleistocene, allowing the comparison of millennial-scale variability between glacial and interglacial states for the past 1.2 Ma. Here we present the early-mid Pleistocene sections from ODP Sites 1094 and 1091, located in the Atlantic sector of the Southern Ocean. We use high-resolution planktic oxygen isotope records combined with magnetic polarity reversal stratigraphies to establish a reliable chronostratigraphy for the 1.2 - 0.65 Ma interval, spanning a latitudinal range from 47 to 53 degrees S across the Polar Front Zone. This common temporal framework enables us to study the timing of the millennial-scale climate variability in the surface South Atlantic as reflected in sea surface temperature records and records of ice-rafted material. Our records document variability in Southern Ocean heat flux and instability of the Antarctic Ice Sheet on millennium to orbital time scales. The data demonstrate that climate variability on the time scale of 3-7 ka is superimposed on orbital driven climate cycles. Such instability, with pacing indistinguishable from that of the last glacial cycle, appears to characterize all observed climate states during the early-mid Pleistocene interval, suggesting that sub-orbital variability has been a fundamental part of the climate system in the Southern Ocean. Furthermore, we find that the high resolution climate records from the Sub-Antarctic region show similar millennial-scale climate oscillations to those observed in surface records from the Subpolar North Atlantic ODP Site 983, implying an impending link between the timing and magnitude of Mid Pleistocene climate variability in both hemispheres. The general association of high lithic fragment abundance with intervals of large planktonic oxygen isotope excursions suggests that the fluctuations is related to regional glacial meltwater pulses in the southern and northern hemispheres. Our study document that sub-orbital variations is constantly present and do not change through the Mid Pleistocene and thus extends the range of climatic boundary conditions associated with rapid climate change.

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CC02 : MOpm25 : G3
Constrains on the Glacial and Climate History of the Antarctic Peninsula Region Since the Last Glacial Maximum

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Available data which constrain reconstructions of glacial fluctuations and climate changes in the Antarctic Peninsula since the Last Glacial Maximum (LGM) include marine geological data (bathymetry, seismostratigraphy and sediment cores), terrestrial glacial-geologic data (morphology, lithostratigraphy and glacial isostasy), terrestrial biostratigraphical data (lake-sediment- and moss-bank cores), and chronological data (primarily ^{14}C dates). It is recognized that detailed reconstructions of the glacial and climatic history are hampered by scarcity of available archives, low resolution in many datasets and chronological problems. It is concluded that the LGM configuration of ice in the Antarctic Peninsula region is poorly constrained both temporally and spatially, but evidently the Antarctic Peninsula LGM ice sheet thickened by 150->500 m and expanded onto the shelf areas. Deglaciation was slow, occurring mainly during the time period >14 ka BP (thousand ^{14}C years Before Present) and ca 6 ka BP, when the present interglacial climate was established in the region. Deglaciation of some local sites was as recent as 4-3 ka BP. After a climate optimum between ca. 4-3 ka BP, the present maritime polar climate was established. It is characterized at a number of sites by expanding glaciers. An important implication of this record of environmental changes is that deglaciation and interglacial warming in this part of Antarctica was out of phase with Northern Hemisphere developments, lagging by a few thousand years. The environmental development, as seen in the geological records from the Antarctic Peninsula, is not evident from the long ice-core records from the high-altitude inland continental plateau. These may not capture signals of environmental change in the peripheral maritime areas of the system.

CC02 : MOpm26 : G3
High-Resolution Study of the Last Glacial Maximum and the Deglaciation from High Latitude European Margins

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Sediment cores from the Svalbard Margin (MD 99-2304, 77° 37.26'N, 09° 56.90'E) and the Vøring plateau (MD 95-2010, 66° 41.05'N, 04° 33.97'E and MD 95- 2011, 66.696° N, 07.639° E) in the Nordic Seas, collected during the Marion Dufresne 1999 and 1995 IMAGES cruises have been studied. The aim of the study is to determine, on a more detailed scale, the relationship between oceanographic changes and the ice sheet variability in the Northern Hemisphere during last glacial maximum (LGM) and the deglaciation (Termination I).

Stable isotope analysis from planktic and benthic foraminifers (*Neogloboquadrina pachyderma* (sin) and *Cassidulina teretis*), Ice Rafted Debris (IRD) and foraminifer abundance in addition to different physical properties and sedimentological methods were used in the study. The measurements give a high resolution dataset spanning from 22 000 to 10 000 ^{14}C yr BP. The records have been dated using ^{14}C Acceleration Mass Spectrometer (AMS) on the planktic foraminifer *N. pachyderma* (sin). The mean sedimentation rates in the studied cores are from 40 to 150 cm / 1000 yr.

During the last glacial maximum, the data records show large variability reflecting changes in surface and deep-water conditions and in the ice sheet covering the Svalbard and Barents Sea. The onset of the deglaciation is recognised by the onset of meltwater spikes at about 15 ka ^{14}C BP. The sequence of oceanographic events can be differentiated by different scenarios or a combination of specific ice-sheet / ocean characteristics. There are reasons to believe that the characteristics have varied significantly from one event to another apparently similar looking event.

CC02 : MOpm27 : G3
Evidence for Instabilities of the Jakobshavn Isbrae Ice Stream from Offshore Stratigraphy in Disko Bugt, West Greenland

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The response of the Greenland Ice Sheet to future climate change is one of the important unknowns in terms of the global climate system. This project, which forms part of the UK's NERC ARCICE programme, aims to try and identify past instabilities in the Jakobshavn Isbrae ice stream, and

the possible driving mechanisms behind these instabilities. This information may help in predictions of possible future responses of the Greenland Ice Sheet.

The Jakobshavn Isbrae ice stream is one of the most important ice streams in Greenland draining approximately 7% of the ice sheet. It is also a highly active fjord system, being one of the largest producers of icebergs in the world. The ice front is known to have retreated by 30 km since 1850. There are a series of pining points in the fjord and below the present day ice stream that suggest catastrophic downdraw may have occurred in the past. Such instabilities of the Jakobshavn Isbrae ice stream could produce significant quantities of icebergs and meltwater emptying into Disko Bugt, and hence into Baffin Bay. Such a process could have important implications for regional palaeoceanography. In order to identify such past instabilities a series of short gravity cores were collected from Disko Bugt at various distances from the mouth of the present day Isfjord. We also recorded a grid of high resolution CHIRP seismic lines from this area to increase our understanding of the character and morphology of the sediments close to such an active ice stream. The foraminifera and sedimentological characteristics of the cores have been studied to identify variations in the flux of icebergs, sediment and meltwater from Jakobshaven Isbrae into Disko Bugt. Radiocarbon dating of basal sections of these cores show a dramatic variation in sedimentation rate within Disko Bugt associated with Jakobshavn Isbrae. Significant variation in ice rafted detritus can be identified in the cores relating to periods of increased iceberg activity. The benthic foraminiferal and stable isotope record can then be used to assess the quantities of meltwater produced by such events, and their likely impact on regional palaeoceanographic patterns.

CC02 : MOpm29 : G3
Mineralogy of Oceanic Sediments Offshore the George V Land (East Antarctica, WEGA Project)

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The circumantarctic oceans represent a unique sedimentary environment where processes are controlled by sea ice and/or the continental ice sheet. Consequently, the depositional record reflects the environmental conditions and detailed studies on oceanic sedimentary successions may reveal the paleoenvironmental changes.

The WEGA (Wilkes Land Glacial History) Project investigated the depositional system of the Wilkes Land (East Antarctica) continental margin in order to reconstruct the late Cenozoic history of the East Antarctic ice sheet and its link with global climate changes. In fact, ice flow lines from the Eastern Antarctic Ice Sheet converge in the Wilkes basin and they originate ice stream and large ice tongues. Their dymanic and ocean currents influence the depositional system on the continental slope and rise.

Eight piston cores, up to 6 m-long, were collected during an oceanographic cruise along an East-West transect on the continental rise. The cores recover progressively older, (Pliocene-Quaternary) hemipelagic sediments mainly comprised of diatom-bearing silty clay, sometimes alternating with foraminifera-bearing silt. Ice-rafted debris (IRD) is sparse.

Preliminary mineralogical data have been obtained on four cores to investigate possible variation in the clay mineral content to be correlated with other parameters and, eventually, different, ancient environmental conditions.

X-ray analyses run on the clay fraction of a large number of samples, collected every 10 / 15 cm, have been performed following classical methods. Semi-quantitative reuslts show that the <2µm fraction is mainly comprised of illite, chlorite, and smectite; kaolinite rarely occurs in minor amount. Variation trends of these minerals with depth (i.e. age) allow to recognize intervals where illite and smectite are usually inversely correlated. Intervals with constant smectite values are characterized by illite and chlorite opposite variations. The limits between intervals with different clay mineral variations correspond to limits between different lithostratigraphic units. However, changes in clay mineral trends also occur inside a single lithostratigraphic unit. As a preliminary hypothesis we can conclude that changes in clay mineral trends reflect changes in sediment supply. These changes are mainly determined by different sediment transport mechanisms and they ultimately reflect the waxing and waning of ice sheet. Further biostratigraphic and sedimentological data are necessary to correlate the mineralogical content changes with depositional mechanisms and dynamics of the Wilkes Land ice sheet.

CC02 : MOpm30 : G3
Lakes and the Deglaciation of the Late Glacial Patagonian Icesheet

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The North and South Patagonian Ice sheets are presently separated by a 100 km long gap. During glacial periods the icesheets expanded and apparently coalesced to form a single ice sheet which stretched from north of the Chilean Lake District to the southern tip of Tierra del Fuego (Caldenius, 1932; Hollin & Schilling, 1981). One impact of such an expanse of ice was the blocking of westward flowing rivers to the Pacific and the re-routing of drainage to the South Atlantic. In Central Patagonia the principal river, the Rio Baker, drains the cross-border lakes of Lago General Carrera (Argentine name: Lago Buenos Aires) and Lago Cochrane (Argentine name: Lago Puerrydon) as well as the eastern outlets of the North Patgonian Icefield, to the Pacific. Field evidence indicates that much of the drainage basin was once occupied by large proglacial lakes which drained via meltwater channels to the east. Mercer (1976) hypothesised that a minimum date for lake drainage could be retrieved by dating the abandonment of these channel. Thus, lake drainage forms a proxy for icesheet separation.

This project relies on new geomorphogical mapping in the area. The initial conclusions are:

• The proglacial lake immediately prior to final drainage covered an area of 6,315 km^2.

• Radiocarbon dating show the lake drained earlier than 13,550 ^{14}C yr BP.

• Modelling suggests that the lake can be dammed by a relatively modest advance of glaciers from the North Patagonian Icefield.

• The North Patagonian Icefield had retreated to within 30 km of its present margins by 13,550 ^{14}C yr BP and no subsequent advance has gone beyond this point. This indicates a lack of any Younger Dryas aged event or an Antarctic Cold Reversal aged event similar in magnitude to that in the Straits of Magellan (McCulloch et al., 2000).

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CC02 : MOpm31 : G3
Eurasian Ice Sheet Limits and Hydrologic Impacts in the Barents and Kara Seas, Russia

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Our field research in northern Eurasia has concentrated on amassing glacial and marine geologic data to iteratively improve the geophysical basis for ice sheet reconstructions. New relative sea-level data from Franz Josef Land, Novaya Zemlya and Vaigach islands help constrain Earth rheology-based ice sheet reconstructions. These models assume a single dome in the Barents Sea, a parabolic ice sheet profile, a western and northern termination at continental shelf edge, and arbitrary eastern and southern margins. Modeled emergence at the ice sheet center compares well with observations. However, there are discrepancies within 200 km of the ice sheet margin. which indicate that the glacier load was more distributive, with multiple domes near the ice sheet margin. Other concerns are that values for mantle viscosity need further refinement. In general, rheological models yield first-order information on ice sheet geometry but provide an imperfect interpretive basis for defining limits. Field data indicates that the Weichselian ice sheet was diminutive barely, if at all, impinging onto the s. Barents and Kara seas coasts. However, an earlier glacial event(s) at c. 70 ka was substantially larger flowing over Yamal Peninsula and associated with glacioisostatic depression of >40 m on northern Novaya Zemlya. Dramatic changes in the hydrology of Eurasia occurred during the last glaciation. Advancing ice sheets diverted discharge from the Arctic Ocean to the Black Sea by damming large rivers. Uncertainty persists on the eastern and northern margin of the Eurasian ice sheet, where 10s to 100s km scale changes would progressively impound more northerly flowing rivers. Ice sheet configurations are based on modifications of the Peltier ice-sheet reconstruction with data defensible minimum, intermediate, and maximum configurations in the Kara Sea, Taymyr Peninsula coast and western North Siberian Lowland, respectively. The minimum ice sheet forms a proglacial lake that fills the Kara Sea with drainage to the north. This proglacial lake concentrated runoff at the eastern-most margin may have limited expansion of the ice sheet. The intermediate ice sheet configuration forms a large proglacial lake equal in volume to 3/4 of the Caspian Sea. The Ob and Yenisei rivers are indirectly blocked with the presence of a contiguous ice sheet between Franz Josef Land, Svernaya Zemlya and the Taymyr Peninsula. Most drainage is routed to the east into the Laptev Sea. The maximum ice sheet extent directly blocks the Ob and Yenisei rivers forming a massive proglacial lake, equivalent in volume to two Caspian seas. Drainage is shifted to the south resulting in expansion of the Caspian and Black seas. These simulations show the importance of the eastern and northern ice sheet margins between Franz Josef Land and Svernaya Zemlya in diverting freshwater from the Arctic Ocean.

CC02 : MOpm32 : G3
Late Quaternary EAIS Melting Event Around the LŸtzow-Holm Bay and Mt. Riiser-Larsen Region

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The S(tm)ya Coast in the LŸtzow-Holm Bay region, east Dronning Maud Land, is located at the margin of East Antarctic ice sheet, where glacial advances and δ^{18}O-depleted water from melting ice at deglacial events may affect the organisms living in shallow-water. The beach deposits in the northernmost part of S(tm)ya Coast are clearly divided stratigraphically into two marine sediment layers including in situ fossil shells of Laternula elliptica, and that the TAMS. ^{14}C ages of fossil shells of the upper layer ranged from 4 to 5 ka without a reservoir correction, and those from the lower layer ranged from 32 to 46 ka (Miura et al., 1998a). Any marine layers and in situ fossil shells were not disturbed by ice sheet loading or scouring. And some fluvial sediments associated with the meltwater can often be observed under the Holocene marine beds or over the older marine beds. The δ^{18} O (PDB) values of 24 fossils in the Pleistocene marine beds ranged from about 2.9 to 4.2 ‰, and 27 fossils in the Holocene beds from about 3.9 to 4.6 ‰, namely the variation of former is relatively wider than the latter one (Miura et al., 1998b, c). In the Mt. Riiser-Larsen region, Enderby Land, the presence of a glacial trimline, indicates the level of the former ice sheet surface, at an elevation of about 500 m a.s.l. Above this level, glacial erratic boulders were not seen, and the bedrock has no glacial polish or striations and is commonly deeply weathered (Zwartz et al., 1998). This melting event occurred at least after the last Interglacial on the basis of TL dating of calcite in the till deposits (Takada et al., 1998). These facts lead us to the following conclusions: (1) the EAIS had possibly retreated from the northern S(tm)ya Coast prior to the LGM, (2) there was more δ^{18} O-depleted meltwater in the northern part of S(tm)ya Coast during the last interstadial (30-46 ka) than in the Postglacial age, (3) the relatively strong fluvial process probably caused by

the ice melting event might have occurred in the LŸtzow-Holm Bay region around 30-46 ka. Nakada et al. (2000) have examined the sea-level variations at eight sites along the coast of Antarctica to investigate the melting history of Antarctic ice sheet complexes. From these calculations, two features are observed: (1) the meltwater occurred at 30-35 ka, and (2) a relatively stable period of about 30-12 ka is required. These features are consistent with our geological and geochemical field data.

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CC02 : MOpm33 : G3
Quaternary Calcareous Nannofossil from Periantarctic Basins: Paleoecological and Paleoclimatic Implications

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The Antarctic Ice Sheet is a key component of the world's climatic system, and a basic understanding of global climatic changes can be gained from studies of the interactions among ice sheet growth, ocean circulation and paleoproductivity. The appraisal of the relationship between temperature (glacial-interglacial cycles), atmospheric CO_2 concentrations and paleoproductivity is also basic to the comprehension of such climate changes. A basic question is whether CO_2 is tied to paleoproductivity and if the latter was higher during glacial or interglacials. Different models have been proposed to explain these relationships, and many approaches have been examined. There seems, however, to be little detailed information on the presence of Quaternary calcareous nannofossil assemblages, although Villa and Wise (1998) recently issued the first report on Pleistocene calcareous nannofossils in southern latitudes higher than 65°S. Modern coccolithophores have only been reported in very high southern latitudes between 69°S and 71°S in the Weddell Sea (Winter et al., 1999), and possible hypotheses for their occurrence are still being discussed. The aim of this work is to monitor the distribution and abundance variation of calcareous nannofossils and calcareous dinoflagellates of the Antarctic region at latitudes south of 65°S. Here we present the first results from several piston cores recovered in periantarctic basins during *Eltanin*, *Deep Freeze*, or *Islas Orchadas* cruises, in particular from the Weddell Sea, Ross Sea, Maud Rise, Bellingshausen Sea, and Bausan Bank. Comparisons with results obtained from the analyses of the Sedano Project, on the sediment drifts off the Antarctic Peninsula (Pudsey and Camerlenghi, 1998), are presented. Surprisingly, rare calcareous nannofossils are present in most of the cores examined and their discontinuous occurrence may indicate key environmental relationships. Tentative correlations of their occurrence to temperature tolerance, ice-free sea surface water (interglacial), nutrient availability, and factors limiting primary productivity are discussed. New data on the presence of nannofossils in the Antarctic Quaternary environment will help augment our information on the paleoecology and paleoproductivity of these organisms as well as for map reconstruction of their distribution in the Southern Ocean.

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CC02 : MOpm34 : G3
Eocene-Oligocene Antarctic and Southern Ocean Climatic Deterioration: Phase Relationships between Climatic and Oceanic Cooling

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A new high-resolution Eocene-Oligocene benthic $\delta^{18}O$ stratigraphy is presented from ODP Site 689 (Maud Rise, South Atlantic). The Late Eocene record contains evidence of distinctive bottom-water cooling and warming trends with a 0.5‰ amplitude and a periodicity of 2-3 m.y., and culminates in a major 1.2‰ shift across the Eocene-Oligocene boundary and the chron C13r/C13n transition. Environmental magnetic records from the CIROS-1 and CRP-3 cores drilled on the Antarctic margin in the Ross Sea also record climatic cooling and warming with a similar periodicity in the Late Eocene and major cooling across the Eocene-Oligocene boundary. The environmental magnetic signal is controlled by changing terrestrial weathering conditions on the Antarctic craton. Sea level shoaling and sedimentary facies indicative of ice grounding across the Antarctic shelf is not apparent in the CIROS-1 record until some 5 m.y. later at the early/late Oligocene boundary, although glacial facies are indicated in the CRP-3 core in the earlier Oligocene. Magnetic polarity stratigraphy allows direct comparison of the CIROS-1, CRP-3, and ODP Site 689 records. These correlations indicate that early Late Eocene episodes of cooling and warming at Maud Rise were initially out-of-phase with terrestrial climate in Antarctica by ~1 m.y. with Antarctic climate appearing to lead bottom water response. By latest Eocene/earliest Oligocene time (chron C15n-C13n), however, Antarctic warming and cooling cycles were in-phase with bottom-water temperatures at Maud Rise, including the major cooling across the Eocene-Oligocene boundary. Despite the significance of the $\delta^{18}O$ shift at the Eocene-Oligocene boundary, it appears to indicate cooling only and Antarctica does not appear to have supported a major ice sheet until some 5 m.y. later in the latest early Oligocene.