The success of a genus in terms of adaptation to environment, abundance, and geographical distribution patterns is recorded. The occurrence patterns are correlated with changing conditions in the physical environment and with evolutionary changes in other marine microfossil groups. Distinct patterns emerged from this study that show potential for further, more detailed analyses.

PP22B MCC: 123 Tuesday 1330h

Antarctic Climate Evolution II *(joint with C, A, OS, GC)*

Presiding: **R B Dunbar,** Stanford University**; M Siegert,** University of Bristol

PP22B-01 1330h INVITED

Antarctic Climate Evolution: The Next Step

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The Antarctic ice sheet plays a special role in the global atmosphere-ocean system due to its influence on Southern Hemisphere climate, on water masses and deep-ocean ventilation and on sea level world-wide. However, its behaviour is still poorly understood, and in particular the nature and timing of its likely response to global warming. In the last decade Antarctic margin drilling by the Ocean Drilling Programme and the Cape Roberts Project, along with land-based studies of glacial deposits and landscape history, have provided a widely accepted view of the formation of ice sheets on Antarctica through Cenozoic times. Although the Antarctic continent has been in a polar position since the early Cretaceous, the first records of a continental ice sheet there are not found until around 34 Ma. From that time on the continent supported temperate ice sheets that responded to Milankovitch forcing. The cool temperate vegetation around the coast declining to sub-polar tundra until around a permanent ice sheet became established around 14 Ma. This most likely continued to respond to orbital forcing, though it may have been more variable in size than the cold ice sheet of Quaternary times. While some regional issues remain unresolved there is now increasing interest in the causes of the major cooling events at around 34, 24 and 14 Ma, and the warming events of the mid Pliocene and MIS 31 and 11. Future work not only involves drilling at key locations to sample strata the record these transitions (eg. ANDRILL), but also the testing and extension of these results through the use of the new generation of climate models and their coupling with ocean, ice sheet and sediment models (ACE: www.geo.umass.edu/ace/). The goal is to simulate Antarctic climate for varying influences, such as atmospheric CO2 levels and changing topography in order to understand the behaviour of ice sheets and shelves, to simulate past behaviour and provide scenarios for possible futures.

PP22B-02 1345h INVITED

Coupled Climate-Ice Sheet Simulations of the Early Cenozoic History of the Antarctic Ice Sheet

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Numerical modeling studies of ancient Antarctic ice sheets have relied on empirical parameterizations based on modern climatologies for their surface mass balance forcing. An alternative approach, using a Global Climate Model (GCM) asynchronously coupled to a dynamical ice sheet model, has been developed, tested, and applied to the early glacial history of Antarctica. The coupled GCM-ice sheet model was used to test the sensitivity of the coupled atmosphere-ocean-cryosphere system to evolving Cenozoic boundary conditions, including paleogeography, atmospheric carbon dioxide, changing orbital parameters, and changes in ocean heat transport. The asynchronous coupling scheme enables long (10^6 year) integrations, simulating not only ice sheet inception, but subsequent ice sheet variability over orbital timescales.

Our results suggest that the combination of declining Cenozoic atmospheric carbon dioxide and an orbital configuration producing cold austral summers triggered snow/ice albedo and height-mass balance feedbacks that allowed a continental-scale East Antarctic Ice Sheet (EAIS) to form in a relatively sudden transition. In the model, the CO_2 threshold for glacial inception is between 3 and 2.5 present. The simulated early Oligocene ice sheets exhibit extreme variability in response to orbital forcing. Changes in ocean heat transport, like those assumed to have occurred in response to the opening of Southern Ocean gateways (Tasmanian and Drake Passages) are shown to have a smaller effect than that expected in the transition from a greenhouse to icehouse climate, having only a minor effect on the timing of major glaciation. In our model, the opening of the Drake Passage is a potential trigger for glacial inception, but only within a narrow range of atmospheric CO_2, reinforcing the importance of pCO_2 as a fundamental boundary condition for Cenozoic climate change.

PP22B-03 1400h

Antarctic Ice and Sediment Flux in the Oligocene Simulated by a Climate-Ice Sheet-Sediment Model

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Models of subglacial deformable sediment and ice-free sediment transport are added to a global climate (GCM)-dynamical ice sheet model. The coupled model is applied to the evolution of early Oligocene Antarctic ice sheets, sediment distributions, and coastal sediment discharge under a range of prescribed atmospheric CO2 and orbital variations. The GCM-ice sheet model uses a computationally efficient asynchronous coupling scheme, enabling long (10 million year) integrations. The sediment component is initialized with a uniform 50m layer of regolith, assumed to have accumulated prior to the onset of widespread glaciation. Subglacial sediment deformation in the upper tens of cm is driven by basal shear stress where the basal ice is melting. The spatial distribution of sediment evolves by bulk transport of sediment under the ice, quarrying of new till by glacial ice in contact with clean bedrock, and fluvial downslope transport of freshly exposed sediment to the continental margin.

With a prescribed gradual decline of atmospheric CO2 over the 10 Ma long simulations, a sudden transition occurs around 2.5 x present CO2, from relatively small land-based ice caps localized on high topography, to a single large East Antarctic ice sheet comparable to today. Much of the pre-existing sediment is transported to the coast by the action of repeated orbital cycles, funneled into continental scale drainage basins and thence to a small number of major discharge sites. The predicted spatial and temporal patterns of sediment discharge are compared with observed distributions and core records of offshore Cenozoic sedimentary deposits.

PP22B-04 1415h

Antarctic Ice Evolution Viewed from NJ and the Deep sea

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Backstripping of mid-Cretaceous to Miocene sections from the New Jersey Coastal Plain (ODP Legs 150X and 174AX) provides a eustatic estimate for 100-8 Ma. Backstripping extracts amplitudes of global sea level from passive margin records by accounting for paleo-water depth variations and progressively removing the effects of sediment loading (including the effects of compaction) and tectonic subsidence. Rapid (less than 1 m.y.) sea-level lowerings of 20-35 m are associated with Cretaceouslower Eocene sequences; eustatic rises approach 50 m in some instances. Middle Eocene lowerings were approx. 45 m. Glacioeustasy is the only known mechanism that can account for these large, rapid changes. 2-D backstripping of Oligocene sequences yields estimates of 20-60 m for eustatic lowerings. 1-D backstripping yields early Miocene amplitudes of up to 40 m, whereas estimates of middle-late Miocene eustatic change are generally lower (20-40 m). We interpret the sea-level estimates in terms of glacioeustasy and reconcile the sea-level and deep-sea oxygen isotopic records. Because large N. hemisphere ice sheets developed during the late Pliocene, we ascribe these eustatic changes to Antarctic ice-volume variations, and thus, provide a prediction for Antarctic cryospheric evolution. Ephemeral small (20 m sea-level equivalent; 30% of the modern East Antarctic Ice Sheet [EAIS]) to medium-sized (35 m equivalent; 50% EAIS) ice sheets existed in Antarctica even during the peak warmth of the Late Cretaceous-early Eocene, although most of the time Antarctica was ice-free. Larger ice sheets (approx. 45 m equivalent, 70% EAIS) developed in the late middle Eocene (46 and 42 Ma). A large (54∓15 mm) earliest Oligocene drop in sea level was associated with development of a large ice sheet (87% EAIS), though sea level again rose by nearly 46∓15 m about 1 m.y. later, suggesting near collapse of the ice sheet. The ice sheet subsequently grew and decayed numerous times in the Oligocene-middle Miocene, testifying to a very dynamic ice sheet between ca. 33 and 14 Ma. By the middle Miocene, the East Antarctic ice sheet had become a permanent feature and sea level changes were primarily controlled by small ice-volume changes in Antarctica and the nascent growth of Northern Hemisphere ice sheets.

PP22B-05 1430h

Subglacial Bed Roughness in East Antarctica and Implications for Ice Sheet Dynamics

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A large airborne radio-echo sounding database was collected from East Antarctica in the 1970s. Flight lines, which make up the survey, were arranged in a grid, with a flight spacing of around 50 km. Navigational records and subglacial bedrock elevations were recorded every 20 seconds (or about 1.67 km). Hence, the RES database is made up of numerous bedrock profiles, each several hundred kilometres in length, in two orthogonal directions. These profiles were used to calculate the bedrock roughness along the flightiness. Spectral analyses were performed on 200 km sections of each flight, with a spacing of 10 km. Roughness coefficients were then calculated at a variety of scales from the spectral results, from which maps of roughness were established. The maps were then compared with ice-sheet modelling results to assess how current ice flow and subglacial temperatures correspond with bed roughness. Roughness maxima, at Ridge B and Dome A, correspond with the centre of the ice sheet where the ice base is very cold. Hence, these regions, either at present or in the past, may not be subject to glacial erosion that would act to smooth the topography. At Dome C the bed is smoother yet is also beneath the ice sheet centre. We suggest that Dome A and Ridge B have been covered by cold ice for several million years. At Dome C, however, we argue that the smoother topography is more consistent with a more dynamic eroding glacial regime than the current ice sheet configuration allows. Hence, the roughness at Dome C may be an artefact of a former ice cover more dynamic over the Dome C region than at present.

URL: http://www.ggy.bris.ac.uk/research/glaciology/personalpp/siegert/mashome.html

PP22B-06 1445h

Neogene History of Antarctic Sea-ice and Development of the Sea-ice Diatom Community

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Sea-ice plays an important role in the modern Antarctic climate system and in this regions linkage

to lower latitude regions. Today, the seasonal sea-ice cover decouples oceanic heat transfer to the atmosphere, which amplifies winters low temperatures and shifts sources of moisture far to the north. The sea-ice zone is an important site for biological productivity and bottom water formation, through cooling and brine exclusion. The absence of the sea-ice during past and future periods of elevated temperatures would significantly impact the biology, oceanography, glaciology and meteorology of the Antarctic region. A unique diatom assemblage is adapted to life in and around the sea-ice, and serves as an increasingly useful proxy to mark the presence, extent and duration of sea-ice cover. This assemblage dominates Antarctic shelf sediments today and back through most of the Quaternary. The oldest fossil diatom flora with a similar composition and structure to that of the modern sea-ice community was identified in a late Miocene mudstone erratic MB-244C in coastal moraine from McMurdo Sound. This assemblage did not persist through to the present day, and it is absent, or significantly reduced, in numerous marine diatom-bearing strata of late Miocene, Pliocene and Quaternary age, including the upper Miocene McLeod Beds of the Battye Glacier Formation, Prince Charles Mountains, the lower Pliocene Sorsdal Formation in the Vestfold Hills, the Pliocene sediments from the DVDP and CIROS drillcores, and the lower Quaternary carbonate unit in the Cape Roberts Project drillcore CRP-1. The sea-ice diatom community likely persisted in low numbers in interior fjords and basins, adjacent to glacier margins during these times. The history of sea-ice development and fluctuation during the Neogene appears to be complex, with substantial variability in sea-ice cover. Core records are currently insufficient to document the details of this history, and variation in the diatom assemblages through times of climate transition, but potential is high to utilize the diatom record as a proxy indicator for sea-ice cover. Sea-ice likely existed in Antarctic waters prior to the late Miocene, and morphological analyses of species within several diatom genera recovered in the erratic sample may provide a means of extending sea-ice interpretations back in time.

PP22B-07 1520h

Timing of West Antarctic Ice Sheet Grounding Events in Ross Sea During the Middle Miocene: Implications on the Phase Relationships with the East Antarctic Ice Sheet

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A new regional seismic-stratigraphic analysis of the Ross Sea outer continental-shelf stratigraphy shows that there were at least 6 grounding events (i.e., advance and retreat of ice in contact with the sea floor) during the middle Miocene. This analysis demonstrates that the extent and thickness of ice on West Antarctic must have been substantial on at least a few occasions. The seismic correlation of the glacial erosional surfaces to available age control at DSDP sites 272 and 273 shows that three of these grounding events occurred during the Middle Miocene Climatic Optimum and thus pre-date the major expansion of ice volume inferred from the middle-Miocene shift on d18O and eustatic records. Therefore, if the global ice volume was indeed low during the Middle Miocene Climatic Optimum, and if the Ross Sea age model is valid, the evolution of the West Antarctic Ice Sheet probably was not a consequence of East Antarctic Ice Sheet expansion over the Transantarctic Mountains onto West Antarctica. This suggests a first-order out-of-phase relationship between the evolution of the East- and West Antarctic Ice Sheets.

PP22B-08 1535h

Numerical Ice-Sheet Modeling of the Long-Term Development of Prydz Bay, Antarctica: Tectonic Controls on Ice-Sheet Dynamics?

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A large quantity of geological data are now available from both offshore and onshore Prydz Bay and the Lambert Graben, East Antarctica, covering the growth and change of the East Antarctic Ice Sheet (EAIS) since early Oligocene time. We have collated much of this information, in order to constrain the rates of deposition of ice-sheet erosional products in this important sector of the EAIS, together with changes in the limits and styles of glaciation. Sedimentological data and indications of past climate from geological archives therefore formed the basis for constructing time-slice snapshots of possible morphological and climatic settings throughout the past 30-35 Ma. All of these data have then been used to constrain, or been tested by, a three-dimensional numerical ice-sheet model, which incorporates grounding-line physics.

The primary concern was to assess likely ice-sheet configurations which can be forced to match the geological data, in particular, examining the possible causes of the onset of ice-stream formation in Prydz Bay after the late Miocene epoch. We suggest that tectonically induced changes in the bathymetry of the Lambert Graben and Prydz Bay are one of the major likely causes of changes in ice-sheet dynamics, and thus ice-sheet extent, in this sector of the EAIS. The results of the numerical ice-sheet modeling show clearly that tectonically induced bathymetric changes are sufficient to alter the glacial environment in this region significantly, in particular by controling the grounding and stability of ice within the Lambert Graben and by focusing ice flow from the surrounding area. The history of positive topographic features such as the bounding Prince Charles Mountains are probably not that significant in controlling ice flow, however. Glacial erosion may also have played a role in excavating the Lambert Graben by promoting fast-flowing ice in a positive feedback. We have also assessed possible changes in mass balance regime (climate) and find these too, to be a significant, but probably less important contributor. The overall outcome of morphological change was probably to thus render this part of the East Antarctic Ice Sheet more sensitive to sea-level change and to different mass balance regimes.

PP22B-09 1550h

Application of Benthic Foraminiferal Mg/Ca Ratios to Questions of Cenozoic Climate Change

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We investigate the evolution of Cenozoic climate and ice volume as evidenced by the oxygen isotopic composition of seawater derived from benthic foraminiferal Mg/Ca ratios to constrain the temperature effect contained in foraminiferal oxygen isotope values values. We have constructed two benthic foraminiferal Mg/Ca records from intermediate water depth sites (Ocean Drilling Program sites 757 and 689 from the subtropical Indian Ocean and the Weddell Sea, respectively). Together with the previously published composite record of Lear et al. (2000) and the Neogene record from the Southern Ocean of Billups and Schrag (2002) we obtain three, almost complete representations of the oxygen isotopic composition of seawater for the past 52 myr. We discuss the sensitivity of early Cenozoic Mg/Ca derived paleotemperatures (and hence the oxygen isotopic composition of seawater) to assumptions about seawater Mg/Ca ratios. We find that during the middle Eocene (49-40 Ma), modern seawater ratios yield Mg/Ca-derived temperatures that are in good agreement with the oxygen isotope paleothermometer assuming ice-free conditions. Intermediate waters cooled during the middle Eocene reaching minimum temperatures by 40 Ma. The corresponding reconstructions of the oxygen isotopic composition of seawater support ice growth on Antarctica beginning at 40 Ma. At the Eocene Oligocene boundary, Mg/Ca ratios (and hence temperatures) from Weddell Sea site 689 display a well-defined maximum. We caution against a paleoclimatic significance of this result and put forth that the partitioning coefficient of Mg in benthic foraminifera may be sensitive to factors other than temperature. Throughout the remainder of the Cenozoic, the temporal variability among the records is similar and similar to longer-term trends in the benthic foraminiferal oxygen isotope record. Two exceptions occur during the early late Miocene and the early Pliocene when minima in the oxygen isotopic composition of seawater suggest reductions in global ice volume that are not apparent in foraminiferal oxygen isotope records. Maximum oxygen isotope values of seawater recorded during the Pleistocene at Southern Ocean site 747 agree well with values derived from the geochemistry of pore waters (Schrag et al., 1996) highlighting the value of the new Mg/Ca calibrations of Martin et al. (2002) and Lear et al. (in press) applied in this study. We conclude that the application of foraminiferal Mg/Ca ratios allows a refined view of Cenozoic ice volume history despite uncertainties related to the geochemical cycling of Mg and Ca on long time scales.

PP22B-10 1605h

Decadal-to-Millennial Oceanographic Variability Along the Antarctic Peninsula: ODP Site 1098 Demonstrates Strong Solar Forcing Signals In The Southern Ocean

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The Antarctic Peninsula is highly sensitive to climate change and is currently experiencing rapid and unusual warming. In 1998, the Ocean Drilling Program triple-cored the Palmer Deep (site 1098: 64^o51'S, 64^o12'W), a large depression off the west coast of the Antarctic Peninsula, to examine Holocene oceanographic variability. More than 50 m of diatomaceous muds and oozes and muddy diamictons were recovered, comprising the first high resolution, continuous, Late Pleistocene through Holocene sediment record from the Antarctic continental margin. As part of a multi-proxy analysis of the site 1098 cores, we analyzed biogenic opal, organic C and N concentrations, and $^{13}C/^{12}C$ and $^{15}N/^{14}N$ isotopic ratios of sedimentary organic matter every 2.5-3 cm downcore (1600 samples, sample interval of about 8 years). We interpret the main changes in these downcore parameters as indicating substantial changes in productivity. In particular, we note that 1) that the lowest productivity of the Holocene occurred during the past 2.5 kyrs b.p., 2) Holocene variability in productivity is large, about a factor of 3, 3) A mid-Holocene productivity maximum is coeval with many mid- and low-latitude Holocene paleoclimate records, and 4) evidence for solar forcing at decadal to centennial periods is strong as is the evidence for precessional forcing over millennial timescales. Given the modern link between sea ice and net annual primary production along the Antarctic margin, it seems likely that episodes of enhanced productivity, both during the middle Holocene and during centennial productivity peaks were associated with reduced ice cover. We explore several mechanisms by which sea ice cover might respond in an fashion consistent with our observations: 1) reduced westerly winds (less evaporative cooling), 2) South Pacific gyre Spin-up (less pole-equator T contrast), 3) more local warm deep water upwelling. It is possible that the basic ENSO dynamic we know from studies of interannual variability in the Pacific also regulates climate change at decadal to millennial timescales. The answer awaits a more complete synthesis of additional Holocene land and marine records but we note that the strongest Southern Oscillation atmospheric pressure anomaly in the Southern Ocean is in the Bellingshausen/Amundsen seas, upwind from our Antarctic Peninsula study site.

PP

PP22B-11 1620h

Provenance of Ross Sea Till From Sand Petrography

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The 125-2000 micron fraction of till samples from cores retrieved beneath the Whillans Ice Stream and Ice Stream C in West Antarctica and samples collected proximal to four outlet glaciers in East Antarctica have distinct compositions. The sand fraction of East Antarctic till samples is dominantly composed of angular intermediate to mafic igneous lithic fragments, quartz-rich lithic fragments, rounded quartz grains, rounded carbonate lithic fragments, angular pyroxene grains, and rounded feldspar grains. The sand fraction of West Antarctic till is dominantly composed of rounded quartz grains, rounded feldspar grains, quartz-rich lithic fragments, and felsic igneous lithic fragments containing quartz, feldspar and phyllosillicates (biotite and chlorite).

We also examined the 125-2000 micron fraction of several till samples from cores retrieved from the eastern Ross Sea. The samples are composed of (1) (25-40 %) rounded quartz grains; (2) (10-36 %) quartz-rich lithic fragments; (3) (8-20 %) quartzite fragments; (4) (5-15 %) felsic igneous lithic fragments containing quartz, feldspar, hornblende, and phyllosilicates (biotite and chlorite); (5) (5-10 %) intermediate igneous lithic fragments containing quartz, feldspar, pyroxene, and amphibole; (6) (<1 %) carbonate grains; and (7) (<1 %) feldspar grains. Compositional similarities in last glacial maximum till from the eastern Ross Sea and till collected from beneath ice streams in West Antarctica indicate the likelihood that eastern Ross Sea sediments were deposited by an advance of the West Antarctic Ice Sheet. Most notable are the compositional similarities in the quartz grain and quartz-rich sedimentary lithic fragment percentages, and felsic lithic fragment percentages and composition. Future work involves sampling numerous last glacial maximum till samples across the Ross Sea using sand petrography as a provenance tracer to determine paleo ice flow paths.

PP22B-12 1635h

Seismic Stratigraphic Correlations Between ODP Sites 742 and 1166: Implications for Depositional Paleoenvironments in Prydz Bay, Antarctica

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Prydz Bay lies at the mouth of the Lambert glacier system and drains approximately 20% of the East Antarctic Ice Sheet. The continental shelf there contains a sediment record of early Cenozoic to late Neogene Antarctic glaciation. New high-resolution seismic reflection data were recorded by the R/V N.B. PALMER in the Prydz Bay basin over the 40 km between ODP Sites 1166 (Leg 188) and 742 (Leg 119) to link acoustic and lithologic features at the drill sites and help decipher regional paleoenvironments. N. B. PALMER Line 01-1-4 confirmed that Site 1166 drilled an older section than Site 742. The preglacial to glacial unconformity at Site 1166 lies about 50 m below Site 742. The Paleogene units mostly truncate or taper out between the drill sites except for a thick early-glacial fluvial-deltaic sand unit at Site 1166 that may extend laterally to the base of Site 742. A flooding surface lies at the top of this sand unit at Site 1166, and not within the unit as previously reported. Prior correlations of thin Pliocene diatomaceous layers within massive diamictites, based on downhole logging and biostratigraphy at the two sites, cannot be confirmed (or denied) by the seismic-reflection data – higher resolution seismic data are needed.

For the study region, we infer a progression from a pre-glacial setting on a low-relief alluvial fan to glaciomarine and subglacial settings. Late Cretaceous lacustrine and lagoonal environments evolved to a late Eocene broad fluvial channel system or outwash plain. Marine transgression infilled and buried the channel system with glacial deposits that were extensively eroded during Oligocene to late Miocene times. Late Neogene environments were mostly subglacial with episodes of reduced ice and biogenic deposition.

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Pan, C., The rotation of ron-rigid Earth, *Eos Trans. AGU, 83*(47), Fall Meet. Suppl., Abstract U41A-05, 2002.