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Pliocene High-Latitude Climate Records

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INTRODUCTION: Pliocene High-Latitude Climate Records

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National and international awareness regarding global environmental change has been heightened over the past several decades due to results from environmental monitoring and modeling efforts. Issues such as increased greenhouse gas production (CO_2, Methane etc.), the debate over global warming, ozone depletion, and sea-level rise, among others, have a direct impact on society and societal needs. Designing policies to respond effectively to such changes requires a better understanding of environmental changes that have occurred in the past, especially during periods of time in which Earth's climate was significantly different than it is today. Therefore, it is in the best interest of society that global change issues be thoroughly investigated to provide policy makers with adequate information for making decisions.

The Pliocene represents a period in the recent geologic past when global average climatic conditions were significantly warmer than present. Associated with this time period are distinct differences from present vegetation distributions, sea-level, sea-surface temperatures, and deep ocean circulation. The high latitudes are the most sensitive to these changes, and their response to warmer climates is important for predicting their response to future climate change. Polar regions play important roles in controlling the earth's climate because they essentially drive oceanic circulation by being the loci of deep water formation. The Arctic and Antarctic regions make up the majority of the Earth's cryosphere, with ice volumes representing a sea-level equivalent in excess of 50 meters.

A workshop sponsored by the U.S. Geological Survey, from July 26 through July 28, 1994, in Herndon, VA, focused on the Pliocene climatic and oceanographic conditions in the Arctic and Antarctic regions, and the relationship of these records to the global Pliocene environment. The objective of the workshop was to gather scientists conducting Pliocene paleoclimate research from the polar regions in order to compare polar records, initiate a dialog between polar workers, and to highlight major polar paleoclimate issues related to the Pliocene. Important and somewhat controversial issues discussed throughout the workshop included:

- *The Arctic land and sea ice record.* It is clear that many issues regarding the Arctic paleoceanographic and paleoclimatic histories remain unresolved (Y. Gladenkov; D. Clark). Marine sediments from the Canada Basin indicate the presence of sea ice in the latest Pliocene and increasing throughout the Pleistocene (R.Z. Poore). In addition, the ice rafted record suggests increased presence of continental ice occurring just prior to the Gauss-Matuyama boundary (R.Z. Poore). Near-shore marine records indicate late Pliocene-early Pleistocene high stands with little associated continental ice (J. Brigham-Grette). Vegetation records from the Russian Arctic indicate conditions warmer in the Pliocene than present.

- *Antarctic ice volume.* The stability of the Antarctic ice sheet has been a focus of considerable scientific debate over the past decade. Paleontologic and sedimentologic evidence for warm atmospheric temperatures and rapidly fluctuating ice volume throughout the Pliocene (D.M. Harwood, P.N. Webb, S.E. Ishman, G.A. Wilson, F. Fleming, R.S. Hill, A.C. Ashworth) have been argued based on the interpretations of geomorphologic (D.A. Marchant), deep sea stable isotopic (M.A. Prentice), and ice-rafted detritus data (D.A. Warnke).

- *Antarctic sea ice.* The extent of Antarctic sea ice in the Pliocene is an important factor in estimating the possible dimensions of the Antarctic ice sheet. Faunal and floral data from the Southern Ocean indicate a southerly shift in the Polar Frontal Zone (J.A. Barron, J.J. Morely). Pliocene sea surface temperatures in the South Atlantic warmer than today indicate a southerly shift in surface isotherms (H.J. Dowsett). These conditions indicate greatly reduced sea ice conditions in the Southern Ocean during the mid-Pliocene.

• *Global Pliocene data and ice volume.* Sea level records from various localities around the globe reflect sea level greater than 25 meters over present day for the Pliocene (G.A. Wilson). Fluctuations in stratigraphic sequences from New Zealand reflect a high frequency of sea level increase and decrease, related to the waxing and waning of the Antarctic ice sheet (G.A. Wilson). Current interpretation of the deep sea stable oxygen isotopic record allow for some reduction of the Antarctic ice sheet (M. Prentice). However, debate still persists over the contribution of ice volume versus temperature to the delta 18 O record. New information, resulting from trace element analyses of deep water ostracodes, records deep sea temperatures and provides a direct measure of temperature versus sea level (G. Dwyer).

In addition, general circulation modelers from NASA's Goddard Institute of Space Science (as in the GISS model) and University of California, Santa Cruz (using the Genesis version of the NCAR climate model) presented the results of initial "base" run experiments to compare and contrast the two different climate models (GISS and Genesis). These experiments demonstrated the importance of particular boundary conditions that drive the models. These important contributions to the workshop provide direction for sensitivity tests of the GCM base runs to determine the realistic limitations placed on environmental conditions in a warm-earth scenario.

Beetle And Seed Fossils From The Meyer Desert Formation, Sirius Group: New Records For Antarctica

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Fossils of a beetle and four vascular plant species have been recovered from a 3.97 kg sample of laminated silts of the Meyer Desert Formation, Sirius Group, Oliver Bluffs, Antarctica. The beetle fossils consist of a tibia and a femur, 1.1 and 2.0 mm in length, respectively. The chitin is opaque and cracked, and is indented by sand grains. Punctuation, sites for the insertion of setae, is clearly evident on both specimens. Based on morphology, the specimens are identified as leg parts of a flightless weevil in the tribe *Listroderini* (subfamily *Cylindrorhininae*). Listroderines are well represented in the southern hemisphere, especially in South America. They are most abundant in wet moorland habitats, frequently in association with patches of *Nothofagus* forest.

More than 100 seeds of vascular plants were recovered from the same sample that yielded the beetle fossils. The seeds are exceptionally well-preserved with interiors filled with authigenic crystals. The seeds are tentatively identified as *Empetrum*, cf. *Ranunculus*, cf. *Carex*, and a species of Rosaceae. None of these taxa presently occurs in Antarctica. *Empetrum* is a common plant of better-drained locations in the Magellanic Moorland vegetation of the wet Pacific Coast of South America, but also occurs in the heath vegetation of drier sites on the basaltic mesetas of Patagonia.

Based on the domination of *Nothofagus* pollen in the Sirius Group, it has been suggested that the vegetation was more depauperate than any presently existing in the regions surrounding Antarctica. The beetle and seed fossils suggest a biota with a higher diversity. In combination with *Nothofagus*, previously described from wood and leaves, and *Dacrydium*, described from its pollen occurrence, the biota would have had similarities with the Magellanic Moorland of the wet, Pacific coast of South America.

The existing non-parasitic insect fauna of Antarctica consists only of springtails (*Collembola*) and midges (Chironomidae). The listroderine weevil is the first tangible evidence that Antarctica had a richer insect fauna. Entomologists have long argued this based on the amphi-Antarctic distribution of many insect species but have never had the proof. Given that the specimen was about 8 mm in length and flightless, it is most improbable that it was transported to Antarctica by wind or water currents. Most probably, it represents a member of a lineage whose ancestors inhabited Antarctica from the time of Gondwanaland.

More insect and plant macroscopic remains can be expected to be found in the Sirius Group as different sedimentary facies are discovered and as larger examples are examined. Potentially, these fossils are important for answering questions relating to (1) the depositional environment of the formation, and (2) evolutionary rates and the dispersion of the fauna.

PRISM Reconstructions Of SST And Sea Ice In The Southern Ocean

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For the initial PRISM 2°x 2° (latitude-longitude) reconstruction of global conditions at 3 Ma, quantitative and semi-quantitative diatom data from 24 Southern Ocean cores were used to infer sea-surface temperature (SST) and sea-ice estimates. These studies suggest that during the mid-Pliocene, SST's were between 4° and 2°C warmer than modern values throughout much of the Southern Ocean south of 45°S.

The Antarctic Polar Front, which is characterized in the modern ocean by SST's of ca. 4-5°C (February) and 1-2°C (August), apparently was shifted by about 6° of latitude to the south in the eastern South Atlantic and Indian Ocean at 3 Ma. The Sub-Antarctic Front (SAF), which forms the northern boundary of the Polar Frontal Zone (PFZ) and which separates diatom-rich sediments in the south from diatom-poor, coccolith-rich sediments in the north, seems to have experienced little (ca. 2°) if any southward displacement in the mid-Pliocene, resulting in an expanded PFZ. In the modern ocean the SAF is characterized by SST's of ca. 7-10°C (February) and 4-5°C (February). South of the 3 Ma PFZ (ca. 56°S), mid-Pliocene Antarctic diatom assemblages were dominated by provincial diatom taxa (*Nitzschia barronii, N. interfrigidaria, Rouxia* spp., *Thalassiosira lentiginosa*, and *T. oliverana*).

Evidence for very much reduced sea-ice in the high-latitude Southern Ocean below the upper part of the Gauss normal-polarity chron (>2.9 Ma) includes a greatly reduced number of sea ice-related diatoms (*Eucampia antarctica, Nitzschia curta*, and *N. cylindra*), as well as the presence of well-preserved diatomaceous sediments in the high-latitude Weddell Sea. Mid-Pliocene diatom assemblages from drill holes adjacent or near to the Antarctic continent - DVDP10 and DSDP 274- contain only rare to absent *E. antarctica* and *N. curta*, and are suggestive of very minimal sea ice. Consequently, only minimal sea-ice is inferred in PRISM reconstructions for the Antarctic coast for the Antarctic summer. Unfortunately, diatoms cannot provide evidence for the Antarctic winter extent of sea-ice. For PRISM reconstructions, winter sea-ice was arbitrarily expanded to about 71°S to conform to the northern limits of the East Antarctic in the mid-Pliocene. Because sea-ice has an SST of -1.6°C, areas predicted to have been covered with sea ice at 3 Ma were assigned an SST of -1.6°C.

Warm Pliocene High Sea-Level Records From Arctic Alaska And Possible Implications For Antarctic Ice Volume 2.8-2.2 Ma

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The Gubik Formation of Arctic Alaska contains deposits that record at least three eustatic high sea-level stands during the mid- to late Pliocene when perennial sea ice was likely absent, permafrost was less widespread, and treeline extended to the coast of the Arctic Ocean (Brigham-Grette and Carter, 1992, for review). The geochronology of these deposits is based upon amino acid geochemistry, paleomagnetic evidence, vertebrate and invertebrate paleontology, and strontium age estimates. The Colvillian transgression (Nulavik member) reached at least 40 m asl and occurred long after the submergence of the Bering Strait (ca. 4 Ma, Gladenkov et al., 1992) but before 2.6 Ma, at a time when boreal forest or spruce/birch woodland, including rare pine, fir, and hemlock, reached the coast (Nelson and Carter, 1992). The Bigbendian transgression (Killi Creek member) reached at least 20 m asl and occurred about 2.6 Ma based on paleomagnetic evidence recording the transition from normal to reversed polarity. While some marine faunas are richer than those of the Colvillian (Brouwers, 1994), pollen evidence suggests forests reaching the coast were more open in character (Nelson and Carter, 1985). The Fishcreekian transgression (Tuapaktushak member) reached at least 25 m asl, but may have reached much higher based on correlative shell material found inland at higher altitudes. This high sea-stand took place sometime between 2.2 Ma and 2.6 Ma and is also characterized by warm marine faunas, but pollen data in regressive deposits suggest conditions on the coastal plain supported herb tundra with larch (Repenning et al., 1987; Nelson, 1994).

All of these transgressions post-date the mid-Pliocene (3.1-3.0 Ma) warming recorded elsewhere in the world, and require that the Arctic Basin remained relatively warm until nearly 2.2 Ma. The Pliocene marine deposits of the Arctic Coastal plain, occur at altitudes of up to 70 m. This area has been tectonically stable for at least the past 125 ka, because shorelines formed during the last interglacial have not been uplifted. We have found no evidence for uplift of the Pliocene marine beds, and so we believe that eustatic sea-level during the Pliocene must have been intermittently higher than present sea-level. Such high sea-levels would seem to require at least periodic reductions in the size of the Antarctic ice sheet accompanied by complete removal of the Greenland ice sheet (cf. Funder et al., 1985; Bennike and Bocher, 1990 for the Kap Kobenhaven Formation which is likely correlative with the Fishcreekian transgression).

Erratics in all of these marine deposits suggest that during periods of high sea-level, glaciers reached tidewater somewhere bordering the Arctic Basin. Warm marine conditions and an ice-free Arctic Ocean may have been conducive to glacierization of portions of the Arctic islands in a manner unlike the late Pleistocene. Shell-bearing tills and extensive glaciation postulated for the Ellesmere Island region may date from this time period (Bell and England, 1992). Marine shells in the most extensive till sheet are likely correlative with the Hvitland beds dated elsewhere on Ellesmere Island to about 2.6 Ma and thought to be correlative with the Bigbendian transgression. The limited amount of amino acid epimerization in shells of this antiquity suggest that air and ground temperatures across the Arctic have been low and severe since the time of the Fishcreekian transgression.

Although the amount of regional uplift is not precisely known, the elevation of the Gubik deposits requires that eustatic sea level was much higher than at present during portions of the middle and late Pliocene. These data, coupled with the warm conditions and lack of arctic sea ice, argue in favor of models calling for a more dynamic Antarctic ice sheet during this interval.

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Global Climate Model Simulations Of The Middle Pliocene, Continued...

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The Goddard Institute for Space Studies (GISS) general circulation model (GCM) was used, previously, to simulate the middle Pliocene climate, for the Northern Hemisphere, based on gridded input data sets compiled by the U. S. Geological Survey's PRISM research. Those data sets and the subsequent simulations employed an 8° latitude by 10° longitude resolution, based on the coarse grid version of the GISS GCM Model II. More recently, we have completed finer resolution simulations of the middle Pliocene climate using a 4° X 5° version of the GISS GCM. Input data were derived from the new, global, PRISM middle Pliocene data sets, which are distributed at a resolution of 2° X 2°.

The results from this new experiment reveal a middle Pliocene global warming of 2.2°C as compared to the simulated current climate. This is a slight increase over the warming found using the 8° X 10° version of the GCM. Much of the warming occurs near the poles, although temperatures increase across most of the globe. Notable exceptions include the tropics, which show little change in temperature, and East Africa, where elevations were higher in the Pliocene, and thus temperatures cooler. The reduction in elevation over Antarctica (resulting from the shrunken ice sheet) and in the western U. S. give rise to large temperature increases in those regions. Those increases can be shown to be primarily the result of temperature adjustments based on the elevation decrease and the lapse rate. However, some warming can be attributed to an albedo decrease caused by the loss of snow and ice and the encroachment of less reflective Pliocene vegetation types in those regions. For example, note that in northern Canada, the one region where snow cover actually increases in the Pliocene, the warming signal is muted.

The hydrological cycle is somewhat intensified in the Pliocene climate, as would be expected in a warmer climate. The intensification is largely driven by the warmer extratropical sea-surface temperatures, which cause greater evaporation from the oceans. The polar regions are especially wet compared with the current climate, and while most continental regions see moisture increases, the United States, Western Europe, and Southeast Asia are simulated as being drier than today. Throughout tropical regions where near-modern SST's were specified, the hydrological cycle does not intensify, weakening slightly. This has the affect, in combination with the reduced pole-to-equator temperature gradient, of damping the thermally-driven Hadley circulation, thus reducing rainfall in the intertropical convergence zone.

As in previous coarse grid simulations, the basic temperature patterns are supported by the terrestrial (mostly palynological) data. The hydrological patterns, however, despite being consistent between soil moisture, surface runoff and precipitation minus evaporation results, reveal large disparities between model and data estimates for

North America and Europe. Although some of this discrepancy arises from the GCM's lack of resolution in high relief terrain, it is likely that new models, with improved clouds, convection, and ground hydrology parameterizations will be required to move forward in this area of comparison. New versions of many of the primary GCMs in the U.S. are poised to appear and most focus on improving their hydrological climatologies. The Pliocene may serve as one climate change testing ground for the next generation GCMs. Stay tuned...

The Pliocene Record in the Central Arctic Ocean

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Pliocene sediment was reported from the central Arctic Ocean more than 25 years ago. A few years later the Pliocene age was challenged, but none of the data subsequently presented have invalidated the original Pliocene age report.

The Pliocene sediment in the central Arctic Ocean includes 2-3 m of silty lutite consisting largely of illite, kaolinite, and chlorite, with lesser amounts of expandable clays, abundant Fe-Mn micronodules, but few fossils of any kind. The Pliocene age is based on extrapolation of sedimentation rates from paleomagnetic boundaries, arenaceous foraminifera with a known Pliocene range, and $^{87}Sr/^{86}Sr$ isotope ratios obtained from Fe-Mn micronodules and compared to established seawater $^{87}Sr/^{86}Sr$ isotope ratios for this time. Notably absent in the central Arctic Ocean Pliocene sediment is coarser-grained ice-rafted debris (IRD) or any indication of measurable surface water productivity.

Early interpretations of the Arctic Ocean Pliocene record included the concept that sea-ice was present during this time, and that ice-cover existed more or less continually to the present. Warming events that may have temporarily removed all or part of the Arctic Ocean's ice were thought to be restricted to the Pleistocene. More recently, published data have suggested that the Pliocene Arctic Ocean was a warmer, perhaps ice-free ocean. GCM modeling experiments with all or parts of the Arctic ice-cover removed were thought to be supported by the Pliocene data generated primarily from the Arctic ocean's margins.

While there is important evidence for a warmer Pliocene Earth, the data to support significant warming in the central Arctic Ocean remains ambiguous. Reevaluation of the data used to support supposed Pliocene warming intervals on the Arctic Ocean's margins suggests that at least some of the implied Pliocene warming events are more likely of Pleistocene age. The central Arctic Ocean's Pliocene record studied to date indicates only that the ocean had very low surface water productivity, extremely low sedimentation rates, and that there is little evidence of much organic activity, all of which is equivocal concerning the presence or absence of sea-ice.

Middle-Pliocene Planktonic Foraminifer Assemblage From ODP Site 704: Paleoceanographic Implications

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Abundant and well-preserved assemblages of planktonic foraminifers have been recovered from middle Pliocene (3.15 - 2.85 Ma) sediments at Ocean Drilling Program Hole 704A. Cyclic changes in the composition of foraminifer faunas indicate high frequency variability in oceanographic conditions. Temperature estimates based upon quantitative analysis of the planktonic faunas have a range of ~12.5°C with average glacial (interglacial) winter temperatures of 3.2° C (9.5° C) and summer temperatures of 6.4° C (13.5° C). Comparison of the SST time series to the published $\delta^{18}O$ record from *Globigerina bulloides* indicates $\delta^{18}O$ is primarily a temperature record prior to 2.85 Ma, dampened by fluctuations in Antarctic ice volume. Increases in ice volume are linked to increases in SST through net transport of moisture toward the pole. After 2.85 Ma, an opposite relationship exists between SST and $\delta^{18}O$ so that increases in temperature are correlated with $\delta^{18}O$ enrichment.

North Atlantic Deep Water Temperature Change During Late Pliocene And Quaternary Climatic Cycles

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We studied the Mg/Ca ratio of shells of the deep-sea ostracode genus *Krithe* to estimate bottom water temperature (BWT) in the deep Atlantic Ocean during late Pliocene and Quaternary climatic cycles. This work was first presented in Dwyer et al (1994) and is described in detail in Dwyer et al (submitted) and Cronin et al (in prep.). Using the preliminary calibration equation T (°C) = 451.7 x (Mg/Ca_{Krithe}) - 2.2 derived from Correge (1993), we calculated bottom water temperature in the PRISM time slice 3.15-2.85 Ma at the following DSDP and ODP sites 610A, 607, 552A, 704A, 658, 659, 541, 502A, and 661 in the North and South Atlantic (Cronin et al, in prep.). We also studied a late Pliocene time series in the interval 3.2-2.3 Ma from DSDP Site 607 (41°N, 33°W, 3427 m water depth) and the late Quaternary interval 200 kyr-present (oxygen isotope stages 7-1) from the nearby *Chain* core 82-24-4PC (42°N, 33°W, 3427 m water depth) to examine bottom water temperature variation during 41kyr obliquity and 100 kyr eccentricity cycles (Dwyer et al, 1994, submitted). Finally, we carried out Mg/Ca and faunal analyses of *Krithe* from transects through the thermocline and into the deep-sea in the Arctic Ocean, Norwegian/Greenland Seas, Little Bahama Banks, Florida-Hatteras Slope, Chilean Fjords, and off Japan in order to improve existing calibrations of Mg/Ca to temperature. Our preliminary conclusions are as follows.

(1) Analyses of ten *Krithe* species from site 607 indicate no obvious interspecific vital effect in the Mg/Ca ratio.

(2) Intraspecific analyses of *Krithe* cf. *pernoides* from high northern hemisphere latitudes showed no vital effect in Mg/Ca ratios among adult individuals of the same species due to shell size, gender, or right/left valve, but there is an ontogenetic variation of increasing Mg/Ca ratios with younger age (ie., early instars).

(3) During the relatively warm interval from 3.2-2.8 Ma, BWT averaged 2.3°C, ranging from a minimum of 1.65° to a maximum of 3.3°C. Minima and maxima average 1.9° and 2.6 °C respectively, with an average "glacial/interglacial" amplitude of about 0.7 °C.

(4) During the interval 2.8 to 2.3 Ma, which spans the initiation of significant continental glaciation in the northern hemisphere, the average amplitude of the glacial/interglacial BWT shift increased to 1.5°C, with an average glacial BWT of 1.4°C; average interglacial BWT was 2.9°C. The absolute glacial minima and interglacial maxima for this period are 0.9° and 3.8°C, respectively, and the average interglacial BWTs for this interval are similar to the present day temperature (2.6 °C).

(5) The Mg/Ca ratios and temperature estimates show a good correlation with the benthic stable isotope records from 3.2-2.3 Ma; there is an apparent 41 kyr periodicity to the Mg/Ca record (Dwyer et al., 1994) which coincides with patterns of ostracode faunal assemblages from site 607.

(6) CH82-24-4PC was heavily sampled, especially in the interval corresponding to the last glacial maximum, but our preliminary data

indicate a large glacial-interglacial shift in BWT (≈ 2.25°C) between isotope stages 7 and 6 and between stages 6 and 5. Interglacial maxima are similar to those of the late Pliocene, averaging 2.7°C with an absolute maximum of 2.9°C. Glacial BWT for isotope stage 6 was 0.7 °C, the coldest observed. Our first approximation of late Quaternary glacial/interglacial BWT change suggests that it was greater during these 100kyr cycles than during 41kyr-cycles of the late Pliocene.

(7) For the 3 Ma time slice reconstruction, the preliminary Mg/Ca data show a gradient in BWT from warmer temperatures in the North Atlantic to cooler temperatures in the South Atlantic, as would be expected if southern source deep bottom water was colder than northern source water. However, this pattern must be confirmed with additional analyses.

The Mg/Ca-derived bottom water temperature estimates provide means by which to separate the temperature component from the deep-sea benthic foraminifer $\delta^{18}O$ record and reconstruct the seawater $\delta^{18}O$ record and an ice volume curve. The resulting curve provides a detailed record of late Pliocene sea level that is generally concordant with ocean margin records of sea-level change. Additional work is underway to improve and expand the Mg/Ca-derived BWT record and to improve our understanding of late Pliocene and Quaternary sea level history. A more detailed analysis of the late Quaternary is also warranted in light of the limited sampling of the *Chain* core.

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Evidence Of Pliocene *Nothofagus* In Antarctica From DSDP/ODP Cores

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Recent interest in the Neogene history of Antarctica revolves, in part, around the presence of plant fossils referable to *Nothofagus* that have been reported from Antarctic sediments estimated to be Pliocene in age. Fossil pollen reported from these sediments most closely resembles *Nothofagidites lachlaniae* (which has a known geologic range of Eocene to Holocene). Previous workers have interpreted these fossils to represent the presence of a single species of *Nothofagus* in Antarctica during the Pliocene.

If *Nothofagus* was living in Antarctica during the Pliocene, then its pollen should be preserved in marine sediments around the continent. To test this hypothesis, we obtained samples from several DSDP/ODP sites that are dated as Pliocene by diatoms. Samples were collected from Sites 274, 693A, 695A, 742A, and 745B, which were selected on the basis of their proximity to the Antarctic continent and continuity of Pliocene sediments. Palynological analysis will focus on documenting the presence and relative abundance of *Nothofagidites lachlaniae* in these Pliocene marine sediments.

Assuming that glaciers were active during the Pliocene in some parts of Antarctica, it is possible that fossils of *Nothofagidites* preserved in Pliocene sediments are reworked from older deposits. Reworked palynomorphs are being deposited today by glacial processes in modern sediments around Antarctica, and previous studies have documented the relative abundance of reworked taxa, including *Nothofagidites lachlaniae*, in modern samples. Comparison of Pliocene and modern assemblages may provide a basis for determining whether *Nothofagidites lachlaniae* is reworked or not. Unusually high abundance of *N. lachlaniae* would favor Pliocene stands of *Nothofagus* as the source rather than reworking from older Cenozoic deposits.

Palynological assemblages from Site 274 samples are sparse and thus relative abundance data may be unreliable. All productive samples examined to date contain reworked palynomorphs, such as *Microcachryidites antarcticus* (Jurassic-Miocene) and *Dilwynites tuberculatus* (Paleocene-Miocene). Although not all of the samples have been examined, preliminary results indicate that *Nothofagidites* cf. *N. lachlaniae* is present in Pliocene sediments from this site. In most samples examined, *Nothofagidites* cf. *N. lachlaniae* is not unusually abundant. In sample D8135-I (Leg 28, Site 274, Core 9, Section 2, Interval 48-52 cm), which is dated at about 3 Ma by diatoms, this species accounts for most of the *Nothofagidites* in the assemblage. The presence and relative abundance of *Nothofagidites* cf. *N. lachlaniae* in sample D8135-I from Site 274 suggests production from Pliocene plants rather than reworking. Assemblages also contain microspores referable to the Isoëtaceae, which suggests the presence of quillworts as part of the Pliocene vegetation on Antarctica. Samples from Site 695A are currently being processed and apparently contain more abundant palynomorphs than Site 274, and may provide corroborative evidence for *Nothofagus* living on Antarctica during the Pliocene.

Solved And Unsolved Paleogeographic Problems Of The Sub-Arctic Pliocene Of Russia

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Geological investigations of the Arctic coast of Russia, and the comparative analysis of information on the Iceland-Greenland region and the North Pacific, formed a basis for correction of paleogeographic and paleoclimatic reconstructions.

The following events appeared to occur in the northern Holarctic:

- Climate fluctuated considerably during the Pliocene. After 3 Ma, the cooling processes became predominant.
- The Bering Strait was opened in the middle Pliocene, but afterwards it was repeatedly closed, providing migrations of terrestrial assemblages.
- Sea transgressions did not expand to the recent Arctic coast of Russia?
- Marine biota migrations in the Arctic and adjacent basins were of asymmetrical character, etc.

Some problems still remain unsolved:

- Distribution of the Pliocene marine sediments on the Arctic.
- A role of the Tule Bridge in isolation of the Arctic basin and distribution of sea currents; its effect on the paleobiota migrations.
- A time of connection of the Arctic and Pacific basins.
- A correspondence of the eustatic and climatic fluctuations in the Arctic Pliocene.
- Paleobiotic migrations (directions, rates, etc.) and causes of their asymmetrical character.
- A correlation of the sub-Arctic Pliocene marine and continental deposits.

Sea-Ice Absence and 3° C Marine Seas - - Is This All it Takes?

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Paleobiogeographic information from the Antarctic shelf and Southern Ocean suggests that early Pliocene marine temperatures were sufficiently high to reduce and perhaps remove sea-ice from the Southern Ocean and most Antarctic regions. The absence of a seasonal blanket of sea-ice leads to significant atmospheric warming of the Antarctic region, as oceanic heat is available throughout the year. This factor, as well a comparison of annual temperature trends for Southern Ocean islands in thermal regimes similar to that of the Antarctic Pliocene, suggest an increase of mean annual atmospheric temperatures around Antarctica more than 15°C higher than today. This places the Antarctic ice sheet into a dynamic glacial regime, as indicated by recent glacial models, and is more than sufficient to support the growth of *Nothofagus* in the Transantarctic Mountains.

The Palynological Record Of Antarctic Neogene Vegetation

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The Antarctic continent has a long history of terrestrial vegetation. The limited records available for the Neogene indicate a progressive loss of taxa through time. The loss of vascular plants in Antarctica may coincide with increased cooling and the development of permanent polar ice sheets sometime after the early Pliocene.

The recovery of a lower Miocene palynomorph assemblage in diatomite clasts from RISP Site J/9 sediment cores, gives us a clearer view of the terrestrial vegetation during the early Miocene. This palynomorph assemblage was deposited at a time of minimal glaciation. The assemblage is considerably different from that recovered in the Sirius Group, arguing strongly against the late Oligocene to early Miocene age of the Sirius Group flora suggested by Burckle and Pokras (1991).

A well-preserved, but considerably lower diversity palynomorph assemblage than present in the above samples, occurs with wood and leaf fossils (southern beech, *Nothofagus*) in the Pliocene Sirius Group of Oliver Bluffs, in the Transantarctic Mountains. No evidence suggests that these palynomorph assemblages are mixed or recycled from older sediment. These palynomorph data enable the reconstruction of Pliocene terrestrial vegetation and help guide discussions of Antarctic glacial history and paleoclimate. These floras may represent the last survivors of the Gondwana vascular paleoflora in Antarctica. Progressive cooling and ice sheet expansion led to local extinction of most flora from the Antarctic continent during the late Pliocene. We are searching for similar records in marine mudstones in DVDP and CIROS drill cores of Southern Victoria Land.

These new palynomorph data from RISP Site J/9 and the Sirius Group provide a clear base, from which we will be able to mark the exit of higher plants from Antarctica. Due to geographic isolation following the break-up of Gondwana continents, the Cenozoic floral record appears to be one of loss (exit) from Antarctica and not of dispersal to Antarctica.

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A Review Of Pliocene Antarctic Paleoclimate And Ice Sheet Response To Global Warmth

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The Sirius Group and its implications for Pliocene deglaciation are well-known. However, if these glacial deposits were unknown, and we take into consideration evidence for elevated sea-level, significant global and polar warming, and reduced Antarctic sea-ice cover during the Pliocene, one would likely predict that evidence such as that unfolding from our studies of the Sirius Group would eventually be discovered. Antarctic geologists would search for stratigraphic evidence of a warmer ice sheet, reduced ice sheet extent and marine incursion. The view that the Antarctic Ice Sheet was a stable and permanent feature through the Pliocene is incompatible with a wealth of global and Antarctic evidence. The stable view is as radical a notion today as the concept of a Pliocene deglaciation was in the middle 1980's.

This paper reviews evidence for a significant ice-volume decrease in Antarctica during the Pliocene, as indicated by (1) recycled marine microfossils in glacial deposits of the Sirius Group and Pagodroma Tillite; (2) by numerous fossiliferous deposits along the Antarctic coastline, particularly that of Marine Plain in the Vestfold Hills; and (3) by paleobiogeographic distribution of diatoms in the Southern Ocean. This evidence indicates higher sea-level, warmer marine and terrestrial conditions, and retreat of the glacial margin during the Pliocene. Early to mid-Pliocene Antarctic paleogeography included (1) a greatly diminished, warmer and wetter ice sheet, compared to the present ice sheet; (2) an extensive austral vascular macroflora extending almost to the South Pole; (3) relatively warm seas (2°C to 6°C) extending into and across broad regions of East and West Antarctica; and (4) a weakly developed seasonal sea-ice belt, present only in isolated regions on the Antarctic continental shelf. The absence of sea-ice resulted in relatively mild winter conditions in Antarctica as oceanic heat warmed the continent and interior seas. This prevented the sharp depression of winter temperatures seen in Antarctica today.

Our initial interpretation of the Sirius Group diatom assemblages called for at least one, perhaps two, marine incursions into the Wilkes and Pensacola basins between 5.0 and 2.5 Ma. New evidence from the benthic oxygen isotope record and eustatic signature in the Wanganui Basin of New Zealand suggest a more dynamic history of ice retreat and advance during the Pliocene. Significantly warmer Pliocene climate may have rendered the East Antarctic Ice Sheet sensitive to the dynamics of orbital climate forcing. Repeated ice sheet growth and retreat would aid repeated isostatic depression of the Wilkes and Pensacola Basins to allow marine incursion evident by recycled microfossils in the Sirius Group.

The late Pliocene reglaciation of Antarctica was accompanied by the onset of the modern polar glacial regime and the development of extensive sea-ice. A portion of the isotopic shift at ~2.4 Ma, thought to represent the initiation of the Northern Hemisphere ice sheets, must also be attributed to the reglaciation of Antarctica. The identity of the Antarctic ice sheet as a potential source for this isotope shift was hidden by the assumption that the Antarctic ice sheet was a permanent and stable feature since the middle Miocene.

Pliocene *Nothofagus* Of The Sirius Group, Transantarctic Mountains

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Nothofagus leaves which were recovered from glacial sediments of the upper Pliocene Sirius Group in the Dominion Range, next to the upper Beardmore Glacier in the Transantarctic Mountains will shortly be described as a new species, tentatively named *N. beardmorensis*. The current altitude of the site is about 1800 m, but there is evidence for substantial post-depositional uplift. The age of the fossil flora is constrained by the presence of recycled (reworked) mid-Pliocene marine diatoms, which must be older than the *Nothofagus* fossils, which are in situ. If this conclusion is correct, and it is assumed that *N. beardmorensis* did not re-invade Antarctica, then we must accept that all pre-Pliocene glaciations must have been at least 15-20°C warmer than today, with higher values during deglacial periods.

The Taxonomic Affinities Of The Fossils

There are three different types of fossil which have been assigned to *Nothofagus* at this site. The pollen has been assigned to *Nothofagidites lachlanae*, which today is produced by both deciduous and evergreen species. This pollen may belong to the fusca a group (subgenus *Fuscospora*) or the fusca b group (subgenus *Nothofagus*). The wood has been compared favorably with *N. betuloides* (evergreen, subgenus *Nothofagus*) and *N. gunnii* (deciduous, subgenus *Fuscospora*). The pieces of wood which have been recovered to date have a small diameter, suggestive of a shrubby growth form, possibly even a ground-hugging habit. The leaves are very close in morphology to several extant deciduous species from southern South America.

The Deciduous Nature Of The Leaves

There are three lines of evidence supporting the deciduous nature of the leaves. First, their taxonomic affinities, mentioned above. Second, the leaves have plicate vernation, which is unique to the deciduous species, where the leaves are folded like a fan in the bud. Third, the fossil leaves occur in dense, but very thin mats, which look very much like a short term event, and probably an autumn leaf fall. Only one of these mats has been discovered to date. These three lines of evidence provide the strongest evidence ever presented for the winter deciduous habit of a fossil plant, and place the issue beyond reasonable doubt.

A Local Source For The Fossils

There are several lines of evidence which support a local source for the fossils. The leaves, as already mentioned, occur in a thin but dense mat. They have organic preservation, but are very thin (as are all the extant deciduous species) and could not possibly be re-worked and left in this condition. Therefore, there is no possibility that they have been re-worked from older sediments. Furthermore, it is highly improbable that the leaves have been transported more than a very few metres, since:

i. The very dense leaf mat would not be expected if they had been transported far, especially by wind. The probable low growth habit, as evidenced by the wood, also argues against mass transport of leaves by wind.

ii. There is no evidence of damage to the very delicate laminas (either mechanical or due to decay), suggesting that there was little wind or water transport and that the leaves were incorporated into the sediment soon after they were shed.

iii. Three different organs of what is almost certainly the same species occur in the sediments, which is very suggestive of a local source. It is unlikely that long distance dispersal would bring three such dissimilar organs into close proximity. All evidence points overwhelmingly to the conclusion that the source plants for these fossils were growing nearby, and probably directly over the site of deposition.

What Climatic Constraints Are Imposed By The Probable Physiology Of *N. beadmorensis*?

Nothofagus is a very conservative genus, and the vast literature on living and fossil species suggests that they evolve very slowly, both morphologically and physiologically. Therefore, we can use the physiological response of living species to infer the physiology of the fossil species. There are two aspects which are of particular interest:

i. Frost resistance. In winter, a deciduous species loses its leaves, but its wood and dormant buds must still survive the low winter temperatures. The available data on frost resistance in *Nothofagus* suggests that minimum temperatures below about -20°C will place plants in jeopardy. Although the data is limited, it is interesting that some of the evergreen species appear to be as frost resistant as the deciduous species (e.g. *N. cunninghamii* cf. *N. gunnii*), and the reason that a deciduous species has survived rather than an evergreen species may be due to the photoperiod rather than frost resistance. Snow cover may have been of some assistance in surviving winter extremes, but this is difficult to judge.

ii. During summer, the plants must reach a temperature substantially above 0°C in order to grow, and more importantly, reproduce. Temperatures in excess of 5°C were probably required for a prolonged period of time. It is also notable that the fossil leaves are substantially larger than some of the deciduous species, which again may be an effect of the photoperiod, but also suggests milder conditions than those experienced for example in alpine Tasmania.

iii. In order to survive there must have been a plentiful supply of liquid water during summer (also suggesting temperatures above 0°C). The open Ross Sea may have been an important local moisture source and may also have had an important effect on the local microclimate.

Finally, it is important to note that *Nothofagus* is notoriously poorly equipped for long distance dispersal. The seeds rarely fall further away from the parent plant than its height, and they cannot stand prolonged immersion in sea water. There are no adaptations for bird or other animal dispersal. This suggests that not only was *Nothofagus* present in Antarctica in the mid-Pliocene, but that it had been present continuously up until that time. However, there is some published evidence for rare long distance dispersal of *Nothofagus* during the Cenozoic, so the option that this species re-invaded Antarctica after a prolonged cold period cannot be dismissed.

Paleoclimatic Implications of a Late Neogene Antarctic Marginal Marine Record

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The Antarctic margin provides us with the best opportunity to construct an ice proximal paleoenvironmental record for Antarctica. Dry Valley Drilling Project Cores 10 (DVDP 10) (77°34'43"S, 163°30'42" E) and 11 (DVDP 11) (77°35'24.3" S, 163°24'40.3" E) in Taylor Valley contain the most complete late Miocene through Recent glacial and glacio-marine sedimentary sequence recovered from the Victoria Land margin, Antarctica. Sedimentologic, paleontologic, and paleomagnetic data have been employed in deciphering the chronology, depositional environments, and paleobathymetry from these late Neogene sediments placing limitations on depositional models constructed for the Ross Sea from seismic stratigraphic records. The presence of diamictons containing abundant and well preserved benthic foraminifers interbedded with siltstones and sandstones containing benthic foraminifer and diatom assemblages indicate fluctuating oceanographic conditions in a polar fjord setting. Paleodepth estimates of 600 mbsl for these sediments requires uplift rates on the order of 100 m/m.y., constraining the timing and uplift of the Dry Valley block of the Transantarctic Mountains (Ishman and Rieck, 1992).

The Southern Ocean record provides a link between Antarctica and global records. Ocean Drilling Program (ODP) Site 704 (47° S, 7° E), South Atlantic Ocean, provides one of the most complete Pliocene-Pleistocene transition sequences in the Southern Ocean (Ciesielski, P.F., et al., 1988). Stable isotopic records from ODP Hole 704A (Hodell and Venz, 1992) show changes from the Pliocene through early Pleistocene. Benthic foraminifers from ODP Hole 704A show deep water fluctuations throughout this time. The fluctuations observed in the faunal and isotopic records are related to significant ice volume and temperature changes. Correlation between the DVDP record and Hole 704A isotopic records show close correlation between the negative excursion in the benthic isotopic record and the Pliocene ice volume minimum. A positive shift in the middle to late Pliocene isotopic record indicates deteriorating climatic conditions in the Southern Ocean accompanied by a shift in the benthic foraminifer assemblage from a northern component deep water assemblage to a Southern Ocean deep water assemblage.

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Pliocene of Northwind Ridge, Western Arctic Ocean

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The Northwind Ridge is a 500 kilometer long, high-standing fragment of continental crust in the Canada Basin of the western Arctic Ocean (Grantz, et al., 1993). The Northwind Ridge is mantled by glacial marine sediments that preserve a record of changing climatic and paleoceanographic conditions during the late Cenozoic (Phillips and others, 1992; Poore and others, 1993, 1994). The thickness of the sediment cap can be up to a few tens of meters, especially in flat lying areas near the crest. The upper part of the sediment cap shows distinct banding caused by the alternation of dark brown muddy beds with gray, olive gray, and tan silty or sandy muds and, less commonly, pinkish white to white clast-rich coarse layers. The lower part of the sediment cap consists of more uniform dark brown to tan muds and silty muds. The section is highly variable and is complicated by unconformities and winnowed intervals.

We are developing an informal stratigraphic framework for correlating and dating the Northwind Ridge late Cenozoic sedimentary sequence that relies on multiple criteria including sediment texture and composition, abundance and character of microfossils, density core logs, magnetic susceptibility and magnetostratigraphy. No single core that we have examined contains a complete section of the sediment cap, but a relatively complete composite section ranging from the late (?) Miocene to Holocene is evident by combining the records of several cores.

Calcareous microfossils are only present in a few isolated intervals of the Pliocene sequence. Initial data suggests that the absence of calcareous microfossils is due to a shallow CCD.

Sand-sized quartz grains and rock fragments along with coarser drop stones occur throughout the Northwind Ridge section. We interpret these grains as evidence for ice-rafting and thus conclude that sea-ice and glacial ice have been present in the western Arctic since late (?) Miocene. Below the Gauss/Matuyama boundary grains >2mm and coarser drop stones are rare and occur sporadically, but they are usually common to abundant in sediments above the Gauss/Matuyama Chron boundary (fig. 1). This change reflects a significant increase in the amount of glacial ice reaching the Arctic beginning at the Gauss/Matuyama boundary. Prior to the Matuyama, glacial ice was probably minor and intermittently present. Our interpretation of the Northwind Ridge magnetostratigraphy indicates that the change in ice-rafting intensity and style in the Northwind Ridge sequence coincides with increased ice-rafting observed in the North Atlantic and corresponds to the development of the first large Northern Hemisphere continental ice-sheets.

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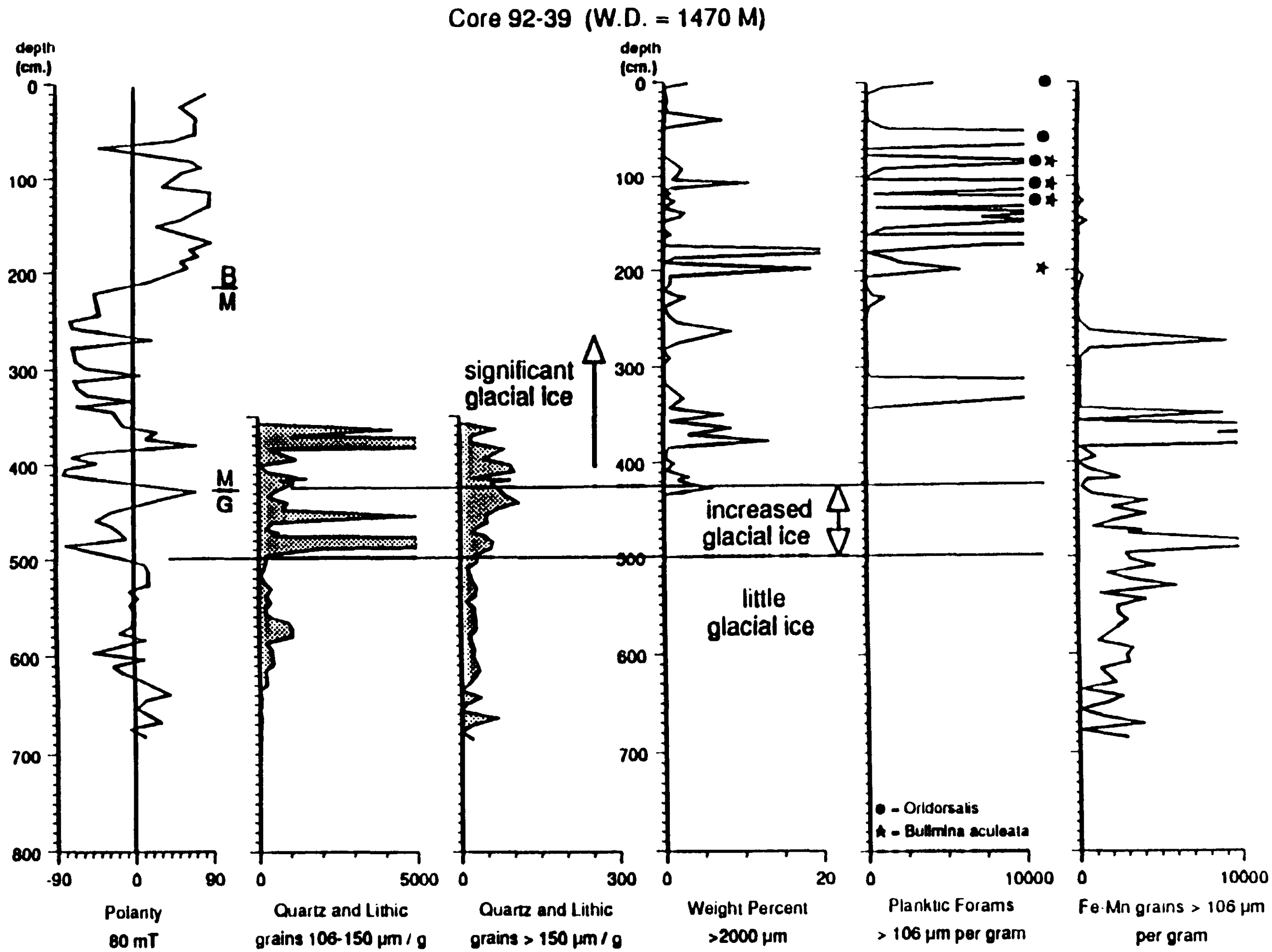

Fig 1. Selected data from Northwind Ridge core 92-39. The Brunhes interval is in the upper 2 m of this core. The change at 420 cm from predominantly reversed polarity above to normal or indeterminate polarity below is the Matuyama / Gauss boundary. Thus, this core extends back into the mid-Pliocene. Other features that have proved usefu for correlating the older part of the record from Northwind Ridge include a distinctive foraminifer-rich bed (egelida sand on fig. 2) and a unit rich in mud clasts (mcu) that can be recognized by very low magnetic susceptibility values and a distinctive saw-tooth pattern in the density log. The sand-sized and coarser quartz and lithic grains from these cores are considered to represent ice-rafting (it is unlikely that sand-sized and larger material is transported out this far from the shelf by turbidity currents). The general increase in grain size upsection seen from 700 to 400 cm reflects a change from a regime with mostly sea ice rafting to a regime sea ice and substantial amount of glacial ice rafting. The > 2 mm sized grains begin to consistently occur at the Matuyama / Gauss boundary which coincides with estimates for the the formation of the first major northern hemisphere ice sheets deduced from oxygen isotope records from deep sea cores and ice-rafting records from the North Atlantic and North Pacific Oceans.

Review Of The Deep-Sea Oxygen Isotope Record Regarding Early Pliocene Antarctic Deglaciation

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I will review the early Pliocene deep-sea oxygen isotope record as it pertains to Antarctic (polar) deglaciation. The tropical shallow-dwelling planktonic foraminiferal $\delta^{18}O$ and deep-water benthic $\delta^{18}O$ records will be emphasized. A significant recent refinement in the tropical planktonic $\delta^{18}O$ record is the divergence of western tropical Pacific planktonic $\delta^{18}O$ (ODP 806, 807) and comparable $\delta^{18}O$ records from the eastern tropical Pacific (DSDP 572) and tropical Atlantic (DSDP 502, ODP 625). Recent high-resolution benthic $\delta^{18}O$ records (ODP 704 and 846) confirm the significant benthic $\delta^{18}O$ depletion patterns previously noted for the early Pliocene.

Three of the more prominent interpretations of the early Pliocene $\delta^{18}O$ record will be evaluated. The extreme deglaciation hypothesis encounters the greatest obstacles especially as regards physical explanation of deglaciation and lower-than-present tropical SST. The stabilist view invoking minimal Antarctic warming and deglaciation encounters fewer obstacles including counter-intuitive behavior of the Antarctic climate and ice-sheet system. The snow-gun hypothesis has been refined and requires smaller Antarctic glaciations than previously. The refinements reflect improved interpretation of the late Pleistocene western tropical Pacific planktonic $\delta^{18}O$ record. The chief obstacle for the snow-gun hypothesis is explaining deepwater significantly warmer than present. Independent data from terrestrial and shallow-marine polar sequences are required to constrain interpretation of the deep-sea oxygen isotopic record.

Modeling Of Mid-Pliocene Climate With The NCAR Genesis GCM

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A climate modeling study was carried out which used boundary conditions created by the USGS PRISM group. The model used for this study is the National Center for Atmospheric Research (NCAR) Genesis model. Genesis is an atmospheric general circulation model (GCM) that is coupled to a land-surface model and contains submodels for snow, sea-ice, and soil. Boundary conditions incorporated into the model were (1) present day continental configuration, with a 35 m sea-level increase over present; (2) present day elevations, (3) Pliocene vegetation cover, (4) Pliocene sea-surface temperatures (SSTs) for 12 months. Present day orbital configuration and pCO_2 were specified. The model was run at 4.5° latitude by 7.5° longitude spatial resolution, with the full annual cycle, for 7 years. It is important to note that the SST's are prescribed in the model and as such the climate that the model produced is (by definition) in equilibrium with those SST's and is greatly influenced by the SST values.

The greatest influence of the warm SST's upon the resulting climate was the result of warmer and moister high-latitudes. Additionally, global mean surface temperature was 3.6°C warmer than the present day control case, and global mean precipitation increased by 8.4 cm/yr over the control case. Zonal winds weakened in the Pliocene case but jet stream and Hadley Cell locations were unchanged. High latitude clouds increased in response to the imposed SST's and low latitude clouds decreased. An interesting result that is somewhat supported by marine data was that the mean annual intertropical convergence zone latitudinal location was located northward of its present position in the Pliocene case.

Comparison of these model results with results from the GISS study and various data from the paleoclimate record show the importance of validating these model results, as well as the need for iterative studies to understand the nature of the Pliocene warm interval. The results suggest certain regions of the globe where we might try to test the model predictions, as well as give a clear indication of where additional data are needed to improve the boundary conditions used in this type of study.

Pliocene Vegetation And Climate In Arctic Russia

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Tundra vegetation occurs today along the Russian Arctic coast under extremely cold climates. During the early and middle Pliocene conditions were quite different, and forests grew along the Arctic coast of Russia, as well as in northernmost Alaska and Canada. Palynological and plant macrofossil data from the Far Northeast of Russia indicate that *Larix*, *Picea*, *Pinus pumila*, *Alnaster*, and tree-*Betula* lived near the coast. Pollen spectra of this age contain only very low levels of *Artemisia*, Chenopods, tundra herbs and other indicators of open vegetation (Giterman et al., 1982; Fradkina, 1991). Forest cover decreased and Arctic vegetation increased across northern Asia between approximately 3.5 Ma and 2.5 Ma (Fradkina, 1991; Volkova, 1991), suggesting pronounced cooling occurred through this time. Shrub-*Betula*, *Alnaster*, moss, and Poaceae increased in importance during this transition, as *Larix*, *Picea*, *Pinus*, and other tree species declined. At the Krestovka section on the Kolyma River in the Russian Far Northeast, Giterman et al. (1982) interpreted palynological data as indicating a late Pliocene sequence of open forest being replaced by treeless vegetation (steppe-tundra?), which in turn was replaced by open larch forest. They also report ice-wedge pseudomorphs in the late Pliocene sediments, indicating the initiation of permafrost. Early Pleistocene sediments from this site contain a complex array of permafrost features, suggesting increasingly cold conditions through the Pliocene-Pleistocene transition.

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Major Deglaciation Of East Antarctica During The Early Late Pliocene? Not Likely: Evidence From The Sub-Antarctic South Atlantic

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We have generated a high-resolution record of coarse-grained ice-rafted debris (IRD) and benthic and planktonic oxygen isotopes (using identical samples) for the interval 3.5 to 2.1 Ma from ODP Site 114-704 (Holes A and B spliced) at 47°S, 7°E, 2532 m depth. Age assignments are based on the Berggren et al. (1985) time scale in order to facilitate comparison with pre-existing datums. Use of the Cande and Kent (1992) time scale would increase all ages by about 5 to 7%. Stratigraphic control is based on benthic oxygen-isotope stratigraphy above, and magnetostratigraphy below, the Gauss-Matuyama boundary. A re-examination of the record revealed that there are two missing time intervals: uppermost Gauss is missing in a core break/hiatus, and the interval 2.377 to 2.294 Ma is also lost in a core break. Between these two core breaks the strong glacial stage 100 and the weak glacial stage 102(?) are identified.

Here we concentrate on the record below the lower core break because in this interval several sections on continental margins show high sea-level stands which have been interpreted in terms of major reductions of Antarctic ice volume. From 3.5 Ma on, across the Early-Late Pliocene boundary at 3.4 Ma, and up to 3.26 Ma there is very little IRD in the samples, but the oxygen-isotope curves show only small, negative excursions (only about 0.2‰ lighter than calculated Holocene values). In the record younger than 3.26 Ma there is only one interval without IRD, extending from 3.095 to 3.074 Ma, yet the benthic oxygen-isotope record (*Cibicidoides*) reveals no warming/reduction in ice volume at this time. We have two planktic oxygen-isotope records. One, based on *Globigerina bulloides*, does allow some warming/ice reduction. There are, however, problems with this particular species. Therefore, a new record was generated, based on *Neogloboquadrina pachyderma* (sinistral). This record, like the benthic one, shows essentially no decline below Holocene values.

After 3.074 Ma, there is almost constant ice-rafting to Site 704, at a distance of more than 2,500 km from the nearest possible source. Despite the low level of IRD in these cores (because of distance and a southern position of the Polar Front at this time), several well-defined ice-rafting episodes can be identified which coincide with positive excursions of the oxygen-isotope curve. These facts are difficult to reconcile with a postulated major deglaciation of East Antarctica, but they do not rule out a disappearance of the West Antarctic ice sheet, particularly in the early Early Pliocene (refer to Hodell and Warnke, 1991, Q.S.R., v.10, p.205-214). Our interpretation is based on one drill site only and on calculated Holocene values, and should be considered within these limitations.

Recent Progress In The Investigation Of Late Neogene Records Adjacent To The East Antarctic Craton-West Antarctic Rift System Lithosphere Boundary

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Impressive strides have been made in the investigation of the Antarctic late Neogene over the past decade, and the assault proceeds with pace and vigor within a variety of fields and sub-fields. As might be expected, attempts at integration of these data provide a full spectrum of agreement and disagreement, highlight clashes of hypothesis and dogma, and lead us to the realization that the total data base leaves much to be desired.

Divergent interpretations of late Neogene terrestrial environments and climate in the Transantarctic Mountains (Webb et al., 1994, Webb and Harwood, 1991, Sugden et al., 1993) have overshadowed many positive developments. The basic tenets of the Webb-Harwood hypothesis ice sheet history and biotic accommodation are intact and even enhanced a decade after presentation and provide, in our opinion, an equally convincing alternative position to that promoted by George Denton, David Marchant, Michael Prentice, David Sugden and their collaborators.

Investigations of seismic stratigraphy from parts of the West Antarctic Rift System basins (Alonso et al., 1992) hold the promise that the Pliocene terrestrial and littoral marine record in and adjacent to the Transantarctic Mountains might eventually be integrated with that of the Victoria Land and Eastern basins, and correlation with Southern Ocean biochronology further reinforced (Harwood and Maruyama, 1992).

Antarctic-Northern Hemisphere Relationships

Recent publications on the late Neogene glacial record of the Yakataga Formation on the northeastern Pacific Alaskan margin (Lagoe et al., 1993), and offshore southeastern Greenland (Larsen et al., 1994) portray a comparable array of marine and terrestrial environments and events to those deduced for the Ross Embayment and invite closer comparisons of timing and inter-hemisphere oceanographic and climatic interactions.

Tectonic History

The occurrence of *in situ* marine and terrestrial Pliocene fossil material, including vascular plants, at elevations of between 1300 and 1700m above present sea level is clearly anomalous and is explained by post-Sirius tectonic uplift of between 350 and 548m/m.y. (Webb et al., 1994; in preparation). The existence of tree taxa at 1700m might be explained by periods of exceptional Pliocene warmth at high southern latitudes (85°). However, the close association of plants and subjacent marine sediments and the sea level datum this implies, makes an original setting near sea level a more reasonable explanation.

Glacial History

The multi-package stratigraphy and intervening hiatuses apparent in both marine and terrestrial successions, the variety of glacigene lithofacies, and the *in situ* marine and terrestrial fossil material, all point to a history of multiple advance and retreat by a dynamic glacier system within Beardmore valley. Beardmore Fjord penetrated almost the complete breadth (+165km) of the Transantarctic Mountains from its junction with the southern Ross Sea, and was at times covered by a "surging" tidewater glacier with a source at the inland end of the valley. It is clear, then, that during this phase of the Pliocene the Beardmore area was not enveloped by an overriding ice sheet.

Paleoceanography, Sea Level Oscillations And Glacial History

Alonso et al. (1992) recognized a suspected Pliocene-Pleistocene succession in the Eastern Basin of the Ross Sea with a thickness of up to 600m. This succession was subdivided into seven seismic units, each separated by distinctive and often widespread erosional boundaries. These authors interpreted the seismic stratigraphy as indicative of multiple ice sheet advance (grounding) and retreat (ungrounding/floating) events and noted a possible association with sea level oscillations. Further, they suggest (p.93), "These fluctuations in grounding line position indicate extreme variations in the Antarctic climate and sea level", and "Ice sheet grounding events do not require a polar climate; they could reflect subpolar to temperate shifts in climate." As noted above, Beardmore Fjord stratigraphy and glacier history also indicates a multiple-event history of ice advance/grounding and retreat/floating, and it is important that a possible glacial and eustatic event relationship between the two areas be examined.

Concluding Comments

Our preliminary investigation of the Beardmore valley suggests that this area has the potential to become a significant southern high latitude Pliocene data point. Clearly, an active rift margin shoulder provides a favorable structural setting for Pliocene studies. The value of the area rests, to a large degree, on our ability to recognize the contribution of glacial, tectonic, and eustatic events to the history of the area.

The most negative aspect of work in this region to date is that age control of specific events is inadequate. The region is far removed from a long-lived volcanic center and ash and flow dating seems unlikely. More intense collecting for microfossils is likely to improve the data base within the marine facies of the Sirius Group, allowing improved correlation to other Trunk Valley fjord systems such as Taylor and Wright valleys (Barrett et al. 1992; Ishman and Rieck, 1992) and with the Ross Embayment rift basins (Alonso et al., 1992). Temporal control of terrestrial facies and event history will prove much more challenging. A serious magnetostratigraphy program should be contemplated.

We cannot escape the fact that our views on late Neogene climate and glacial history are seriously at odds with the stabilist ice sheet arguments of Sugden et al. (1993).

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A Direct, High-Resolution, Southern Hemisphere Record Of Late Neogene Glacioeustasy, Important Constraints, And A Possible Stratotype For Ice Volume, Sea-Level And Climate Change

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Two independent records of Late Neogene (2.0 - 6.0 Ma.) glacioeustasy are presented: one of Antarctic ice volume from East Antarctica and the other of eustatic sea level from the South Wanganui Basin, New Zealand. The sea level record from New Zealand is unequalled in its resolution and provides important constraints for other studies and models of individual events and extents of global climate change. Such a record has the potential to be a Late Neogene glacioeustatic and climate change stratotype.

Glacial deposits in the Transantarctic Mountains (Sirius Group; McKelvey et al., 1991) and sediments at the Antarctic continental margin provide direct evidence of Antarctic ice sheet fluctuation. Evidence for deglaciation includes the occurrence of Pliocene marine diatoms in Sirius Group deposits (Harwood 1986), which are sourced from the East Antarctic Interior (Webb et al., 1984, Webb and Harwood, 1991). K/Ar and $^{39}Ar/^{40}Ar$ dating of a tuff in the CIROS-2 drill core confirms their Pliocene age at high latitudes (78°S) in Antarctica (Barrett et al., 1992). Further evidence for Antarctic ice volume fluctuation is recorded by glaciomarine strata from the Ross Sea sector cored by the CIROS-2 and DVDP-11 drill-holes (Ishman and Rieck, 1992, Barrett and Hambrey, 1992, Wilson, 1993). Magnetostratigraphy integrated with Beryllium-10, K/Ar and $^{39}Ar/^{40}Ar$ dating provides a high resolution (+ 50 k.y.) chronology of events in these strata.

In the Wanganui Basin, New Zealand, a 5 km thick succession of continental shelf sediments, now uplifted, records Late Neogene eustatic sea level fluctuation. In the Late Neogene, basin subsidence equalled sediment input allowing eustatic sea level fluctuation to produce a dynamic alternation of high-stand, transgressive, and low-stand sediment wedges. This record of Late Neogene sea level variation is unequalled in its resolution and detail. Magnetostratigraphy provides a high resolution chronology for these sedimentary cycles, as well as magnetic tie lines with the Antarctic margin record in McMurdo Sound.

These two independent records of Late Neogene glacioeustasy are in good agreement and record the following history: The Late Miocene and Late Pliocene are times of low 'base level' glacioeustasy (here termed glacialism, rather than glacial), with growth of continental-scale ice sheets on the Antarctic continent causing a lowering of global sea level. The Early Pliocene was a time of high 'base level' glacioeustasy (here termed interglacialism, rather than interglacial), driven by collapsing of continental-scale ice sheets to local and subcontinental ice caps. The middle Pliocene is marked by a move into glacialism with an increasing 'base level' of glacioeustatic fluctuation. Higher-order glacial advances and associated eustatic sea-level lowering occurred at approximately 3.5 and 4.3 Ma, separating the Early Pliocene into 3 sea-level stages. Still higher-order glacioeustatic fluctuations are recognised in this study, with durations of 50 Ka and 100 - 300 Ka. The 100 - 300 Ka duration cycles are prominent during interglacialisms, and the 50 Ka duration cycles are prominent during glacialisms. These shorter duration fluctuations in glacioeustasy have already been recognised as glacial/deglacial cycles from detailed studies of the Quaternary.

Four orders of sea-level fluctuation are recognized within the Late Neogene, these are of approximately 0.05 Ma, 0.1-0.3 Ma, 2 Ma, and 4 Ma in duration. The 2 Ma and 4 Ma duration cycles are subdivisions of the third order cyclicity recognized by Vail et al. (1991) (referred to here as cyclicity orders 3a and

3b). The 0.1-0.3 Ma duration cycles are a subset of the fourth order cyclicity recognized Vail et al. (1991), and the 0.05 Ma duration cycles are a subset of the 5th order cyclicity recognised by Vail et al. (1991). 3a, 3b and 4th order sea level fluctuations are driven by fluctuations in the volume of the Antarctic Ice Sheet. Fifth order sea level fluctuations are also suggested to be at least partially driven by fluctuations in the volume of the Antarctic Ice Sheet. Milankovitch cyclicities in glacioeustasy (<100 Ka., fifth order cyclicity) are prominent in the geologic record at times when there is large scale glaciation (glacialism) of the Antarctic continent (e.g., for the Pleistocene). Conversely, at times when the Antarctic continent is in a deglaciated state (deglacialism), fourth order cyclicity is more prominent, with Milankovitch cyclicities present at a parasequence level.

This new glacioeustatic composite record differs markedly from the lower resolution Haq Sea Level curve (Haq et al., 1987, 1988) for the same time interval, this is due to the increased resolution, more accurate dating methods and a new understanding of the sedimentary sequences recording sea level changes. At known time intervals the new record is in direct agreement with other records of sea level events, such as those from the U.S. Middle Atlantic Coastal Plain (Krantz 1991), Enewetak Atoll (Wardlaw and Quinn, 1991), the Sea of Japan (Cronin et al., in press), and from Eastern Kamtchatka, Russia (Gladenkov et al., 1991). In detail and extent the glacioeustatic composite record mimics the oxygen isotope proxy record of the same time interval (Shackleton et al., 1993), suggesting that the isotope signal is more closely driven by ice volume variation. However, changes in the late Pliocene sea surface temperature record (Dowsett et al., in press) also appear to be synchronous with the Wanganui Basin sea level record.

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