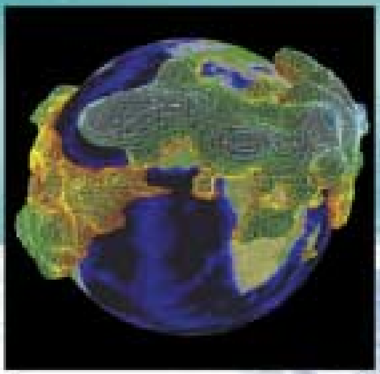
CLIMATE CHANGE



Fossil Thermometers for Earth's Climate

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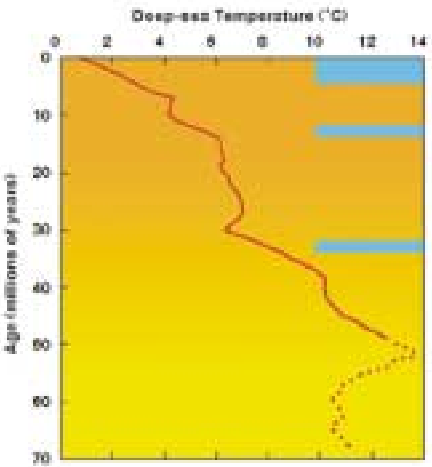
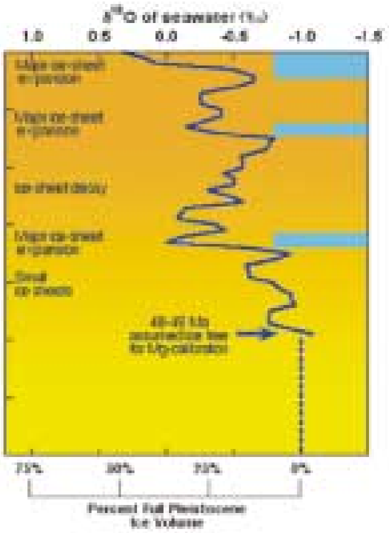
Cold-blooded reptiles living within the Arctic Circle, mangrove swamps along the south coast of England: We know that Earth's climate was much warmer than today in the Cretaceous and early Cenozoic time periods. A long-standing problem in Earth Sciences, however, has been to quantify exactly how much warmer. Matching up past temperatures with estimated levels of carbon dioxide should help modelers predict the effects of future global warming. The 'cleanest' overview of global temperature change on Earth over the past 100 million years comes from the deep oceans because here the signal is insulated from seasonal and other short-term 'noise'.



Until recently, our records of deep-sea temperature change relied almost entirely on the relative proportions of oxygen-16 to oxygen-18 in the calcite shells of fossil benthic foraminifera. Foraminifera are single-celled animals about the size of a pinhead that live on the sea floor and are found in the deep ocean sediments collected by the Ocean Drilling Program. This method works because the ratio of these two isotopes of oxygen incorporated into the fossil shell is dependent on the temperature at which the animal lived. But there is a problem. The ratio recorded by the fossil foraminifera is also sensitive to the ratio of oxygen-16 to oxygen-18 in the seawater, which in turn, shifts back and forth with changes in the global volume of ice on Earth. This change is because the lighter isotope (oxygen-16) is preferentially evaporated from seawater, transported to the poles where it falls as snow and is locked up in glaciers. In this way, growth of large icecaps will deplete average seawater of oxygen-16, making it relatively enriched in oxygen-18.

In a recent study we re-examined these same fossils for the trace amounts of magnesium (Mg) present as an impurity in their calcite ($CaCO_3$) shell (Lear *et al.* 2000). Foraminifera live today in many parts of the ocean, and we know that the amount of Mg impurity increases systematically with the temperature of the water in which they live but, crucially, is independent of global ice volume (Rosenthal *et al.* 1997). By applying the temperature-Mg relationship found in modern shells to the fossil shells, we were able to calculate the temperature of the deep ocean over the past 50 million years.

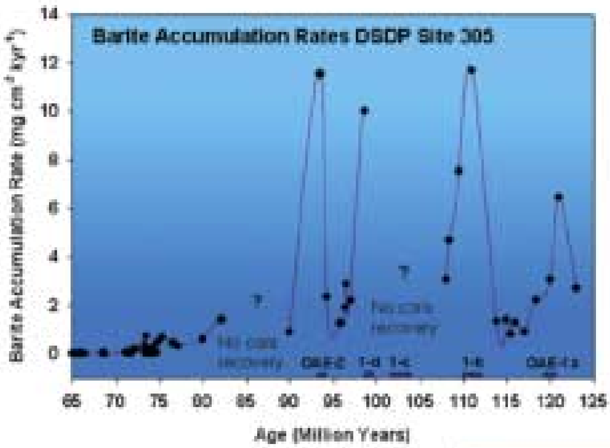
We then compared these Mg-temperatures to the existing record of oxygen-16 to oxygen-18 of the foraminifera shells, to calculate the ratio of the two oxygen isotopes in seawater over the past 50 million years. This process allowed us to calculate, for the first time, global ice volume over the past 50 million years. We found three distinct time intervals during which the oceans were suddenly depleted in the oxygen-16 isotope. These times must correspond to large and rapid growth of polar ice sheets, and are shown as blue shaded boxes in the figures. In fact, the timing of these events correlates with other evidence for ice growth, such as sea level falls and the occurrence of large rocks in deep-sea sediments dropped from icebergs far from land. Interestingly, the first of these ice-building events that happened 33 million years ago is not associated with a cooling of deep sea temperatures as recorded by the magnesium content of the foraminifera shells. Perhaps the Antarctic continent was already cold enough to support an ice sheet but too dry until 33 million years ago, when, for some reason, snow started to fall.

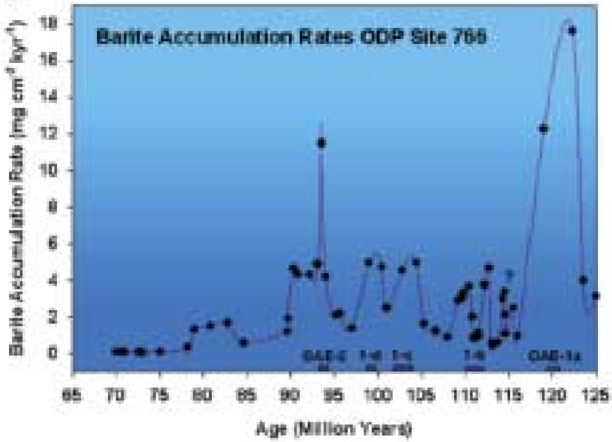


Deep-sea temperatures determined from the magnesium content of forminifera (above) and the ratio of oxygen-16 to oxygen-18 ($\delta^{18}O$) of seawater which is a measure of global ice volume (right).

Tales of Black Shales

Barite Accumulation Rates in Cretaceous Sediments





Adina Paytan, Stanford University, USA

Several times during the middle of the Cretaceous period, between 125 and 80 million years ago, organic-carbon-rich black shales were deposited over large areas of the ocean floor. These black shales provide valuable information about past climates. Organic matter is supplied to the sediment when ocean-dwelling organisms die and sink to the ocean floor — but the story doesn't end there. The organic matter is subsequently consumed via respiration — a process in which oxygen is used to burn-down organic molecules. Accordingly, organic matter accumulation in marine sediments depends on their production rate in the water column and on their destruction rate via oxidation, which in turn depends on the oxygen content of the oceans. During the mid-Cretaceous episodes described above, supply of organic matter to the sediment overwhelmed the process of respiration, which resulted in high organic carbon accumulation. Two opposing models have been offered to explain the increased burial rates of organic matter during these episodes: high biological productivity and ocean stagnation.

The high productivity model is based on the suggestion that a higher rate of oceanic biological productivity resulted in rapid supply of organic matter to the sediment. Moreover, extensive use of oxygen for consumption of these elevated levels of organic matter resulted in rapid lowering of the oceanic dissolved oxygen content, thereby producing a positive feedback and enhancing organic carbon accumulation. In contrast, the ocean stagnation model hinges on the suggestion that external physical processes — such as temperature and evaporation — induced intense vertical gradients of temperature and salinity, which resulted in stable stratification and reduced the oxygen supply to deep water thereby increasing preservation of organic matter.

To determine which one of these situations was prevalent in the mid-Cretaceous, scientists examined the accumulation rates of the mineral barite in several Deep Sea Drilling Program cores (see figures). Since barite forms in environments in association with decaying organic matter, its formation is directly related to productivity. The accumulation rate of barite has been found to peak during these mid-Cretaceous episodes, which implies that the high accumulation of organic matter during these episodes is a result of increased productivity that overwhelmed respiration in the open ocean environment. In contrast, no barite has been observed in the sediments in cores from shallow depth. This could be a result of either low productivity in coastal areas or from low barite preservation in sulfate reducing sediments, which are wide spread in shallow sites during the mid-Cretaceous.

The episodes of widespread organic carbon burial during the mid-Cretaceous most likely affected climate through sequestration of carbon dioxide, providing negative feedback to the greenhouse climate that was prevalent at that time. Similar processes may come into play in the assessment and regulation of potential future greenhouse conditions.

The Suffocation of an Ocean

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Sedimentary records from the Cretaceous period (140-65 million years ago (Ma)) reveal several dark, laminated, carbon-rich intervals, known as black shales, indicating that the ocean floor was prone to oxygen-poor (anoxic) conditions.

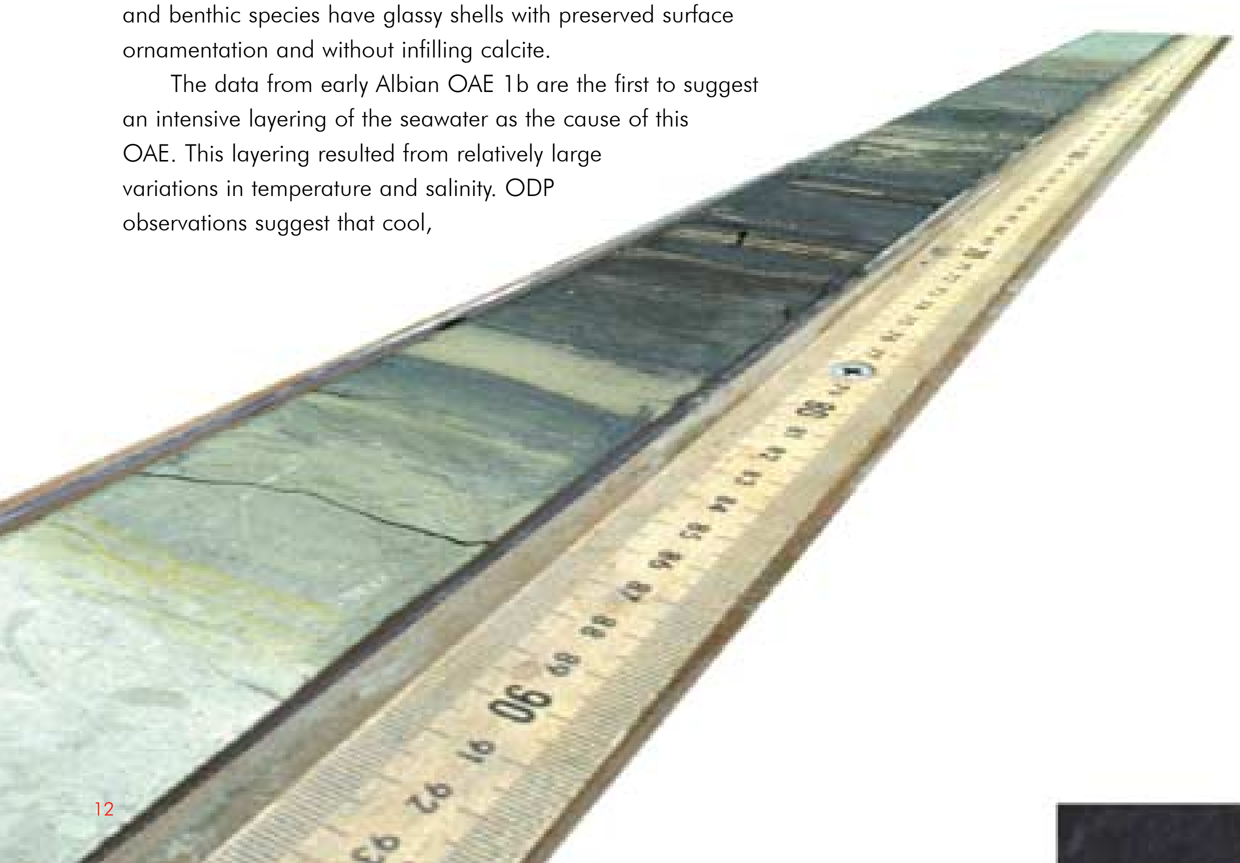
Data from the Deep Sea Drilling Project and Ocean Drilling Program show that many of these black shales occur simultaneously in the world's oceans. Such intervals of concurrent black shale deposition on a super-regional to global scale are called Ocean Anoxic Events (OAEs) and are typical for the mid-Cretaceous time period (120-85 Ma).

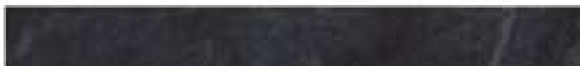
The Cretaceous OAEs are periods of high carbon burial and drawdowns in atmospheric carbon dioxide (CO_2) during the mid-Cretaceous greenhouse climate and, in many cases, they caused significant biological turnover. Most OAEs are attributed to high ocean biological productivity and export of carbon that led to preservation of organic enriched dark shales. However, the primary factors triggering OAEs remain uncertain. During Leg 171B, ODP drilled mid-Cretaceous black shales in the western subtropical Atlantic off Florida. Scientists recovered sediments that include a 46 cm thick succession of laminated black shale, representing an OAE that occurred 112 Ma, known as early Albian OAE 1b. This record of OAE 1b is unusual for most OAE sediments because the foraminifera are extremely well preserved and can be used to study the geochemical record of the event. Both planktic and benthic species have glassy shells with preserved surface ornamentation and without infilling calcite.

The data from early Albian OAE 1b are the first to suggest an intensive layering of the seawater as the cause of this OAE. This layering resulted from relatively large variations in temperature and salinity. ODP observations suggest that cool, oxygen- and salt-rich surface waters rapidly experienced warmer, oxygen-poor and less saline conditions. No synchronous modifications are observed for the bottom-water. These differences between surface and bottom caused an intensive layering of the ocean. They are documented by the large differences of $\delta^{18}O$ between planktic and benthic foraminifera and suggest that black shale deposition was triggered by a reduction in ventilation of the water column. The termination of OAE 1b was caused by a gradual reduction of the differences between surface and bottomwater and enabled oxygen to be transported into the deeper waters.

Although the OAE has many similarities with the Plio-Pleistocene Mediterranean sapropel record, the geographical extent of the OAE is much larger. This feature together with a ~46,000 year history of deposition, notably at least four times longer than any of the Quaternary sapropels, suggests that the entire North Atlantic and western Tethys constitute a considerable carbon sink.

Analysis from the cores indicate that up to 80 percent (by weight) of sedimentary organic carbon deposited during OAE 1b is derived from a type of single-celled organism, the so-called *Archaea,* that obtains food through chemical reactions. These microbes underwent a massive expansion during this Oceanic Anoxic Event that may have been a response to the strong stratification of the ocean described above. Indeed, the sedimentary record suggests that OAE 1b marks a time in Earth history at which many groups of microbes adapted from high-temperature environments, such as the white and black smokers of the deep-sea, to low temperature environments.





Early Albian Oceanic Anoxic Event 1b

Blake Nose, ODP Site 1049C

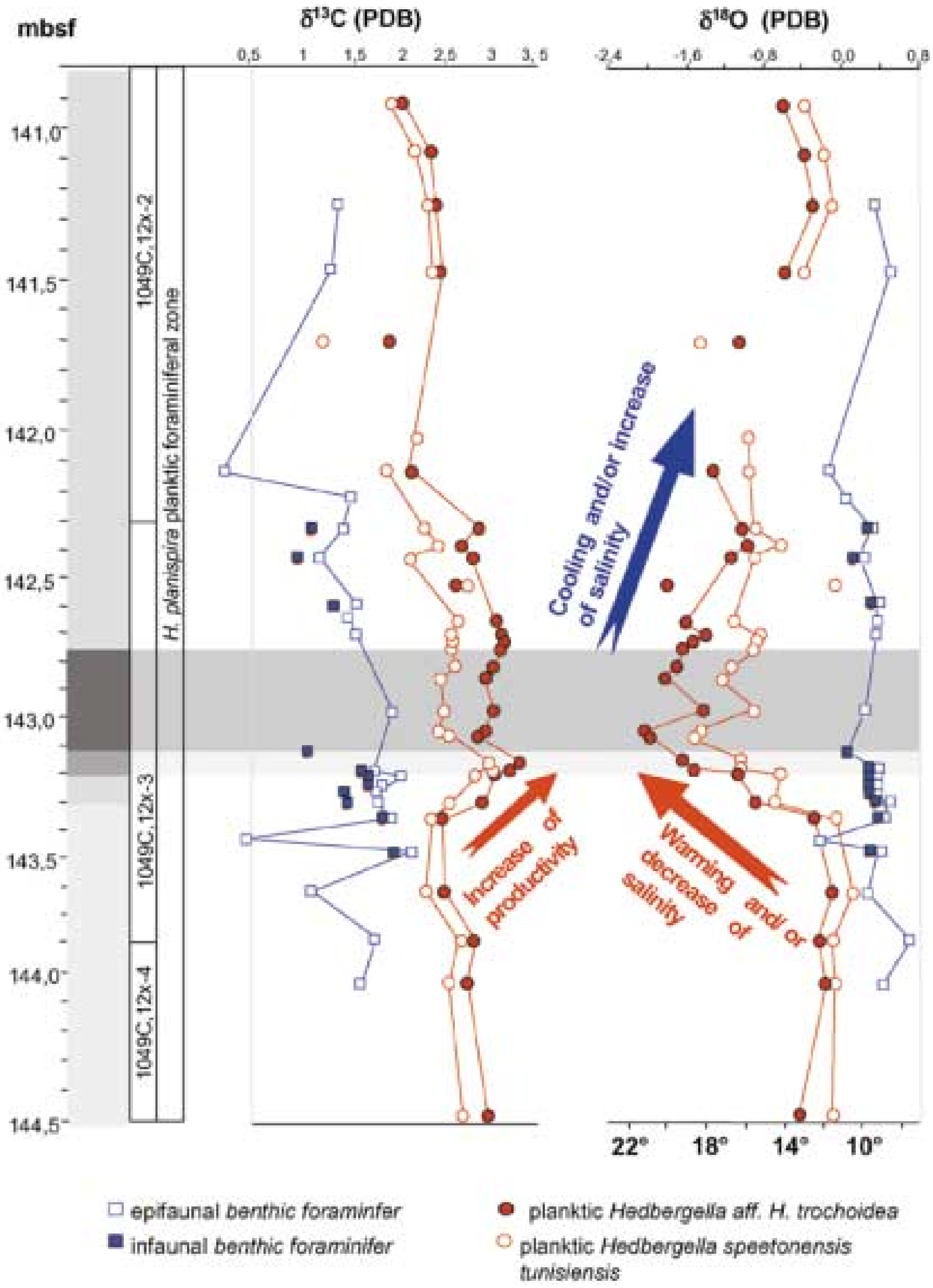


Figure 1. Location of ODP Site 967.

Earth's Orbit and the Mediterranean

Rolf Wehausen and **Hans-J. Brumsack,** Institute for Chemistry and Biology of the Marine Environment, Oldenburg University, Germany

ODP cores from the eastern Mediterranean Sea provide a record of climate change that can be linked to astronomical cycles. These cores reveal sapropels, which are black layers rich in organic matter, sulfides, and heavy metals, indicating that the Eastern Mediterranean has frequently become an oxygen-depleted basin during the past 5 million years. These intervals result from both the 21,000 -year cycle of Earth's orbital precession and the unique basin structure of the Mediterranean. The Eastern Mediterranean is semi-enclosed, with only one shallow connection (Strait of Sicily) to the Western Mediterranean, and contains deep subbasins (up to 4,000 meters): features that cause the environment to be very sensitive to changes in surface water density. Currently, strong evaporation of seawater results in a high salt concentration and high surface water density. During times of sapropel formation, the salt-driven deep water formation of the Eastern Mediterranean slowed considerably because of a higher freshwater contribution, which in turn lowered the surface water density. At the same time, marine plankton grew faster due to a more efficient recycling of nutrients from the subsurface.

ODP Site 967 (Figure 1) is located in the southeastern part of the basin where the most important freshwater source is the Nile River. Each time a perihelion occurred during a Northern Hemisphere summer (i.e., during maximal Northern Hemisphere summer insolation, the Earth's annual closest approach to the sun), the East African monsoon was much more intense than today. This process lead to a strong flood of the Blue Nile in the Ethiopian highlands and subsequently to a strong Nile runoff into the Eastern Mediterranean (Rossignol-Strick, 1983).

The frequent switch over from more arid and nutrient-poor conditions to more humid and nutrient-rich conditions every 21,000 years is not always expressed in form of a sapropel or by an increase in bioproductivity. But each cycle is, however, documented by the chemical composition of the land-derived fraction of Eastern Mediterranean sediments (Wehausen and Brumsack, 1999 and 2000). One specific geochemical parameter, the ratio of titanium (Ti) versus aluminium (Al), was found to provide an exceptional cyclic record that is near-linear and related to changes in Northern Hemisphere summer insolation (Lourens *et al.*, 2001). This element ratio reflects changes in the relative contribution of Saharan dust versus Nile-derived material (Figure 2).

Such a quantitative climate proxy record like the Ti/Al ratio offers, for the first time, the possibility to perform a statistical comparison between geological information and different astronomical solutions (Loutre, 2001). This new approach supports the crucial role of late Cenozoic Mediterranean sediments in the establishment of astronomical timescales (Hilgen *et al.*, 1997).

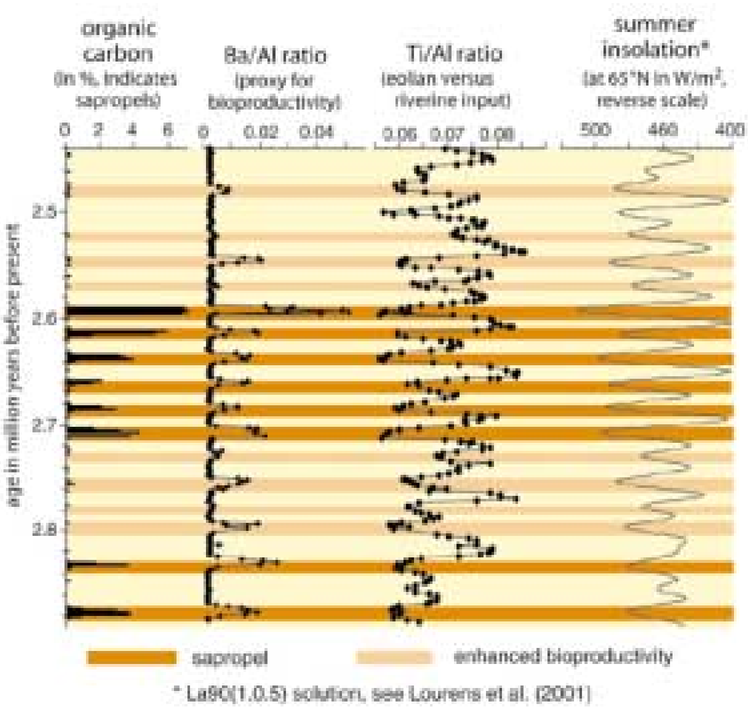


Figure 2. Pliocene sediment sequence from ODP Leg 160 Site 967, south of Cyprus, Eastern Mediterranean

History of the Antarctic Ice Sheet

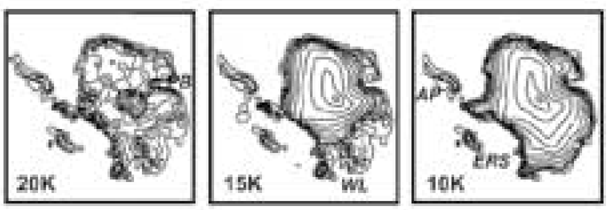
Peter Barker, British Antarctic Survey; **Angelo Camerlenghi,** OGS Italy; **Phil O'Brien,** Australian Geological Survey, **Alan Cooper,** US Geological Survey

Before 2-3 million years ago (Ma), the only large ice sheet in the world lay in Antarctica. Its history, however, was poorly understood because of disagreement and ambiguity among the main low-latitude proxies of ice sheet volume (sea level and benthic oxygen isotopes). Knowledge of all three (the ice sheet, sea level, oxygen isotopes) is crucial to understanding global paleoclimate.

In 1998, ODP began sampling sediments carried to the Antarctic margin by ice that contain a record of ice sheet history. Scientists used glaciological models to determine four areas for drilling in the margin. The model shows ice volume vs. temperature and where ice sheets smaller than today's would lie. For instance, the first place where ice from a growing ice sheet would reach the margin (flowing down the Lambert Graben Valley) was most probably Prydz Bay (PB). The narrow, more northerly Antarctic Peninsula (AP) should be the last part to be glaciated and give a higher-resolution (if shorter) record.

The first ODP expedition, Leg 178 to the western Antarctic Peninsula margin, gave a detailed record of glaciation over the past 10 million years. The second, Leg 188 to Prydz Bay, dated the earliest stages of ice sheet development to about 35 Ma. What about the times between 35 Ma and 10 Ma? The proxy measurements suggested dramatic changes, not only at latest Eocene glacial onset but also 30 Ma (mid-Oligocene), 24 Ma (Oligocene-Miocene boundary), and 13-15 Ma (middle Miocene). What was the ice sheet doing at these times? For answers to these questions, the model points towards drilling the Wilkes Land (WL) margin, probably the last part of East Antarctica to be glaciated, and the Eastern Ross Sea for a record of West Antarctic ice sheet history.

Findings from Leg 178 also raise new questions. Leg 178 drilling shows the Antarctic Peninsular ice sheet stayed large enough to migrate regularly to the shelf edge throughout the past 10 million years of major climate change. This showed it was sensitive to sea-level change (as now), but NOT to temperature changes (Figure 1d). Moreover, the glaciological model suggests the entire Antarctic ice sheet was similarly insensitive. But, there HAS been regular sea-level change, not only since 2-3 Ma, driven by Northern Hemisphere ice sheets, but also before then, when the only cause of regular sea-level change was Antarctic grounded ice. Did the Antarctic ice sheet essentially act independently of the rest of the world's climate for a while? As they say in these parts, more research is needed.



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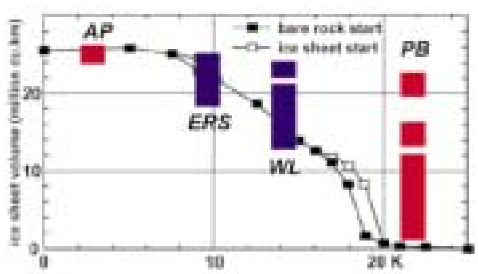

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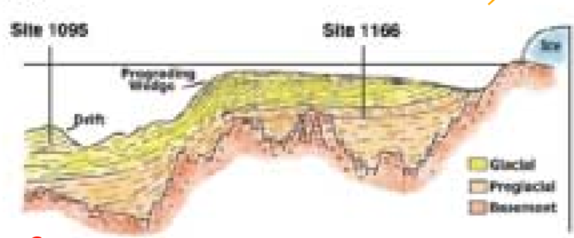
Figure 1. **a)** the geography of smaller ice sheets **b)** Antarctic ice sheet volume versus change in mean annual temperature at sea level and target regions for drilling, with **c)** a schematic Antarctic margin showing sedimentary environments, results of drilling, **d)** the enigma of ice volume insensitivity to global (oceanic) climate change, from Leg 178 to the Antarctic Peninsula, **e)** latest Eocene glacial onset from Leg 188 to Prydz Bay and **f)** the benthic oxygen isotopic curve (an ice sheet volume proxy with key ranges of AP and PB shelf samples marked.



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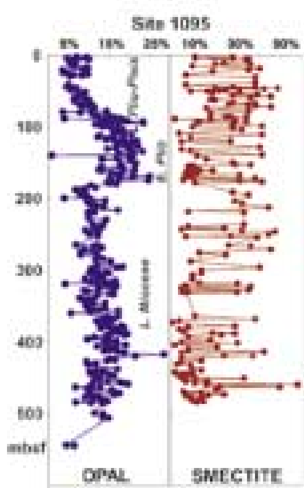

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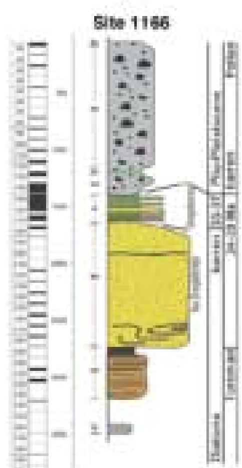

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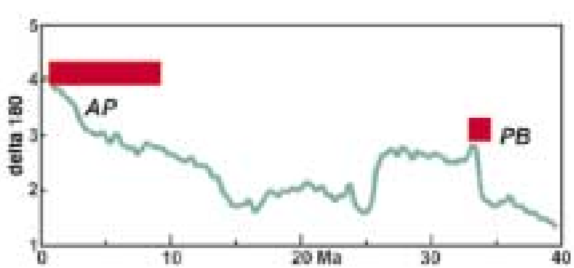

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Clues to Global Warming found in Antarctica

Eugene Domack, Hamilton College, USA

The results of drilling in the Palmer Deep, an ocean basin in Antarctica, have given scientists the first glimpse of the pace of rapid climate and oceanographic change in the Southern Ocean for our present climate. This record is particularly important now that rapid warming in the Antarctic Peninsula region has resulted in catastrophic collapse of ice shelves and changes in the region's ecosystem. Palmer Deep's extreme depth, greater than 1400 m, and its proximity to a mountainous coastline that remains heavily glaciated (Figure 1), make it a unique setting for drilling. In addition, Palmer Deep faces the broad expanse of the Southern Ocean and adjoining waters of the South Pacific. The climatic setting across the Palmer Deep is also unusual in that temperature regimes undergo a transition from dry, polar to warmer, melt-dominated climates. Hence, sediments at the bottom of the Palmer Deep have the potential to record fluctuations in these environmental characteristics over time.

The 50 meters of sediment recovered at Site 1098 in the Palmer Deep contain a remarkable sequence of diatom ooze and sandy mud that provide a record of climate over the past several thousand years. Early in the record (13 to 11.5 thousand years ago) sediment layers were deposited yearly (Figure 2) when ocean productivity (diatom) blooms alternated with glacial meltwater (silt/sand) pulses.

These annual layers do not persist and are replaced by sediments that contain more glacial debris that probably were released by meltwater and icebergs when channels and straits opened along the nearby Antarctic coast. High productivity returned to the Palmer Deep between 7 to 4 thousand years

Figure 1. (Above) View over the Palmer Deep site toward Anvers Island and the glacial elevations typical of the surrounding landmass.

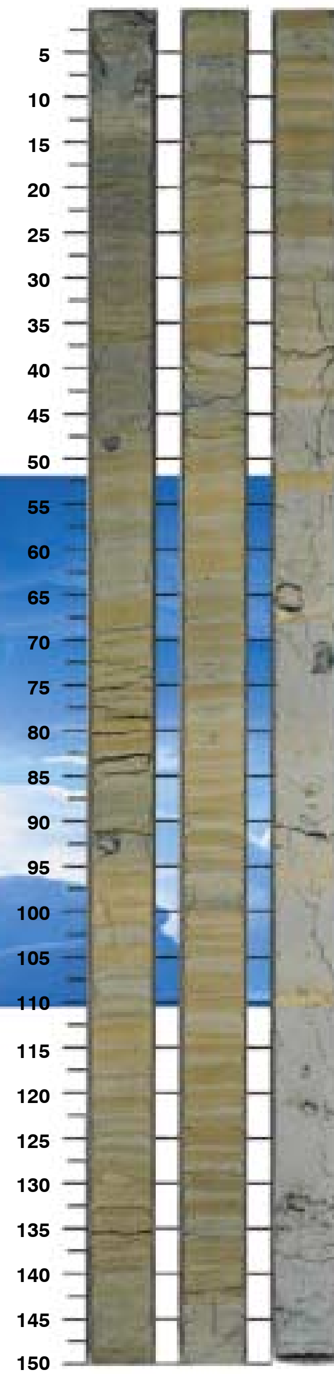


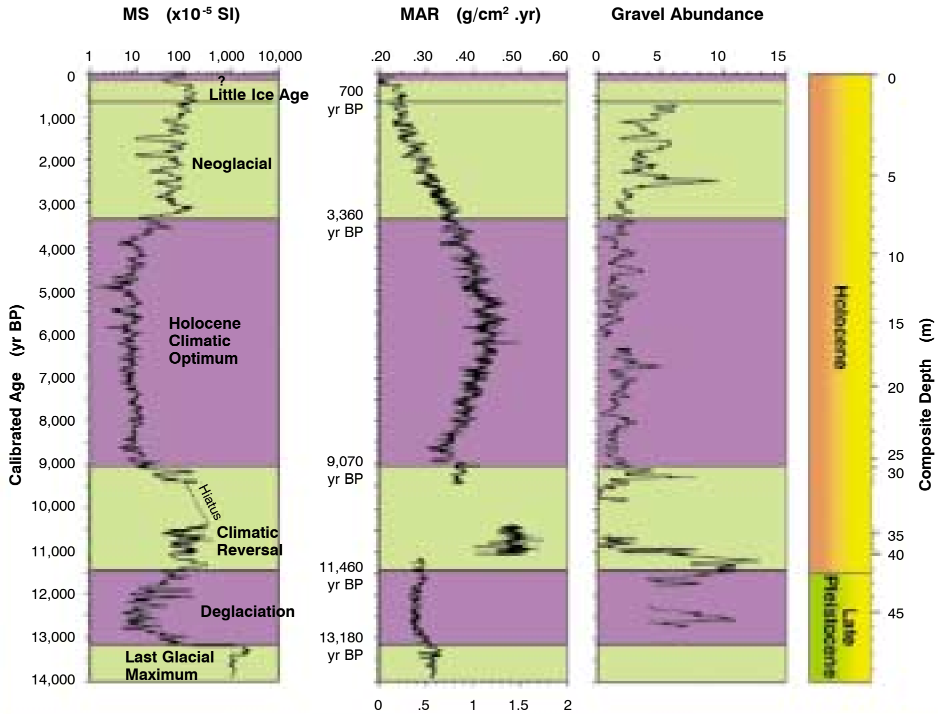
Figure 2. (Right) Annual seasonal layers of olive green (diatom ooze) and grey (diatom sandy, mud).

ago as shown by thin layers of diatom ooze and mud that contain warm water diatoms (single celled algae) and high amounts of organic carbon.

Succeeding these conditions are indications of more severe ice cover and less sedimentation of biological material, which is marked by a reduction of organic matter preservation and increased iceberg debris (Figure 3). This event took place around 3200 years before present and marks the onset of renewed glacial conditions or a neo-glaciation. It is within this interval that pronounced cycles of 200 and 400 years duration express themselves in the composition of the sediment. The timing of these changes coincides with solar oscillations known to have periods of 200 years. The processes responsible for such changes in sediment character are still not adequately understood but are likely related to changes in the strength of the westerly winds. These winds dominate the atmosphere and surface ocean of the mid high latitudes of the Southern Ocean and it is not surprising that they can find expression in the sediments of the Palmer Deep which lies facing the vast expanse of the Southern Ocean and its wind-driven circumpolar current.

Perhaps other sites like the Palmer Deep await us and can provide additional constraints on our understanding of the ocean-ice sheet climate system of the Antarctic.

Figure 3. Calibrated age (in calendar years) of the Palmer Deep core, Site 1098, versus magnetic susceptibility (MS), mass accumulation rate (MAR) and ice rafted debris (gravel) concentration. Note rapid ~two hundred year oscillations in MS over the past three thousand years and overall decrease in MAR since the middle Holocene.



The Rise of Panama

Gerald H. Haug, ETH, Zürich, Switzerland; **Ralf Tiedemann,** GEOMAR, Kiel, Germany

The Earth's climate system has experienced large changes during the past few million years. This long-term evolution from extreme warmth with ice-free poles to a globe with bipolar glaciation and massive continental ice sheets can be linked to plate tectonic processes that altered the climate system. The final closure of the Central American Seaway has been a key candidate to cause the transition from pronounced Pliocene warmth to the onset of major ice sheet growth in the Northern Hemisphere between 3.1 and 2.7 million years ago.

Through cores obtained by ocean drilling, scientists found that the gradual shoaling of the Central American Seaway during the Pliocene altered the distribution of freshwater and heat in the global ocean. Surface- and deep-water circulation changes in the Atlantic, Pacific, and Arctic Oceans occurred as a consequence of the restriction of interbasin surface-water exchange by the tectonic closure of the Central American Seaway between about 4.6 and 2.7 million years ago. The altered oceanic circulation patterns increased thermohaline heat and moisture transport from low to high northern latitudes (Haug and Tiedemann, 1998; Haug *et al.,* 2001). The closure of the Central American Seaway initially pushed the climate system toward warmer conditions, the so-called Pliocene Warm Period between 4.6 and 3.1 million years ago. However, the change in physical boundary conditions ultimately preconditioned the global climate system towards major ice sheet growth in the Northern Hemisphere, which started between 3.1 and 2.5 million years ago.

Modern Pacific-Caribbean Sea Surface Salinity Contrast

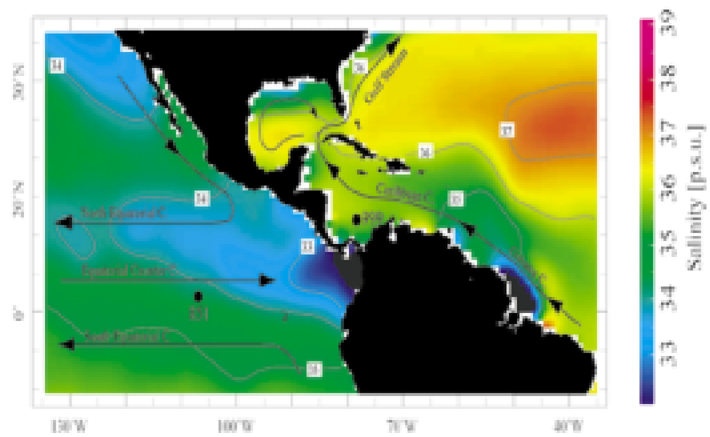


Figure 1. Major surface ocean currents of equatorial west Atlantic-Caribbean Sea and eastern equatorial Pacific and surface ocean salinities in per mil *(colors and small numbers)*. Large circles indicate locations of ODP Sites 999 and 851.

Pacific-Caribbean comparison of planktic δ18O-records

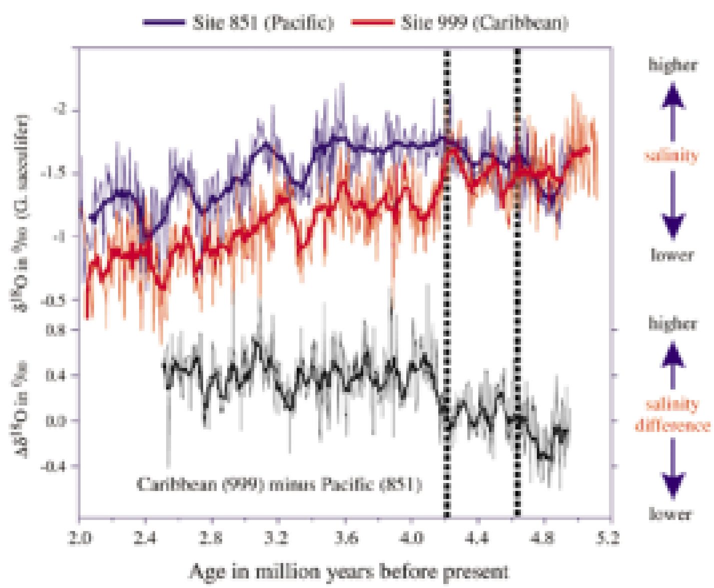


Figure 2. The planktonic foraminifera stable isotope records from ODP Sites 999 (Caribbean Sea) and 851 (equatorial east Pacific) span a time interval 2.2-5.3 million years before present and indicate the evolution of sea surface salinities in the Atlantic/Caribbean and Pacific during the uplift of the Central American Isthmus. The modern salinity contrast developed between 4.7 and 4.2 million years ago.

Gateways to Glaciation

Although many people associate plate tectonics with earthquakes and volcanoes, relationships exist between plate tectonics, ocean current circulation, sedimentation, and climatic changes. The reconfiguring of oceans and continents, particularly the opening and closing of oceanic gateways and associated changes in thermohaline circulation and heat transport, play an important role in global climate change. Two recent ODP expeditions addressed these interrelationships, one near Panama and the other near Antarctica.

Antarctic-Australia Separation

Neville F. Exon, Geoscience Australia
James P. Kennett, Department of Geological Sciences, UC Santa Barbara, USA
Mitchell J. Malone, ODP College Station, USA and the Leg 189 Science Party

During the Cenozoic era, between 37 and 33.5 million years ago, Australia separated from Antarctica and drifted northward, which opened the Tasmanian Gateway and allowed the Antarctic Circumpolar Current (ACC) to develop. This current began to isolate Antarctica from the influence of warm surface currents from the north, and an ice cap started to form. Eventually, deepwater conduits led to deepwater circulation between the southern Indian and Pacific Oceans and ultimately to ocean conveyor circulation. Continuing Antarctic thermal isolation, caused by the continental separation, contributed to the evolution of global climate from relatively warm early Cenozoic "Greenhouse" to late Cenozoic "Icehouse" climates.

Using DSDP results, Kennett, Houtz *et al.* (1975) proposed that climatic cooling and an Antarctic ice sheet (cryosphere) developed from ~33.5 million years ago as the ACC progressively isolated Antarctica thermally. They suggested that development of the Antarctic cryosphere led to the formation of the cold deep ocean and intensified thermohaline circulation. Leg 189 gathered data that support this hypothesis.

Leg 189 continuously cored marine sediments in the Tasmanian Gateway, which was once associated with a Tasmanian land bridge between Australia and Antarctica. The bridge separated the Australo-Antarctic Gulf in the west from the proto-Pacific Ocean to the east. This region is one of the few in the Southern Ocean where calcareous microfossils are preserved well enough to provide accurate age dating. The Leg 189 sequences described by Exon, Kennett, Malone *et al.* (2001) reflect the evolution of a tightly integrated and dynamically evolving system over the past 70 million years, involving the lithosphere, hydrosphere, atmosphere, cryosphere and biosphere.

Before 33 Ma
Australia drifting north
Tasmanian land bridge in place
No circum-Antarctic current
No Antarctic ice sheet
Warm climate and oceans
Mudstone near land bridge

After 33 Ma
Australia separated off
No Tasmanian land bridge
Circum-Antarctic current
Antarctic ice sheet
Cooling climate and oceans
Calc. ooze near land bridge

The most conspicuous changes in the region occurred over the Eocene–Oligocene transition (~33.7 million years ago) (Figure 1) when Australia and Antarctica finally separated. Before the separation, the combination of a warm climate, nearby continental highlands, and considerable rainfall and erosion, flooded the region with siliciclastic (silicate minerals — mainly clay and quartz) debris. Deposition kept up with subsidence and shallow marine sediments were laid down. After separation, a cool climate, smaller more distant landmasses, and little rainfall and erosion, cut off the siliciclastic supply. Pelagic carbonate deposition could not keep up with subsidence, so the ocean deepened rapidly.

Leg 189 confirmed that Cenozoic Antarctic–Australia separation brought many changes. The regional changes included: warm to cool climate, shallow to deep water deposition, poorly ventilated basins to well-ventilated open ocean, dark deltaic mudstone to light pelagic carbonate deposition, microfossil assemblages dominated by dinoflagellates to ones dominated by calcareous pelagic microfossils, and sediments rich in organic carbon to ones poor in organic carbon.

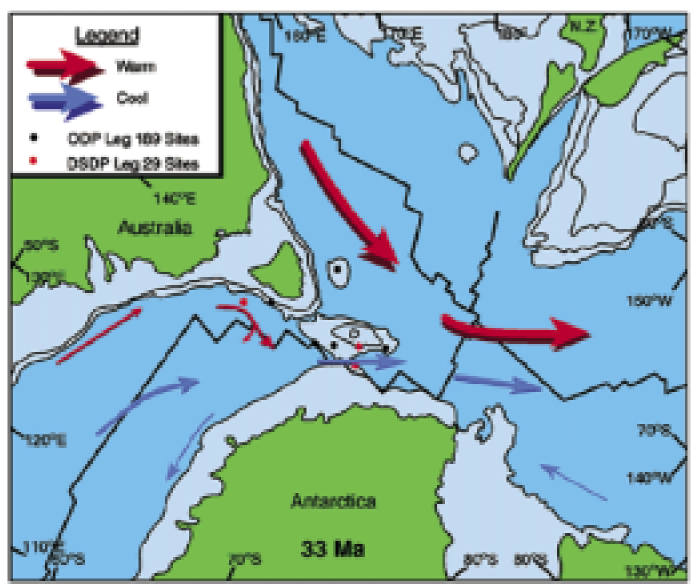


Figure 1