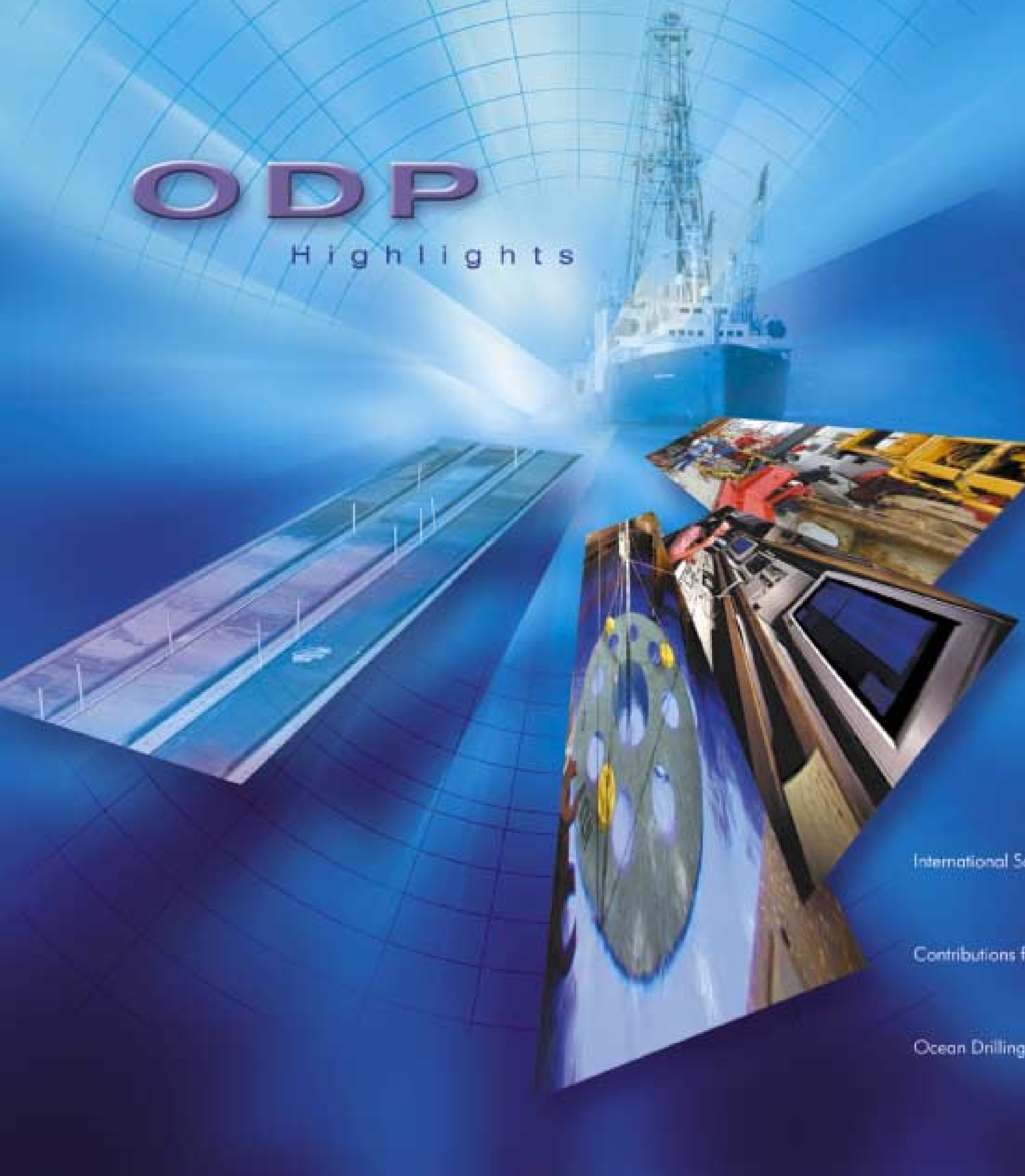
ODP

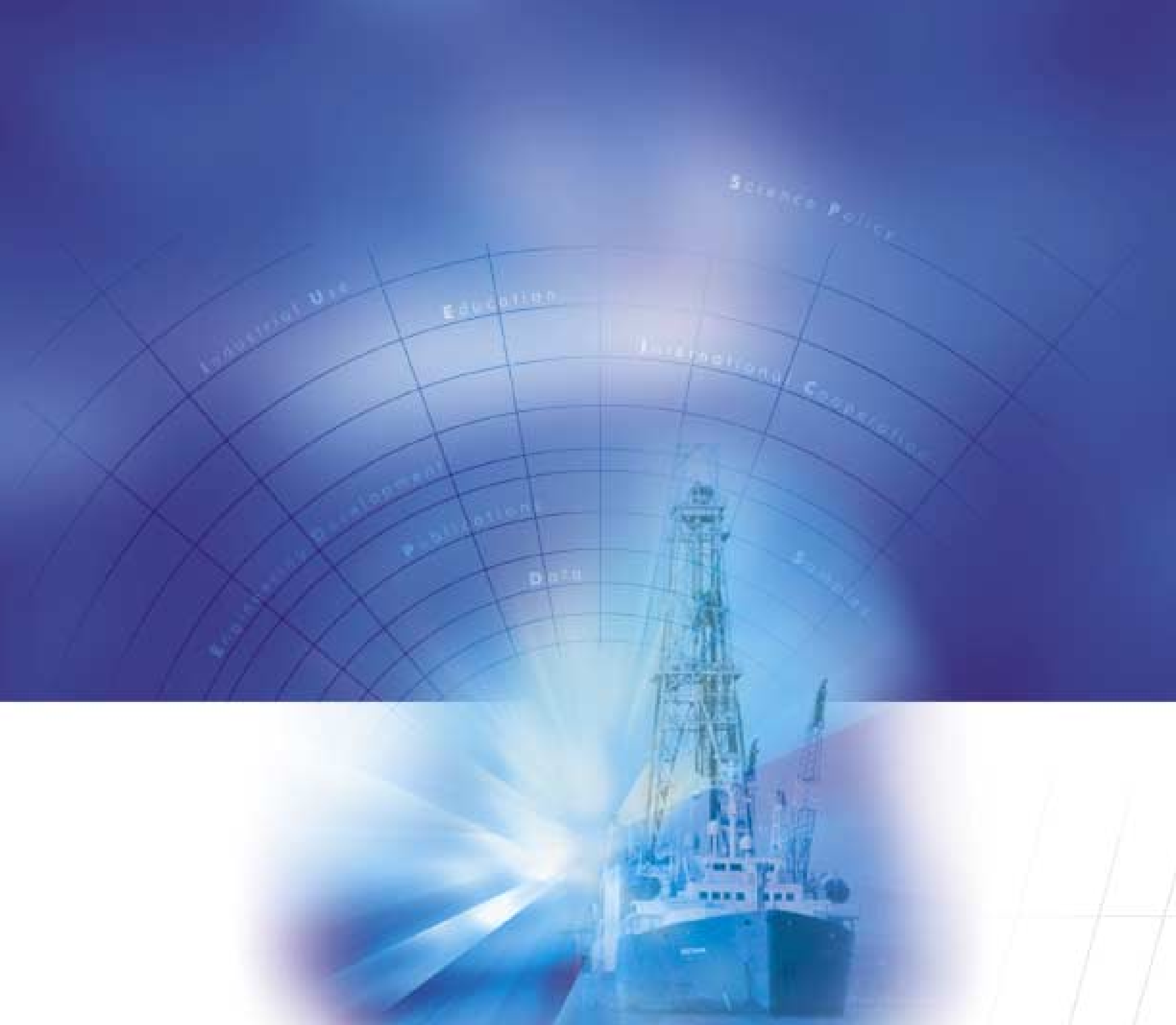
Highlights



International Scientific

Contributions from the

Ocean Drilling Program



OCEAN DRILLING PROGRAM

The Ocean Drilling Program is an international partnership of scientists and research institutions organized to explore the evolution and structure of the Earth. ODP provides access to a vast array of geological and environmental information recorded far below the ocean waves in seafloor sediment and rock. By studying ODP cores and downhole logs, we gain a better understanding of Earth's past, present, and future. Many outstanding scientific discoveries have been made through ocean drilling. This brochure was published in the final year of ODP to recognize a few of ODP's "highlights," illustrating the rich diversity of accomplishments by the international scientific community.

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A BRIEF HISTORY OF THE OCEAN DRILLING PROGRAM

Today's Ocean Drilling Program builds upon a foundation of nearly 40 years of scientific ocean drilling planning and study. It all began with the drilling of a trial hole into the oceanic crust prompted by the Mohole Project. The Deep Sea Drilling Project (DSDP) commenced in 1968, focused on confirming the young hypothesis of sea floor spreading. Scripps Institution of Oceanography ran drilling operations using the vessel *Glomar Challenger,* and the Joint Oceanographic Institutions for Deep Earth Sampling (JOIDES), a group of four U.S. universities, provided scientific advice. As drilling proceeded, scientists realized that in addition to establishing the scientific basis for sea floor spreading and then plate tectonics, many other interesting scientific studies could be accomplished through drilling.

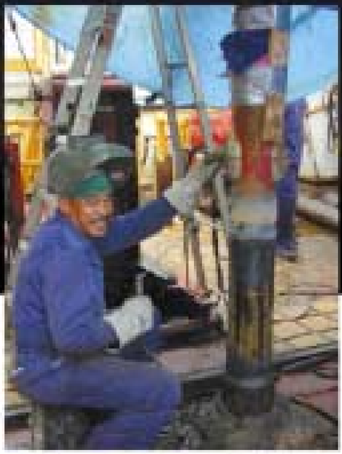
Greater interest in ocean drilling allowed more stable funding and an increase in the number of institutions involved in the program. In 1973, the PP Shirshov Institute of Oceanology, Moscow, became the first non-US JOIDES member. By 1975, the number of U.S. institutions had grown to nine and four more international participants were helping to fund the program. The importance of adding new participating institutions has been more for the additional intellectual stimulus and ideas than for the additional funding, although both are important.

In 1983, the final leg of DSDP took place and a year later, a new program, the Ocean Drilling Program (ODP), began using the *JOIDES Resolution* as its drilling vessel. Throughout ODP, participation from U.S. institutions and the international community has continued to grow. Joint Oceanographic Institutions Inc. (JOI), the prime contractor for the drilling program, has expanded to eighteen U.S. members and the program is being funded by 22 international partners.

ODP has traversed the world's oceans, from the Arctic Ocean to the Weddell Sea, collecting sediment and rock samples, recording downhole geophysical and geochemical information, and establishing long-term borehole observatories. As of June 2002, ODP has collected 695,112 feet of core. The deepest hole, 504B, has been drilled to a depth of about 2 km over several legs, the latest being Leg 148 (see p. 24).

A third great ocean drilling adventure is about to begin. The Integrated Ocean Drilling Program (IODP) will start on 1 October 2003. Funding will be contributed equally between Japan and the United States, and other countries are also hoping to participate. This program will have three drilling platforms: a riser drilling vessel supplied by Japan (*Chikyu,* meaning Earth, was launched in January 2002 in Okayama, Japan); a non-riser drilling vessel provided by the United States, which could be an upgraded *JOIDES Resolution* or other similar vessel; and an ability to use alternative platforms for high-latitude drilling and drilling in shallow water. These vessels will help IODP achieve its science goals, which revolve around three main themes: the deep biosphere and the subseafloor ocean; environmental change, processes and effects, including climate change; and solid Earth cycles and geodynamics.

With the advent of the new program, it is important to enunciate clearly some of the great advances that have been made in our understanding of the Earth from the past drilling programs. *ODP Highlights* has been produced by a team of scientists drawn from the international scientific parties of many of the recent drilling legs of the *JOIDES Resolution.* They have been divided into major categories such as "Climate Change" and "Microbiology" to reflect the diverse contributions of the program. The latter illustrates that the drilling program is always attempting to keep abreast of new research areas, and Microbes represent



one of the new initiatives that will be tackled in IODP, following on from successful research done to date (See p. 6).

Drilling has answered many questions about the Earth. For instance, we now know that the new paradigm of plate tectonics offers tremendous new insights into the way Earth works, including better understanding of natural hazards such as earthquakes and volcanoes. From studies of marine sediments, there is a much better understanding of natural climatic variability, and a beginning of understanding how to factor global change into planning for the future.

But drilling has also shown how little we know of the sediment and rock under the oceans. So far, we have drilled about 1700 holes. This represents one hole for an area about the size of Colorado, or 75% of the area of Japan. If the map of drilled sites is studied (p. 32), one can realize how much of the ocean floor remains to be explored. There is a lot more that we can discover, and that we should discover! As Cesare Emiliani said "The next few decades are likely to witness deep environmental crises, crises we will be able to cope with only through a clear understanding of the complex, delicate system, of which we are part."

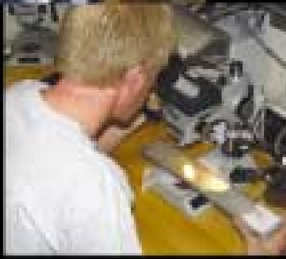
Chris Harrison
Chair, JOIDES Executive Committee

After labeling the core, scientists perform various whole-core analyses. They run the core through a Multi-Sensor Track System that analyzes various properties, including density, porosity, and magnetic properties. In addition, scientists spend time measuring other physical properties of the core before it heads off to the next station.

As soon as the deck crew hears, “Core on deck,” everyone prepares to process, sample and analyze the core. Technicians carry the core to the catwalk where they cut it into 1.5-meter sections. Technicians then move the core to the core receiving station. Here they attach more permanent labels, record the depth below the sea floor from which each section is taken, and the core officially enters the ODP database.

Every core’s life begins when the crew lowers drill string through the moon pool down to the sea floor. When the drill string reaches the seafloor, the crew lowers core barrels through the drill pipe. These core barrels collect rocks and sediment from beneath the sea floor. When at a drill site, core collection occurs every 90 minutes, on average, 24 hours a day.

There, the core is split lengthwise into two halves, the "working half," from which scientists sample and use aboard the *JOIDES Resolution,* and the "archive half," which is kept in pristine condition and is saved for future research.



Scientists describe the archive half by documenting the core's composition, grain size, and color. Other aspects of the core, such as disturbance due to drilling or interesting inclusions, are also noted. In addition, the shipboard photographer takes several pictures of the core for research purposes.

LIFE OF A CORE

While some of the scientific party describe the archive half of the core, other scientists are busy taking samples from the working half. The pieces of the core selected for sampling are identified with colored flags and then carefully removed and either analyzed on the ship or stored for post-cruise research. There are twelve different laboratories onboard the *JOIDES Resolution,* which are fully equipped and staffed by highly trained technicians to enable measurement and analysis of the chemical, paleomagnetic, and physical properties of the core. With 1,115 square feet of highly organized laboratory space, the scientists studying these cores find themselves on a "floating university."

When the scientists finish the preliminary onboard descriptions of each core, both the working half and archive half are sent to the refrigerated storage facility in the Hold of the ship. When each cruise comes to an end, all the cores collected are sent to onshore repositories where they are carefully curated and stored in a temperature controlled environment for future research use. There are four onshore repositories, one in Germany at the University of Bremen, and three in the United States, at the East Coast Repository located at the Lamont-Doherty Earth Observatory in New York, the Gulf Coast Repository located at Texas A&M University, and the West Coast Repository located at Scripps Institution of Oceanography in California. Between these four repositories, ODP stores more than 210 kilometers of core, which scientists can use for future studies.

Microbes: Life Deep Beneath the Seafloor

David C. Smith, University of Rhode Island, USA

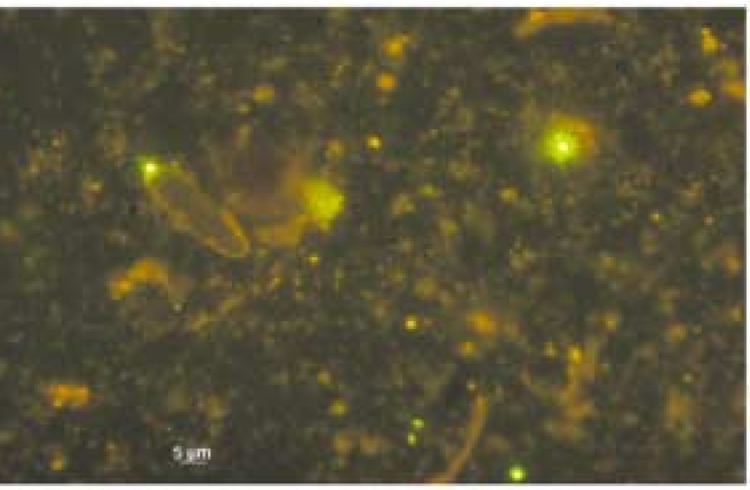


Figure 1

Eduard Suess first articulated the concept of the biosphere in 1875. A decade earlier, Jules Verne wrote of fantastic life forms inhabiting the Earth's interior in his classic "Journey to the Center of the Earth". Both men may have been surprised to find that their ideas, one rooted in science and the other in fantasy, would converge a century later deep beneath the ocean floor. Cores recovered by the Ocean Drilling Program are yielding an incredible view of life in deeply buried marine sediments (Figure 1). Finding life within the sediments is not surprising, but the great depths at which life occurs is changing the way we view the limits of life on Earth and possibly beyond.

Although Verne envisioned gigantic beasts in the subsurface, in truth, this realm is inhabited exclusively by microorganisms that exhibit great diversity in their metabolic capabilities. At its most basic level, life is a series of redox reactions, where the energy from the flow of electrons from donor to acceptor is captured to provide the energy to support basic metabolic functions. Microorganisms are exceptionally clever at exploiting even the smallest redox potential to sustain life. While most surface-dwelling organisms rely on oxygen, microbes use compounds of sulfur, manganese, iron, and carbon dioxide in the anoxic subsurface. This activity is clearly reflected in the geochemistry of the sediments (e.g. depletion of sulfate down core due to sulfate-reducing bacteria, the buildup of methane from the growth of methanogenic archaea or methane oxidation by microbial consortia at shallower depths). While ODP has recently focused on the study of life in the deep biosphere, in some sense the program has a long history in this area of research. The extensive global downhole geochemistry data allows us to predict the occurrence of specific types of microbes and calculate their metabolic rates.

To date, microorganisms have been found in sediments collected at depths as great as 800 meters below sea floor and there is no reason to believe that we have reached the bottom of the biosphere. While the great depths are impressive, even more so are the numbers at which the microbes occur. Extrapolation of microbial abundance in recovered cores to a global scale suggests that ~10% of the total biomass on Earth occurs in the marine subsurface.

Microbiology has become an integral part of the Ocean Drilling Program. The *JOIDES Resolution* now has a well-equipped microbiology laboratory that is integrated with the chemistry laboratory (Figure 2). Sea-going scientists are able to collect uncontaminated samples from recovered cores for onboard experiments (e.g. cultivations, radiotracer studies) or preserve samples for shore-based studies (e.g. nucleic acid analysis, biomarker characterization). The results of these studies will shed further light on how the Earth and its inhabitants have co-evolved.

Figure 1. Image of microorganisms in sediment cored during ODP Leg 201. Figure 2. Scientists onboard the *JOIDES Resolution* use the microbiology lab for their research.

Figure 2

Breaking Through Barriers

Martin Hovland, Statoil, Norway

Gas hydrates are crystallized gas and water that form under high pressure and low temperatures in the deep sea. These natural gas reserves could potentially contain as much energy as all other forms of fossil fuels combined, but are poorly understood.

ODP's extensive scientific and safety review process has allowed it to make discoveries in areas previously off limits to drilling — including areas with hydrates. An anomalous sub-seabed boundary known as the "Bottom Simulating Reflector" (BSR) was discovered about 30 years ago in deep water. It represents a barrier formed between sediments containing frozen gas hydrates located above sediments charged with free gases. Because the BSR was interpreted as a dangerous barrier to drill through, it was avoided in all drilling campaigns until the mid-1980s, when ODP Leg 112, off Peru, intentionally pierced through it without incident. Since then, BSRs have been penetrated on several other ODP legs, including Leg 146 on the Cascadia Accretionary Margin in the Pacific Ocean, and Leg 164 on the Blake Ridge off North Carolina in the Atlantic Ocean.

Breaking through the BSR has placed ODP at the forefront of gas hydrate research. The scientific results of these pioneering drilling campaigns have provided us with much needed basic knowledge on the dynamic fluid flow and gas hydrate formation mechanisms in deep ocean sediments important for possible future industrial drilling for hydrocarbon exploration and exploitation.

For example, a recent expedition, Leg 204, examined hydrates offshore Oregon in an area known as Hydrate Ridge. Among the most surprising findings of Leg 204 was that hydrate is forming very rapidly below the seafloor. Scientists also gained an understanding of the importance of sediment properties, such as composition and size of grains, in the distribution of hydrate within the sediments, which may provide clues to their locations.

The safe drilling shown in these difficult operations, where all possible cautionary action was implemented, has demonstrated the value of having panels of experts to overlook and review each and every hole to be drilled. In the case of the BSR-penetration, ODP's Pollution Prevention and Safety Panel, which reviews each drilling site, finally allowed and approved these campaigns.

Figure 1

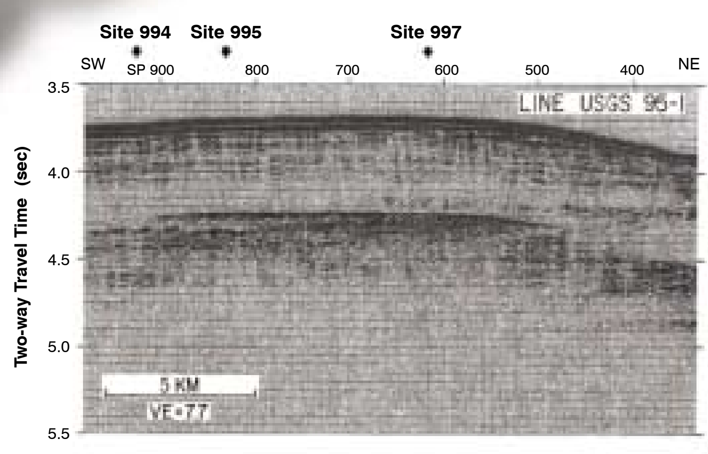


Figure 2

Figure 1. Hydrate sample collected on ODP Leg 204.
Figure 2. Seismic reflection profile (USGS 95-1) showing the BSR collected from Cape Hatteras during ODP Leg 164.

Treasure in the Making Under the Sea Floor

Fernando Barriga, University of Lisbon, Portugal
Ray Binns, CSIRO Division of Exploration and Mining, Australia
Jay Miller, Texas A&M University, USA and Leg 193 Shipboard Party

Much excitement surrounded the preparations for ODP Leg 193 when the *JOIDES Resolution* planned to drill a tremendously promising target: a modern analogue to the rich ancient massive sulfide deposits well known on land as major mineral resources for metals such as copper and gold. This feature, a hydrothermal field located in the Manus Basin north of Papua New Guinea, is known as PACMANUS and could one day become the first deep-sea mine for metallic resources. Drilling this site looked particularly tempting in view of its geological setting, which is very different from the mid-ocean ridges previously investigated, and because the hydrothermal field, on the surface, is composed of chimneys extremely rich in copper and gold (beside zinc and other metals). Also, study of the chimneys revealed the involvement of an unusually high proportion of magmatic fluid. Leg 193 was devoted not so much to investigate the orebody itself, but rather to understanding the geological framework of what on land are prime mining targets.

Drilling operations were not easy. The host rocks at PACMANUS were expected to be hard, glassy, silica and alkali-rich volcanic rocks, lithologies (rock types) never drilled before in the submarine environment. We took with us all the drilling paraphernalia that ODP could provide for hard and brittle rock. New tools were included, such as the advanced diamond core barrel and the newly- developed hammer drill. All proved invaluable in various situations. Lithologies encountered, however, were mostly very soft and fractured rocks, but more than once the ingenuity of the operations engineers and crew made success possible. Another key component was logging, both after and while drilling, which provided essential information complementary to that provided by the cores recovered.

The main result of Leg 193 was to show that the PACMANUS volcanic sequence, under a cover of about 30 meters of fresh lava, is intensely (often 100%) altered, both physically and chemically, though commonly with good preservation of original igneous textures that allowed reconstruction of its architecture. The main alteration minerals are clays and other sheet silicates, silica minerals, and anhydrite. The rocks are typically soft and light colored, white to light gray and greenish, in strong contrast with the hard, black rocks from which they are derived. We expected to evaluate the relative weight of magmatic versus seawater-derived hydrothermal fluids. Our initial conclusion was that, in contrast with the overlying chimneys, subseabed mineralization and alteration is largely dominated by a seawater-derived component. Magmatically-derived fluids may have passed through footwall rocks with minor alteration only, possibly through large, open fractures. Breccias (coarse rocks composed of broken rock fragments) abound, from true fragmental lava crusts formed during submarine eruptions to hydrothermal breccias generated *in situ* through extreme alteration and local fluidization and loss of coherence. The Leg 193 core documents these processes as never before. Processes related to this "hydrothermal corrosion" may create the necessary space for precipitation of sulfide minerals from hydrothermal fluids.

We drilled right under the rich chimney field Roman Ruins (Hole 1189B), but did not core the fragile chimneys themselves. Under the cover of fresh rhyodacite, we attained extremely fast coring speeds (87 m cored in 8 hours of overall operations) and we only recovered about 1% of the drilled interval. The latter consists of a few handfuls of small fragments of massive sulfides and deeply altered volcanic rock, abundantly cemented and partly replaced by anhydrite/gypsum and quartz. Collectively, these data suggest that the rock is very incoherent, probably with many trapped pockets of fluid. In detail, a number of possibilities are conceivable. Based on the observations mentioned above, and on extensive well logging, it appears likely that the original volcanic sequence is being replaced by sulfide-anhydrite-silica assemblages, largely incoherent, with altered rhyodacite remnants.
A rather exciting possibility is that this may be the actively forming precursor to a "subhalative" massive sulfide body, demonstrating in action a process believed responsible for creation of "giant orebodies" of this style in ancient sequences. We may have drilled PACMANUS before it was itself ready to mine, but nevertheless our results will provide new guidelines for future land-based mineral exploration.

Set of photographs from Hole 1189B, drilled through the Roman Ruins vent field. Sample numbers below 10R01 correspond to the Upper Sequence, in which 87 meters were drilled in about 8 hours of total operations (see text). The "rock" referred to in individual captions was originally glassy rhyodacite/dacite (acid to intermediate) now completely altered into clays, silica and anhydrite in variable proportions. All scales are in millimeters.

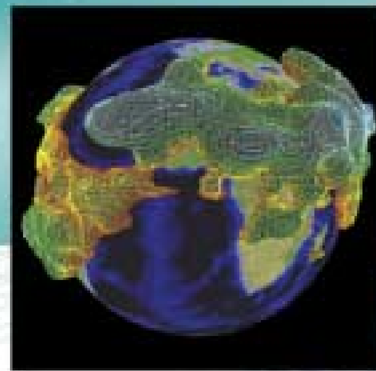
Development of pseudo-breccia on flow-banded volcanic rock (with exotic fragment of siliceous material, dark, on the left hand side). Note the development of alteration stains cutting the flow-banding. Differential alteration can transform the rock into pseudoclasts surrounded by a matrix that originally had the same composition. About 170 meters below surface.

Fragments of breccia composed of fragments of deeply altered rock, cemented by a matrix (dark) composed of iron and copper sulfides (pyrite and chalcopyrite) and anhydrite. About 90 meters below surface.

Rock intensely veined and with vesicles filled by quartz and anhydrite /pyrite (white and gray). Note partial replacement of the volcanic rock. About 120 meters below surface.

A true sea-floor breccia, with a variety of rock fragments, believed to result from the accumulation of volcanic rubble on the sea floor. About 200 meters below surface.

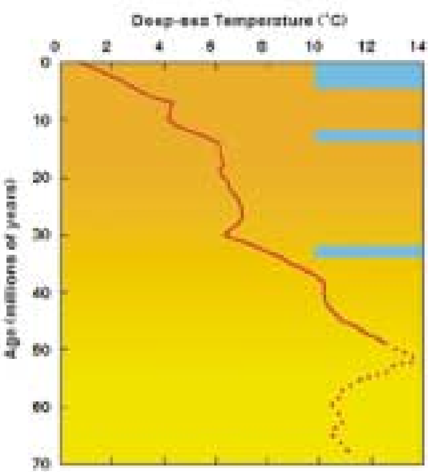
CLIMATE CHANGE



Fossil Thermometers for Earth's Climate

Carrie Lear, Institute of Marine and Coastal Sciences, Rutgers University, USA; **Harry Elderfield,** University of Cambridge, UK; and **Paul A. Wilson,** University of Southampton, UK

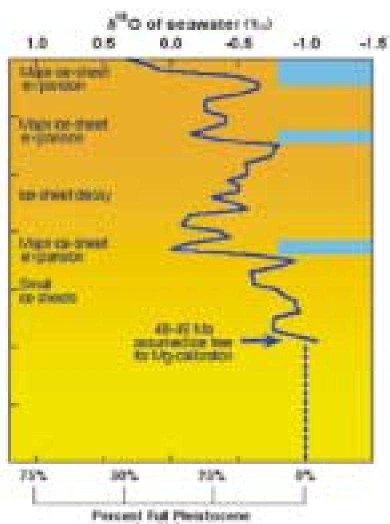
Cold-blooded reptiles living within the Arctic Circle, mangrove swamps along the south coast of England: We know that Earth's climate was much warmer than today in the Cretaceous and early Cenozoic time periods. A long-standing problem in Earth Sciences, however, has been to quantify exactly how much 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.

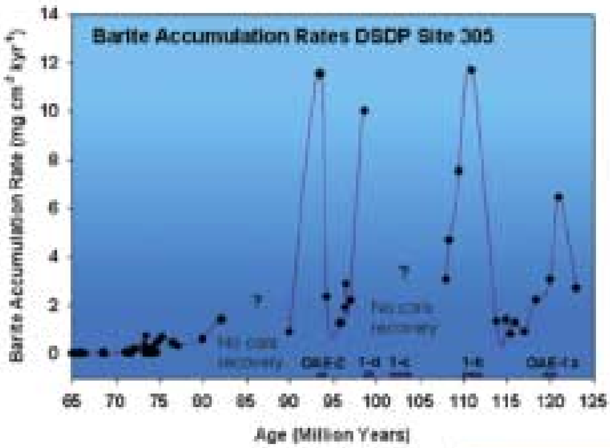
We then compared these Mg-temperatures to the existing record of oxygen-16 to oxygen-18 of the foraminifera shells, to calculate the ratio of the two oxygen isotopes in seawater over the past 50 million years. This process allowed us to calculate, for the first time, global ice volume over the past 50 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.

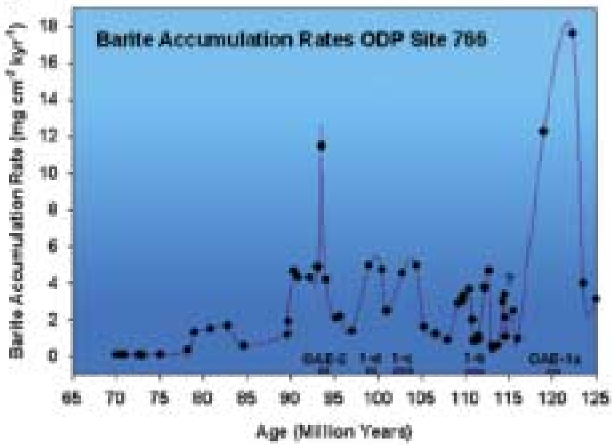


Deep-sea temperatures determined from the magnesium content of forminifera (above) and the ratio of oxygen-16 to oxygen-18 ($\delta^{18}O$) of seawater which is a measure of global ice volume (right).

Tales of Black Shales

Adina Paytan, Stanford University, USA





Barite Accumulation Rates in Cretaceous Sediments

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

Jochen Erbacher, Marine Geology and Deep Sea Mining, Federal Institute for Geosciences and Natural Resources, Germany; **Brian T. Huber,** Smithsonian Institution, USA; **Richard Norris,** Wood Hole Oceanographic Institution, USA

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.

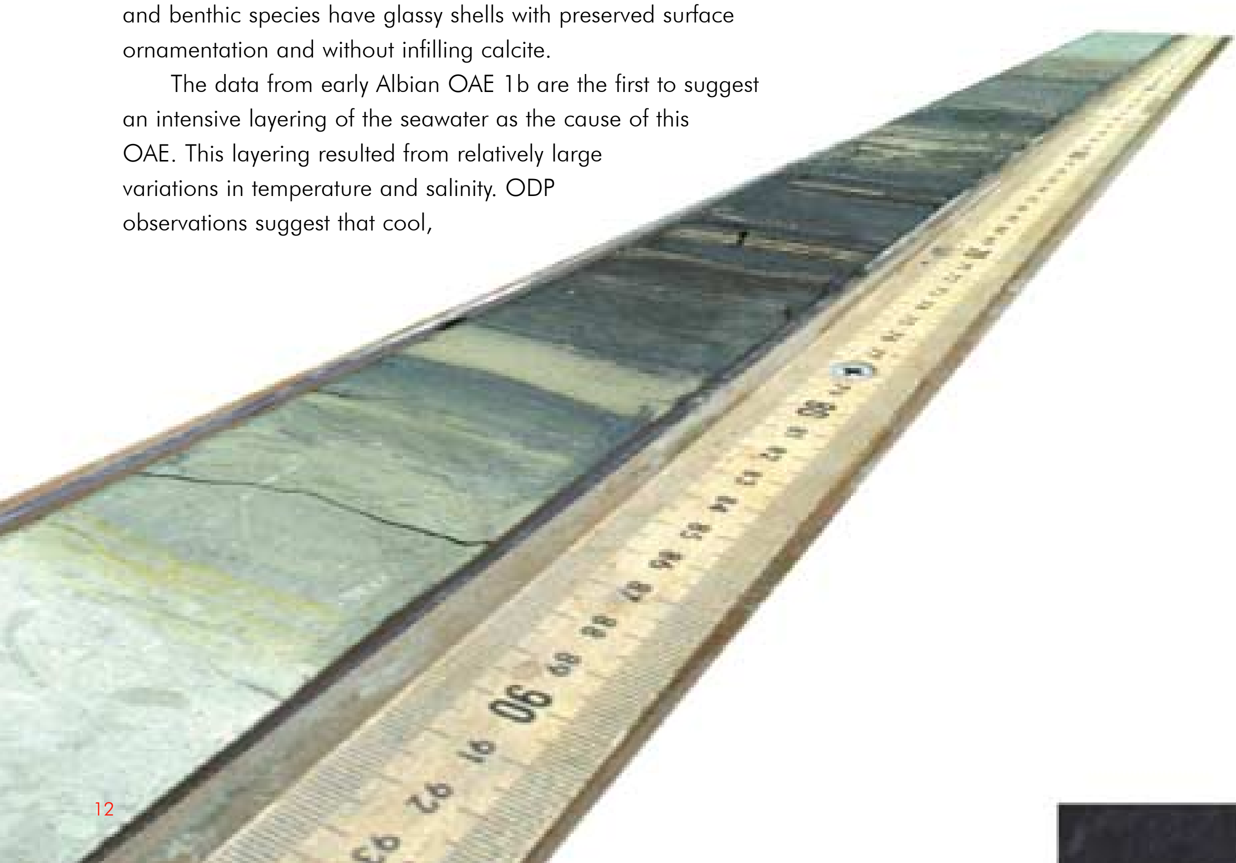
Data from the Deep Sea Drilling Project and Ocean Drilling Program show that many of these black shales occur simultaneously in the world's oceans. Such intervals of concurrent black shale deposition on a super-regional to global scale are called Ocean Anoxic Events (OAEs) and are typical for the mid-Cretaceous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

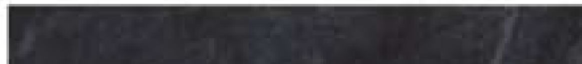
The Cretaceous OAEs are periods of high carbon burial and drawdowns in atmospheric carbon dioxide (CO_2) during the mid-Cretaceous greenhouse climate and, in many cases, they caused significant biological turnover. Most OAEs are attributed to high ocean biological productivity and export of carbon that 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

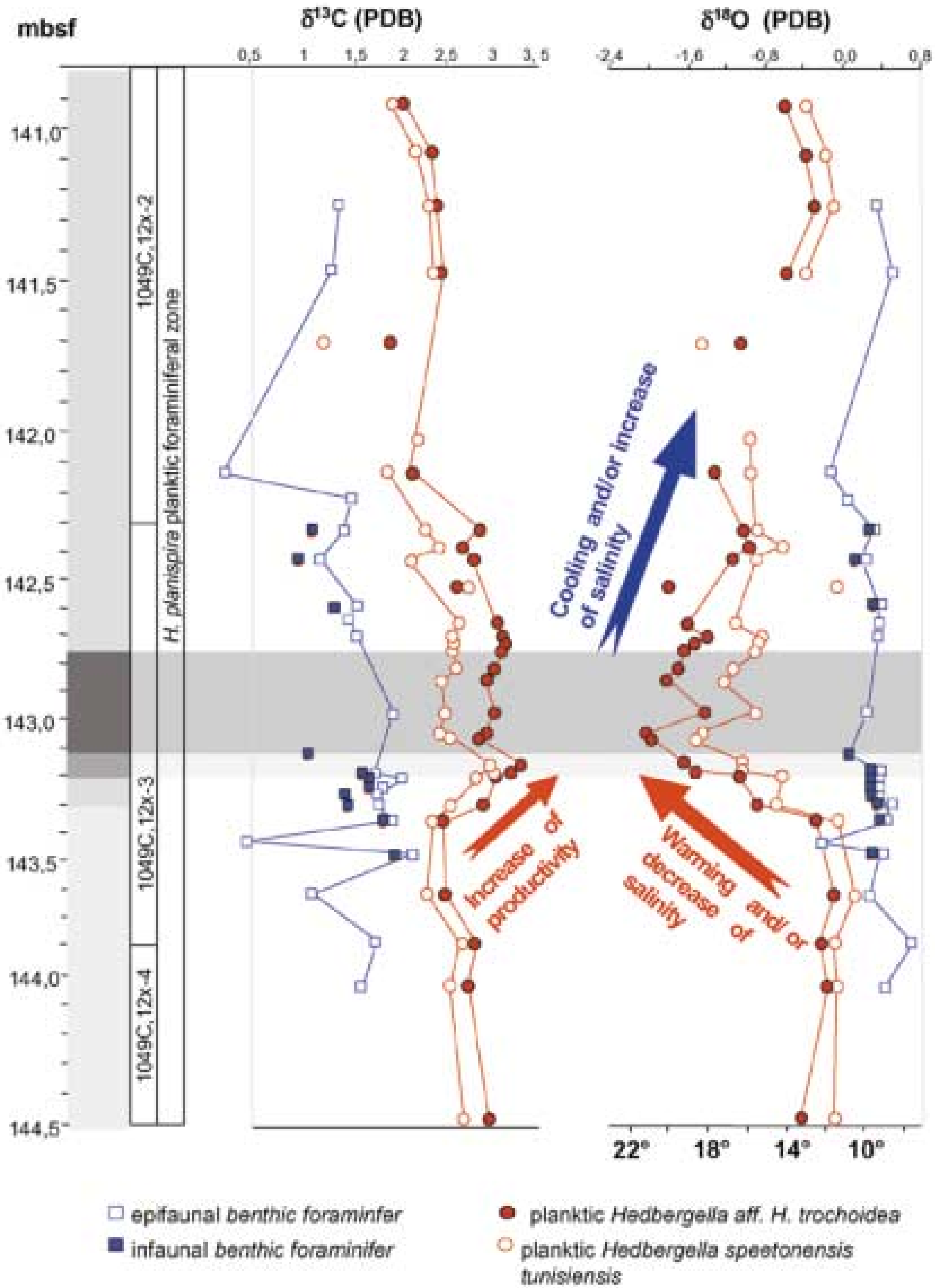


Figure 1. Location of ODP Site 967.

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).

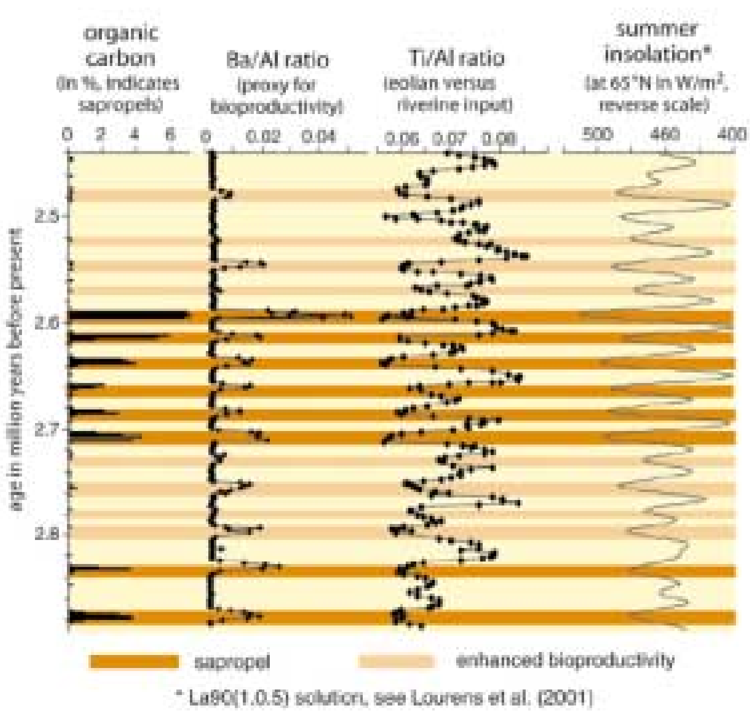


Figure 2. Pliocene sediment sequence from ODP Leg 160 Site 967, south of Cyprus, Eastern Mediterranean

History of the Antarctic Ice Sheet

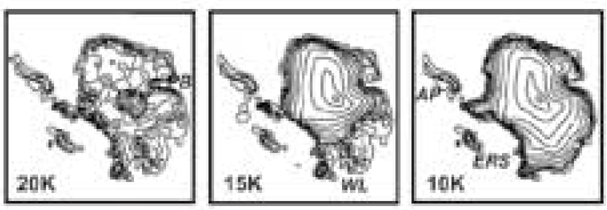
Peter Barker, British Antarctic Survey; **Angelo Camerlenghi,** OGS Italy; **Phil O'Brien,** Australian Geological Survey, **Alan Cooper,** US Geological Survey

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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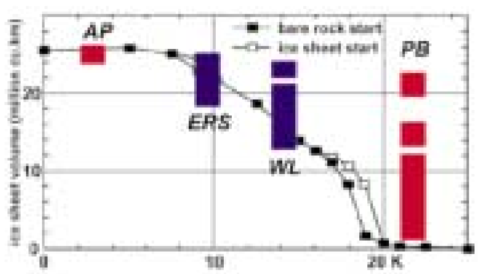

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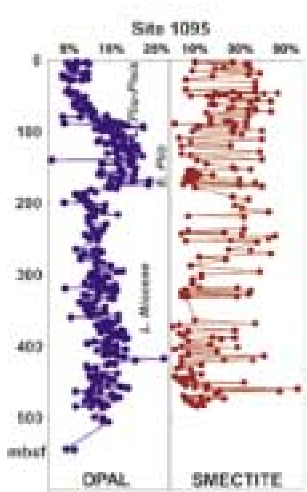
Figure 1. **a)** the geography of smaller ice sheets **b)** Antarctic ice sheet volume versus change in mean annual temperature at sea level and target regions for drilling, with **c)** a schematic Antarctic margin showing sedimentary environments, results of drilling, **d)** the enigma of ice volume 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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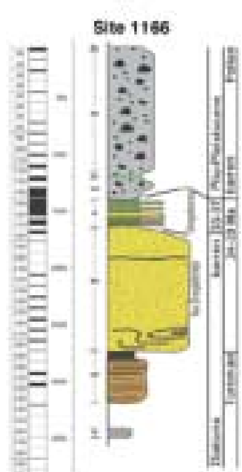

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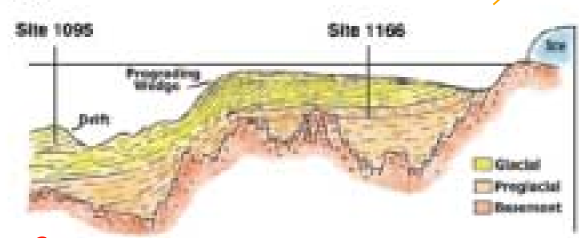

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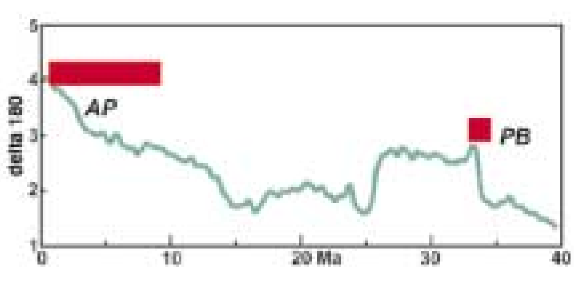

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Clues to Global Warming found in Antarctica

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.

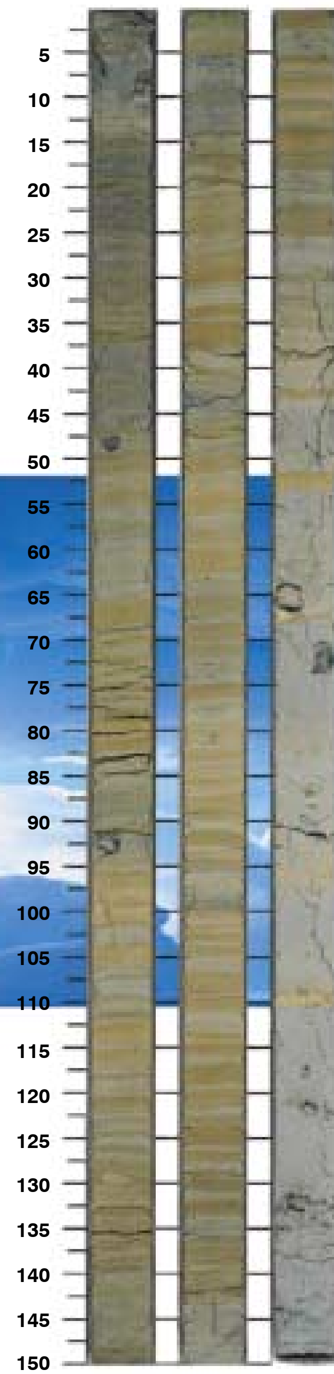


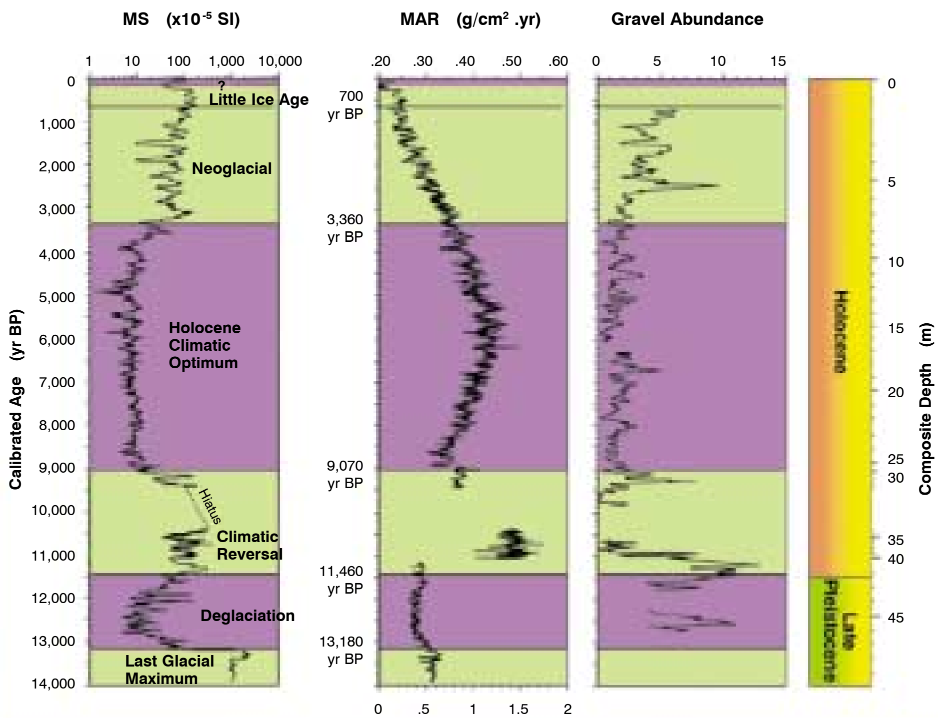
Figure 2. (Right) Annual seasonal layers of olive green (diatom ooze) and grey (diatom sandy, mud).

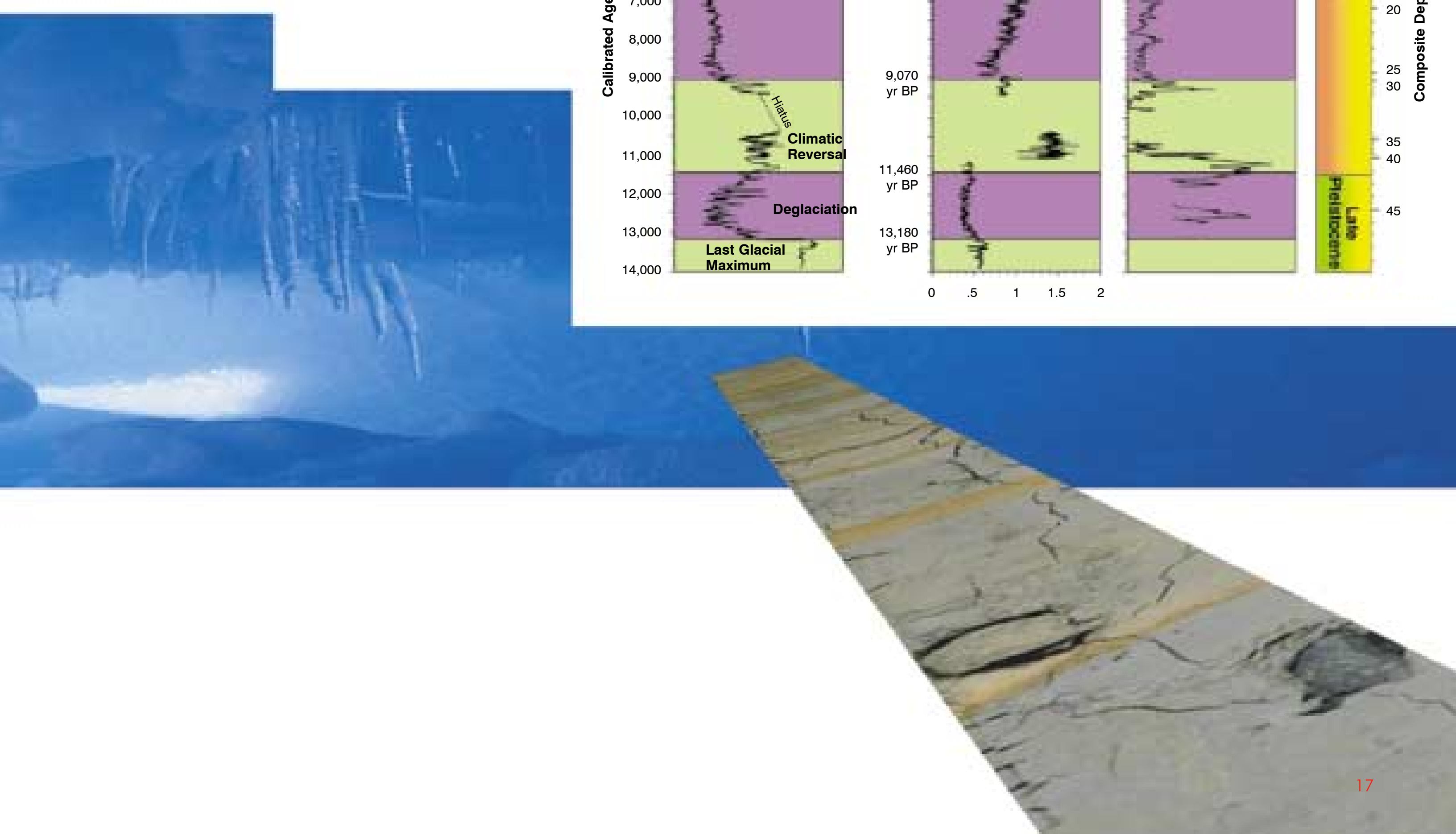
ago as shown by thin layers of diatom ooze and mud that contain warm water diatoms (single celled algae) and high amounts of organic carbon.

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.





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.

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

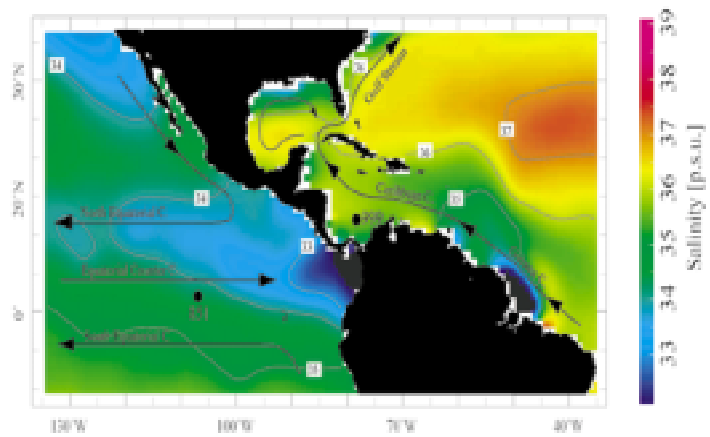


Figure 1. Major surface ocean currents of equatorial west Atlantic-Caribbean Sea and eastern equatorial Pacific and surface ocean salinities in per mil *(colors and small numbers)*. Large circles indicate locations of ODP Sites 999 and 851.

Pacific-Caribbean comparison of planktic δ18O-records

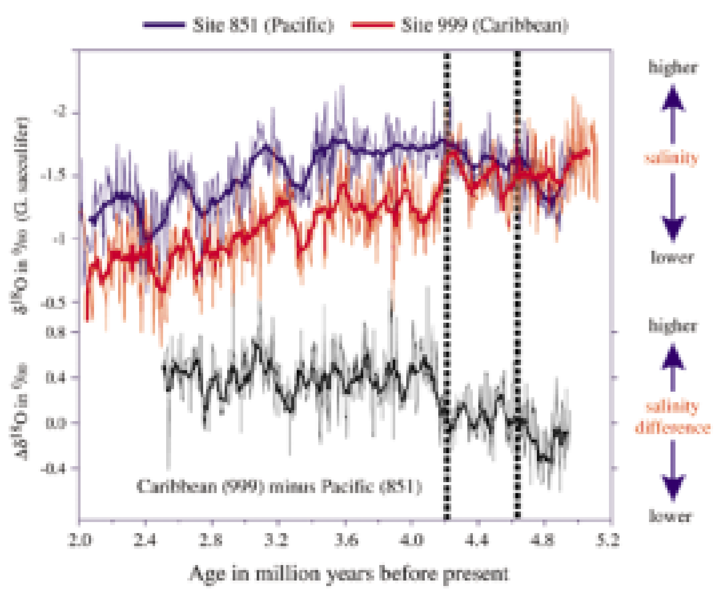


Figure 2. The planktonic foraminifera stable isotope records from ODP Sites 999 (Caribbean Sea) and 851 (equatorial east Pacific) span a time interval 2.2-5.3 million years before present and indicate the evolution of sea surface salinities in the Atlantic/Caribbean and Pacific during the uplift of the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

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.

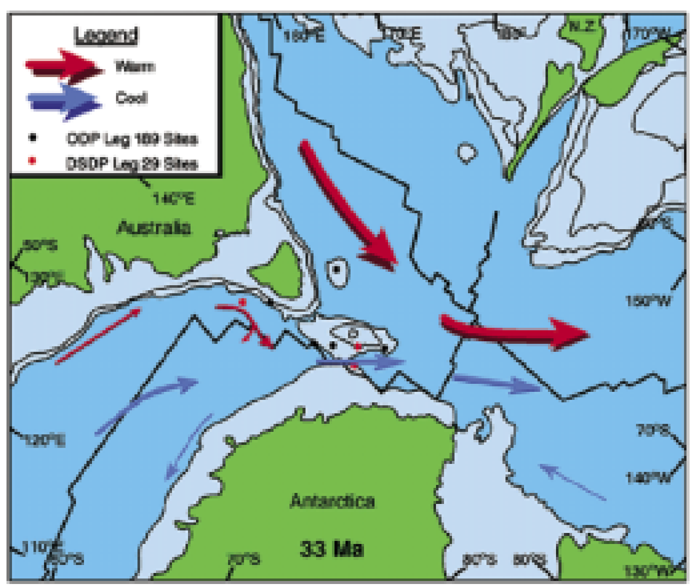


Figure 1

The Lost World: Environmental Effects During the Formation of a Giant Volcanic Province

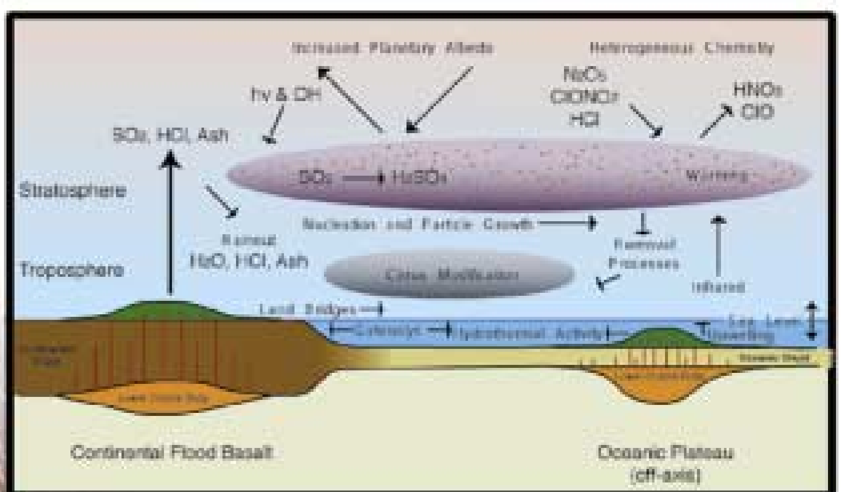
Millard F. Coffin, The University of Tokyo & Japan Marine Science and Technology Center; **Fred A. Frey,** Massachusetts Institute of Technology, USA; **Paul Wallace,** University of Oregon, USA and ODP Leg 183 Scientific Party

Large igneous provinces (LIPs) form when extraordinary amounts of mantle-derived magma enter regions of the Earth's crust. The intense igneous activity during their creation temporarily increases the flux of mass and energy from the mantle to the crust, hydrosphere, biosphere, and atmosphere, with many possible global environmental effects.

During Mesozoic and Cenozoic time, LIPs have typically formed in geologically brief (1-10 million year) episodes. The youngest LIP formed ~15 million years ago. On continental lithosphere, LIPs are also known as continental flood basalts, which are relatively well studied. Several are associated with mass extinctions and environmental changes, although causal relationships and feedback loops are not well understood. On transitional and oceanic lithosphere, respectively, divergent volcanic margins and oceanic plateaus are relatively understudied, with drilling being the primary means of sampling. Ocean drilling at the two most voluminous LIPs on Earth, the Kerguelen Plateau/Broken Ridge in the southern Indian Ocean and the Ontong Java Plateau in the western Pacific, has provided information on the processes that form LIPs and their potential environmental consequences.

The uppermost crust of both the Kerguelen Plateau and Broken Ridge is dominated by the products of massive magmatism. Physical characteristics of the LIP lava flows together with wood fragments, charcoal, pollen, spores and seeds in the shallow water sediments overlying igneous basement, show that large portions of the Kerguelen Plateau and Broken Ridge formed islands. After their formation, the islands gradually subsided by as much as several thousand meters to their present water depths.

The large volume and long duration of subaerial basaltic volcanism on the Kerguelen Plateau and Broken Ridge, combined with the high latitude of the plateau, would all have contributed to potential global environmental changes involving climate, sea level, oceanic anoxia, seawater composition, biological radiations, and extinctions. The eruption of enormous volumes of basaltic magma during their formation released volatiles such as carbon dioxide (CO_2), sulfur (S), chlorine (Cl), and fluorine (F). Because the LIP formed at high latitudes, where the tropopause is relatively low, the effects of these eruptions could have been intensified because large basaltic eruption plumes can transport SO_2 and other volatiles into the stratosphere. Sulfuric acid aerosol particles that form in the stratosphere after such eruptions have a longer residence time and greater global dispersal than if the SO_2 remains in the troposphere; therefore they have greater effects on climate and atmospheric chemistry. During the final stages of plateau construction, highly explosive felsic eruptions likely injected both particulate material and volatiles (SO_2, CO_2) directly into the stratosphere. Significant volume of explosive, subaerial felsic volcanism, undiscovered until 1999, would have further contributed to the effects of this plume volcanism on the global environment.



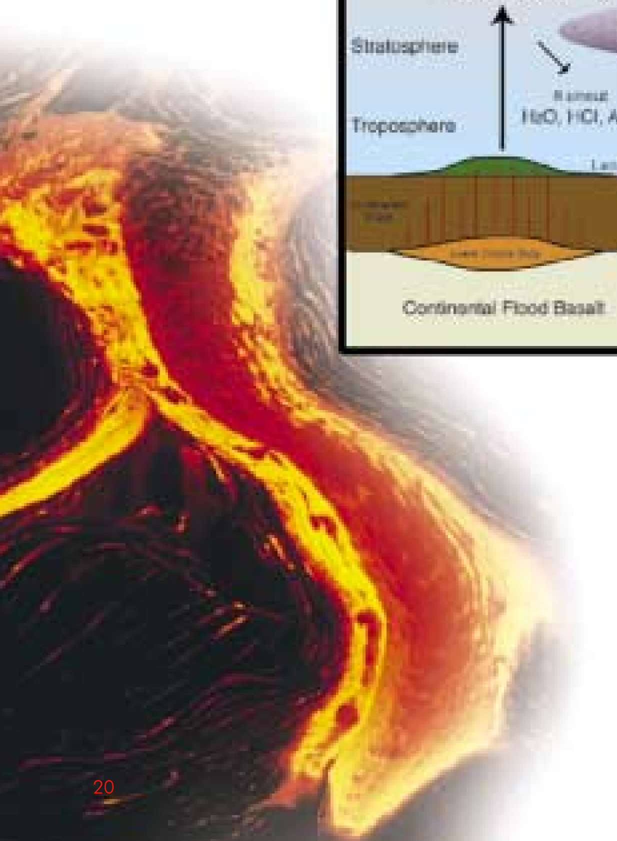


Figure 1. Environmental effects of LIP formation. LIP eruptions can perturb the Earth-ocean-atmosphere system significantly. Note that many oceanic plateaus form at least in part subaerially.

Rupturing Continents Exposed Mantle Rocks

Bob Whitmarsh, Southampton Oceanography Centre,
UK and the ODP Legs 149 and 173 Shipboard Scientific Parties

Until about 140 million years ago, a narrow shallow seaway lay between Europe and North America. But then a major rift began to separate the European and North American plates, leading to the formation of the Atlantic Ocean. During this process, the continental crust, normally about 35 km thick, was stretched and thinned to breaking point and the intervening space was filled by oceanic crust formed by seafloor spreading at the mid-Atlantic ridge. However, unlike some other continental margins, there is very little evidence that any significant volcanic activity accompanied this rupturing of the Earth's continental crust. A long-standing problem has been to work out how seafloor spreading, itself principally a volcanic process, began. Was it essentially instantaneous or did it begin more gradually and, if so, how?

A combination of geophysical measurements and studies of drill cores obtained by ODP at ten sites off Portugal has now solved the mystery. The geophysicists measured the thickness of the crust from variations in the speed of sound under the continental margin and found that, although the continental crust thinned as expected towards the ocean, it broke up when the crust had been thinned to about 7 km. Oceanward of this point, a crust-free zone up to 170 km wide of the underlying continental mantle layer was exposed at the seafloor. On the landward side of the zone, other geophysical evidence suggests that a number of isolated and relatively small elongated bodies of molten rock were first intruded into the mantle. As the zone of deformation moved oceanwards, more and more molten rock was emplaced until eventually a continuous layer of such rocks, that is oceanic crust, was produced.

The final puzzle was to explain how the broad zone of mantle could be exhumed between the thinned continental crust and the oceanic crust. This puzzle was solved when it was realized that a class of mainly sub-horizontal dislocation surfaces (or faults) from a similarly formed continental margin, now exposed in the Alps, could provide the mechanism whereby mantle was exhumed without producing significant vertical offsets across the faults. Such a concave-downward fault, as well as a diagrammatic representation of how the continental margin off Portugal may have evolved, is shown in the diagram. Many of the rock cores have now been dated using isotopes to demonstrate that the focus of stretching of the crust and mantle migrated from the continent towards the ocean, apparently at an increasing rate.

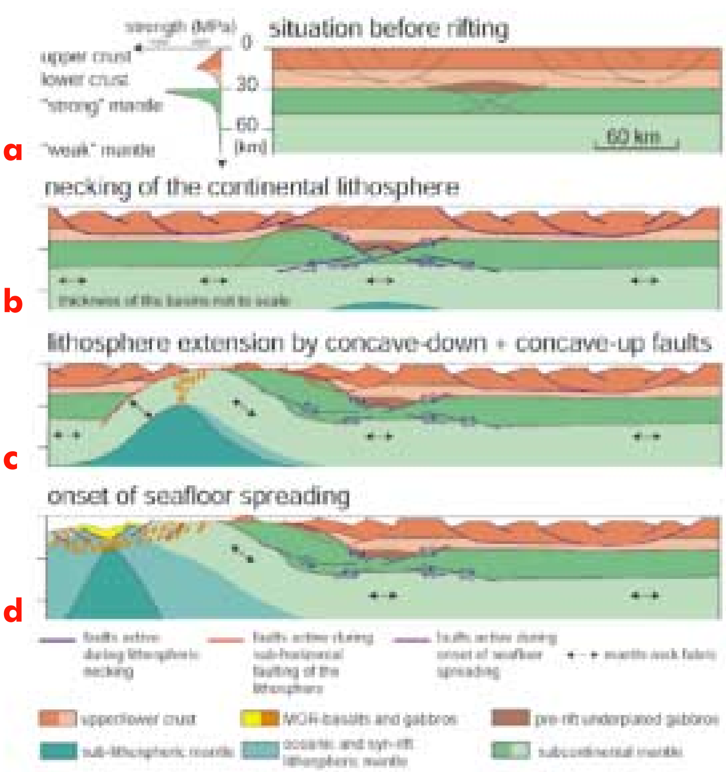


Figure 1. Conceptual lithosphere-scale model of the development of a rifted magma-poor margin relative to a fixed right-hand edge. **a)** Initial situation with crust locally thickened by pre-rift underplated gabbro. **b)** Initially the upper mantle necked beneath the gabbros, allowing the asthenosphere to rise. Elsewhere, ductile flow of the lower crustal rocks determined where rift basins formed at the surface. **c)** Later, the rising asthenosphere started to influence the rifting. Then, rifting was localized at the margin of the relatively weak unextended, or only slightly extended, crust. Note the change in extensional geometry from concave-upward to one or more concave-downward faults. **d)** The asthenosphere ascended close to the surface and melts were intruded into, and even extruded onto, sub-continental mantle. Deeper mantle layers were exhumed oceanward. Eventually, increasing melt production led to the creation of 'continuous' oceanic crust. Seafloor spreading had begun. *(This figure is reproduced from Whitmarsh et al., 2001, Nature, Vol. 413, pp. 150-154.)*

When Did the Himalayas Get High?

Louis A. Derry, Department of Earth and Atmospheric Sciences, Cornell University, USA
Christian France-Lanord, Centre des Recherches Pétrographiques et Géochimiques, France

Millions of years of erosion from the Himalayas have created a huge sedimentary structure in the Bay of Bengal, known as the Bengal Fan. The Bengal Fan is the world's largest sediment accumulation, and its volume is estimated to be 5-10 times the volume of the portion of the Himalayas presently above sea level. ODP Leg 116 recovered sediments from the Bengal Fan representing 20 million years of deposition, providing a uniquely valuable archive of Himalayan uplift and erosion and weathering processes.

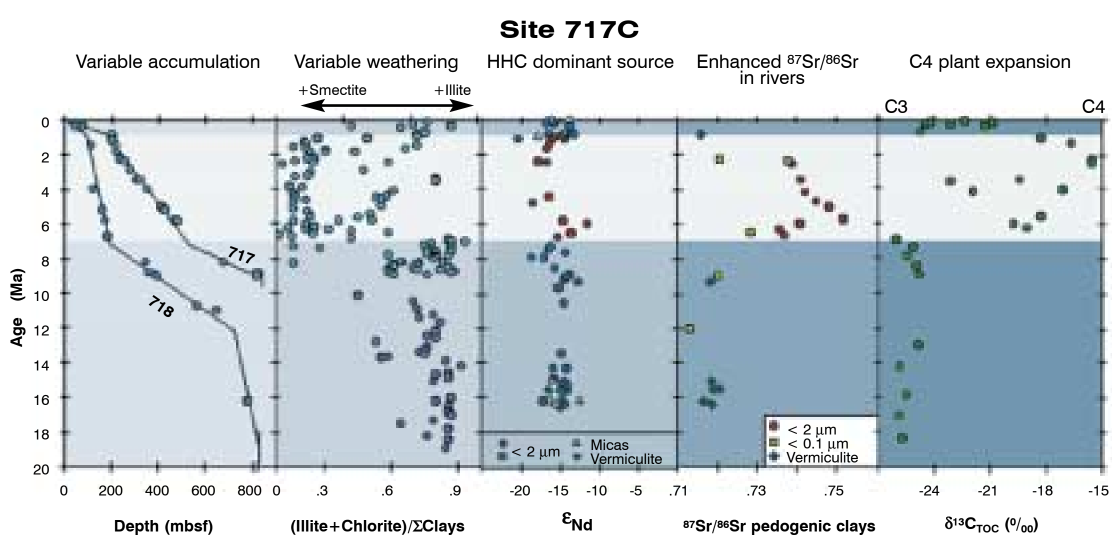
These ODP data can be used to test hypotheses about the formation of the Himalayan mountain belt and the impact of weathering fluxes on ocean chemistry. Cores revealed that the Himalayas were uplifted at least 20 million years ago, 10 million years earlier than scientists originally projected.

One of the most intriguing sediment intervals recovered by ODP Leg 116 was deposited during latest Miocene to Pliocene times, approximately 7.4 million years ago (Ma). Coupled changes in sedimentation rate, clay mineralogy, the $^{87}Sr/^{86}Sr$ ratio of pedogenic clays, and the d^{13}C of organic carbon all imply significant environmental change in the Himalayan region at this time.

The cores indicate that a sequence of rocks known as the High Himalayan Crystalline series (HHC) has been the dominant source of the sediment to the Bengal Fan since the early Miocene. The cores show a period of increased weathering intensity that appears to be related to decreased sediment delivery. The weathering took place mostly in the low elevation floodplain of the Ganges system.

The rapid accumulation of sediment in the Bay of Bengal results in the storage of large amounts of organic matter, most of which is derived from terrestrial sources. Since the late Miocene, a significant fraction has been derived from C4 grasses in the floodplain region. This grass carbon is closely associated with the highly weathered clays, and it appears that the enhanced weathering occurred in the newly developed grasslands of the foreland basin. A picture emerges of decreased sediment flux and longer residence time in the foreland, under conditions of increasing seasonality. Although work on other ODP sites from the Arabian Sea suggests increasing monsoon intensity and a possible connection to uplift, the Bengal Fan records decreased sediment transport but more intense chemical processing of this material in the foreland. Not until millions of years later do high flux rates and low weathering intensity recur.

Figure 1. Data from Bengal Fan sediment recovered in Hole 717C. From left to right: **1)** Sediment accumulation rate and **2)** clay mineralogy show decreased erosion but increased weathering from 7.4 to 1 Ma. However, **3)** neodymium isotopic composition of bulk sediment and individual minerals shows little variation, indicating that the HHC remained the main source of sediment since before 18 Ma. **4)** Strontium isotopic composition from clay interlayer sites record changes in the weathering environment associated with changing clay formation, which occur at the same time as **5)** shifts in carbon isotopic composition of buried organic carbon indicate a change from trees and shrubs as the dominant carbon source to grasslands. The coupled changes in clay mineralogy, strontium and carbon isotope ratios indicate an increase in the importance of floodplain processes that may have been aided by decreased sediment flux.



Mud Volcanoes in the Eastern Mediterranean

Achim J. Kopf, Scripps Institution of Oceanography, USA
Alastair H.F. Robertson, University of Edinburgh, UK

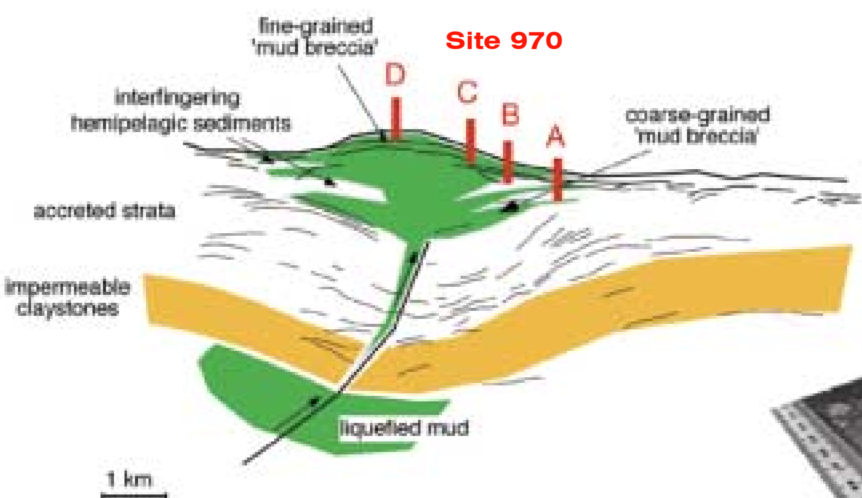
In 1995, ODP conducted the first scientific ocean drilling of active mud volcanoes, which are dome-shaped seafloor highs composed of clay-rich mud (Robertson *et al.,* 1996). Mud volcanoes occur almost everywhere on Earth, but are commonly associated with compressional tectonics at convergent margins (Higgins and Saunders, 1974). ODP Leg 160 drilled two mud volcanoes, the Milano and Napoli domes, at the backstop of the mud-dominated Mediterranean Ridge accretionary complex. This complex was created by subduction of the African plate beneath the Eurasian plate to the north. Only by drilling could the age, subsurface structure, and processes of mud volcanism be determined.

The main results were, surprisingly, that both mud volcanoes were periodically active for more than one million years and that they are dominated by multiple debris flows composed of fragments of claystone, sandstone and limestone in a muddy matrix. The most probable origin of the mud is that it was derived from overpressured fluid-rich sediment located beneath the Mediterranean Ridge accretionary complex within the subduction zone. The recognition of a debris flow origin of the "mud breccias" changed earlier views involving an origin as viscous mud intrusions.

The inward dip of the seismic reflectors towards the volcanic center suggests that progressive collapse of the volcano cone has taken place through time. Early eruption constructed a cone of unstable sediment fragments, including muddy debris flows. Voluminous outpourings of mud flows then followed, interspersed with pelagic accumulation, eventually constructing the present cones (Figure 1).

Post-cruise research focused on the depth of origin of the solid and fluid phases as well as on the quantification of mud and fluid discharge. The mud domes drilled occur along deep-seated backthrust faults some 150 km behind the toe of the accretionary prism (Kopf *et al.,* 1998). A considerable volume of previously accreted sedimentary rocks was remobilized as pieces within a mud matrix (Kopf, 1999). Research also shows that the fluid discharge through mud volcanoes in this part of the Mediterranean Ridge exceeds that of the frontal prism elsewhere (e.g., Alaska, Nankai; see Kopf *et al.,* 2001). Mud volcanism thus has an important role in the flux of water, solids and gases into the ocean in accretionary settings (Deyhle and Kopf, 2001), especially where involved in continental collision such as the Mediterranean Ridge.

Milano mud volcano
Mediterranean Ridge accretionary prism



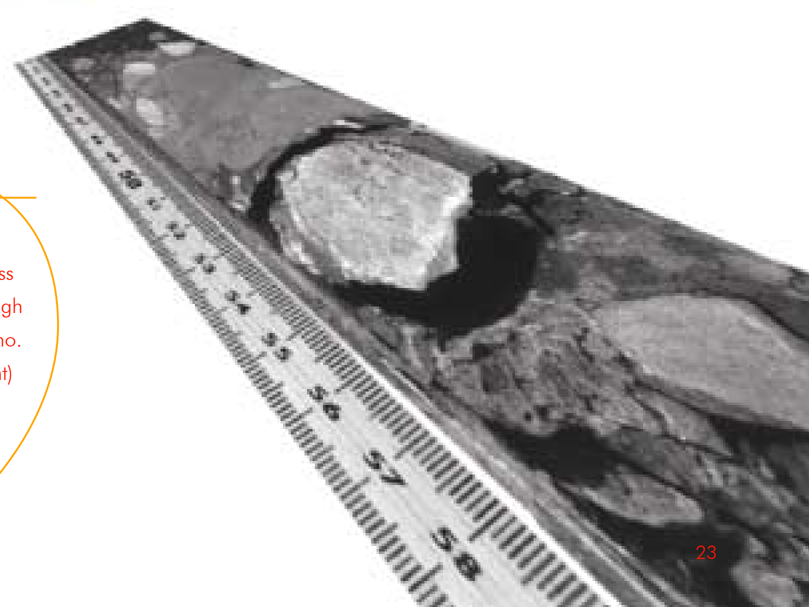


Figure 1. (above) Schematic cross section through Milano mud volcano.
Figure 2. (right) Mud breccia core from Hole 970A.

Into the Deep Ocean Crust

Benoît Ildefonse, CNRS, Université Montpellier 2, France
Henry Dick, Woods Hole Oceanographic Institute, USA
Mathilde Cannat, CNRS, IPG Paris, France

In the early 1970s, scientists defined the architecture of the oceanic crust by comparing the seismic signature of the crust in the oceans to the various pieces of oceanic crust in rocks found on continents (ophiolites). Drilling the entire thickness of the oceanic crust has been a challenge since the very beginning of the scientific oceanic drilling efforts in the early 1960s. Between 1979-1993, ODP drilled Hole 504B to a depth of 2111 meters below the sea floor — making it the deepest scientific hole drilled in the ocean. Drilling has allowed sampling of the upper crust, but the lower crust remains poorly sampled. However, considerable progress has been achieved with the few hundreds of meters cored in tectonically exposed crust: Hess Deep in the Pacific Ocean and the Mid-Atlantic Ridge.

The second deepest hole in the hard rocks of the oceanic crust was drilled at the Southwest Indian Ridge on the Atlantis Bank, a flat-top platform located east of the Atlantis transform fault (Dick *et al.,* 2000). 1.5 km of rock were drilled during two Legs, in 1987 and 1997, with an exceptionally high recovery in hard rocks of about 86.5%. The rocks, dominantly olivine gabbros, recovered at Hole 735B are unique in many aspects. This long section of lower crust contains two main intrusive bodies, which are divided into several smaller units and contain numerous layers, often associated with high-temperature shear zones.

The core displays all types of deformation structures. It shows a continuum of deformation styles, ranging from magmatic flow to low-temperature ductile and brittle flow, which demonstrate the fundamental role of tectonics in the accretion processes at slow-spreading ridges.

The discontinuity of the oceanic crust accreted at slow-spreading ridges has been demonstrated by dredging, submersible investigations, and previous drilling at the Mid-Atlantic Ridge (e.g., Cannat, 1996). The nature of Hole 735B provides evidence for a strongly heterogeneous lower ocean crust, and for the inherent interplay of deformation, alteration and igneous processes at slow-spreading ridges. It is strikingly different from rocks sampled from fast-spreading ridges and at most well-described ophiolite complexes. These findings emphasize the remarkable diversity of tectonic environments where crustal accretion occurs in the oceans.

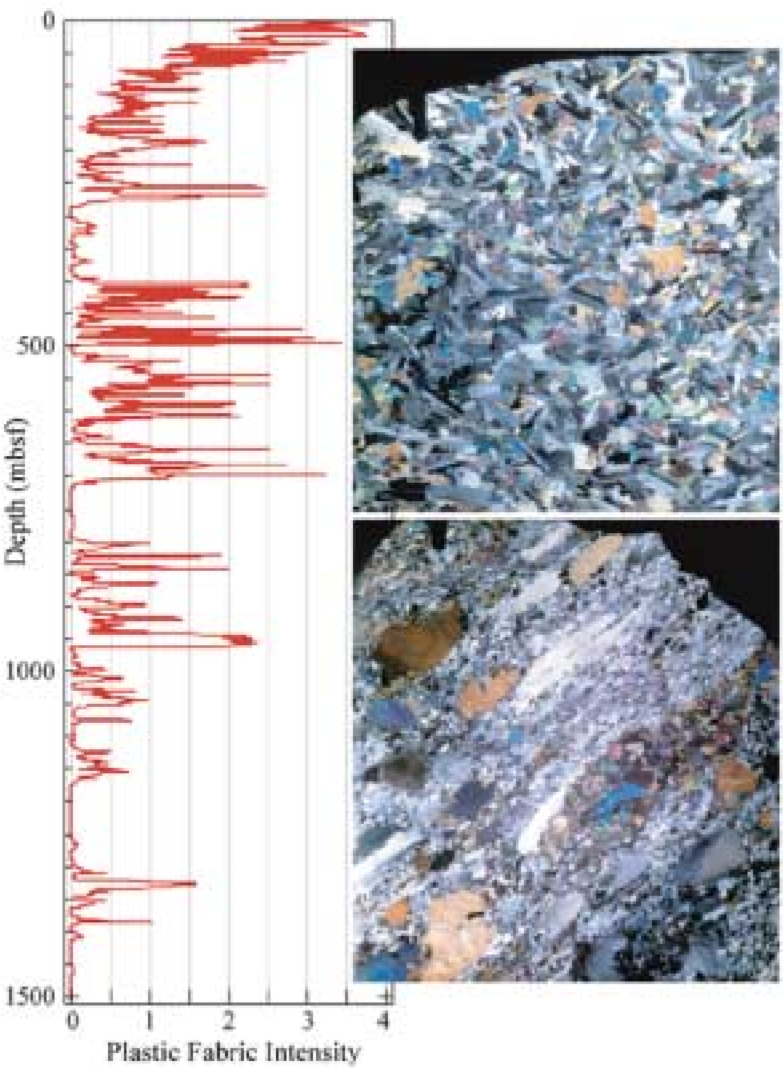


Figure 1. Downhole variations in solid-state deformation intensity, ranging from 1=weakly deformed to 4=highly deformed (mylonite). The microphotographs (width=6 cm) show examples of a magmatic structure (upper photo) and of a high-temperature mylonite (lower photo).

The Earth's Next Move

Kiyoshi Suyehiro, Japan Marine Science and Technology Center

Oceanic plates travel long distances from oceanic ridges and are ultimately destroyed at oceanic trenches. Over a long geological time period, this process creates mountain belts on the continental side of the trench. We can experience a tiny fragment of this process through earthquakes. Large earthquakes are prone to occur at plate subduction zones, but there are, however, trenches without any significant records of large earthquakes. That is, the plate subduction may proceed with or without earthquake slips. In the real world, subduction probably proceeds with a mixture of these modes in time and space, often between the trench and the coast, where the rocks show brittle behavior. In order to understand how this is controlled, we must grasp how the earth is being strained or unstrained by the subduction process. The study of the earthquake activity alone does not provide the complete picture.

Because oceanic trenches are located more than 100 km offshore, there is no way to accurately sense this process from land. It is critically important to close in on the target, which is exactly what ODP Leg 186 accomplished offshore NE Japan in 1999 (Figure 1). Two crustal deformation observatories were successfully implanted more than 1000 m below the sea floor by the *JOIDES Resolution* in water depths of about 2000 m. The sensors can detect seismic motions, tilts, and strains in a broad observational window, that is, with high sensitivity, wide frequency range and wide dynamic range, comparable to or better than state-of-the-art sensors in use on land (Figure 2). These sensors are cemented at the bottom of the holes to assure the best possible coupling to the surrounding rocks.

The sensors are located about 10 km above the subducting plate boundary and 50 km apart. Within this small area, the seismic characteristics drastically differ in that one site is seismically active but the other site is aseismic. The question is, if the incoming plate is proceeding at about 9 cm/year over a long period of time, say 100 years, then what makes this difference? Is the incoming plate slipping with no friction in the aseismic part, or is it quietly storing strain energy to be released by a large future earthquake? Alternatively, is it releasing energy in a previously undetected manner? Is the active part always slipping due to the earthquakes? Answering yes or no from observations to any one of these questions leads to a different mechanism operating to make the incoming plate slip past the overriding plate.

Earthquakes are devastating manifestations, but only represent a portion of the total energy storage and release involved at the plate subduction zone. If we miss any significant strain event, be it stationary or episodic, and try to predict the future, it will be like playing chess without seeing the whole board yet having to make the next move. The observatories installed by ODP will help us see the whole board and better predict these natural hazards.

Figure 1. (above) Photograph of sub-sea station offshore Japan taken from Dolphin 3K (remotely operated underwater vehicle, "ROV"). The cylindrical superstructure sits on top of the re-entry cone and houses the power supply, recorder unit and controller unit for the borehole sensor package embedded 110 m below. ROVs periodically make electrical connections to communicate with the station, exchange the data recorder, and update the system.

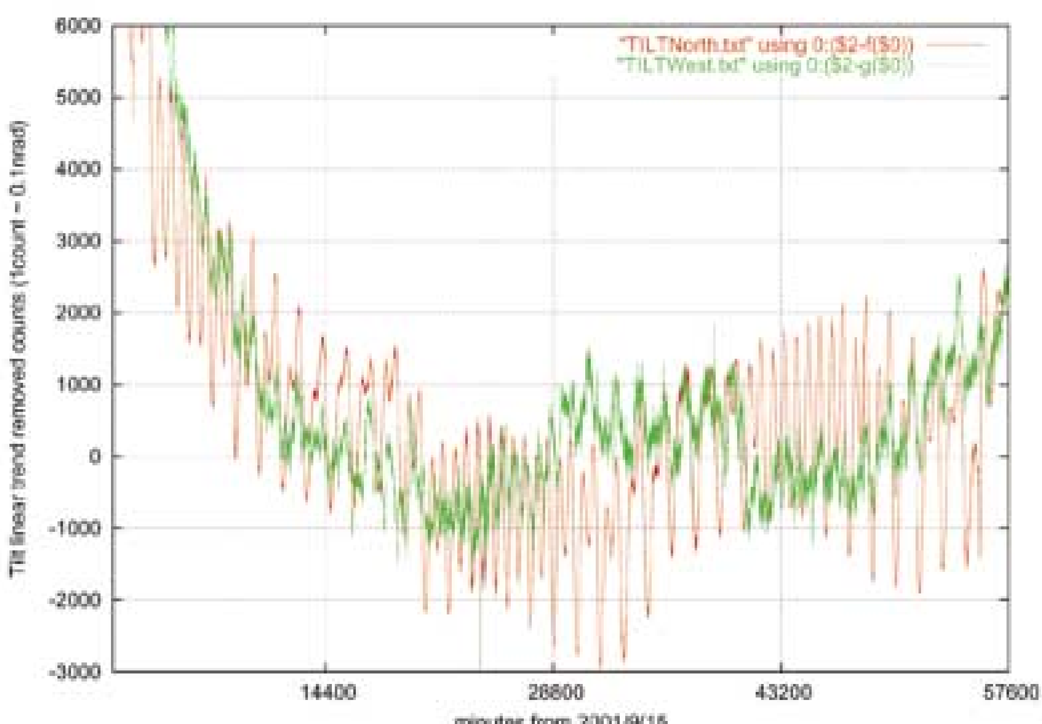


Figure 2. (right) A tiltmeter is one type of instrument used in underwater observatories that measures changes in the tilt of the Earth's surface. This tiltmeter record shows how the earth is responding to tidal forces, plate deformation and long-term tectonic forces. A state-of-the-art sensor is required to record the tidal signals.

Looking Beneath the Seabed

Gerardo J. Iturrino and **David Goldberg,** Lamont-Doherty Earth Observatory, USA

In recent years, ODP has devoted considerable time and effort to looking deeper into the Earth's crust and studying active dynamic systems. Some of these systems occur in subduction zones, regions that are characterized by the world's largest earthquakes. Recent studies of the processes occurring at subduction zones have established that fluids play a major role in their physical and chemical evolution. During Leg 193 in the Manus Basin near Papua New Guinea, ODP attempted to determine how fluids and metals derive from underlying magmatic sources and from the leaching of wall rocks by circulated water. Scientists also aimed to identify probable fluid pathways and chemical gradients within the hydrothermal system and establish a hydrological model (Binns *et al.,* 2002). During Leg 196 in the Nankai Trough offshore Japan, the scientific objectives focused on understanding the structural and hydrological evolution of the plate-boundary fault and determining the geographical extent and timing of progression of deformation (Mikada *et al.,* 2002). In both of these cases, logging while drilling (LWD) techniques helped in understanding the extent and geometry of subsurface structures.

The introduction of LWD techniques into ODP have brought to bear a critical technology on the collection of continuous geophysical records where, in the past, core recovery has been notoriously poor and wireline logging nearly impossible. As of April 2002, ODP had devoted seven legs to drill 22 LWD holes. Technological advancements have also provided more options for the type of the data being acquired during LWD operations. Recent deployments have used the borehole-imaging Resistivity at Bit (RAB) tool. This tool provides images of the borehole close to the bit with a vertical resolution of a few inches. Three, 1-inch button electrodes provide shallow, medium, and deep resistivity measurements as well as images, using the Earth's magnetic field as a reference while the drill string and RAB tool rotate. Processing of LWD images requires accurate timing and conversion of the raw electrical resistivity values into a continuous image.

Figure 1 shows images obtained through LWD and the type of information they provide. Leg 193 delineated probable fluid pathways within the system and provided constraints for a hydrological model using the fracture patterns observed in the LWD images. The images also show the relationship between volcanological, structural, and hydrothermal features in the PACMANUS hydrothermal system. In comparison to similar hydrothermal systems at mid-ocean ridges, Leg 193 results show distinct structural relationships associated with magmatic events and provide a basis for interpreting ancient ore environments. Leg 196 LWD results provided constraints on the distribution of physical properties and stress near the toe of the Nankai accretionary prism. The observation of the regional stress regime directly from LWD images corroborates, and perhaps quantifies, models for sediment accretion at plate boundaries. This information may also help to guide the selection of future drilling in the Nankai Trough. Our ability to use improved LWD techniques in active systems has proven essential for understanding environments where coring and wireline logging operations have been limited in the past.

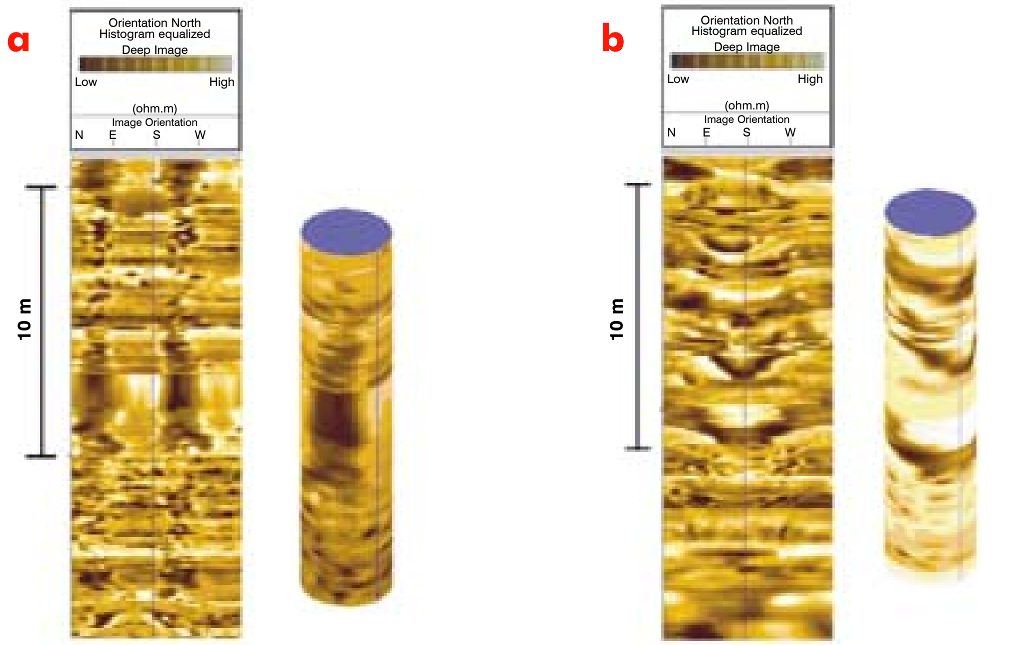
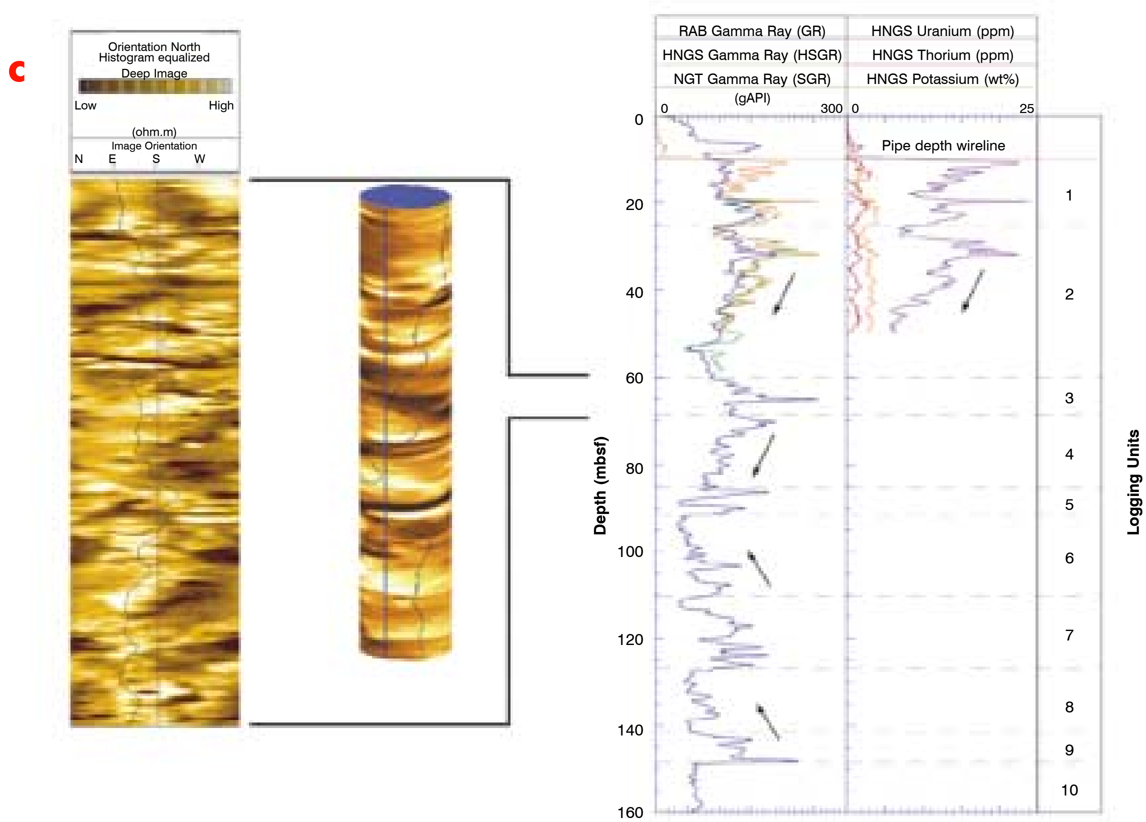


Figure 1. A series of Logging While Drilling (LWD) images obtained with the Resistivity at Bit (RAB) tool. **a)** Borehole breakouts indicative of the direction of minimum horizontal stress in the Nankai Trough. Both 2D and 3D perspectives illustrate their NE-SW orientation in consolidated clay-bearing sediments. This orientation is perpendicular to the maximum stress caused by the subduction processes in this area. **b)** Open dipping fractures near a fault zone in clay-bearing sediments from the Nankai Trough. **c)** A series of fractures and a gamma-ray curve superimposed on images from the Manus Basin. High gamma-ray values correlate with fractures and in many instances are indicative of uranium anomalies and high temperature fluid flow. Arrows show alteration trends.



Subseafloor "Rivers" of Fluid and Heat

Andrew Fisher, Institute for Geophysics and Planetary Physics and Department of Earth Sciences, University of California, USA

Fluids are present throughout Earth's crust and move vast quantities of heat and chemicals between oceanic and lithospheric reservoirs. Fluids contribute to production of continental crust, generation of explosive volcanism, lubrication of plate boundary faults, formation of hydrates and mineral resources, and development and support of biological communities. Some of the greatest challenges in marine hydrogeology are resolving the depths and distances over which flow occurs, and determining the nature of formation properties and driving forces that cause this flow. To meet this challenge, ODP scientists recognized the value of monitoring conditions within the seafloor, and developed technology to install observatories in a wide range of settings.

Several observatories have been installed at a seafloor spreading center in Middle Valley in the Pacific Ocean, off the western coast of North America (Figure 1). This is a place where new seafloor is created, so the observatories allow monitoring of "zero-age" crust. Two holes were drilled, cased and sealed in Middle Valley during ODP Leg 139, establishing the first long-term borehole observatories in the seafloor. Hole 858G was drilled in the Dead Dog vent field, within a few tens of meters of several clusters of active chimneys discharging fluids at temperatures up to 280 °C (Figure 2). Another hole (857D) was drilled 1.6 km south of the Dead Dog vent field through sediments and sills ("hydrothermal basement"). Geophysical and hydrogeological experiments were completed, and both holes were sealed with observatories (including temperature sensors, fluid samplers, and pressure gauges) and left to equilibrate. The observatories were visited by submersible and remotely-operated vehicles over several years, and reinstrumented during ODP Leg 169.

Pressure records downloaded from the observatories after 14 months suggested that, after correcting for differences in fluid density, the difference in fluid pressure between basement fluids in Hole 858G relative to fluids in Hole 857D was very small, equivalent to about 1-2 atmospheres of pressure. This small pressure difference is responsible for driving rapid flow of water to the vent field from the surrounding formation. This observation requires that hydrothermal basement below the vent field at this spreading center is extremely permeable (Figure 3).

Determining that basement permeability is very high is important because it means that small changes in pressure can travel long distances, and that fluids can move freely within the crust, greatly influencing the chemistry, biology and physical properties within the seafloor.

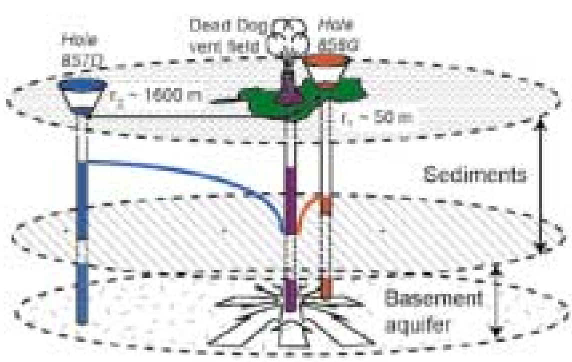


Figure 2

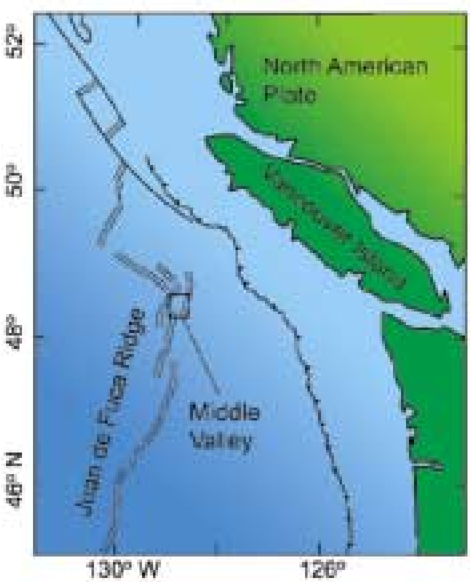


Figure 1

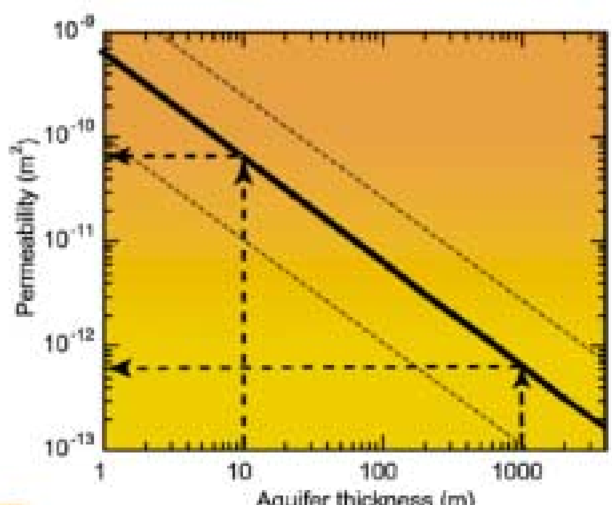


Figure 3

Watching Plates Move with CORK Observatories

Earl Davis, Pacific Geoscience Centre, Geological Survey of Canada; **Keir Becker,** Rosenstiel School of Marine and Atmospheric Science, University of Miami, USA

Beneath much of the seafloor of the world's oceans, formation fluids circulate through the igneous crust and overlying sediments, transferring heat and chemicals between the interior and exterior of the Earth. CORK (Circulation Obviation Retrofit Kit) instrumentation was originally developed to document this flow through observations of temperatures, pressures, and compositions of formation fluids made well after drilling ends. Over the first decade of CORK monitoring experiments installed in a variety of ODP holes, a number of observations have been made that range well beyond the original objectives of understanding fluid circulation.

One particularly exciting aspect of CORK results is the unanticipated information provided about plate deformation (extension, compression, shearing, faulting, etc.) and associated earthquakes. CORK records show that fluid pressure and temperature respond to tectonic deformation, which often involves earthquakes but may also occur aseismically. Theory developed to account for how fluid pressure responds to seafloor tidal loading (another outgrowth of CORK observations) can be applied with little modification to explain the response to tectonic deformation. In fact, the observations of the former provide an excellent calibration for the latter. Data from CORKS have also shown that long-lasting changes in mechanical and hydrologic properties, inferred from changes in the formation-pressure response to seafloor tidal loading, result from plate strain, most notably at sites that are close to the location of earthquakes.

Changes in fluid pressure have been observed at sedimented ocean crustal sites as far as 120 km from relatively small earthquakes in the vicinity of the Juan de Fuca Ridge (Figure 1). They show that regional plate strain is observed to be greater than that which would be generated by seismic slip alone. During a series of small earthquakes on the ridge axis that began with a magnitude 4.6 earthquake, the strain observed at four CORK sites was equivalent to that which would have been produced by a much stronger, magnitude 6 event. Most of the displacement of the "spreading event" that was the cause of the plate strain and earthquakes must have taken place aseismically. Thus, research from CORKS is helping to explain the relationship between episodic plate motion and deformation and earthquake energy release.

CORK monitoring continues on the axis and flank of the Juan de Fuca Ridge (where a new swarm of seismic activity has taken place recently), the flank of the Costa Rica Rift, and the Nankai and Mariana subduction zones. New installations were just completed at the Costa Rica subduction zone. It is our hope that long-term hydrologic monitoring at all of these sites will provide new knowledge and understanding of earthquake rupture and plate strain processes, and the role of water in both.

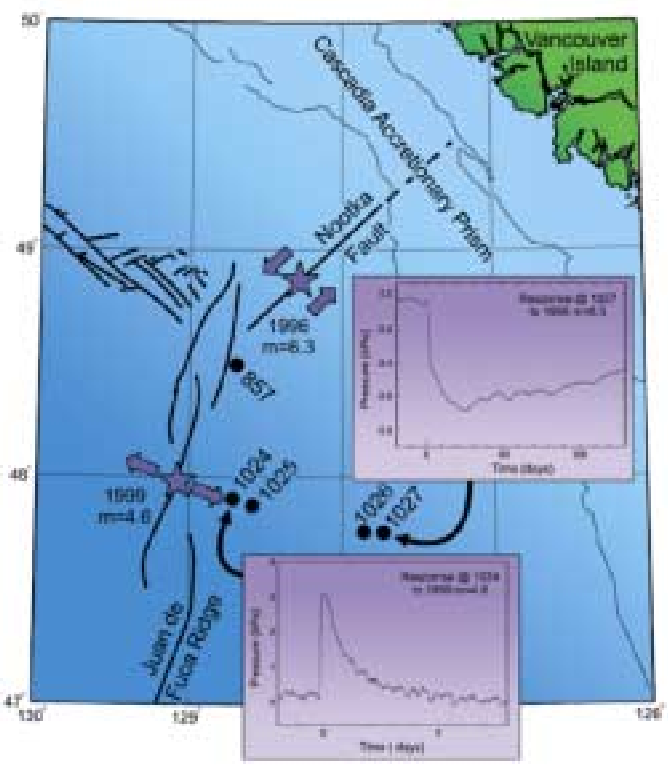


Figure 1. Examples of pressure changes through time associated with seismic fault slip events in 1996 and 1999 (Stars). Pressures increase where the formation is compressed and decrease where it is extended, then return to unperturbed levels at rates that depend at each site on routes for hydrologic "drainage". Pressure and temperature changes associated with earthquakes have been observed in all of the instrumented holes shown.

REFERENCES

Barker, P.F., and Camerlenghi, A., Synthesis of Leg 178 results: glacial history of the Antarctic Peninsula from Pacific margin sediments, in P.F. Barker, A. Camerlenghi, G.D. Acton, and A.T.S. Ramsay, Eds., *Proc. ODP, Sci. Res*., 178 [Online]. Available from World Wide Web: http://www-odp.tamu.edu/publications/178_SR/synth/synth.htm., 2002.

Becker, K., Morin, R.H., and Davis, E.E., Permeabilities in the Middle Valley hydrothermal system measured with packer and flowmeter experiments, in Davis, E.E., Mottl., M.J., Fisher, A.T., and Slack, J.F., Eds., *Proc. ODP Sci. Res*., 139, 613-626, 1994.

Binns, R.A., Barriga, F.J.A.S., Miller, D.J., *et al.*, 2002. *Proc. ODP, Init. Repts.,* 193 [Online]. Available from World Wide Web: http://www.-odp.tamu.edu/publications/193_IR/193ir.htm.

Brown, K.M. The nature and hydrogeologic significance of mud diapirs and diatremes for accretionary systems, *Journal of Geophysical Research*, 95, 8969-8982, 1990.

Cannariato, K.G. and Ravelo, A.C., Pliocene-Pleistocene evolution of the eastern Pacific surface water circulation and thermocline depth, *Paleoceanography,* 12, 805-820, 1997.

Cannat, M., How thick is the magmatic crust at slow spreading oceanic ridges? *Journal of Geophysical Research — Solid Earth*, 101, 2847-2857, 1996.

Davis, E., and K. Becker, Borehole observations record driving forces for hydrothermal circulation in young oceanic crust, *Eos, Trans. Am. Geophys. Union*, 79 (31), 369,377-378, 1998.

Derry L.A. and France-Lanord C., Neogene Himalayan weathering history and river 87Sr/86Sr: Impact on the marine Sr record. *Earth & Planetary Science Letters,* 142, 59-76, 1996.

Derry L.A. and France-Lanord C., Himalayan weathering and erosion fluxes: Climate and tectonic controls, in W. Ruddiman and W. Prell, Eds., *Global Tectonics and Climate Change*, 289-312, 1997.

Deyhle, A., and Kopf A., Deep fluids and ancient pore waters at the backstop: Stable isotope systematics (B, C, O) of mud-volcano deposits on the Mediterranean Ridge accretionary wedge, *Geology,* 29, 1031-1034, 2001.

Dick, H.J.B., *et al.*, A long *in-situ* section of the lower ocean crust: results of ODP Leg 176 drilling at the Southwest Indian Ridge, *Earth & Planetary Science Letters*, 179, 31-51, 2000

Erbacher, J., Huber, B.T., Norris, R., Markey, M., Intensified thermohaline stratification — a possible cause for Cretaceous oceanic anoxic events. *Nature*, 409, 325-327, 2001.

Exon, N.F., Kennett, J.P., Malone, M.J. *et al.*, *Proc. ODP, Init. Repts*., 189, 2001.

France-Lanord C. and Derry L. A., Organic carbon burial forcing of the carbon cycle from Himalayan erosion, *Nature*, 390, 65-75, 1997.

France-Lanord C. and Derry L.A., d13C of organic carbon in the Bengal fan: source evolution and transport of C3 and C4 plant carbon to marine sediments, *Geochimica et Cosmochimica Acta*, 58, 4809-4814, 1994.

Goldberg, D., The role of downhole measurements in marine geology and geophysics, *Reviews of Geophysics*, 35-3, 315-342, 1997.

Haug, G.H., and Tiedemann, R., Effect of the formation of the Isthmus of Panama on Atlantic Ocean thermohaline circulation, *Nature* 393, 673-676, 1998.

Haug, G.H., Tiedemann, R., Zahn, R. and Ravelo, A.C., Role of Panama uplift on oceanic freshwater balance, *Geology,* 29, 207-210, 2001.

Higgins, G.E., and Saunders, J.B., Mud volcanoes; their nature and origin, *Verh. Naturf. Ges. Basel*, 84, 101-152, 1974.

Hilgen, F.J., Krijgsman, W., Langereis, C.G., and Lourens, L.J., Breakthrough made in dating of the geological record, *Eos, Trans. Am. Geophys. Union,* 78, 288-289, 1997.

Hovland, M., Francis, T., Claypool, G. and Ball, M., Strategy for scientific drilling of marine gas hydrates, *JOIDES Journal*, 25(1), 20-24, 1999.

Huybrechts, P., Glaciological modelling of the Late Cenozoic East Antarctic ice sheet: stability or dynamism, *Geografiska Annaler*, 75A, 221-238, 1993.

Jones, C.E., and Jenkyns, H.C., 2001. Seawater strontium isotopes, oceanic anoxic events, and seafloor hydrothermal activity in the Jurassic and Cretaceous, American Journal of Science, 301: 112-149.

Kennett, J.P., Houtz, R.E. *et al.*, *Init. Reps. DSDP*, 29, 1975.

Kerr, A.C., 1998. Oceanic plateau formation: a cause of mass extinction and black shale deposition around the Cenomanian-Turonian boundary? Journal of the Geological Society, 155: 619-626.

Kopf, A., Fate of sediment during plate convergence at the Mediterranean Ridge accretionary complex: volume balance of mud extrusion versus subduction-accretion, *Geology,* 27, 87-90, 1999.

Kopf, A., Klaeschen, D., and Mascle, J., Extreme efficiency of mud volcanism in dewatering accretionary prisms, *Earth & Planetary Science Letters,* 189, 295-313, 2001.

Kopf, A., Robertson, A.H.F., Clennell, M.B., and Flecker, R., Mechanism of mud extrusion on the Mediterranean Ridge, *GeoMarine Letters* 18(3), 97-114, 1998.

Kuypers, M.M.M. *et al.*, Massive expansion of marine archae during a mid-Cretaceous oceanic anoxic event, *Science*, 293, 92-94, 2001.

Larson, R.L., and Erba, E., 1999. Onset of the mid-Cretaceous greenhouse in the Barremian-Aptian: igneous events and the biological, sedimentary, and geochemical responses, *Paleoceanography,* 14: 663-678.

Lear C. H., Elderfield H., and Wilson P. A., Cenozoic deep-sea temperatures and global ice volumes from Mg/Ca in benthic foraminiferal calcite, *Science,* 287, 269-272, 2000.

Lourens, L.J., Wehausen, R., and Brumsack, H.-J., Geological constraints on tidal dissipation and dynamical ellipticity of the Earth over the past three million years, *Nature*, 409, 1029-1033, 2001.

Loutre, M.-F., Sediments to planetary motion, *Nature,* 409, 991-992, 2001.

Mikada, H., Becker, K., Moore, J.C., Klaus, A., *et al.*, 2002. *Proc. ODP, Init. Repts.,* 196 [Online]. Available from World Wide Web: http://www.-odp.tamu.edu/publications/196_IR/196ir.htm.

Moore, J.C., and Vrolijk, P., Fluids in accretionary prisms, *Reviews of Geophysics,* 30, 113-135, 1992.

O'Brien, P.E., Cooper, A.K., and Richter, C., *et al.*, *Proc ODP, Init. Repts*., 188, 2001.

Robertson, A.H.F., Scientific Party of ODP Leg 160, Mud volcanism on the Mediterranean Ridge: Initial Results of Ocean Drilling Program, Leg 160, *Geology,* 24, 239-242, 1996.

Rosenthal Y., Boyle E. A., and Slowey N., Environmental controls on the incorporation of Mg, Sr, F and Cd into benthic foraminiferal shells from Little Bahama Bank: prospects for thermocline paleoceanography, *Geochimica et Cosmochimica Acta* 61, 3633-3643, 1997.

Rossignol-Strick, M., African monsoons, an immediate climate response to orbital insolation, *Nature*, 304, 46-49, 1983.

Stein, J.S., and Fisher, A.T., Multiple scale of hydrothermal circulation in Middle Valley, northern Juan de Fuca Ridge: physical constraints and geologic models, *Journal of Geophysical Research*, 106 (B5), 8563-8580, 2001.

Wehausen, R., and Brumsack, H.J., Chemical cycles in Pliocene sapropel bearing and sapropel barren eastern Mediterranean sediments, *Palaeogeogr., Palaeoclimatol., Palaeoecol*., 158, 325-352, 2000.

Wehausen, R., and Brumsack, H.J., Cyclic variations in the chemical composition of Eastern Mediterranean sediments: A key for understanding sapropel formation, *Marine Geology*,153, 161-176, 1999.

Wignall, P.B., 2001. Large igneous provinces and mass extinctions, *Earth Science Reviews,* 53: 1-33.

Whitmarsh R.B., Manatschal G. and Minshull T.A., Evolution of magma-poor continental margins from final rifting to seafloor spreading, *Nature*, 413,150-154, 2001.

Zachos, J, *et al.*, Trends, rhythms and aberrations in global climate, 65 Ma to present, *Science*, 292, 686-693, 2001.

Zoback, M., Moos, D., Mastin, L., and Anderson, R.N., Well bore breakouts and *in situ* stress, *Journal of Geophysical Research*, 90, 5523-5530, 1985.

Where can I learn more about specific ODP legs? Are the scientific results of each leg published?

In addition to appearing in scientific journals worldwide, ODP science is published in four stages: **Scientific Prospectus:** A precruise plan is published two to three months before each cruise. **Preliminary Report:** A summary of the shipboard scientific results and technical operations is issued two to three months after each cruise. **Proceedings of the Ocean Drilling Program, Initial Reports:** A detailed summary of the scientific and engineering results including visual core descriptions and core photographs is published one year postcruise. **Proceedings of the Ocean Drilling Program, Scientific Results:** A series of peer-reviewed papers that describe the results of shore-based studies related to a leg. Reports are available on the web <http://www-odp.tamu.edu/publications/> or through the ODP Science Operator Texas A&M University. In addition, a database with more than 18,000 citations related to scientific ocean drilling is available online at <http://odp.georef.org/dbtw-wpd/qbeodp.htm>

Can I use the cores for scientific research? How?

Samples of ODP cores are stored in four repositories — three in the United States and one in Germany — and are available for scientific research. The exact procedure for obtaining cores, including the location of the cores and contact information for the repositories, is explained on the Science and Curation Services website <http://www-odp.tamu.edu/curation/>.

Where did the money come from to fund ODP?

International participation in this scientific ocean drilling effort is one of its most distinctive features. Funding for ODP was provided by eight international members representing over 20 countries: United States; Germany; Japan; the United Kingdom; the Australia/Canada/Chinese Taipei/Korea Consortium for Ocean Drilling; the European Science Foundation Consortium for Ocean Drilling (Belgium, Denmark, Finland, Iceland, Ireland, Italy, The Netherlands, Norway, Portugal, Spain, Sweden, and Switzerland); the People's Republic of China; and France.

If ODP is so successful, why did it end in September 2003?

As the *JOIDES Resolution* completed its final ODP expedition in 2003, scientists knew that ocean drilling research was not complete. Research on ODP cores did not end at this time, only the active phase of drilling. The winding down of ODP was scheduled many years ago, when scientists realized that ocean drilling would continue to evolve and a new program would be needed to continue advancing deep ocean research. A new program, the Integrated Ocean Drilling Program, began in October 2003 to build upon and advance discoveries made during ODP.

How do I learn more about ODP's successor, the Integrated Ocean Drilling Program? How do I become involved in IODP?

The IODP <http://www.iodp.org> website provides general information about IODP, its vessels, how to submit proposals, and apply to sail.

CREDITS

Editors
Kasey White, Science Writer/Outreach Coordinator, Joint Oceanographic Institutions

Elspeth Urquhart, International Liaison, JOIDES Office

Review Process
Science Steering and Evaluation Panels: Interior (ISSEP) and Environment (ESSEP) led by Timothy B. Byrne, ISSEP Chair and Gilbert F. Camoin, ESSEP Chair

ODP Photos
ODP/TAMU Photography Department

Additional Images
Earth Temperature Image (p. 10), Research Systems, Inc.; Images of Earth, NASA; Preliminary concept for "Life of a Core" and source image for "ODP Leg Map", Jennifer Anziano, Joint Oceanographic Institutions

Design
De Atley Design

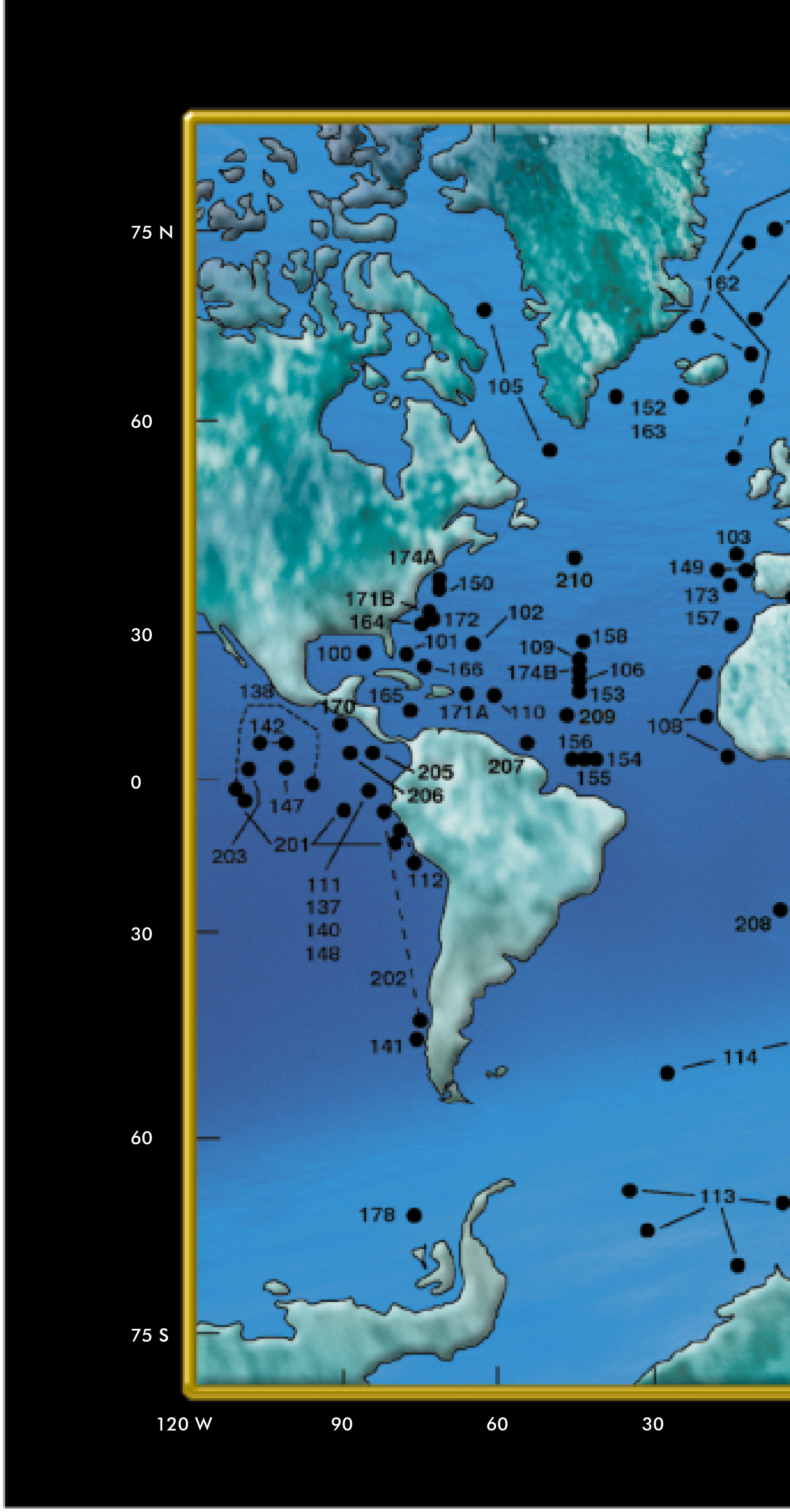
Publication of *ODP Highlights* was supported by the Ocean Drilling Program under the sponsorship of the National Science Foundation and participating member countries. Reprints of *ODP Highlights* were supported by the U.S. Science Support Program. Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of NSF.

CONTACTS FOR MORE INFORMATION

Joint Oceanographic Institutions
1201 New York Avenue, NW, Suite 400
Washington, DC 20005
http://www.joiscience.org

ODP Logging Services
Borehole Research Group
Lamont-Doherty Earth Observatory
PO Box 1000, Route 9W
Palisades, NY 10964
http://www.ldeo.columbia.edu/BRG/ODP/

ODP Science Operator
Texas A&M University
1000 Discovery Drive
College Station, TX 77845-9547 USA
http://www-odp.tamu.edu/



ODP Legs
100-210

Joint Oceanographic Institutions

1201 New York Avenue, NW

Suite 400

Washington, DC 20005, USA

Phone: (202) 232-3900

Fax: (202) 462-8754

http://www.joiscience.org

December 2004