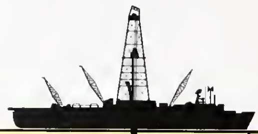
Oceanus

Volume 36, Number 4, Winter 1993/94

25 Years of Ocean Drilling



Geological Time Scale
25 Years of Ocean Drilling

Era	Period	Period or epoch and its length	Beginning (years ago)	Development of life on the earth
CENOZOIC ERA	*Quaternary Period*	Holocene Epoch *10 thousand years*	10 thousand	Humans hunt and tame animals, develop agriculture, use metals, coal, oil, gas, wind and water power, and other resources
CENOZOIC ERA	*Quaternary Period*	Pleistocene Epoch *2 million years*	2 million	Modern humans develop and mammoths, woolly rhinos, and other animals flourish but die out near end of epoch
CENOZOIC ERA	*Tertiary Period*	Pliocene Epoch *3 million years*	5 million	Sea life, birds, and many mammals similar to modern ones spread around the world, humanlike creatures appear
CENOZOIC ERA	*Tertiary Period*	Miocene Epoch *19 million years*	24 million	Apes in Asia and Africa, other animals include bats, monkeys, whales, primitive bears and raccoons; flowering plants and trees resemble modern ones
CENOZOIC ERA	*Tertiary Period*	Oligocene Epoch *14 million years*	38 million	First primitive apes, development of camels, cats, dogs, elephants, horses, rhinoceroses, and rodents; huge rhinoceroslike animals disappear near end of period
CENOZOIC ERA	*Tertiary Period*	Eocene Epoch *17 million years*	55 million	Plentiful birds, amphibians, small reptiles, and fish joined by primitive bats, camels, cats, horses, monkeys rhinoceroses, and whales
CENOZOIC ERA	*Tertiary Period*	Paleocene Epoch *8 million years*	63 million	Flowering plants plentiful; invertebrates, fish, amphibians, reptiles, and mammals common
MESOZOIC ERA		Cretaceous Period *75 million years*	138 million	First flowering plants; horned and armored dinosaurs common; plentiful invertebrates, fish, and amphibians; dinosaurs disappear at end of period
MESOZOIC ERA		Jurassic Period *67 million years*	205 million	Dinosaurs at maximum size; first birds, shelled squid; mammals are small and primitive
MESOZOIC ERA		Triassic Period *35 million years*	240 million	First turtles, crocodiles, dinosaurs, and mammals; fish resemble modern kinds
PALEOZOIC ERA		Permian Period *50 million years*	290 million	First seed plants (cone-bearing trees)
PALEOZOIC ERA	*Carboniferous Period*	Pennsylvanian Period *40 million years*	330 million	First reptiles, giant insects live in forests where coal later forms; plentiful fish, amphibians, scale trees, ferns, and giant rushes
PALEOZOIC ERA	*Carboniferous Period*	Mississippian Period *30 million years*	360 million	Many coral reefs and abundant crustaceans, fish, and amphibians; trilobites nearly gone
PALEOZOIC ERA		Devonian Period *50 million years*	410 million	Swampy forests, the first amphibians and insects, and many fish, including sharks, armored fish, and lungfish
PALEOZOIC ERA		Silurian Period *25 million years*	435 million	Spore-bearing land plants appear
PALEOZOIC ERA		Ordovician Period *65 million years*	500 million	Tiny graptolites in branching colonies join the common trilobites, mollusks, and corals
PALEOZOIC ERA		Cambrian Period *70 million years*	570 million	Trilobites, some mollusks, and jawless fish
Precambrian Time		*Almost 4 billion years (?)*	4.5 billion (?)	Bacteria about 3.5 billion years ago; coral, jellyfish, and worms in the sea 1.1 billion years ago

Source: The World Book Encyclopedia (1992)

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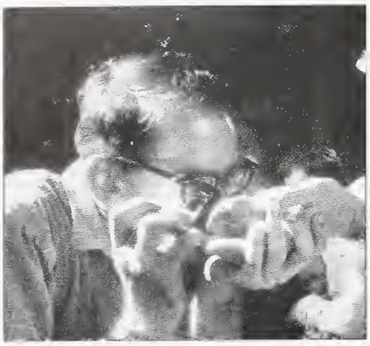
25 Years of Ocean Drilling



Fritz Goro

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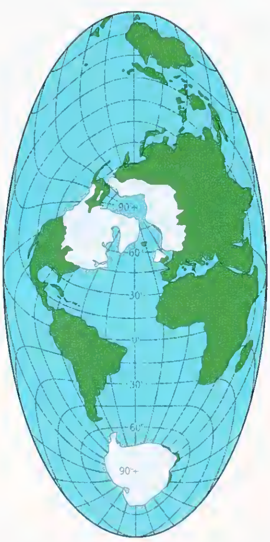

Jayne Doucette/WHOI Graphics

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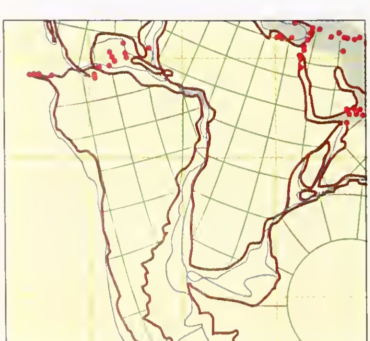

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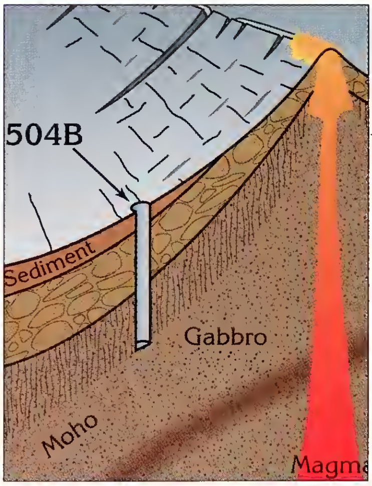

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This issue of *Oceanus* magazine is the last in its current format. Beginning with the Spring 1994 issue, the magazine will focus on research at the Woods Hole Oceanographic Institution rather than "international perspectives on our ocean environment."

Paid subscriptions will be fulfilled with a combination of the magazine in its revised format, the tabloid newsletter *Woods Hole Currents*, and *Ocean Explorer*, a lively newsletter written for junior-high-school-age students. Information about how to continue receiving these publications will be made available as *Oceanus* subscriptions expire.

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Oceanus

International Perspectives on Our Ocean Environment

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25 Years of Ocean Drilling

An Introduction

This section provides a general look at the accomplishment of 25 years of ocean drilling, a bit of history, a broad description and a personal account of drilling work at sea, a map of drill sites, a glossary, and brief comments from participating countries. A geological time scale is located on the inside front cover for easy reference.

The Times, They Are A-Changing

25 Years of Ocean Drilling

Bruce Malfait

The scientific return on the ocean drilling investment is abundantly obvious in the articles of this volume.

Change has been constant in the long and successful history of the ocean drilling programs supported by the US National Science Foundation and its international partners. During its 25-year history, ocean drilling has continually encountered new problems, new politics, and new programs. Each has been addressed through the scientific community's determination and commitment to preserving its capability to sample oceanic sediments and crustal layers. The scientific return on this past investment is abundantly obvious in the articles of this volume—and the potential returns from future investments promise to be equally rewarding.

The current Ocean Drilling Program (ODP) is the successor to the Deep Sea Drilling Project (DSDP), a global reconnaissance of the ocean basins. Although begun in 1968 as a US initiative, the program's remarkable success led to growing international participation and interest. In 1974, five nations (France, the Federal Republic of Germany, Japan, the United Kingdom, and the Soviet Union) accepted a formal commitment to cooperatively plan and conduct the project, as well as to financially support the operations. This International Phase of Ocean Drilling (IPOD) continued until 1983. Although *Glomar Challenger* had reached the limits of her capabilities, DSDP's remarkable scientific success, the new questions it had generated, and the international cooperation and focusing of research efforts it had spawned demanded an increased capability for drilling.

Within 18 months of *Challenger's* retirement, the Ocean Drilling Program (ODP) was organized, international participation was coordinated, and a new drill ship (*JOIDES Resolution*) was contracted and outfitted. It sailed for its first cruise in early 1985. This remarkable accomplishment reflects the enormous dedication of the Joint Oceanographic Institutions Inc. (prime contractor for ODP), Texas A&M University (science and ship operator), Lamont-Doherty Earth Observatory (logging operator) and the international science community to organize and plan the new program. With ODP, two new partners, Canada (later joined by Australia) and the European Science Foundation Consortium (representing 12 European countries), joined the list of nations providing scientific expertise and resources in addressing geologic and oceanographic problems on a global scale.

JOIDES Resolution has now operated in all oceans. It has drilled above the Arctic Circle and within sight of the antarctic continent. More than 1,200 scientists from 25 nations have sailed on the vessel. Larger scientific parties have allowed for increased student participation and training aboard ship. The state-of-the-art laboratories support rapid yet complete initial sample analyses that provide immediate scientific results that guide subsequent shore-based studies. Nearly 1,000 additional scientists have used these data and requested samples from the program's core and data archives for continuing study. The geochemical and geophysical logging capability (studies of the drill hole and its surroundings with a variety of instruments) is unsurpassed in either academia or industry, and has provided remarkable new data for earth studies.

What is the Future of Ocean Drilling?

The Ocean Drilling Program as presently structured will end within 10 years—however, our need to drill and sample ocean sediment and crust will continue. The ocean drilling community has begun to identify its future priorities and to forge direct links with a number of major new international initiatives that require ocean drilling. Expansion of the Global Seismic Network (for monitoring earthquakes) into the oceans is being closely coordinated with ODP. Recent drilling in the Arctic has supported implementation of the Nansen Arctic Drilling Program. ODP is recognized as a major contributor to the US Global Change Research Program because of its emphasis on climate and ocean history. ODP and the continental drilling communities are increasing their cooperation as they begin to face similar problems in drilling high-temperature environments and developing new logging and experiment programs.

The success of one drill ship has, of course, generated the need for additional platforms to expand the options available for addressing the scientific questions of the future. Japan has begun to plan construction of a next-generation drill ship [humorously] referred to in the ocean drilling community as *Godzilla Maru*. The new vessel would provide sampling capability for deep crustal and sedimentary holes, and allow deep drilling with a riser system (use of a second pipe surrounding the main drill string to circulate drilling fluids and prevent any oil or gas deposits encountered from "blowing out" the drillhole). In Europe a smaller drill ship is under discussion to focus on shallow drilling for sedimentary studies and experiments deployed in drill holes. The ability to drill in shallow water from jack-up platforms to address global sea-level history will be an important requirement in future ocean drilling. And, of course, *JOIDES Resolution* will be a highly capable ship into the next century.

Identifying the priority research questions to be addressed, justifying the proper mix of platforms to be used, and formulation of a new operational plan with increased international participation will be critical activities for the US and international communities in the coming years. Marshalling the necessary resources to support the next generation of ocean drilling will be an equally important task.

Bruce Malfait is the Program Director for the Ocean Drilling Program at the National Science Foundation, a position he has held since 1987. Malfait received his Ph.D. in marine geology at Oregon State University. He joined the National Science Foundation in 1974 as an Assistant Program Director in the International Decade of Oceanography Program. In 1980 he became an Associate Program Director in the Submarine Geology and Geophysics Program.

An Abridged History of Deep Ocean Drilling

Arthur E. Maxwell

In April 1961, CUSS I *drilled the first deep sea hole in 3,800 meters of water off Guadalupe Island, Mexico.*

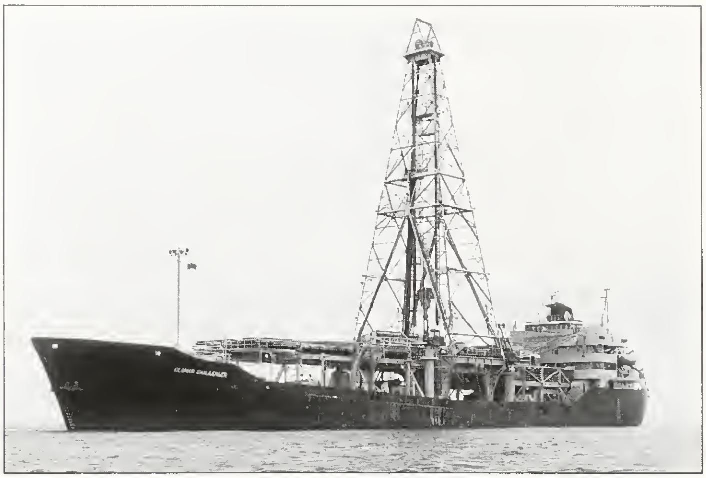
This issue of *Oceanus* concerns 25 years of ocean drilling for scientific purposes. However, the decade preceding these 25 years represents one of the most exciting and controversial periods of earth-science research. The full impact of the success of scientific ocean drilling would be incomplete without a brief recapitulation of this tumultuous period.

The Mohole

As near as can be reconstructed, the history of deep ocean drilling began in 1957, when Walter Munk (Scripps Institution of Oceanography) and Harry Hess (Princeton University) suggested that a combination of increased capability to drill deeply into the earth and continuing development of offshore drilling techniques would allow oceanographers to sample the material beneath the boundary of Earth's crust and mantle. This boundary, which lies about 10 kilometers below the ocean surface and some 30 to 40 kilometers beneath the top of the continental crust, is called the Mohorovicic discontinuity, after the Croatian geologist who first discovered it. More commonly, it is referred to as the Moho.

Later that year, several members of an informal group known as the American Miscellaneous Society refined the idea at a breakfast meeting at Walter Munk's La Jolla home. The unconventional American Miscellaneous Society, or AMSOC, was born in the Office of Naval Research in 1952, when a number of scientists formed a loose affiliation to look at the lighter side of heavier problems. Contrary to its normal modus operandi, AMSOC took seriously the initiative to drill to the Moho. An AMSOC committee was formed, and chaired by Gordon Lill of the Office of Naval Research. Next, AMSOC submitted a proposal for a feasibility study to the National Science Foundation (NSF), only to be turned down, not because of the proposal's merit, but for lack of a formal organizational structure. Not to be disenfranchised, the AMSOC committee reestablished itself as an official National Academy of Sciences/National Research Council committee and resubmitted the proposal—this time successfully. Thus, the AMSOC Mohole project was born.

Willard Bascom (a specialist in ocean engineering on the National Academy staff) became major-domo of the project and immediately set off to prove feasibility. His tack was to utilize a barge, *CUSS I*, originally owned by Continental, Union, Shell, and Superior oil companies and recently acquired by the newly established Global Marine Exploration company. *CUSS I*'s main assets were a drilling rig plus four large outboard motors for positioning the barge in deep water. In April 1961, *CUSS I* drilled the first deep sea hole in 3,800 meters of water off Guadalupe Island, Mexico. The hole penetrated about 200 meters of sediment with ages up to 25 million years, and beneath that recovered 14 meters of basalt. This represented the first verification that layer "2" under the ocean floor was basalt, and proved the concept of deep sea drilling. It was indeed a momentous occasion.



DSDP/WHOI Archives

In August 1968, Glomar Challenger *began the first of DSDP's epic 96 legs. From 1968 until 1983, the ship traveled over 600,000 kilometers, covering the world's oceans and collecting more than 97 kilometers of core. The scientific results from these cruises can only be described as nothing short of revolutionary.*

Following this heady success, AMSOC recommended proceeding to the next goal—the Moho. However, this recommendation carried with it a seed of dissent that later grew to proportions nearly fatal to ocean drilling. The dissent centered on the question of whether there should be a single ship designed to drill all the way to Moho, or whether the Moho ship should be preceded by a vessel designed primarily for coring sediment and developing the prerequisite skills for deep ocean drilling. With a scientific community nearly equally divided on these two strategies, trouble was inevitable. Nonetheless, the extent of the subsequent conflagration was anticipated by none.

In spite of its initial successes, other factors caused AMSOC to lose its favored lead-role position in the Moho project by late 1961, and the AMSOC group was relegated to advisory capacity, forcing NSF to seek a new prime contractor. The project's lucrative financial and prestige factors brought a large industry response, including some unlikely partners. There were five leading contenders: a partnership of Socony Mobil Oil, Texas Instruments, General Motors, and Standard Oil of California; another of Global Marine Exploration, Shell Oil, and Aerojet-General; plus the individual companies Brown and Root; Zapata Off-Shore; and General Electric. Competition was intense, with members of the California, Colorado, and Texas congressional delegations actively supporting their constituents. After thorough and repeated reviews, including considerable wrangling at high government levels, NSF selected Brown and Root to be the prime contractor. Because Brown and Root had not ranked highly in early evaluations of bids, protests were loud and many. Much attention was drawn to the fact that Brown and Root was located in the Texas congressional district of Albert Thomas, who at the time was chairman of NSF's appropriations committee. Texas was also the home state of then Vice President Lyndon B. Johnson. What should have been a routine governmental contract negotiation had suddenly become a *cause célèbre*.

Simultaneous with the unfolding contractual controversies, the scientific community was engaged in what might be considered open warfare over the one-ship/two-ship issue. Ironically, the primary proponents for each strategy were both located at Princeton, namely, Harry Hess (professor), who opted for proceeding directly to Moho, and Hollis Hedberg (part-time professor and vice president for exploration at Gulf Oil Corporation) for the intermediate sediment coring approach. The issue was hotly debated in journals and at scientific meetings, each side essentially accusing the other of scientific chicanery. It was not science at its most glorious moment. In the end, NSF decided there would be a single ship that would drill sediments as its first phase. This decision satisfied few. Brown and Root, as prime contractor, proceeded with a single-ship design utilizing the relatively new semisubmersible technology. The initial cost estimate was $47 million, more than double AMSOC's original estimate. This proved to be a harbinger of more escalations. In 1965, a San Diego shipyard was selected to build the Brown and Root design at a cost of $30 million; by this time the estimated overall cost of the project was $127 million. This factor-of-six escalation over initial AMSOC estimates caused alarm in both the scientific community and Congress, so much so that Congress passed a law in 1966 forbidding NSF to proceed. Project Mohole was officially dead.

JOIDES, DSDP, and IPOD

After such intense and divisive activity, the speed of reconciliation was surprising. Even before Mohole's official demise, the four major oceanographic laboratories, Scripps, Woods Hole Oceanographic Institution (WHOI), University of Miami Institute of Marine Sciences, and Lamont Geological Observatory of Columbia University, under the respective leadership of Roger Revelle, Paul Fye, F.G. Walton Smith, and Maurice Ewing, united to form Joint Oceanographic Institutions for Deep Earth Sampling (JOIDES). In 1965, Lamont proposed that JOIDES use the drill ship *Caldrill* off Florida. Anxious for unity, NSF supported this JOIDES effort. Its success led NSF to encourage JOIDES to continue. In 1966, Scripps was designated as the operating member of JOIDES and was given a $12.6 million NSF contract to establish the Deep Sea Drilling Project (DSDP).

In August 1968, *Glomar Challenger,* operated by Global Marine Exploration, began the first of DSDP's epic 96 legs. From 1968 until 1983, *Glomar Challenger* traveled over 600,000 kilometers, covering the world's oceans and collecting over 97 kilometers of

Roger Revelle, right, and Bill Riedel (both of Scripps Institution of Oceanography) aboard CUSS 1 *examine basalt recovered during Mohole drilling in 1962. The rock came from the first deep sea hole drilled, off Guadalupe Island, Mexico.*

Fritz Goro

core. The scientific results from these cruises far exceeded expectations; they can only be described as nothing short of revolutionary. During this period, major advances were also made in deep sea drilling technology. In the mid-1970s, DSDP changed its character and name when non-US participants joined JOIDES in providing scientific guidance and support for the program. These countries included: the USSR, the Federal Republic of Germany, Japan, the United Kingdom, and France. With the inclusion of official international participation, DSDP became known as the International Phase of Ocean Drilling or IPOD.

Ocean Margin Drilling

DSDP

The author, center, along with Jim Dean, foreground, and Dick Von Herzen, Co-Chief Scientist, removing a core aboard Glomar Challenger *on DSDP Leg 3 in 1968.*

Shortly after IPOD's inception in 1976, the US members of JOIDES, which by now numbered nine, incorporated to form Joint Oceanographic Institutions Incorporated (JOI). In 1993, the JOI members are: Scripps Institution of Oceanography, Lamont-Doherty Earth Observatory (LDEO), University of Hawaii's School of Ocean and Earth Science and Technology, University of Miami's Rosenstiel School of Marine and Atmospheric Science, Oregon State University's College of Oceanography, University of Rhode Island's Graduate School of Oceanography, Texas A&M University's College of Geosciences and Maritime Studies, University of Texas's Institute for Geophysics, University of Washington's College of Ocean and Fishery Sciences, and Woods Hole Oceanographic Institution.

This was a first step in restructuring the management of ocean drilling. JOI assumed the legal role of management. Actual planning still involved all participants through a JOIDES executive committee. The executive committee, in turn, established a planning committee and a series of panels to provide scientific and technical advice. As the IPOD phase of ocean drilling was approaching its planned 1979 conclusion, a long-range plan was deemed essential. Consequently, the JOIDES executive committee convened the first of several meetings on the future of scientific ocean drilling (FUSOD) in Woods Hole in 1977. The meeting, noting the past great scientific successes of the program, recommended that a different vessel, *Glomar Explorer*, constructed in the early 1970s for a failed attempt to raise a Soviet submarine that sank in the Pacific, be engaged to provide the increased capability required by science. The Woods Hole meeting, combined with another in Houston (HUSOD), led to the formation of the Ocean Margin Drilling program (OMD) in 1980. OMD had significantly different aspects. First, there were to be a limited number of deep holes requiring riser or cased drillholes. This scenario carried OMD beyond the bounds of existing technology. Second, OMD was to be supported half by NSF and half by 10 petroleum companies: Atlantic-Richfield, Cities Service, Conoco, Exxon, Mobil, Pennzoil, Phillips, Standard of California, Sunmark Exploration, and Union. Following industry practice, as part of the planning, a synthesis was initiated of all data in the regions of interest. However, before this was completed, an apparent decision-making mismatch between government and industry—not the scientific caliber of the proposed program—caused industry to terminate its support in late 1981. At that time *Glomar Explorer* was dropped from further consideration as a drill ship. Surviving remnants of OMD are its atlases of regional data syntheses. Within a year OMD was born and dead, without drilling a single hole. Consequently, IPOD was extended to 1983. (As a footnote, OMD had been curiously silent about international participation.)

Ocean Drilling Program

Between 1987 and 1993, ODP has slowly transformed from a US program with international support to a truly international program.

Because OMD appeared not to include all IPOD participants, JOI resolved to plan a long-range, *international* program. An international Conference On Scientific Ocean Drilling (COSOD) was held in 1981 at the University of Texas. In 1983, Texas A&M University proposed a plan to use *SEDCO/BP 471*, which was larger, newer, and offered much greater capability than *Glomar Challenger*. The new program, known as the Ocean Drilling Program (ODP), with JOI as the prime contractor and Texas A&M as the science operator, was approved by all participants. *SEDCO/BP 471*, known to the scientific community as *JOIDES Resolution*, was outfitted with a seven-story scientific laboratory. Its first ODP cruise began in January 1985. Subsequently, in 1987, some 340 scientists from 20 countries participated in COSOD II, hosted by the European Science Foundation in Strasbourg, France. This meeting was convened to redefine the scientific objectives of ODP through 1993 and beyond.

Between 1987 and 1993, ODP has slowly transformed from a US program with international support to a truly international program. In addition to the US, participants at the present time include: Canada-Australia, France, Germany, Japan, the United Kingdom, and the European Science Foundation (representing Sweden, Finland, Norway, Iceland, Denmark, Belgium, the Netherlands, Spain, Switzerland, Italy, Greece, and Turkey). Many ODP activities are based outside the US. This internationalization has led to a significant strengthening of the program, and the next decade of ocean drilling is currently being planned.

The Deep Sea Drilling Legacy

The legacy left so far by the DSDP, IPOD, and ODP drilling programs, in addition to the manifold scientific and technical contributions, are some 182 volumes of reports requiring 9 linear meters of shelf space. Further, about 182 kilometers of core recovered from the drilling are available to scientists in repositories located at Scripps, L-DEO, and Texas A&M. Data from site surveys and down-hole logging associated with the drilling programs are housed in repositories at L-DEO. These data represent an incalculable future resource available to scientists worldwide.

As a founder of the American Miscellaneous Society, since 1957 Art Maxwell has cajoled many on the virtues of ocean drilling programs. But noting he has served time at the Scripps Institution of Oceanography, the Office of Naval Research, the Woods Hole Oceanographic Institution, and The University of Texas at Austin, he anticipates time off for good behavior. He is currently Director of the Institute for Geophysics at the University of Texas at Austin.

ODP

*The "JOIDES" in the ship's name stands for Joint Oceanographic Institutions for Deep Earth Sampling. The name reflects the international commitment from the program's 20 member countries. The "*Resolution*" honors an earlier ship, HMS* Resolution*, commanded more than 200 years ago by Capt. James Cook. Cook's intrepid explorations into the Pacific and Antarctic regions highlighted England's second great Age of Discovery.*

At left, JOIDES Resolution *works in choppy seas. Below, top to bottom, drill-floor crew members make up drill pipe, the hard-rock guide base is ready for descent to the seafloor, and drillers remove hard rock from the core barrel.*

ODP

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ODP

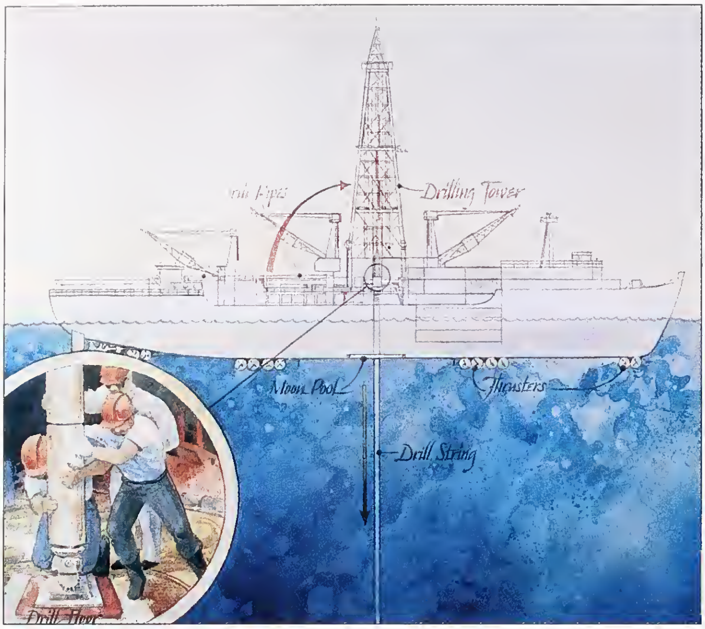
Work Aboard *JOIDES Resolution*

Vicky Cullen

The drillship *JOIDES Resolution* is outfitted with the most modern laboratory, drilling, and navigation equipment. The ship is 143 meters long and 21 meters wide, and its derrick rises 61.5 meters above the water line. A computer-controlled system regulates 12 powerful thrusters in addition to the main propulsion system to stabilize the ship over a specific drill hole located in water as deep as 8,235 meters. The drilling system can handle 9,150 meters of drill pipe, enough for drilling in all but the deepest parts of the world ocean.

In the most common drilling sequence, the four-coned tungsten-carbide roller bit that will cut into the seafloor is attached to the drill pipe along with its stabilizing weights. This assembly is lowered from the drill floor to the "moonpool," a seven-meter-diameter hole in the bottom of the ship, where it passes through a funnel-shaped guide horn into the water. The seven-member drill-floor crew employs various mechanical and hydraulic devices to extend the drill string down toward the seafloor. Twenty-eight and a

John Crompton



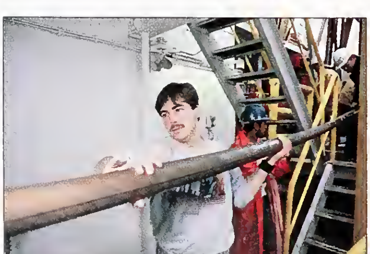
half meter lengths of pipe weighing 874 kilograms are moved from their racks, lifted by the drawworks at the base of the drilling tower, threaded onto the drill string, and then lowered. In 5,500 meters of water, it takes 12 hours for the drill bit to reach the seafloor. Just before its arrival, an electric motor begins to rotate the drill string to drive the core bit into the sediment. Surface seawater is pumped down the drill pipe to remove cuttings and cool the bit. The drill string is decoupled from the surface motion of the ship by a heave compensator, a huge shock absorber built into the derrick so that cores can be cut and lifted smoothly.

Above: Please see inside back cover for caption. Below: An ODP technician carries a 30-meter core from the drill floor to the cutting rack, where it will be cut into 1.5-meter sections (bottom photo).

An inner core barrel just above the bit at the bottom of the drill string is retrieved by a wire cable that travels down the center of the drill pipe. When the bit has advanced by an interval that matches the length of the inner core barrel (9.5 meters), the core barrel is pulled up through the drill string and delivered to the laboratory. Another core barrel is then lowered to receive the next core. It takes an hour and 40 minutes for a core barrel to make the round trip in 5,500 meters of water.

Drilling technique and equipment vary as different types of material are cored. When the target is soft sediment that would be considerably altered by the rotation of the drill bit, water pressure is used to drive the hydraulic piston corer developed by DSDP through the bit and into the sediment. When alternately hard and soft materials are encountered, a rotating extended core barrel pushes ahead of the bit in soft sediment and then retracts within the drill string when the core bit is needed to cut through harder material.

ODP



ODP

An important recent advance in technology now allows drilling in bare rock. Previously, at least 50 to 100 meters of soft sediment were required to stabilize the bottom of the drill string before hard rock could be drilled. With the new technique, a guide base filled with cement stabilizes the drill string, and specially designed drilling motors drive the bit without rotating the entire string. This process reduces damaging vibration and drill-string fatigue that would otherwise occur in coring young rock that has no sediment cover.

Each scientific cruise (called an ODP leg) lasts about two months. A normal shipboard party includes approximately 24 scientists, half from the US and two each from the other ODP partners. The scientific party typically includes the following:

- paleontologists who provide age determinations for cored sediment, and rock and environmental descriptions for the time of deposition based on the fossils found in the cores,
- sediment geologists who describe cores and provide compo-

sitional, environmental, and tectonic interpretations,
- petrologists who describe and classify the rocks recovered,
- magnetics specialists who study the magnetic reversals Earth has experienced as they are recorded in seafloor sediments and basement rock,
- geophysicists who consider the physical properties, such as density and heat flow, of the sediments and rocks and also interpret the general geologic setting of the site, and
- geochemists who study fluctuations of organic and inorganic material in the cores and monitor recovered samples for the presence of hydrocarbons.

An ODP technical support staff is responsible for collecting, recording, and preserving core materials and archiving routine scientific data. They also operate the shipboard computer system and maintain and repair laboratory and other equipment.

ODP shipboard operations run 24 hours a day with members of the scientific party standing 12-hour watches so that someone from each scientific discipline is always available. A well-established routine is initiated, night or day, when a core arrives in the laboratory in its plastic tube or "liner." It begins with measuring the length of the core, cutting it into sections for study and storage, coding the top and bottom of the core with colored caps, and clearly marking the liner with the core's original location on the seafloor.

The paleontology staff on duty immediately begins to examine fossils found at the bottom of the core to determine the age of the oldest material sampled. A chemist checks for gas pockets, bubbles, or frothing within the liner, indications of hydrocarbon presence. If these are found, drilling at the site is reevaluated and perhaps terminated. For safety reasons, every effort is made to avoid drilling into hydrocarbon accumulations that might erupt through the drillstring.

The core is then taken to the Physical Properties Laboratory where the Gamma Ray Attentuation and Porosity Evaluator (known as "the GRAPE") measures density by determining the amount of radiation able to pass through the core. Other physical measurements include determination of the strength of the cored material and of thermal conductivity for studies of the earth's heat flow.

When the whole-core analyses are completed, the core is split lengthwise, and the halves are moved to separate tables. One half becomes the working section and the other is preserved as the archive section. Small samples of the working half are removed according to the cruise sampling plan and the dictates of direct observation. The archive section is photographed and a geologist writes a rigorously detailed description of it before it is boxed for long-term storage under refrigeration.

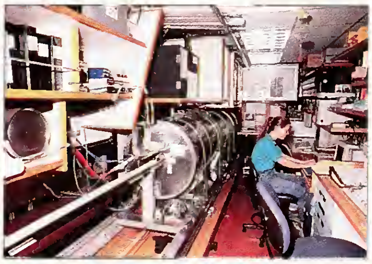
As initial analyses of each core are completed, the data are entered into the computer for display on terminals throughout the laboratory complex. Scientists working anywhere on the ship can track the arrival of new samples and become immediately involved in their analysis if appropriate.

Depending on the hardness of the sediments or rocks being cored and the depth of drilling, cores are delivered from the drill

Top to bottom, technicians measure a core's density, porosity, and velocity characteristics with the Multi-Sensor Track System, split cores lengthwise, use the cryogenic magnetometer to record magnetic reversals in a core, and employ the ship's extensive computer network.


ODP


ODP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Half of each core is preserved intact as the archive section, and the other half is extensively sampled and described. Thin sections (top photo, below) allow study of the finest core detail. Tiny flags in the bottom photo mark sampling locations.

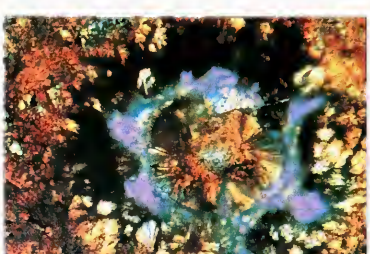
floor to the laboratories at intervals ranging from 20 minutes to five or six hours. Each one follows the routine described above before core samples are taken to specialized laboratories for intensive study.

In the Paleomagnetics Laboratory, a state-of-the-art magnetometer reads the record of Earth's magnetic field changes, information that helps determine the ages of rocks cored and at what latitude they were originally formed.

Paleontologists retreive microfossils from sediment samples with sieves, chemicals, filters, and centrifuges, in some cases recovering millions of tiny skeletons from a sample smaller than your thumb. Light microscopes are used to identify and examine fossil species at magnifications up to 2,000 times. This analysis provides information on the age of the sediment and climatic conditions at the time of its deposition. The climate and water conditions preferred by certain species can be inferred from the preferences of their living relatives. Then the conditions of ancient ocean represented by a section of core can be determined by identifying the proportions of similar fossil species found there. As shell forms common to certain periods of earth history become known, the fossils can be used to determine the age of the sediments in which they are found.

The finest details of rock and consolidated sediments are studied with thin sections of these materials cut with diamond saws and polished to a high gloss for study under special microscopes. Two of the four shipboard petrological microscopes can photograph the minerals, and each of the microscopes can be connected to a video camera so that scientists can view the thin section on a screen. Petrologists also study and classify mineral structures with an x-ray diffractometer, which identifies minerals by characteristic scattering patterns of x-rays passing through cored samples.

ODP



ODP

The Chemistry Laboratory is equipped for detailed analyses of the elements contained in sediments and rocks and in the water they contain. Determination of elemental variations along a core helps to reveal the history of the ocean recorded as the sediments were deposited over millions of years.

Once all core has been recovered from a particular drill site, the resulting borehole usually becomes a geochemical and geophysical laboratory itself. Characteristics of the layers of sediment and rock penetrated by the drill bit are determined with sophisticated instruments specially designed for this downhole work, which is called "logging." A discussion of downhole measurements begins on page 129.

Two Months Before the Derrick: Life Aboard *JOIDES Resolution*

Suzanne O'Connell

Why would anyone go to sea for two months? Leave the comforts of home and work, friends and family—especially family—for 64 days of exploring arctic ocean paleoclimate, sleeping on a bunk bed in a small, windowless room, sharing your life with people you barely know? Leaving children is especially hard—some people just won't do it. Still, there is no shortage of people willing to be part of a 28-person ODP scientific party. Some, despite the hardships, are almost regulars. On the Arctic Gateways Leg, one participant left his wife of three weeks, another an eleven-week-old baby. About half of the scientists had sailed before; for me and several others, it was the fifth cruise.

So why do it? Professionally the answer is easy: It's a chance to be part of the university of the seas. You have the opportunity to work with an international team of scientists, exploring critical questions about Earth's history. Everything is arranged to allow you to focus completely on your work, rather like an extended scientific retreat. If you're lucky, not only will you come away with answers and exciting new science questions, but also with new colleagues, people you will work closely with for the rest of your professional life.

But it is also a gamble, a sort of scientific lottery. Even though years of preparation are involved to ensure that the best sites are selected, there are always surprises. While surprises may enhance the science, they also can mean your particular interests go unfulfilled.

My most recent gamble ran from July 28 to September 24, 1993, as sedimentologist for Arctic Gateways, ODP Leg 151. From Saint John's, Newfoundland, we sailed past Iceland to the high northern latitudes. Though *JOIDES Resolution* has an ice-strengthened hull, a Finnish icebreaker accompanied us to scout for ice, protect us from ice flows, and, in the event of an emergency, rescue us.

Although the list of cruise objectives was extensive, I was particularly interested in investigating the relationship between the opening of many small arctic basins and our planet's major cooling during the last 50 million years. These small, drowned seas link the present-day Arctic Ocean with the North Atlantic, allowing cold Arctic Water to become part of North Atlantic Deep Water, and to have a major climatic influence as it flows south. Our goal was to use the cores retrieved from these basins to help us understand the initial cooling and the intense high-northern-latitude glacial and interglacial cycles that began roughly 3 million years ago and intensified 750,000 years ago. The entire shipboard

Top: Finnish icebreaker Fennica *holds back ice flow as* JOIDES Resolution *crew member performs hull maintenance. Bottom: Scientists and ship and operations personnel gather around "colorful" mid-Eocene cores at Site 913.*

Photos in this section courtesy of Suzanne O'Connell except as indicated party was there to address these questions, and each day's work brought us closer to the answers.

Everyone worked a 12-hour shift; mine was noon to midnight. Around 11:30 a.m., I'd hear the shower (shared with the adjacent room) turn on. When it stopped, I'd roll out of my top bunk, and, by way of desk and chair, make my way to the floor. Outside my door, the rumpled dirty clothes I'd left the night before would be cleaned and folded. A quick shower, dress, and I was off to the "lab stack," where there are seven tiers of science work spaces. I'd first stop by the x-ray lab where Wendy Autio, a marine specialist from Minnesota and also my roommate, had fresh coffee and a croissant waiting (the lab is also known as "Wendy's Hard Rock Cafe"). Of course, I could have gone to the galley, but the coffee there was terrible, too terrible even for a java junkie like me. Coffee and croissant in hand, I'd climb the stairs to the core lab. At the watch change it was usually bustling, with eight sedimentologists, four physical properties specialists, two paleomagnetists, two to four core samplers, and many technicians, as well as the odd "tourists"—people like geochemists, loggers, and co-chief scientists based elsewhere in the lab stack but passing through to see the cores and to hear the old watch briefing the new.

A marine technician prepares X-ray diffraction samples for mineralogy studies.

As the lab cleared after the watch change, we four sedimentologists would parcel out jobs. I'd usually start with smear slides, samples that fit on the head of a toothpick, the primary instrument for determining the type of sediment in a core. After swirling sediment and water on a glass slide, drying the sample on a hot plate, and covering it with optical cement or Canada balsam, I'd examine it under a microscope to estimate its sand, silt, and clay content, and then the composition percentage of such elements as quartz, feldspar, mica, glauconite, and various microfossils such as foraminifera, nannofossils, diatoms, and radiolaria. As I sat at my microscope, University of Miami physical properties specialist Julie Hood worked at a nearby computer. At this time of the day, she was often yelling the names of night-shift co-workers, lamenting data entries or calculations that made no sense to her. (By the end of the cruise, Julie's laments became a good-humored joke that we all shared and loved.)

Graduate students take a break in their 12-hour shift to practice juggling.

At 2 p.m., I took my two-hour turn at the sampling table, where the drill began with carefully recording the core location of each sample into the database. Then we sealed the sediment samples in plastic bags for shore-based studies, work that would go on for one to two years to answer questions that could be only loosely addressed during the cruise. My sampling partner, Jim Briskow, a British downhole logging specialist, was also a good juggler. My son is enamored of juggling, and I've always wanted to learn to juggle. So, during the weeks of the cruise, I slowly worked my way up to sometimes getting nine continuous passes of the three balls. Of course, other people wanted to learn too—Jerry McManus, a sedimentologist from Lamont-Doherty Earth Observatory, and David Williamson, a French paleomagnetist, both became very good. Annyk Myhre, the Norwegian co-chief scientist, was adept at juggling with two balls in one hand—she recommended that anyone who wanted to sail as a future co-chief scientist practice the two-handed juggle!

At 4 p.m. I became a sedimentologist again, trading places at the sampling table with Thomas Wolfe from Germany to begin describing cores. Depending upon the complexity of the core, this could take from 30 minutes to several hours. Generally, the most varied cores, requiring the most description, were retrieved at the start of the hole, where recovery is fastest. If cores arrived on deck every half hour and it took two hours to describe a core, there was bound to be a problem. However, coring went more slowly as the sediment became stiffer with depth, and several days were usually devoted to downhole logging once coring was completed, so we could catch up. We never had cores from the previous site still waiting to be described when the next site's cores began to arrive, though sometimes it was close.

After Thomas finished sampling, we'd all walk down the stairs to "The Portuguese Restaurant" (so named because the cooks are Portuguese). The menu, listed on a large white board, changed with every meal but always included cheese, bread (baked fresh daily), desserts, salads, and fruit. Garry Brass, a geochemist from the University of Miami, and Julie Hood usually joined us for dinner. The tables were meant for five, but since they were round, we sometimes managed eight. More than any other cruise I've been on, dinner on Leg 151 was a wonderful time to relax and tell jokes and stories.

Back in the core lab for the seven-to-midnight stretch brought a chance to really delve into the cores. Each new, unique core records a bit of earth's history, something that may never have been seen before or may never be seen again. I encountered a beautifully preserved Ordovician Rugosa coral dropstone in a core that couldn't be more than 3 million years old, thin beds of bright blue

JOIDES Resolution

Fo'c'sle Deck (forward)
Library, hospital, and living quarters

Deck 1: Hold
Refrigerated core storage and freezer

Deck 2: Lower 'Tween
Refrigerated core storage, cold storage, and second-look lab

Deck 3: Upper 'Tween
Electronics shop and photography lab

Deck 4: Main
Computers, computer-user room, science lounge, and offices

Deck 5: Fo'c'sle
Paleontology lab, microscope lab, chemistry lab, thin-section lab, and X-ray lab

Deck 6: Bridge
Core handling, sampling, and description, physical properties lab, and paleomagnetics lab

Deck 7: Lab House Top
Downhole measurements lab

Poop Deck (aft)
Underway geophysics lab

and purple clays, and black minerals that faded as I tried to describe them. Each core's information was put into a graphic database for publication in the *Initial Results* volume at the end of the cruise.

Shortly before midnight the lab would fill again as members of the midnight-to-noon shift appeared for the between-shift exchange of information. Occasionally, there was a midnight meeting of the entire scientific party to discuss the site just completed and to plan for the next sites, but midnight was usually decision time: dinner? the gym? the library? a movie? reports? and certainly, e-mail (electronic mail). I'd usually have something to eat, and then check my e-mail. Leg 151 was my first experience with shipboard e-mail. There had always been radio phone patches, but static on the line, having to say "over" each time you finished talking, and knowing any number of people both on and off the ship were listening made it less than ideal for all but the most minimal communication. On my first cruise, Leg 74, it didn't make much difference since there was no one I was particularly interested in calling. This leg was different as I had left a husband and child at home. Three-year olds do wonderful things, and dads describe them so well!

A micropaleontologist studies tiny fossils in a core sample to determine the age and origin of a particular core stratum.

ODP

Styrofoam cylinders replace core samples as they are removed.

Even on the best e-mail days, reading and responding rarely took more than an hour at the computer. With caloric intake high and life sedentary, I generally went to the gym at least every other day, but usually not until 2:30 or 3:00, when I could have the place to myself.

Many nights we spent some time writing reports on the work we'd been doing. Although few of us, if any, found writing easy, it certainly helped to solidify ideas, and because so much of the work was collaborative, the camaraderie made it a more pleasant experience. The four of us whose first language was English tended to do most of the writing, but everyone contributed to the discussions.

Scientists often work in isolation as they generate initial data sets, and then seek out other scientists with similar interests to discuss interpretations or obtain additional information. One of the real joys of working aboard *JOIDES Resolution* (or its predecessor, *Glomar Challenger)* is the sharing of information with people in your own and other fields. It must be one of the best places in the world to experience how different areas of science complement one another. For example, we sedimentologists could tell that material had been ice rafted, but we didn't know when. The paleontologists and paleomagnetists could identify the time for us. When we found unusual layers of sediment, we gave samples to the chemists and a day or so later they could provide its composition.

Another advantage of the ocean drilling program is the special opportunities it provides to women. I first heard about *Glomar Challenger* as an undergraduate at Oberlin College. Helen Forman, a radiolarian micropaleontologist and the wife of the former geology department chair, had been on several cruises. I don't think I ever met her, but I do remember that the male faculty spoke about her participation in the program with awe in 1972 and 1973, when the program was still young. It sounded wonderful to me, a personal and scientific adventure story, and at least one other Oberlin female student was also impressed: Kathy O'Neal was a seagoing curator aboard *Glomar Challenger* for several years, and her initial inspiration came from the same stories.

Twenty years later, here I am, having completed my fifth cruise and with my own credits for people—all women to my knowledge—who had their first introduction to this program through me: Audrey Meyer, former manager of science operations and current US Science Advisory Committee (JOI/USSAC) Chair; Gretchen Hampt, former seagoing curator and chemistry technician, and now graduate student at the University of California, Santa Cruz, soon to sail on Leg 154; and Sara Harris, a USSAC fellow and graduate student at Oregon State University, also scheduled to sail on Leg 154.

JOI/ODP

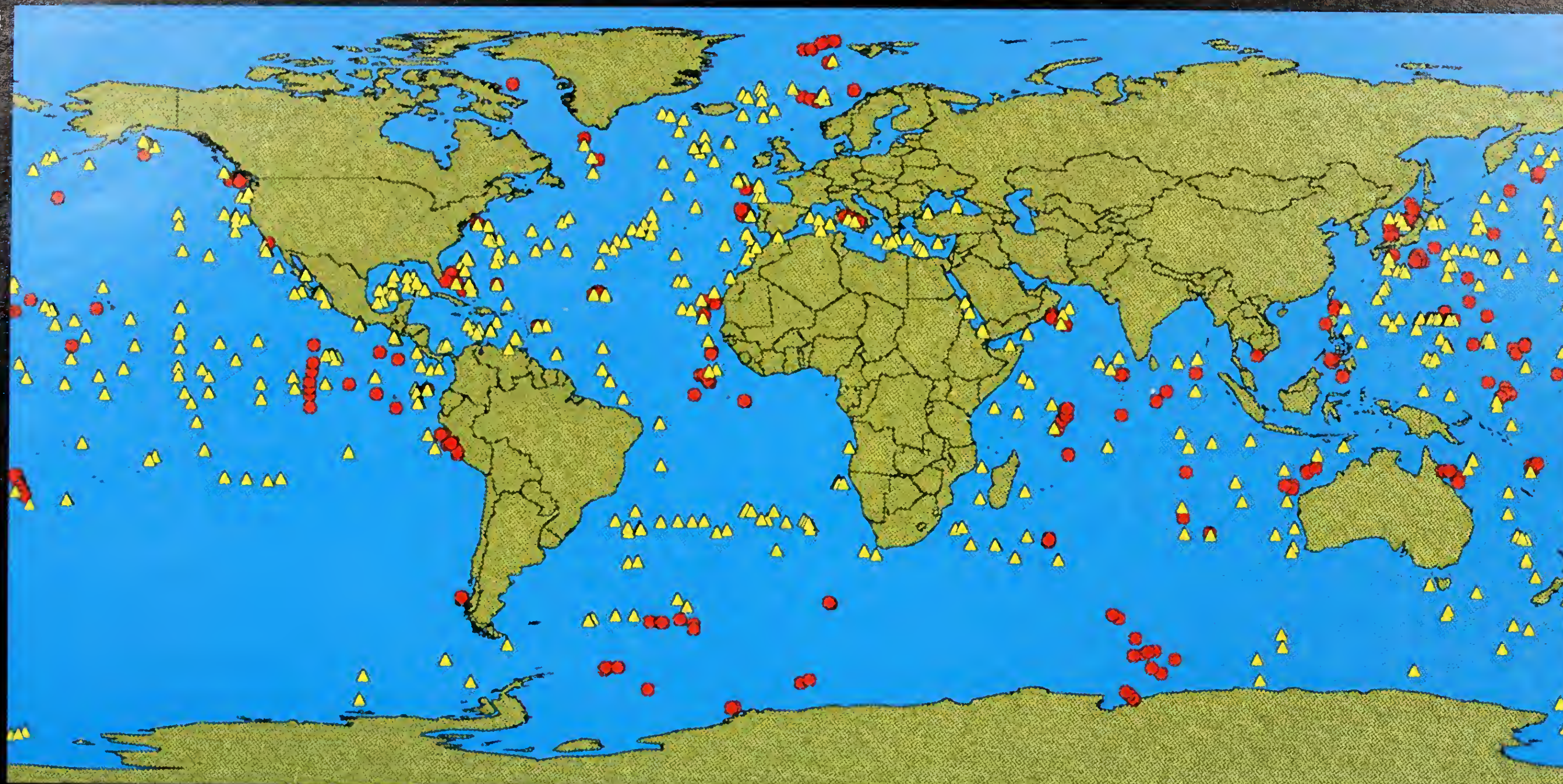
Some 80,000 meters of ODP cores are archived at Texas A&M University, Lamont-Doherty Earth Observatory of Columbia University, and Scripps Institution of Oceanography at the University of California, San Diego.

There are still no women among those who run the ship, do the drilling , or prepare the food, and as in the rest of the field, women are a minority in the science party; still, the program does offer women a wonderful way to begin and build a scientific career.

Participation in a cruise doesn't end with the docking of the ship. At the October 1993 Geological Society of America meeting in Boston, Massachusetts, I presented a paper entitled "Arctic Gateways—High Latitude Paleoenvironmental Change: Preliminary Results from ODP Leg 151." The post-cruise work will continue for many years as my colleagues and I build on the work begun during Leg 151 and share the ocean drilling experience with other scientists.

Vicky Cullen is manager of publications, graphic services, and public information as well as Editor of Oceanus *for the Woods Hole Oceanographic Institution. She also does occasional publication work for other oceanographic organizations and agencies; this description was written for a brochure on the Ocean Drilling Program published in 1987 by Joint Oceanographic Institutions Inc.*

Suzanne O'Connell grew up on an Ordovician carbonate continental shelf in western Massachusetts and went further west to college. Throughout the last two decades she has made repeated but unsuccessful attempts to leave college academics, and during this time accrued enough degrees to become a college professor. Currently at Wesleyan University, she tries to instill information about the blue part of our planet in both suspecting and unsuspecting students. On her most recent ODP leg she learned to juggle—somewhat.

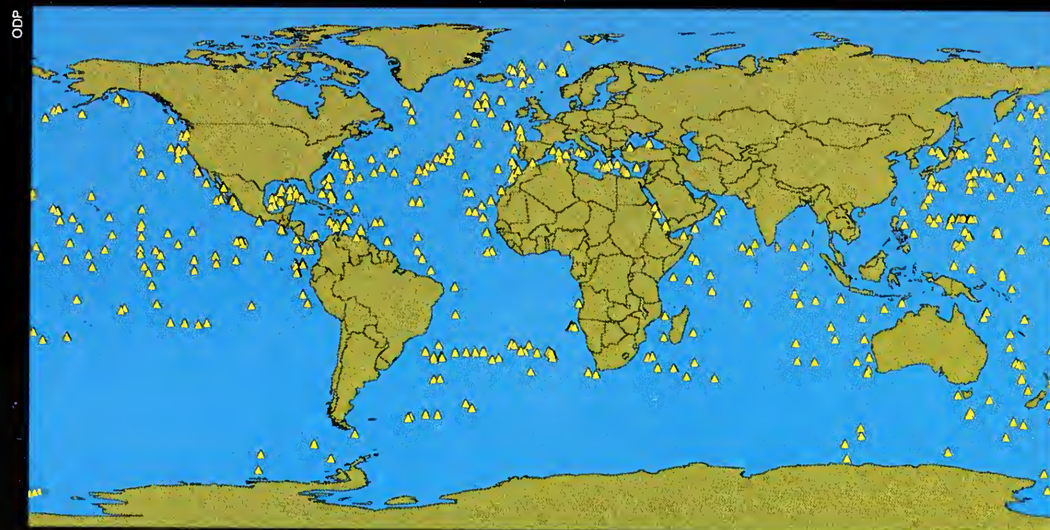


ODP

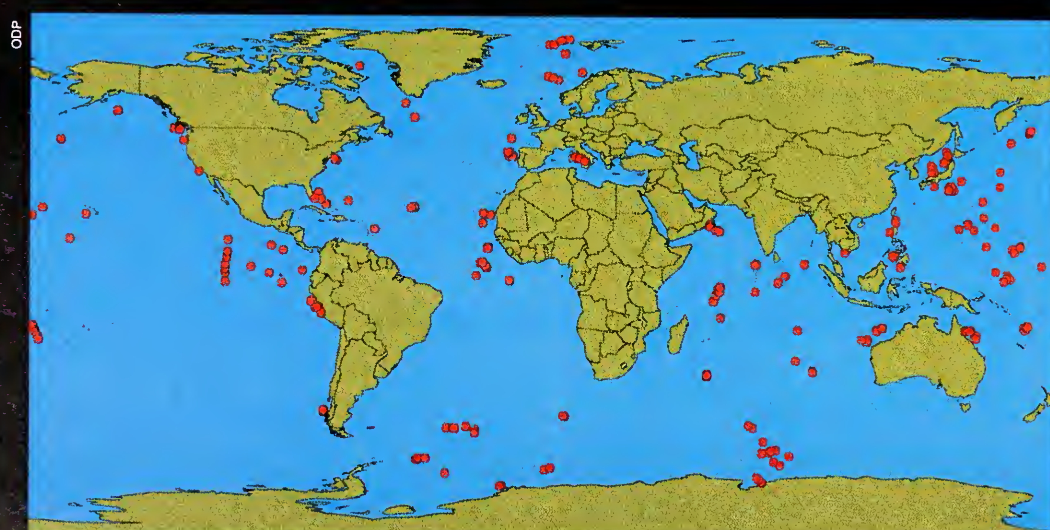
Deep Sea Drilling Project and Ocean Drilling Program Sites

Deep Sea Drilling Project and Ocean Drilling Program

Drill Sites 1968–1993



Deep Sea Drilling Project Sites



Ocean Drilling Program Sites

In the last 25 years, ocean drilling has provided information to thousands of scientists around the world. Begun in 1968 as a US initiative, the Deep Sea Drilling Project (DSDP) evolved into a multinational effort, the International Phase of Ocean Drilling (IPOD), in the mid-1970s. In 1983 the Ocean Drilling Program (ODP) began as an international program and today has 19 countries actively participating.

Nearly 2,000 holes have been drilled in over 900 sites around the world. The 182 kilometers of core recovered from these holes, along with the logging data collected after coring is completed, provide scientists with an invaluable scientific resource.

Deep Sea Drilling Project

Leg	Area	Sites (#Holes)	Core Recov'd
1968			
1	Gulf of Mexico	1-7 (11)	181.40 m
2	North Atlantic	8-12 (12)	216.20 m
3	South Atlantic	13-22 (17)	761.10 m
1969			
4	Central Atlantic	23-31 (16)	393.00 m
5	North Pacific	32-43 (14)	868.00 m
6	North Pacific	44-60 (35)	684.70 m
7	Central Pacific	61-67 (15)	934.00 m
8	Central Pacific	68-75 (15)	1,208.43 m
9	Central Pacific	76-84 (17)	1,540.10 m
1970			
10	Gulf of Mexico	85-97 (14)	732.00 m
11	North Atlantic	98-108 (15)	636.70 m
Reentry Trials		109-110	
12	North Atlantic	111-119 (13)	839.50 m
13	Mediterranean	120-134 (28)	640.53 m
14	Central Atlantic	135-144 (17)	406.10 m
15	Caribbean	146-154 (16)	1,227.00 m
1971			
16	Central Pacific	155-163 (12)	1,268.50 m
17	Central Pacific	164-171 (10)	905.00 m
18	North Pacific	172-182 (15)	1,215.06 m
19	Bering Sea	183-193 (16)	1,062.30 m
20	North Pacific	194-202 (13)	163.50 m
21	Tasman & Coral Seas	203-210 (14)	1,384.30 m
1972			
22	Indian Ocean	211-218 (11)	1,379.70 m
23	Arabian Sea	219-230 (17)	1,427.00 m
24	Indian Ocean	231-238 (11)	1,994.40 m
25	Indian Ocean	239-249 (13)	790.10 m
26	Indian Ocean	250-258 (13)	1,179.10 m
27	Indian Ocean	259-263 (5)	960.30 m
28	Ross Sea	264-274 (16)	1,406.30 m
1973			
29	Tasman Sea	275-284 (16)	1,181.93 m
30	South Pacific	285-289 (9)	1,162.00 m
31	Philippine Sea	290-302 (17)	1,233.80 m
32	North Pacific	303-313 (13)	737.20 m
33	North Pacific	314-318 (8)	887.10 m
34	South Pacific	319-321 (6)	231.00 m
1974			
35	Antarctic Ocean	322-325 (4)	192.00 m
36	South Atlantic	326-331 (10)	576.90 m
37	North Atlantic	332-335 (9)	415.30 m
38	Norwegian Sea	336-352 (18)	1,802.00 m
39	Atlantic	353-359 (11)	1,060.10 m
40	South Atlantic	360-365 (7)	1,502.00 m

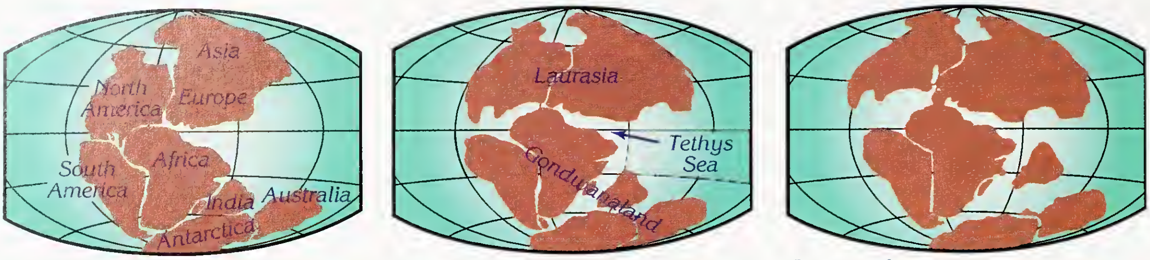
Leg	Area	Sites (#Holes)	Core Recov'd
1975 *(International Phase of Ocean Drilling Begins)*			
41	South Atlantic	366-370 (7)	1,673.00 m
42	Med., Aeg., Black Seas	371-381 (17)	1,944.00 m
43	North Atlantic	382-387 (6)	955.90 m
44	North Atlantic	388-394 (15)	577.10 m
45	North Atlantic	395-396 (3)	327.00 m
1976			
46	North Atlantic	396A-396B (2)	63.64 m
47	North Atlantic	397-398 (7)	1,813.10 m
48	North Atlantic	399-406 (10)	1,229.00 m
49	North Atlantic	407-414 (11)	881.00 m
50	North Atlantic	415-416 (5)	356.40 m
51	North Atlantic	417-,417A-D (5)	460.80 m
1977			
52	North Atlantic	417D-418A(3)	336.00 m
53	North Atlantic	418A-418B (2)	404.00 m
54	Central Pacific	419-429 (18)	459.20 m
55	North Pacific	430-433 (11)	406.60 m
56	North Pacific	434-437 (7)	497.00 m
57	North Pacific	438-441 (10)	1,415.50 m
58	Philippine Sea	442-446 (9)	1,591.10 m
1978			
59	Philippine Sea	447-451 (7)	1,160.40 m
60	North Pacific	452-461 (17)	833.20 m
61	Central Pacific	462 (2)	726.00 m
62	North Pacific	463-466 (5)	635.00 m
63	Gulf of California	467-473 (11)	1,522.20 m
64	Gulf of California	474-481 (14)	1,632.70 m
1979			
65	Gulf of California	482-485 (15)	750.00 m
66	Central Pacific	486-493 (14)	1,838.50 m
67	Central Pacific	494-500 (15)	1,192.49 m
68	Central Pacific	502-503 (8)	860.78
69	Central Pacific	504-505, 501 (7)	455.61 m
70	Central Pacific	506-510, 504B (33)	478.84 m
1980			
71	South Atlantic	511-514 (6)	822.80 m
72	South Atlantic	515-518 (12)	1,543.95 m
73	South Atlantic	519-524 (13)	1,049.40 m
74	South Atlantic	525-529 (11)	1,830.70 m
75	South Atlantic	530-532 (8)	1,443.49 m
76	North Atlantic	533-534 (4)	982.10 m
77	Gulf of Mexico	535-540 (8)	1,077.70 m
1981			
78	North Atlantic	541-543, 395A,B (8)	841.00 m
79	North Atlantic	544-547 (9)	1,088.50 m
80	North Atlantic	548-551 (8)	1,480.00 m

Leg	Area	Sites (Holes)	Core Recov'd
81	North Atlantic	552-555 (8)	1,180.30 m
82	North Atlantic	556-564 (10)	757.00 m
83	Central Pacific	504B (1)	107.00 m
1982			
84	Central Pacific	565-570 (11)	1,042.50 m
85	Central Pacific	571-575 (17)	2,073.60 m
86	North Pacific	576-581 (11)	954.50 m
87	North Pacific	582-584 (14)	1,176.00 m
88	North Pacific	581 (3)	44.60 m
89	Central Pacific	585-586, 462A(7)	872.20 m
90	Coral & Tasman Seas	587-594 (18)	3,707.00 m
1983			
91	Central Pacific	595-596 (6)	110.10 m
92	Central Pacific	597-602, 504B (20)	296.68 m
93	North Atlantic	603-605 (7)	1,678.20 m
94	North Atlantic	606-611 (22)	3,395.00 m
95	North Atlantic	612-613, 603 (5)	967.08 m
96	Gulf of Mexico	614-624 (20)	1,670.80 m
	Totals	**635 (1,112)**	**97,053.91 m**

Ocean Drilling Program

Leg	Area	Sites (Holes)	Core Recov'd
1985			
100	Gulf of Mexico	625 (3)	281.40 m
101	Bahamas	626-636 (19)	1,429.00 m
102	Western Atlantic	418 (0)	0 m
103	Galicia Bank	637-641 (14)	593.90 m
104	Norwegian Sea	642-644 (8)	1,695.00 m
105	Labrador Sea/Baffin	645-647 (11)	1,884.40 m
106	Mid-Atlantic Ridge	648-649 (12)	12.00 m
107	Tyrrhenian Sea	650-656 (11)	1,908.00 m
1986			
108	Northwest Africa	657-668 (27)	3,842.50 m
109	Mid-Atlantic Ridge	395,648, 669-670 (5)	12.00 m
110	Lesser Antilles	671-676 (10)	1,897.70 m
111	Panama Basin.	504, 677-678 (5)	428.00 m
112	Peru Margin	679-688 (27)	2665.60 m
113	Weddell Sea	689-697 (22)	1,944.00 m
1987			
114	South Atlantic	698-704 (12)	2,297.00 m
115	Mascarene Plateau	705-716 (22)	3,075.00 m
116	Bengal Fan	717-719 (10)	991.60 m
117	Oman Margin	720-731 (25)	4673.00 m
118	SW Indian Ridge	732-735 (20)	447.00 m
119	Prydz Bay	736-746 (22)	2,102.00 m
1988			
120	S Kerguelen	747-751 (12)	1,082.00 m
121	Broken Ridge	752-758 (17)	1,824.00 m
122	Exmouth Plateau	759-764 (15)	2,445.80 m
123	Argo Abyssal Plain	765-766 (5)	1,080.20 m
124	SE Asia Basins	767-771 (13)	2,122.00 m
125E	Luzon Strait	772-777 (15)	156.00 m
1989			
125	Bon/Mar	778-786 (15)	1,019.00 m
126	Bon Mar II	787-793 (19)	2,127.70 m
127	Japan Sea I	794-797 (10)	1,655.00 m
128	Japan Sea II	794, 798-799 (9)	1,548.00 m
129	Old Pacific Crust	800-802 (5)	469.00 m
1990			
130	Ontong Java Plateau	803-807 (16)	4,821.61 m
131	Nankai Trough	808 (7)	735.99 m
132	West/Central Pacific	808-810 (11)	164.69 m
133	N/E Australia	811-826 (36)	5,505.00 m
134	Vanuatu	827-833 (16)	2,044.20 m
135	Lau Basin	834-841 (18)	1,248.90 m
1991			
136	OSN-1	842-843 (6)	66.00 m
137	Hole 504B	504 (1)	8.80 m
138	E Equatorial Pacific	844-854 (42)	5,536.80 m
139	Sedimented Ridges	855-858 (23)	932.90 m
140	Hole 504B	504 (1)	47.70 m
141	Chile Triple Junction	859-863 (13)	1,018.80 m
1992			
142	East Pacific Rise	864 (3)	0.50 m
143	Atolls & Guyots -I	865-870 (12)	1,075.70 m
144	Atolls & Guyots -II	801, 871-880 (21)	1,087.70 m
145	N Pacific Transect	881-887 (25)	4,321.70 m
146	Cascadia	857, 888-893 (20)	1,190.30 m
147	Hess Deep	894-895 (13)	122.80 m
1993			
148	Hole 504B	504, 896 (2)	81.43 m
149	Iberian Abyssal Plain	897-901 (10)	1,531.81 m
150	New Jersey Sea Level	902-906 (11)	4,034.50 m
151	Atl. Arctic Gateways	907-913 (18)	3,004.60 m
152	E Greenland Margin	914-919 (13)	1,256.80 m
	Totals	**306 (758)**	**87,547.03 m**

Drilling sites planned for 1994 include the Mid-Atlantic Rise near the Kane Transform, the Ceara Rise, the Amazon Fan, the North Barbados Ridge, and the TAG (Transatlantic Geophysical Profile) site in the Atlantic.



Permian - 265 million years ago **Triassic** - 222 million years ago **Jurassic** - 171 million years ago

Glossary

accretionary complex (accretionary prism)—*sediment assembly scraped from a subducting crustal plate and added to its overriding plate*

basalt—*medium gray to black igneous rock that constitutes the uppermost 2 to 3 kilometers of oceanic crust*

bioclastic rock—*a biochemical sedimentary rock consisting of fragmented remains of organisms, for example, limestone composed of shell fragments*

calcareous—*containing calcium carbonate; used with a rock name, it generaly implies that as much as 50 percent of the rock is calcium carbonate*

chert —*(syn: flint) dense, extremely hard sedimentary rock consisting mainly of interlocking quartz grains*

clastic—*descriptive term for sediment or rock composed primarily of pre-existing rocks or minerals*

conjugate margins—*continental margins that originated on opposite sides of a spreading center, such as the margins of eastern South American and western Africa*

continental margin—*area from the shoreline to the abyssal ocean floor, including the continental shelf, slope, and rise*

décollement—*a detachment structure associated with folding and overthrusting characterized by independent patterns of deformation in the rocks above and below the boundary*

deltaic—*describing the sedimentary deposit of gravel, sand, silt, or clay formed where a river enters a body of water*

detachment fault—*special category of low-angle normal fault due to the downhill sliding of rocks from an uplifted region*

diagenesis (adj: diagentic)—*sum of the physical, chemical, and biological changes in sediment after its deposition*

diapir—*a general term to describe any body that has been able to flow and to intrude the surrounding rock*

dike—*a thin, platelike pluton that intrudes preexisting structures*

dropstone—*a piece of rock that is transported from its place of origin by ice (such as an iceberg) and deposited on the seafloor, usually as a result of the ice melting*

fault—*rock fracturing that displaces the sides of the fracture relative to one another*

fault block—*unit of Earth's crust bounded completely or partly by faults*

gabbro—*a group of granular, dark-colored igneous rocks composed largely of plagioclase and clinopyroxene*

hot spot—*heat source from deep within Earth's mantle, surface manifestation of a rising plume of hot mantle, such as the Hawaiian Islands*

hydrology—*study of the occurrence, distribution, movement and properties of water*

ice rafting—*transport of rock and other materials by floating ice*

igneous rock—*a rock formed by the crystallization of magma*

IPOD—*International Phase of Ocean Drilling*

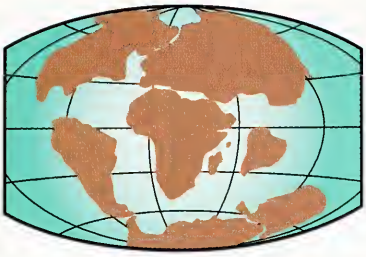
JOIDES—*Joint Oceanographic Institutions for Deep Earth Sampling*

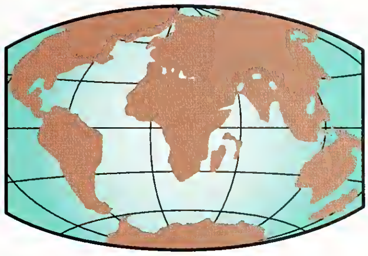
log—*a spatially continuous record of the physical and chemical properties of the formations penetrated by a borehole*

metamorphism—*structural and mineralogical changes in solid rock caused by physical and chemical conditions that differ from those under which the rocks initially formed*

Nansen Arctic Drilling Program (NAD)—*An internatinal research effort designed to understand, through future arctic drilling, environmental change in the arctic and the history of its geolocial evolution (member nations include Canada, France, Germany, Japan, The Netherlands, Norway, Sweden, United Kingdom, US, and Russia)*

offset drilling—*siting holes where tectonic processes have exposed rocks of deep origin on the seafloor*





Left: Continental positions in geologic time frames. Below: Schematic drawing of JOIDES Resolution *relocating a previously drilled hole. Sound bouncing between the ship's hydrophones and sonar beacons near the reentry cone, along with powerful thrusters, aid pinpoint navigation.*

oölite—*a sedimentary rock, usually a limestone composed mainly of small round calcareous particles that resemble fish eggs*

ophiolite—*sequence of igneous rock of oceanic crustal origin that has been pushed up onto a continent by plate collision*

passive margin—*continental margin in the interior of a lithospheric plate where continental and oceanic crusts are fused together (at active margins, oceanic crust is subducted beneath continental crust as plates collide)*

pluton—*general term for an intrusive rock body*

reentry cone—*guide horn placed in a drillhole to aid entry of the drill string at a later time*

sediment—*solid material that has settled out of liquid suspension that has been transported by wind, water, or ice; loose sediment such as sand, mud, and till may become consolidated to form coherent sedimentary rock*

serpentine—*a mineral formed by the hydrothermal alteration of olivine. The resulting rock, serpentinite, is generally considered to have been derived from oceanic crust altered in the presence of water*

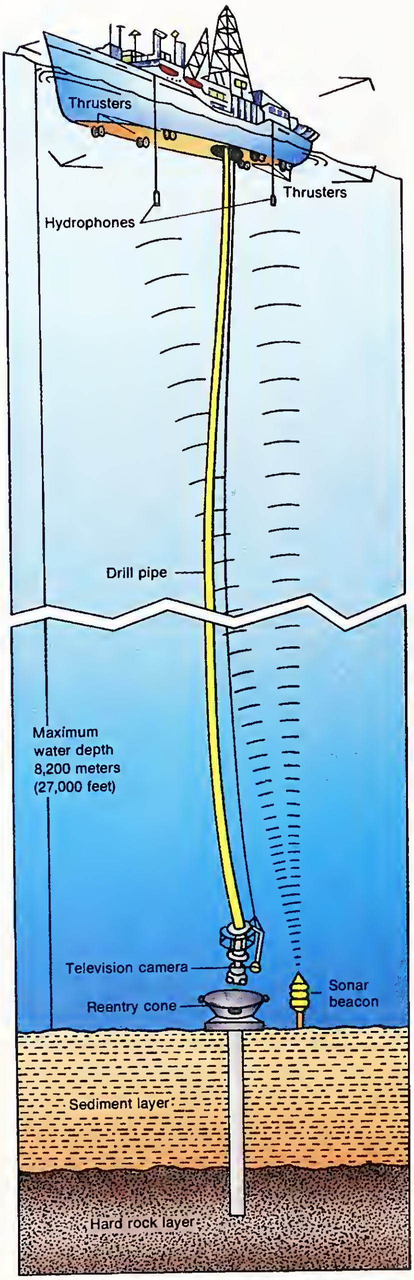
Southern Ocean—*all the water around Antarctica*

subaerial—*formed, existing, or taking place on the land surface (contrast with subaqueous)*

subduction zone—*area of crustal plate collision where one crustal block descends beneath another, marked by a deep ocean trench caused by the bend in the submerging plate*

tuff—*rock composed of volcanic-ash fragments cemented or consolidated by the pressure of overlying material*

turbidite—*sediment deposited by a turbidity current, a water flow caused by an excessive load of suspended sediment. Such currents flow downslope at very high speeeds and spread horizontally, gradually dropping their sedimentary load as the current slackens and the water comes to rest*



ODP Member Reports

The member reports, written from a variety of viewpoints, collectively provide some idea of the history of various nations' participation in ocean drilling, tell who some of the key players have been and how individual members structure their participation in drilling activities, offer ideas for the future of drilling, and, in one case, note with regret they will no longer be able to participate.

Australia

Ian Metcalfe

Australian geoscientists' involvement in ocean drilling began with planning and fieldwork for early 1970s DSDP work in Australasian waters and subsequent shore-based studies on the resulting cores. Although the Consortium for Ocean Geosciences of Australian Universities (COGS) was created in 1974 to promote Australian participation in the International Phase of Ocean Drilling, funding constraints prevented the country's formal presence in the drilling programs until 1988, when Australia and Canada joined ODP together as a consortium member. In the meantime, however, COGS maintained ties with the ocean drilling community and helped to develop drill site proposals for the Australasian region.

The benefits Australia currently enjoys from ODP participation are in large part due to those geologists who provided many years worth of energy and impetus for membership in ODP, notably Roye Rutland, Peter Davies, and David Falvey (all of Bureau of Mineral Resources—BMR) and Keith Crook (ANU), along with many others, and also to the foresight of the Australian Research Council, which declared ODP membership to be a national research priority in 1988.

Following Australia and Canada joining ODP as a consortium member, the Minister for Resources appointed an Australian ODP Council, formed by representatives of the four major funding agencies, and the Australian ODP Secretariat was established at the University of Tasmania. Since 1992, the Secretariat has been housed at the University of New England in the Department of Geology and Geophysics.

Australian involvement in ODP has been particularly strong in legs drilled in the Indian Ocean (especially off the Northwest Shelf), and a number of Australian scientists were invited contributors to the American Geophysical Union's *Indian Ocean Review*. One of the major discoveries from the Northwest Shelf drilling was the recovery of Triassic sediments and the identification of previously unknown potential hydrocarbon resources (see "Spinoffs for Oil Exploration," page 120). Another highlight of Australia's ODP involvement was the exceptionally successful Leg 133 BMR-instigated program off the Great Barrier Reef .

To date, 26 Australian scientists have participated in ODP legs. Many of them have been eager, young scientists and graduate students in the course of establishing their careers. Besides the obvious benefits of working shoulder-to-shoulder with international experts for two months, these participants report that the ODP experience has dramatically broadened their scientific horizons, brought them into new research projects, extended their international contacts, and, importantly, developed confidence in their own abilities as research scientists. In addition, numerous shore-based scientists are working on ODP samples in Australian laboratories, and ODP benefits many Australian geologists indirectly via exposure to new concepts and ideas through seminars, conferences, papers and teaching.

Ian Metcalfe is the Science Coordinator for the Australian ODP Secretariat.

Canada

John Malpas

Canada became a member of the Ocean Drilling Program in 1985, giving Canadian scientists the chance to participate directly in an international research venture and access core samples and research results of truly global significance. Becoming one of the first five partners in the program was a result of considerable effort by several members of the Canadian earth science community, including the late William Hutchinson and the late Michael J. Keen. Working with the Geological Survey of Canada sector, together with the National Science and Engineering Research Council and the federal Department of Fisheries and Oceans, they established a funding base for national participation.

However, despite significant Canadian participation in planning, as well as shipboard and shore-based research, the federal government has found it difficult to provide a funding level sufficient to maintain Canada's participation as an independent member. This, in part, resulted in the 1988 formation of a consortium with Australia, in which the two partners have since worked closely and successfully. Although Canada is a geographically large maritime nation, its scientific base is relatively small and widely scattered. Nevertheless, since 1985, more than 84 Canadian scientists and technicians have been involved in the Ocean Drilling Program. Some have developed drilling proposals of national and international interest, including those resulting in Leg 105 to the Labrador Sea and Baffin Bay, and Leg 139 to the Middle Valley area of the Juan de Fuca Ridge.

In Canada, ODP has a two-tiered administrative structure: The Canadian Scientific Committee (CSC) oversees the program's scientific aspects, and comprises scientists acting as consortium representatives on JOIDES panels; the Canadian Council implements the overall policy that governs ODP in Canada, and looks after the administrative and financial aspects of Canadian participation in the program. The Canadian Secretariat coordinates the program in Canada and acts as the day-to-day CSC operating arm. CSC and Canadian Council members are selected from the industry, government, and university communities, providing the best possible cross section of the geoscientific community.

The program has had a significant impact on Canadian marine geosciences, with a number of national successes. There have also been a wide variety of spinoffs; for example, drilling the Juan de Fuca Ridge required successful implementation of the first major marine environmental impact study, which was undertaken by the Geological Survey of Canada. The scientific community, having gained access to some of the most inaccessible areas on the globe, as well as more parochial targets, has undoubtedly benefited from consortium membership. While we acknowledge that there will be a continuing struggle to ensure that Canadian marine geoscientists can fully participate in this global program, we look forward to a second ten years as ODP members.

When not on an airplane to the sunny climates of Cyprus, New Zealand, or Australia (anywhere away from the foggy Rock!), John Malpas is the Director of the Canadian Secretariat for the Ocean Drilling Program and Chairman of the Canadian Council. He is also the Dean of Graduate Studies at Memorial University of Newfoundland. Malpas has been involved with the Ocean Drilling Program from its infancy, and with the program's predecessor, DSDP. His research focuses on ophiolites and the origin of oceanic crust.

European Science Foundation

G. Bernard Munsch

The idea of establishing an Ocean Drilling Program (ODP) consortium of European countries first came from the US National Science Foundation in March 1983 to the European Science Foundation. The idea was rightly perceived as potentially beneficial for all parties concerned: the countries who could not afford individual ODP membership themselves, the Ocean Drilling Program, and the European Science Foundation (ESF).

The first step was to assess interest level among scientists in these countries. Not surprisingly, interest appeared to be quite high. Though many scientists in these countries had participated in the pre-international phase of the Deep-Sea Drilling Project, there were very few involved during the International Phase of Ocean Drilling, although some had kept themselves informed about drilling activities. This discovery cleared the way for the ESF to proceed.

The main difficulty, as usual, lay in the next step: converting interest into funding. The problem was that the ESF, despite its name, has no resources of its own and can only operate using funds obtained from its member organizations and sometimes other entities (such as ministries and companies); hence the need to convince a sufficient number of these to provide funds. No wonder it took nearly three years of countless meetings and all sorts of other steps—and sometimes dramatic developments that nearly resulted in abandonment—before the nascent consortium eventually managed to obtain the full requested membership fee from its 25 constituent organizations in 12 countries: Belgium, Denmark, Finland, Greece, Iceland, Italy, Netherlands, Norway, Spain, Sweden, Switzerland, and Turkey.

The next significant challenge was to build up a suitable management structure for a consortium that was first of its kind in the Ocean Drilling Program—*and* get it to work. Legal and financial matters were easiest to settle, with the ESF speaking and acting on behalf of the entire group vis-à-vis the international community. A more difficult task was to divide *fairly* among the various members, whose contributions ranged from 2 percent to 20 percent of the consortium's membership fee, the various ODP benefits, such as representation on JOIDES panels (one seat on each panel for the consortium as a whole), numbers of shipboard participants and co-chief scientists, and quotas for ODP publications. In addition, the consortium needed a mechanism to make fair decisions that took due account of financial contributions while preserving minorities' rights. To this end, two committees were set up, one for management and one for science, each with one representative per country. Decisions were to be reached by consensus, and by vote only if a consensus was impossible (to date, a vote has never been necessary).

Complicated though it may seem, this machinery has not only worked (with minor adjustments) since June 1986, it has even inspired others. Above all, this system has enabled the ESF consortium to act as a full

G. Bernard Munsch holds a Ph.D. in theoretical chemistry from the University of Strasbourg (the most continental place in France), and knew next to nothing about earth sciences and even less about the ocean when he joined the staff of the European Science Foundation in 1983. Having thus a naive and totally unprejudiced mind made him the obvious choice to be the officer-in-charge of ODP affairs, a duty he carried out for close to six years.

ODP partner while strengthening its cohesion, despite the inevitable conflicts of interest. In this respect, this structure may be judged to have successfully stood the test of time, the best proof of which may be the recent ESF renewal of ODP membership.

France

Yves Lancelot

The French earth and ocean science community has long been an active, demanding, passionate participant in the ocean drilling programs (perhaps too demanding for some members of the JOIDES community).

Along with those of several other non-US countries, French scientists were involved in the early phases of DSDP in the late 1960s and early 1970s when the concept of "global tectonics" was just emerging. At that time, France had just launched a major effort to organize modern ocean research on a large scale with the creation of a specialized agency, the Centre National por l'Exploitation des Océans (CNEXO), which later became the Institut Français de Recherche pour l'Exploitation de la Mer (IFREMER).

The "golden sixties" gave us modern ships, a fresh supply of young brains, and enough money to engage in global international ventures. In France, as in many countries, marine geosciences were abruptly placed at the forefront of earth sciences by DSDP's early success and the fierce debates provoked by some of its astounding discoveries, such as the evolution of the Atlantic and the desiccation of the Mediterranean. Nevertheless, it took the vision of some key individuals at CNEXO (notably Jacques Debyser and Xavier Le Pichon) and the enthusiasm of shipboard participants returning from early *Glomar Challenger* cruises to persuade our government to enter the JOIDES community when IPOD began in 1975.

From then on it was "natural" (I was tempted to say "routine") for the following years to send French scientists off to the drillship every two months, to regularly hear about great achievements, leg after leg, and to successfully maneuver proposals into the system, helping to promote a strong French ocean drilling community of several hundred scientists. Funding was assured for this well-organized community for several years, based on the program's outstanding scientific achievements and the active participation of French scientists. The financial commitment, today exceeding $6 million (US) per year including salaries, was very significant within the national earth science research budget, but French participation regularly passed all evaluations with flying colors. During the last two or three years, however, ugly clouds of reduced funding began looming over the horizon and some scientists realized that long-term participation could be in real danger. We had to prepare for the future by consolidating our position in the French earth science community, which was growing rapidly outside the drilling community, if we were to justify further participation in the program.

We identified two ways to improve our position. The first was to secure better ODP interaction with other major research programs in order to demonstrate that drilling is indeed a key element in earth sciences. (Although this effort continues, it is still not completely achieved today.) This meant increasing community support by bringing new disciplines and "new blood" into the program. Step by step, new communities are indeed coming closer to the drilling program, particularly since the evolution of drilling is opening new research possibilities. High-resolution sediment studies are bringing part of the "global change" community into ODP, and the "offset drilling" strategy (drilling in mid-ocean ridge fracture zones for closer access to Earth's mantle), along with emphasis on drilling deep into the ocean crust, has helped to develop the international effort to coordinate and expand ridge-crest research. The spectacular development of in situ downhole observations, measurements, and experiments now attracts more geophysicists and geochemists than ever before. All this, of course, is in addition to the program's traditional geodynamics aspects.

Another way to secure the French

community's long-term participation in the program was to develop a strategy for removing the "routine" coloration that any long-lasting program acquires over the years. It has become clear to many of us that the future will necessarily demand some decentralization of the program, and that a better adaptation of the tools to the tasks becomes critical if we are to face the increasing demands of the community. Very deep drilling will some day require a large riser-equipped platform that may have to stay on one drill site for many months. Paleoceanography and global change approaches should rely on the rapid recovery of numerous well-preserved and relatively short sediment sections from all over the world ocean. In situ downhole experiments also need more ship time. This prompted France to propose, during the 1987 COSOD II conference in Strasbourg, that the program become multi-platform after 1998.

France, like all of its "neighbors," must face the organizational and political challenge of building a truly European scientific "community," sharing facilities as well as manpower. DSDP and ODP have demonstrated how powerful the sharing of a major facility such as a drilling vessel can be in bringing a large community together. The need for a multi-platform program may become a major opportunity for developing an efficient partnership, both within Europe and between Europe and the rest of the world. We are convinced that the development of a European state-of-the-art vessel specially equipped for high-resolution coring and downhole experimentation could best assure our long-term commitment to the international drilling program of the future.

Yves Lancelot spent some of his early years of research at Lamont-Doherty Geological Observatory, before becoming DSDP's Chief Scientist at Scripps Institution of Oceanography. After being one of the most French of the American scientists, he was perceived by his French colleagues as one of the most American of the French scientists and decided to simply become one of the most European of the European scientists. Much to his and many others' surprise, he has finally settled down in Marseille, as head of the CNRS's Laboratoire de Géologie du Quaternaire, specializing in paleoclimatology and paleoceanography.

Germany

Helmut Beiersdorf

The Federal Republic of Germany was one of several countries that responded to the 1972 US invitation to help plan a new program based on early DSDP accomplishments. When the International Phase of Ocean Drilling (IPOD) was initiated in 1975, 20 German scientists had already been members of *Glomar Challenger* scientific parties.

During the early 1970s, Eugen Seibold and Hans Closs were among those most instrumental in organizing German participation in ocean drilling. Seibold was at that time Chairman of the Senate Commission for Oceanography of the Deutsche Forschungsgemeinschaft (DFG, the German equivalent to the US National Science Foundation), while Closs was Head of the Department of Geophysics of the Bundesanstalt für Bodenforschung at Hannover, FRG (now Bundesanstalt für Geowissenschaften und Rohstoffe, BGR, the Federal Institute for Geosciences and Natural Resources). Friedrich Wilckens of the Federal Ministry for Research and Technology (BMFT) and Franz Goerlich of DFG also contributed significantly to forming and maintaining a "critical mass" of German DSDP scientists.

Although most of the scientists initially approached by DFG and BMFT were enthusiastic about the possibility of working with the world's best drilling researchers, others were concerned about the limited number of German marine geoscientists, fearing that this resource would quickly become exhausted if each DSDP leg required a German scientist to go to sea and then concentrate for a year or two on the resulting data and samples. On the other hand, it was expected that the number of seagoing scientists would increase with time as a consequence of guaranteed participation in each *Glomar Challenger* cruise and the increasing number of German research cruises that would be dedicated to surveying drilling targets. In fact, the number of German scientists involved in ocean drilling has more than tripled since the country became an IPOD member.

Germany's IPOD science plan, finalized on February 13, 1973, called for DFG and BMFT to share ODP membership costs, and for DFG to be responsible for scientific activities related to IPOD. This arrangement continues today, with BGR coordinating the German scientific contribution and providing administrative assistance to DFG. There is close cooperation between the ODP community and the German continental drilling program.

The German geoscientific community submitted 49 ODP-related proposals to the DSDP/ODP Schwerpunktprogram (Priority Program) for the period from July 1993 to June 1994, and the Priority Program review board recommended 45 of them for funding. In both 1992 and 1993, approximately 3.75 million deutsche marks were allocated to the Priority Program for research, as well as for travel to ODP cruises and meetings, maintaining the German ODP office at BGR, and distributing such information as ODP Proceedings, German ODP circulars, panel meeting reports, etc. In addition, along with host institutions, BGR organizes an annual German ODP colloquium, and several million deutsche marks are allocated annually to support surveys of potential ODP drill sites by the German long-range research vessels *Meteor*, *Polarstern*, and *Sonne*.

Since Germany became a member of IPOD, 166 German scientists have participated in drilling cruises, and some 150 scientists currently involved in research based on the drilling program assure continued German support of the Ocean Drilling Program into the next century.

A refugee from East Germany in 1960, Helmut Beiersdorf went to Goettingen (West Germany) to study geology. Following completion of his doctorate at the University of Goettingen, he joined the Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) at Hannover, specializing in the exploration of seabed mineral resources. This took him on many research cruises in all oceans, including a Glomar Challenger *cruise. He is Head of Basic Geology and Marine Geology at BGR, coordinates the ODP Priority Program, and represents the German Ocean Drilling Program community on the JOIDES Executive Committee.*

Great Britain

Robert B. Kidd and James C. Briden

Britain was one of the founding members of the International Phase of Ocean Drilling (IPOD) which began in 1975, but British scientists had, in fact, participated in earlier phases of the Deep Sea Drilling Project aboard D/V *Glomar Challenger*. Individual British marine geophysicists were particularly active in the planning and execution of drilling legs that extended theories of seafloor spreading and established the early evolution of the North Atlantic and the breakup of the southern continents to form the Indian Ocean.

UK sedimentologists and stratigraphers were heavily involved in the development of paleoceanography as a subdiscipline based on studies of oceanic sedimentary sequences. Their special interests included drilling on the Pacific seamounts, and in the Mediterranean Sea, the Indian Ocean, and around Antarctica.

During the IPOD phase, the British community was particularly interested in studies of continental margin evolution. Participating scientists called for greater emphasis on logging and downhole instrumentation in the overall drilling effort, a continuing theme that has subsequently paid great dividends in the development of scientific ocean drilling.

Toward the end of DSDP, UK scientists were very active in paleoceanographic studies that became possible with the advent of hydraulic piston coring. This technique extended undisturbed high-resolution stratigraphy from levels of conventional surface core sampling (10 to 30 meters) to depths of hundreds of meters. This work included studies of North Atlantic climate and water-mass circulation and of sediment distribution on submarine fans.

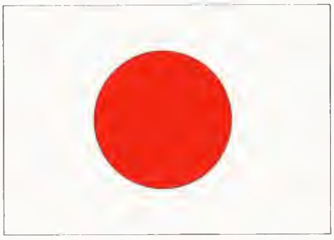
As members of JOIDES, British scientists recognized that pressing issues in geoscience, such as the linkages between ocean history and global climate change, the evolution of continental margins, and the effects that fluids and gases emanating from the ocean floor have on the ocean's geochemistry, required a platform with increased capability. Our community was therefore frustrated when, as DSDP was succeeded by the Ocean Drilling Program (ODP) utilizing *JOIDES Resolution*, funding difficulties caused a brief hiatus in British participation from 1984 to 1986.

Happily Britain did become a full ODP partner in 1986. Since then the British scientific community has been extremely active in the program, with particular interest in the Indian Ocean and Southern Ocean campaigns, and in the Pacific ODP program. The first two have generated major synthesis studies, drawing together the results of both DSDP and ODP drilling in these areas. British scientists have chaired a number of the JOIDES advisory panels in recent years, and UK proponents have figured prominently in preparation for the current Atlantic and Mediterranean programs.

One feature of British ODP participation has been the widening of the disciplinary science base within its ODP community to include microbiologists, more geochemists, downhole logging specialists, and development engineers, as well as geologists whose primary interests had been in land-based geological studies far removed from marine geology. Recognizing this widening of interest and increased importance of ODP to British science, the Natural Environment Research Council was the first of the non-US funding agencies to sign the Memorandum of Understanding ensuring continuation of the JOIDES partnership through 1998. Britain will host the first JOIDES Office to be located in a non-US partner country when coordination of the JOIDES advisory structure rotates from the University of Washington, Seattle, to the University of Wales, Cardiff, for two years beginning October 1994.

Rob Kidd grew up in the West Wales seaport of Milford Haven, where his family, made up of generations of seafaring Navy- and trawler-men, encouraged him to get an education and not go to sea. After a research career spanning over 30 cruises, he still blames his intoxication with marine geology on a first post-graduate expedition in the Mediterranean Sea in 1969 that gave him the mistaken impression that research cruises could all be 10 days long! His primary interests are in deep marine sedimentary processes. He holds the Chair of Marine Geology at the University of Wales, Cardiff and represents the UK on the JOIDES Planning Committee. He was Head of ODP Science Operations at Texas A&M University for the program's first two years (1984 to 1986).

James C. Briden is Director of Earth Sciences for the Natural Environment Research Council in UK, having casually thrown away tenure as Professor of Geophysics at the University of Leeds. Previously a landlubbing paleomagnetist who wallowed in the Paleozoic, the Precambrian, and in directional statistics, he was lured into love with marine geoscience through representing UK on the JOIDES executive committee, of which he is chair-elect. He is a Murchison Medallist of the Geological Society of London, and a Frequent Flyer on most of the world's airlines.



Japan

Noriyuki Nasu and Kazuo Kobayashi

Japan was first invited to become an international member of DSDP by a letter from William Nierenberg, Director of the Scripps Institution of Oceanography and chairman of the JOIDES Executive Committee, to Noriyuki Nasu, Director of the Ocean Research Institute, University of Tokyo. Japanese earth scientists knew and appreciated the Deep Sea Drilling Project and were enthusiastic about membership. Nasu secured official and budgetary support from the Japanese Government and the Ministry of Education, Science and Culture (Monbusho) eventually became the sponsor. Japan joined IPOD at its start in 1975 and has continued as a member through DSDP and ODP to the present.

The Japanese Ocean Drilling Committee, organized within the Ocean Research Institute, consists of eminent scientists from across Japan, both geographically and administratively. The committee has the authority to decide how Japan will participate in various international and domestic ocean drilling activities. Nasu was Japan's representative to the JOIDES Executive Committee until April 1, 1984, when he retired from the University of Tokyo. He was succeeded by Kazuo Kobayashi, who served until his retirement in early 1993. Asahiko Taira, whose contribution to this volume appears on page 95 is the current international ODP coordinator for Japan.

A total of 57 Japanese scientists actively participated in 52 IPOD legs (Legs 44A to 96), and 91 scientists in 45 ODP legs (Legs 106 to 151). There were six Japanese co-chief scientists in IPOD and seven in ODP. Japanese researchers have especially contributed to drilling activities in the Japan Trench, the Nankai Trough, and the Shikoku, West Philippine, and Japan Sea back-arc basins. They have also had special interest in the deepest ocean-crust drilling in the east equatorial Pacific and in such environmental cruises as the Indian Ocean monsoon leg.

A number of Japanese geophysicists and engineers have contributed to comprehensive downhole experiments, including seismic and electromagnetic measurements, in the Yamato Basin (southeastern Japan Sea) working aboard *JOIDES Resolution* and support vessels such as *Tansei-Maru*, provided by the Japanese team.

Japan has contributed many drilling-site survey cruises using R/V *Hakuno-Maru* and other vessels, particularly in the northwestern Pacific Ocean around Japanese islands. Ocean drilling work in these areas has contributed significantly to understanding subduction processes and back-arc-basin tectonics.

The Japan Marine Science and Technology Center (JAMSTEC) is now promoting a plan for a new ocean drilling vessel with financial and administrative support from Japan's Science and Technology Agency. Using marine-riser technology, the new ship aims to overcome the present difficulty in achieving deeper penetration caused by both possible danger of hydrocarbon blowout and hole instability. The initial target for riser length is 2,000 meters; with continuous effort, we will try to reach 4,000 meters. The length of the drill pipe will be 10,000 meters. We hope that this new drilling facility will provide world geoscientists with the opportunity for further scientific exploration of the vast ocean floor, and eventually for a sound understanding of our living Planet Earth.

Noriyuki Nasu is Professor of the University of the Air and Professor Emeritus of the University of Tokyo, where he served as Director of the Ocean Research Institute from 1968 to 1972 and 1980 to 1984. He served for many years on various ocean drilling committees. Nasu's research interest is marine geology, and he served as a co-chief scientist of Leg 57, which explored the Japan Trench.

Kazuo Kobayashi is now Science Advisor for the Japan Marine Science and Technology Center and Professor Emeritus of the University of Tokyo, where he was a Professor of the Ocean Research Institute from 1967 until early this year. He has been a member of the JOIDES Active Margins Panel, the Planning Committee, and, in the immediate past, the Executive Committee. His research interests range from paleomagnetism to tectonic processes in the subduction zones. He served as a co-chief scientist for Leg 58, drilling in the Shikoku and northern Philippine Sea back-arc basins.

Russia

Nikita A. Bogdanov

In the second half of the 1960s, after geophysical investigations had proved the structural differences between continental and oceanic crusts, both Russian and American scientists decided to drill deep holes to better understand the Conrad and Mohorovicic (Moho) discontinuities (boundaries between the upper and lower continental crust and between the crust and mantle, respectively). Thus competition that began between the former Soviet Union and the US with the atomic bomb and continued during the initial steps toward conquering space extended into earth sciences as well.

In 1967 the Former Soviet Union began drilling a super deep hole on the Kola Peninsula, with the primary objective to reach the Moho boundary. In the US, deep sea drilling started in 1968. This tough confrontation (characteristic of the cold-war epoch) did not, however, affect scientific cooperation: Close contacts developed between Russian and American scientists from the earliest phases of deep sea drilling. As far back as 1971, Russian scientists A.P. Lisitsyn and V.A. Krasheninnikov participated in the US Deep Sea Drilling Project, and in 1974 the USSR Academy of Sciences became the first foreign partner in this successful project.

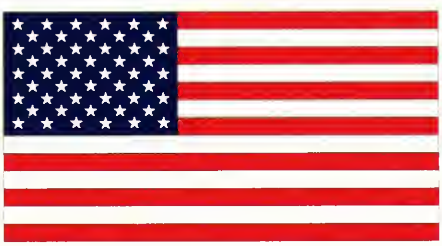
From the very beginning of DSDP, Russian scientists have been especially interested in the drilling programs' data on deep sedimentation and the stratigraphy of upper Mesozoic and Cenozoic sediments. Though systematic ocean drilling supported the plate-tectonic concept of Earth's evolution and every new cruise brought new geophysical and geological data confirming it, in our country, where this concept was not readily accepted, scientists focused on the drilling results that were inconsistent with plate tectonics. However, most of the small group of Russian scientists who participated in *Glomar Challenger* cruises from 1974 to 1981 returned home as ardent defenders of this concept. As new data on seafloor geology was gradually assimilated, more and more supporters of modern plate tectonics appeared in our country, and by the mid 1980s the majority of USSR marine geologists supported plate-tectonic theory.

Despite being slow to accept lithospheric plate motion, Russian geologists were among the world leaders of ocean drilling, especially in the first stage, from 1968 to 1980. Their interest in oceanic crust was sparked by the abundance of ophiolite rocks found on the vast former Soviet Union territory. (Ophiolites are segments of oceanic crust found on land—now known to be pushed into the continents by plate collisions). The age of these ophiolites ranges from late Cretaceous at the Pacific Ocean coast to late Precambrian in Altai, Central Asia. Dredging the ocean floor helped confirm the identities of ophiolitic sections, but Russian marine geologists and geophysicists who participated in the Deep Sea Drilling Project did not fully accept this view until 1981, when a dike complex was penetrated in Hole 504B. Today, nobody doubts the similarity of oceanic crust and continental ophiolites, though they may differ in chemical composition. It is a pity that continental geologists' ideas about the advantages of offset drilling over super deep drilling for studying crustal magmatic rocks was given no priority by the ODP Planning Committee. Offset drilling of holes 250 to 300 meters deep would reveal details about the small-scale transitions between crustal layers that cannot be obtained from deeply drilled holes (1,500 meters or so).

Russian scientists participated continuously in deep sea drilling from 1974 to 1981, when their participation was interrupted because of the political climate at the height of the cold war. In 1991 with great support from Joint Oceanographic Institutions Inc. and the US National Science Foundation, Russian scientists returned, only to retreat the following year for economic reasons. Despite a less-than-encouraging economic situation for scientific investigation in our country, our scientists remain optimistic—and the optimism brings rewards: The past year and a half of our participation in ODP has been the most fruitful. We collected much data on lithology, stratigraphy, and other Pacific geology fields, mainly pertaining to this region's Cenozoic history. Unfortunately, since no deep sea drilling has yet been done in seas adjacent to Russia or the Arctic, our scientists can so far only correlate Pacific drilling results with those from distant Kamchatka and the Aleutian Islands. Using material they collected while on cruises and data obtained from studying ODP core samples and the *Initial Reports* and *Scientific Results* volumes, Russian scientists have published 16 separate books and several hundred scientific articles. The largest recent review of ocean drilling results was a catalog of all deep sea drilling cores from the Pacific and the Atlantic in geological and geophysical atlases for these oceans.

Russian scientists have maintained close contacts with NSF, even during the periods when they were unable to participate in *Glomar Challenger* or *JOIDES Resolution* cruises. We have always felt like full partners of ODP, as we have been kept apprised of drilling results and ODP activity by Texas A&M University. Unfortunately, economic complications dictate that our partnership and publication flow will cease this year. Nevertheless, Russian scientists consider it fortunate that with the help of American scientists and other ODP partners they have had 20 years of deep sea drilling involvement.

Nikita A. Bogdanov has been chairman of the Russian Committee on the Deep Sea Drilling Project (DSDP) and then the Ocean Drilling Program (ODP) since 1980. He is Director of the Institute of the Lithosphere, a member of the Russian Academy of Sciences, and a Moscow State University professor.



United States

Ralph Moberly

In his keynote address at the 1976 International Geological Congress in Sydney, Philip H. Abelson, a geophysicist who was then president of the Carnegie Institution, listed deep sea drilling with Apollo as programs whose geological samples form the basis for revolutionary advances in science. Great depth and range of new knowledge is chronicled in hundreds of articles published by ocean drilling scientists, and numerous review papers, including those in this issue of *Oceanus*, summarize that knowledge.

This review from the US perspective provides not another detailed account of the discoveries, but rather mentions something of the development of late 20th-century science, with examples both from the science itself and the participants.

Future historians and philosophers of science will find ocean drilling abrim with significant patterns—changing science paradigms, the international aspects of science, the interplay of technological and scientific advances, and the funding and direction of science. The predominance of American scientists and institutions in the early years of ocean drilling, and indeed the very concept and fruition of ocean drilling itself, were but two facets of the overall position of American science after World War II. Thus science historians will find an immense American contribution to the many successes—and occasional failures—of drilling.

Several of the earliest DSDP legs confirmed that an American theory, seafloor spreading, was an acceptable explanation of a mainly non-American concept, continental drift. The ages of samples overlying identified magnetic anomalies aided the quantification of seafloor spreading into the more-inclusive paradigm of plate tectonics.

Early DSDP co-chief scientists became American Princes of Serendip, accidentally discovering evidence that did not fit with existing models of earth processes, that instead brought new insights. To take only one example, finding records of igneous activity in oceanic settings other than on the ridge crest, above subduction zones, or as traces of hot spots in time led to fruitful theories about the origin of back-arc basins, and about mid-plate volcanism from giant mantle plumes.

Piston cores and early ocean-drilling cores gave birth to a new earth science discipline, paleoceanography. In response to requests by marine scientists, American DSDP engineers developed the hydraulic piston corer, which allowed recovery of long sections from many oceans and many latitudes, and the new paleoceanographic focus in the earth sciences grew to maturity. Paleoceanography is concerned with evidence from microfossils, isotopes, sediments, and hiatuses that reveal, for instance, how the changing distribution of seaways affected ocean circulation and Earth's climate.

Ocean drilling has provided a generation of American scientists some perspective into the often complex and changing relationship between those who pursue science and those who fund the pursuit. The demise of the Mohole project in 1966 showed that mandated programs might literally live or die with the life and death of a congressional leader (see "An Abridged History of Deep Ocean Drilling," page 8). Years later, the demise of Ocean Margin Drilling showed how difficult it is in the US for a government agency to design a plan for science and operations and then impose it on industry and on individual scientists in academic institutions. Yet industry, government agency, and academic partnerships are the norm for most of our international ocean drilling partners. A succession of science plans and budgets has demonstrated that the US and its partners can stretch their own operating modes to accommodate others' modes. After some initial weakness, Joint Oceanographic Institutions Inc., born of the US part of Joint Oceanographic Institutions for Deep Earth Sampling (JOIDES) but later to subsume its parent, showed that complex international programs can be managed successfully.

Science devours new ideas. New hypotheses lead to proposals for new drilling legs that will help test theories. The demand for new postulates and better information on which to plan drilling constitutes a demand for the cross-fertilization of ideas. At first, the JOIDES advisory panels and the shipboard scientific parties were composed mainly of scientists from the US oceanographic community and those with ties to early ocean drilling advocates such as the American Miscellaneous Society and the Long Cores Committee. Later, a broader sector of US academic, federal, and industrial earth scientists became involved, with occasional non-US participation. Formation of the International Program of Ocean Drilling and such international advisory workshops as COSOD (Conference on Scientific Ocean Drilling), ended the American predominance in drilling advice and leg cruise participation. Today, ocean drilling is closely attuned to such international efforts as Nansen Arctic Drilling, Global Sedimentary Geology, Federation of Digital Seismic Networks, and InterRidge, the international ridge-crest research effort. I know of no one deeply concerned with drilling who has not applauded the internationalization of what was once a closely restricted American venture.

Ralph Moberly's first oceanographic cruises were on a US Navy Agor *in the North Atlantic in 1952 and 1953. He had been on the Pacific earlier, and knew it would be warmer. Most of his professional life has been at the University of Hawaii, in teaching, in marine geology, and in the frustrating lower levels of science administration. Participation on several legs of ocean drilling, on the Planning Committee of JOIDES, and in the past 25 years' of cabals in dark rooms and at bars gave him the viewpoint for this article.*

Ocean Drilling Science

For 25 years the Deep Sea Drilling Project and the Ocean Drilling Program have been the international test-bed of fundamental earth science hypotheses. From the dynamics of plate tectonics to the composition of ocean crust to the history of ocean circulation, these scientific drilling programs have provided vital information—actual samples from the seafloor— to confirm the ideas that have guided our current understanding of the earth. Equally important but generally unknown are the many times when samples of the seafloor provided by drilling have shown that a seismic reflector was misidentified or that the timing of a proposed sequence of events was wrong, disproving hypotheses that scientists had formed based on data collected by other methods. On the following pages, scientists describe some of ocean drilling's research accomplishments—this volume doesn't provide space for many, many more that are detailed in the scientific literature and official drilling program reports.

Because sampling in the third dimension, beneath the seafloor, is so obviously a requirement of earth science and because the long-term continuity of drilling programs has made them a "given," we are in danger of taking ocean drilling for granted. If we don't take ocean drilling for granted, its next phase is likely to be more experimental. We envision a program with more than one drillship. One large and very capable ship would likely stay in one place for long periods of time, drilling the very deep holes needed to sample the lower crust and thick sedimentary sequences. The other ship or ships would be engaged in a variety of tasks, some like today's, but with more emphasis on installing geophysical and geochemical sensors and observatories on and below the seafloor.

This experimental ocean drilling program will provide the tools for and be more integrated with other earth science programs. It will drill the necessary seafloor holes and help greatly to install the seafloor observatories required by InterRIDGE (**Inter**national program of mid-ocean **R**idge **I**nter**d**isciplinary **G**lobal **E**xperiments), the seismometers required by the Ocean Seismic Network, and the drillhole reentry cone "corks," flowmeters, and other downhole sensors required by geochemists and hydrologists. The program will provide opportunities for a variety of between-hole measurements that will broaden our scale of understanding beyond the drill's several-inch-diameter probe. With the ability to drill deeper and through very thick sediments, ocean drilling will be able to join with continental drilling to profile the continental margins as part of scientific drilling programs that are not labeled by the presence or lack of water overlying the objectives.

—Thomas E. Pyle and Ellen S. Kappel

Pyle and Kappel are Director and Associate Director, respectively, of the Ocean Drilling Program. They are based at Joint Oceanographic Institutions Inc. in Washington, DC.

PALEOCEAN-OGRAPHY

Paleoceanography from a Single Hole to the Ocean Basins

Through Seismics and Logging

Larry A. Mayer

Changes in climate or ocean circulation will result in changes in the types of sediment that accumulate on the seafloor.

Scientific ocean drilling has revolutionized our understanding of Earth and ocean history. The remarkable results gleaned from ocean drilling cores have allowed us to begin to piece together detailed records of the changes in ocean conditions and climate over the past 40 million years. While we are constantly improving the temporal resolution at which we can see these changes (see "Details That Make the Difference," page 45), we are often frustrated by the limited spatial resolution of our drill holes. Ocean drilling is expensive and time-consuming; we are often faced with trying to interpret the climatic and oceanographic history of the ocean basins from a relatively small number of widely spaced drill holes. To address this frustration we have called upon remote geophysical techniques originally developed for oil exploration, including seismic profiling and downhole logging to attempt to extend the paleoceanographic results of a single borehole over large areas of the ocean basins.

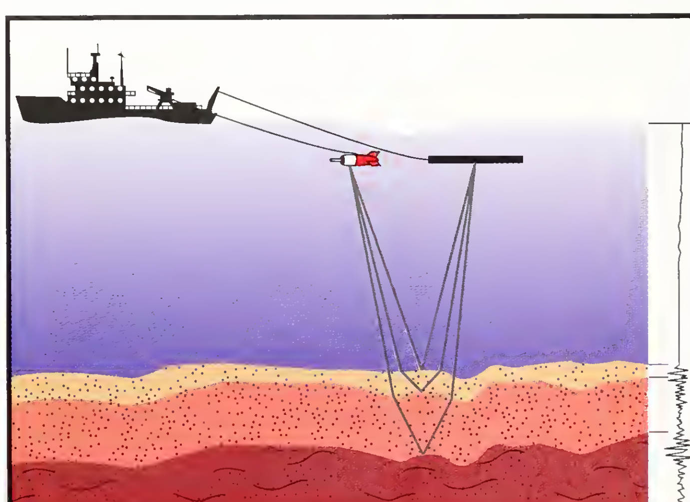
Seismic Profiling

Seismic profiling is a geophysical technique that allows us to remotely image subsurface features both on land and at sea. In order to produce a seismic profile, we generate seismic (elastic, for example, sound) waves using a variety of sources such as explosives, compressed air, and steam. When the seismic wave traveling through the earth encounters a rapid change in the properties of the rocks, some of its energy is returned (reflected) back to the surface while the remaining energy continues on, encountering deeper layers. The returned energy is received by a series of microphonelike devices (geophones on land, hydrophones at sea), then recorded and displayed both on paper and computers. Seismic profiling is, in essence, a scaled-up version of the medical ultrasound technique that provides images of a fetus *in utero*. For marine work, the seismic energy source is typically the release of compressed air through a device known as an airgun, and the receiver is a long (often several kilometers) array of hydrophones, both of which are towed by the survey vessel at speeds up to 10 knots. Successive echoes are aligned on a recorder and the resulting image, the seismic profile, is a continuous record of subsurface structure that looks very much like a geological profile; the individual horizons on the seismic profile are referred to as seismic reflectors.

Historically, seismic profiling has been used in oil exploration to delineate subsurface geometric relationships (faults and folds in the rocks) that may trap oil and gas. In the paleoceanographic application of seismic profiling we are not primarily concerned with the geometry of the layers; rather, we seek to associate a particular seismic reflector (or group of reflectors) with a particular paleoclimatic or paleoceanographic event. Our basic premise is that changes in climate or ocean circulation will result in changes in the types of sediment that accumulate on the seafloor—changes that are large enough to cause seismic reflection. For example, during times of intensified wind circulation (perhaps during glacial periods), the productivity of ocean waters may change, causing different planktonic organisms to dominate the surface waters. As the type of plankton changes, so does the accumulating sediment below because it is primarily composed of planktonic skeletons. As sediment composition varies in response to climatic and oceanographic factors, a series of layers is deposited whose different properties may give rise to seismic reflections. If we can relate a particular seismic reflector to a given oceanographic or climatic event (as determined from the study of drilled cores), we have a means for continuously tracing the event's spatial distribution.

Sounds Good, But...

While the prospect of tracing oceanographic events by seismic profiling sounds reasonable, the reality is often not so simple. When we examine the sediment cores, we find property changes for the most part on scales of centimeters to tens of centimeters. Unfortunately, the seismic profiling equipment used for deep sea work generates waves on the order of meters long that can only resolve layers of the same dimension. Also, we measure the variations in sediment properties in the drill hole as a function of depth below the seafloor, but our seismic records are measured as a function of the amount of time it takes the seismic wave to travel to the subsurface horizon and back (seismic travel time). If we are going to relate seismic reflections to changes found in drillhole cores,



E. Paul Oberlander/WHOI Graphics

A marine seismic profiling system. The research vessel tows the seismic source (red and white airgun) and receiving system (hydrophone array). Seismic waves travel through the water column into the seafloor and are reflected from layers that have relatively rapid changes in physical properties. The echoes are aligned on a recorder and displayed. The position of the seismic reflectors is measured as a function of the time it takes the seismic wave to travel from the source to the reflector and back (seismic travel time).

we must find a way to convert seismic travel time into depth below the seafloor.

Downhole Logging and Seismic Modeling

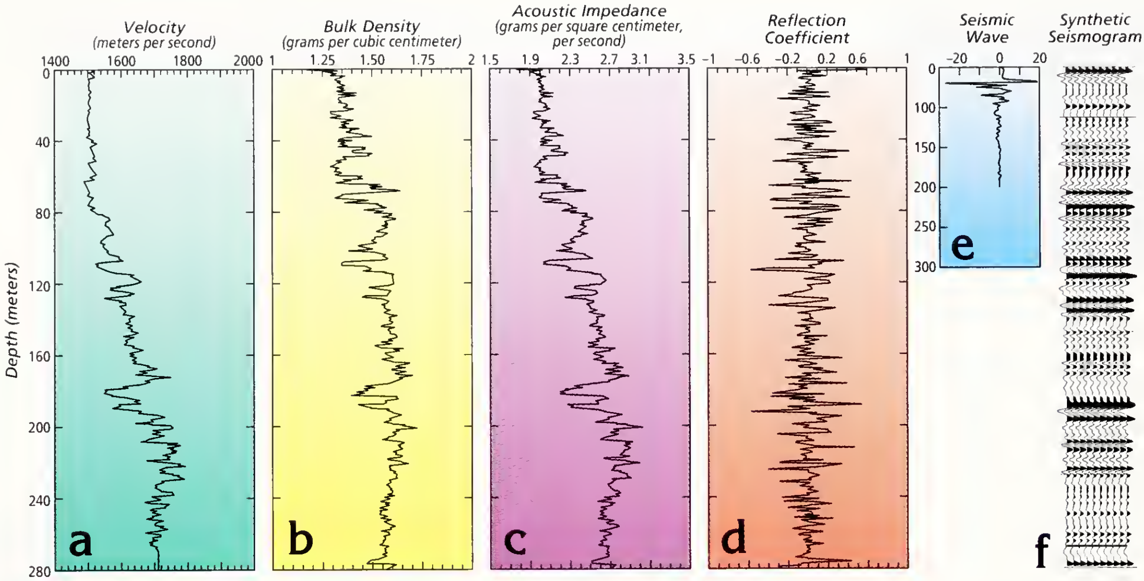
We can address both of the problems described above using our basic knowledge of sound-wave propagation to produce a model of the seismic wave's interaction with the earth. Once generated, a seismic wave will happily travel along at a speed that is a function of the physical properties of the material in which it is traveling. Nothing much will happen to the wave (except that it will gradually lose energy as it gets farther away from the point where it was generated—this is called attenuation) until it encounters a rapid change in material properties. The property that determines the seismic wave's behavior is known as the "acoustic impedance" or hardness, which is, in turn, a function of the speed of sound in the material and the saturated bulk density (or weight per unit volume) of the material. When there is a change in acoustic impedance, some energy is reflected and some energy continues on; the amount reflected depends on the abruptness and magnitude of change.

Deep sea reflectors appear to be linked to continental-margin reflectors that are associated with major changes in global sea level.

With this knowledge and a little computer wizardry we can model how a seismic wave that is several meters long will interact with impedance changes that are on the order of centimeters. First we must know what the acoustic impedance changes are. We can directly measure both sound speed and bulk density in the laboratory on cores recovered from the drill hole (and we often do), but this is both time-consuming and inaccurate because samples measured in the lab do not necessarily have the same properties as the in situ material. Instead, we use the technique of downhole logging, which involves lowering specially designed instruments into the borehole after coring. A wide range of instruments are available that can make in situ measurements of the properties of the rock surrounding the borehole, including sound speed and bulk density (see "Borehole Measurements Beneath the Seafloor," page 129 and "DSDP/ODP Downhole Measurements in Hole 504B," page 79). Logging thus provides a nearly continuous record of the changes in sound speed and bulk density down the length of hole, from which we can easily calculate changes in acoustic impedance. The sound-speed log has another benefit. As mentioned before, to figure out where to look for the changes that cause seismic reflectors, we must first convert seismic travel time, the amount of time it took for a seismic wave to travel to the reflector and back, into sub-bottom depth. This can be done if we know how fast the seismic wave travels through the earth; the depth will be this measured travel time multiplied by the speed divided by two.

Before we run our model we also must determine exactly what the seismic wave looks like. We do this by hanging a hydrophone far below our ship, firing the seismic source, and actually measuring the shape of the outgoing seismic wave. With a measurement of the downhole variations in acoustic impedance (from logging) and our measurement of the seismic wave's shape, we now have all the information we need to model the interaction of the relatively long seismic wave with the fine-scale changes in acoustic impedance.

The modeling begins with calculation of a parameter called the "reflection coefficient," which is the rate of acoustic impedance change.



Jayne Doucette/WHOI

Then, following millions of multiplications and additions (clearly a job for a computer), we mathematically move the seismic wave through the impedance changes. The product of this process (known as convolution) is a "synthetic seismogram" that, if we have done everything properly, should represent the fine-scale changes of impedance as filtered, or smeared out, by the long seismic wave. The synthetic seismogram should also look something like the actual reflection profile.

Seismic modeling. These data are from ODP Site 844 in the eastern equatorial Pacific. Downhole logging is used to make detailed measurements of the speed of sound and the bulk density of the rocks surrounding the borehole. These are combined to calculate acoustic impedance (or hardness) and the reflection coefficient. The reflection coefficients are mathematically combined with a replica of the seismic wave produced by the airgun to produce a synthetic seismogram.

Equatorial Pacific Reflectors and Paleoceanographic Change

Over the past few years we have applied this modeling approach to several drilling legs in the central, western, and eastern Pacific Ocean. In our first study, in the deep central equatorial Pacific (DSDP Leg 85), we identified a number of regionally traceable seismic reflectors ranging in age from 3 to 22 million years old. By using synthetic seismograms we showed that most of these reflectors were impedance changes caused by dissolution of the calcareous component of the sediment as it accumulated on the seafloor. This dissolution was in response to major changes in deep ocean chemistry and circulation that appear to be linked to climatic and tectonic events (for example, the closing of the Isthmus of Panama about 3 million years ago, or the isolation of the Mediterranean Sea about 6 million years ago). Most intriguingly, these same deep sea reflectors appear to be linked to continental-margin reflectors that are associated with major changes in global sea level, indicating a clear connection between margin and deep sea and continental margin processes.

Having established the ability to use the seismic record to investigate the deep sea's response to regional and perhaps global oceanographic and climatic events, we then turned to other areas of the Pacific. On ODP Leg 130 we found reflectors in the western equatorial Pacific representing some of the same events we identified in the central Pacific. Here, however, the reflectors were not caused by dissolution, but instead appeared to be related to changes in the sediment's physical properties resulting from increased bottom-current activity (increased currents carry away fine material and change the material's bulk density). On ODP Leg 138 in the eastern equatorial Pacific, we again found several of the same reflectors, but here some of the reflectors were caused by changes in bulk density due to massive outpourings of siliceous organisms (diatoms, which represent high productivity) rather than dissolution or increased currents.

In combining seismic profiling, downhole logging, and seismic modeling, we are extending the experimental results of discrete drillholes far beyond the borehole. What we are seeing in the seismic record is the ocean's response to regional and sometimes global events. While these reflectors are found in widely diverse regions of the oceans, the processes responsible for creating them differ from region to region. By determining the mechanism of reflector formation in each region we can begin to map, over large areas (and through geologic time), the distribution of these processes. In this manner, we can piece together a global picture of the ocean's response to tectonic and climatic change, and further understand the fundamental workings of the earth-ocean system. ■

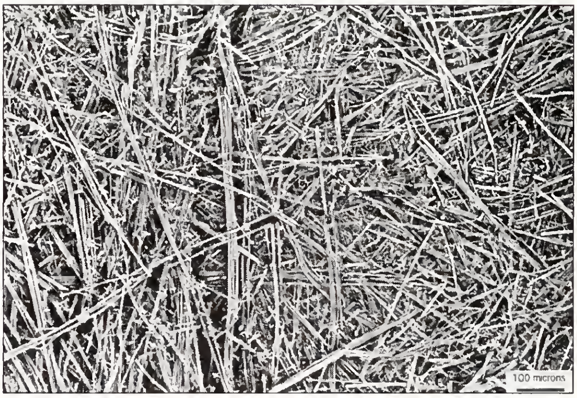
Larry Mayer has always had a tough time making choices—as a graduate student at Scripps Institution of Oceanography he couldn't decide between geophysics and paleoceanography so he ended up with two advisors and tried to do both (paleogeophysics???). He continues this fence-walking today, and as a result cannot be considered an expert in either field. He survives by only talking about geophysics with paleoceanographers and only talking about paleoceanography with geophysicists. He is presently the Natural Sciences & Engineering Research Council Chair in Ocean Mapping at the University of New Brunswick in Canada where his research deals with sonar imaging and remote classification of the seafloor. He continues to have strong a interest in the paleoceanography of the equatorial Pacific, particularly in the midst of a Canadian winter.

Details That Make the Difference

Nick Shackleton and Simon Crowhurst

In studying the oceans, as in studying astronomy, improvements in data resolution can be crucial to identifying the natural processes at work. However, in the early years of ocean drilling, techniques were more profligate even than the Hubble space telescope in their loss of high-resolution data. Only recently have improved sediment-recovery techniques realized their full potential for revealing information about geologically rapid processes recorded in deep sea sediments.

During the first 15 years of ocean drilling, most sites really were only "drilled," but the past decade has brought increasing use of two other techniques: downhole logging and hydraulic piston coring. Logging, passing sensors down through the hole to examine surrounding sediments, allows us to learn more about the core sections and is particularly valuable where sediment recovery is poor. In the upper 200 meters (usually soft, unconsolidated sediments), drilling too often brings back homogenized slurries that have lost all but the largest-scale information about the sediment. However, advanced piston coring, which drives the core barrel through the sediment by hydraulic pressure, yields almost perfect recovery of soft, unlithified sediments that would be severely disturbed by rotary drilling. This technique's potential was first demonstrated during DSDP's Leg 64 in 1970, when the prototype hydraulic piston corer, brought aboard *Glomar Challenger* halfway through the cruise, performed spectacularly well in recovering laminated sediments in perfect condition at Site 480 in the Gulf of California. No trace of the laminations had been visible in equivalent material recovered by rotary coring at nearby Site 479. More recently, similar laminated sediment was recovered from the open ocean at several of the sites cored during Leg 138 (see photo above), forcing us to reject the notion that laminated sediments invariably imply deposition in an anoxic water mass, such as the Gulf of California. Alan Kemp (University of Southampton) and Jack Baldauf (Texas A&M University) have shown that the laminations at the Leg 138 sites were created by mats of



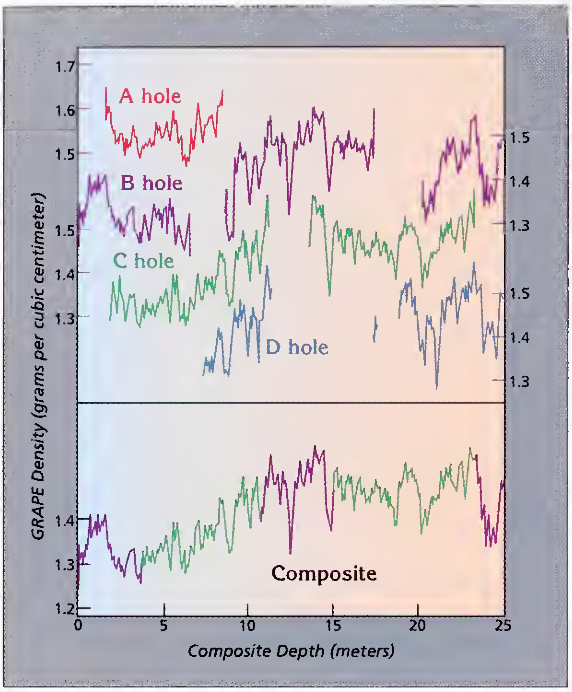
ODP

Laminated diatom ooze was recovered from Site 851.

the diatom *Thalassiothrix* that episodically blanketed the seafloor during intervals of very high surface productivity, and suppressed bioturbation.

The main thrust of recent paleoceanographic research based on ocean drilling is investigation of the whole Neogene period (the past 20 million years) with the same degree of detail previously available only for the late Quaternary (a fraction of the past one million years). The conventional view of earth history holds that high-frequency environmental variability was confined to the Quaternary, with its characteristic ice-age cycles, and that variability observed in outcrops of older rocks was only of local significance. We are now learning that this was a false picture. ODP Leg 138, with author Shackleton in the scientific party, provides just one example of a drilling leg largely or entirely devoted to high-resolution paleoceanography. It was, however, enormously successful in a number of ways, and the rest of this article focuses on it as a case study in high-resolution paleoceanography.

Jack Cook/WHOI Graphics



Data from several holes drilled at one site were combined to fill in gaps between cores to provide a more complete picture (composite at bottom) of the site's geological history.

Filling in the Blanks: Gaps in Sediment Cores

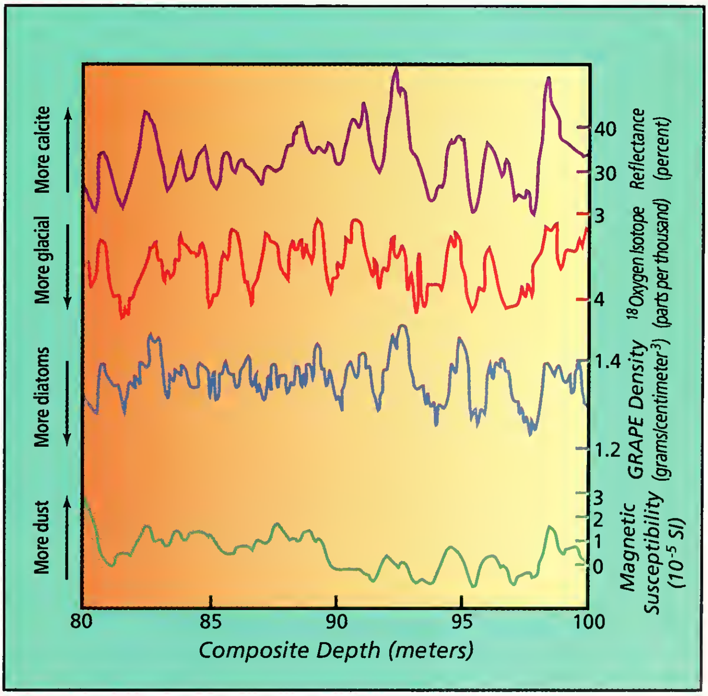
Gaps in the sequence of sediments recovered at many earlier drilling sites were disappointing. These gaps occur between successive cores as the drill string is driven further into the sediment. However, if several holes are drilled within a few tens of meters of each other, it should be possible to fill one hole's gaps using sediment from an adjacent hole, provided that the gaps in the second hole are vertically offset from those in the first. All too often, this has not been successfully achieved. The co-chief scientists on Leg 138, Larry Mayer (University of New Brunswick) and Nick Pisias (Oregon State University), made it their prime objective to recover a complete section at each site. Substantial innovation was required to speed up ship-board analysis procedures, to be certain that we did not pull pipe and sail away until the sedimentary section had indeed been fully recovered. As each 9.5-meter core was recovered, high-resolution GRAPE (Gamma Ray Attenuation Porosity Evaluator) density, magnetic susceptibility, and color-reflectance scans were obtained. (GRAPE density and magnetic susceptibility data are routinely collected, but the digital color scanner was a new device developed by Alan Mix (Oregon State University) and used for the first time on Leg 138.) These data, from each of the holes drilled at a site, were compared to ensure that we had successfully covered every core-to-core gap with material from another hole. That this was a feasible objective in itself indicates the pervasiveness of high-frequency lithological variability: We never recovered sediment so monotonous that we could not recognize and correlate details.

Sedimentary variations may reflect the impacts of many types of environmental variability. For example, there is evidence in the high-resolution data from a late Pliocene section of Site 846 for variability in several different components of the climate system: local surface-water productivity, global ice volume, seafloor dissolution of carbonate, and the influx of wind-blown dust from adjacent continents. It is also evident that, although there are similarities between the various records, they are certainly not identical. For example, we can see major oxygen-isotope cycles (reflecting global ice volume) spaced at about 2-meter intervals between 80 and 90 meters in the figure below; we know from work here and elsewhere that these reflect glacial cycles controlled by changes in the obliquity of Earth's rotational axis that occur with a regular period of 41,000 years. At the same time, the GRAPE density record shows shorter cycles about 1-meter thick (very clear at about 85 meters) that reflect changes in surface productivity, which controls the diatom concentration in the sediment. These changes appear to be governed by climatic alternations linked to astronomical cycles with a period of about 21,000 years. The blue-band color reflectance shows similar cycles, probably because in this band calcite is more reflective than biogenic silica (although both calcareous and siliceous sediments appear white to the human eye). Magnetic susceptibility arising from the terrigenous dust component of the sediment is higher in the more reflective (whiter) sediment, suggesting that in the diatom-rich part of each cycle the terrigenous material is more diluted by the increased flux of biogenic material to the seafloor.

Subtle quasi-cyclic variations in earth-sun orbital geometry, known as "Milankovitch cycles" (see page 53) are believed to be largely responsible for Quaternary glacial variability—the "Ice Ages." We are now learning that these orbital changes also affected climate in earlier times, and perhaps throughout earth history. Earth's climatic and biological response to such orbital variations appears to have changed slowly through geological time, and as it did so, the nature of the signal left in the sediment also changed. For example, during the last million years, the waxing and waning of huge polar ice sheets left a strong isotopic signal in the chemistry of sediments over large areas of the world's oceans. Studies of sediments recovered on Leg 138 show that during the last 20 million years, changes in regional biological productivity, probably related to wind strength, were well marked even when the oxygen-isotope variations were small and irregular.

Calibrating the Geological Time Scale

Once we recognize that cyclic signals represent the response of climate and ocean circulation to variations in Earth's orbital geometry, we can use them to accurately calibrate the geological time scale. The Milankovitch astronomical



Major cycles that reflect global ice volume are evident at about 2-meter intervals in these portions of oxygen isotope, GRAPE density, magnetic susceptibility, and color reflectance records from Site 846. The shorter cycles clearly present in the density record, and visible to a lesser degree in the reflectance data, indicate changes in surface productivity.

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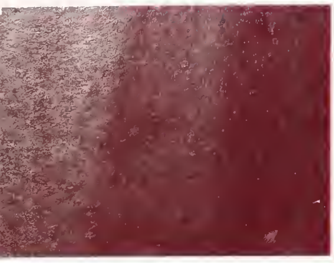

cycles have been calculated for the past 10 million years by André Berger and Marie-France Loutre (Institut d'Astronomie et de Géophysique G Lemaitre, Université Catholique de Louvain), and more approximate calculations can be made for 100 million years into the geological past. The figure below plots portions of GRAPE density variation data from two sites against calculated orbital variations. We have calibrated orbital variations for the whole of the past 6 million years (back to the latest Miocene), and we have also made detailed correlations between all the sites drilled, by matching GRAPE density cycles back through more than 10 million years. Since Fritz Hilgen (Institute of Earth Sciences, Utrecht) and his colleagues have independently calibrated cycles in Pliocene sediments exposed in southern Italy with astronomical cycles, this means not only that the last 6 million years of earth history are calibrated with a precision approaching a few thousand years, but also that each lithological cycle observed in southern Italy can be uniquely associated with a particular cycle in the sediments of the equatorial Pacific, a truly astonishing match across time and distance.

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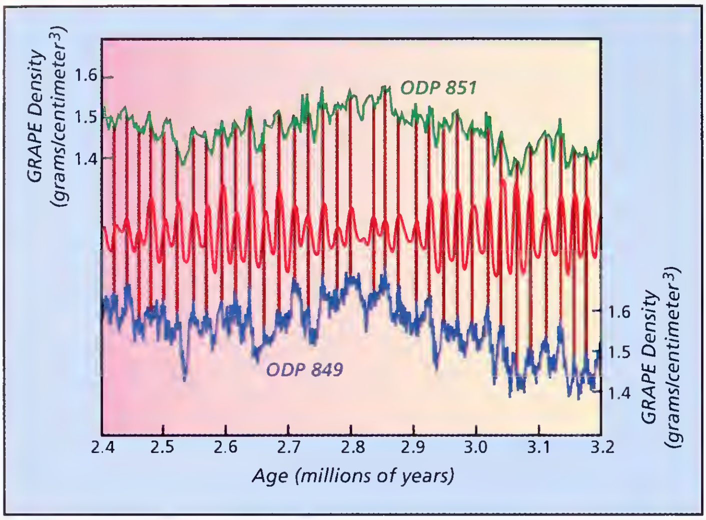

GRAPE density records from Sites 849 and 851 show remarkable correlation with orbital calculations (red line) for the period from 4 to 3 million years ago.

This in turn permits exploration of climate-change mechanisms, and the ocean's response to external forcing. Understanding these processes is essential for developing and testing computer models of Earth's climate system, including models intended to predict climatic response to human activities such as carbon-dioxide production. Equally important, a true calibration of the rates of climate change, biological evolutionary change, sea-level change, and so on, are crucial to our understanding the geological record. The high-resolution records recovered by ocean drilling are making enormous contributions in paleoclimatology, paleoceanography, and many other aspects of geology. ■

Nick Shackleton transmuted his early interest in the physics of sound into paleoclimatology, and with John Imbrie and Jim Hays he published the 1976 paper "Variations in the Earth's Orbit—Pacemaker of the Ice Ages," which is widely regarded as having provided the first conclusive evidence that the Milankovitch orbital variations were responsible for major climatic change in the geological past. He is Director of the Subdepartment of Quaternary Research, Cambridge University, UK. His recent research focuses on improving the resolution of geological time scales and clarifying the interaction of climate-related processes in the Neogene. He has also managed to pursue a keen interest in collecting and playing clarinets.

Simon Crowhurst worked for a Cambridge, UK, company making industrial robots before moving to the Godwin Laboratory four years ago to become a research technician working with Professor Shackleton on the astronomical "tuning" of data from ocean cores.

Early History of the Oceans

Hugh C. Jenkyns

Since ocean crust is created by seafloor spreading and destroyed by subduction, the sedimentary record of ancient oceans can only be found as far back as the Jurassic (about 170 million years ago) by drilling into the oldest parts of the oceans themselves. Continents, however, are potentially immortal and drilling into their margins may reveal older sedimentary rocks. As a counterpoint to these studies, sediments and fossils exposed on land but formed in oceans or their margins can be investigated by the geologist. Such rocks typically occur in mountain chains formed where continents have collided and fragments of all-but-vanished oceans have been preserved. Clues to the history of ancient oceans can be gleaned from studying all these different types of evidence, but the record is tantalizingly incomplete and interpretations are often tentative.

The Triassic Tethys

In the latter part of the 19th century, European geologists realized that certain marine sedimentary rocks and fossils found in the Himalayas and East Indies were identical to those already known and documented from

Jack Cook/WHOI Graphics

View of the late Triassic world, indicating the areas where Tethyan sediments and fossils are found. The shaded area indicates the possible extent of the ancient Tethyan seaway during the latest part of the Triassic period. Drilling during ODP Leg 122 off northwest Australia found limestones and fossils identical with their Alpine counterparts.

Jack Cook/WHOI Graphics

View of the Late Jurassic world, indicating the suggested geometry of the Tethyan Ocean in the Alpine-Mediterranean region and showing its connection to the proto-Atlantic (green-shaded areas). Shallow-water banks, like the present-day Bahamas, bordered both these oceans (tan-shaded areas). Although the oldest shallow-water limestones drilled by DSDP/ODP in the Blake Plateau-Bahama complex are Cretaceous in age, similar environments existed during the Jurassic.

the Alps. Most of these were dated as Triassic in age (about 210 million years old) and were interpreted as deposited in a peri-equatorial seaway that girdled half the Earth, along whose length faunas could freely migrate. This seaway was named "Tethys," after the sister and consort of Oceanus, god of the sea, in Greek mythology. Examination of the assumed pattern of continents and oceans during the Triassic Period shows how this ancient seaway must have stretched from southern Europe and northern Africa across India to lands farther east. Just how much farther east was revealed on ODP Leg 122, which cored Triassic sediments off northwest Australia. These, the oldest sediments cored by ODP, include white limestones of shallow-water origin, rich in sponges, mollusks and corals, that are indistinguishable from those found in Austria, northern Italy, and Sicily. Indeed these fossils would not be out of place in a museum in Vienna. A snapshot of the latest Triassic world would reveal a discontinuous band of reefs and tropical carbonate sediments running approximately east-west for thousands of kilometers.

The Jurassic Atlantic

The story of Tethys continues with the revelation that Jurassic sediments cored in the easternmost and westernmost Atlantic are similar to those found in the Alpine-Mediterranean domain and locally in the Himalayas. First cored on DSDP Leg 11, and subsequently on Legs 41, 44, 50, 76, and 79, upper Jurassic sediments (about 155 million years old) include characteristic red nodular limestones and light-colored chalks that could equally derive from outcrops in Austria, Spain, or Italy. Essentially, this discovery meant that the Tethys must have continued westward along the proto-Atlantic into the Caribbean. Indeed the sedimentary history of the early Atlantic Ocean and its margins provide an exact analog for the evolution of the Tethys. The Blake Plateau and the Bahama Bank complex, for example, drilled on DSDP Leg 44 and ODP Leg 101, have their counterparts in the limestone mountains of Italy, Croatia, and Greece.

The Jurassic Pacific

Two DSDP legs, 61 and 89, were dedicated to finding the oldest crust and sediment in the Pacific before these elusive rocks were finally found. The early attempts were frustrated by the presence of Cretaceous basalt that blankets much of the older Pacific Plate. (More of this anon.) Unlike the Atlantic's Jurassic sediments, deposited when that ocean was small and narrow, deposits of equal age in the Pacific were laid down in a super-ocean that covered half the globe. The nature of the Pacific Jurassic was finally revealed on Leg 129. Unlike the Atlantic, whose Jurassic sediments are dominated by the skeletal remains of calcareous plankton, the coeval Pacific record of 160 to 150 million years ago shows clay and siliceous microfossils deposited in depths below which calcium carbonate could not be preserved. Vividly red-brown in color, the silica-rich and clay-rich layers alternate, probably in accordance with astronomically influenced climatic changes that affected the fertility of the surface waters and hence plankton productivity over intervals of tens to hundreds of thousands of years.

The Cretaceous of the World Ocean

The Cretaceous has been cored in many places across the world ocean, and our knowledge of the paleoceanography of this period is commensurately greater than that of the Jurassic. Two aspects of Cretaceous oceanic geology are of particular significance. The first takes us back to Leg 61, the first scientific cruise that tried unsuccessfully to find the Jurassic of the Pacific Ocean. What was incidentally revealed was the presence of voluminous flows and intrusions of basalt across much of the Cretaceous Pacific Plate, associated with such submarine volcanic edifices as seamounts and plateaus. A further discovery of this leg, echoing findings of Legs 17 and 33, was the presence of redeposited shallow-water microfossils of Caribbean affinity in deep-sea sands. The episode of seamount-building volcanism must have provided atoll-like stepping stones that facilitated westward migration of these reef-associated faunas during the Late Cretaceous (65 to 80 million years ago). Subsequent studies show that this migration route was used by other shallow-water fossil groups. Caribbean faunas penetrated as far west as the Middle East, while the Atlantic apparently remained an insuperable barrier.

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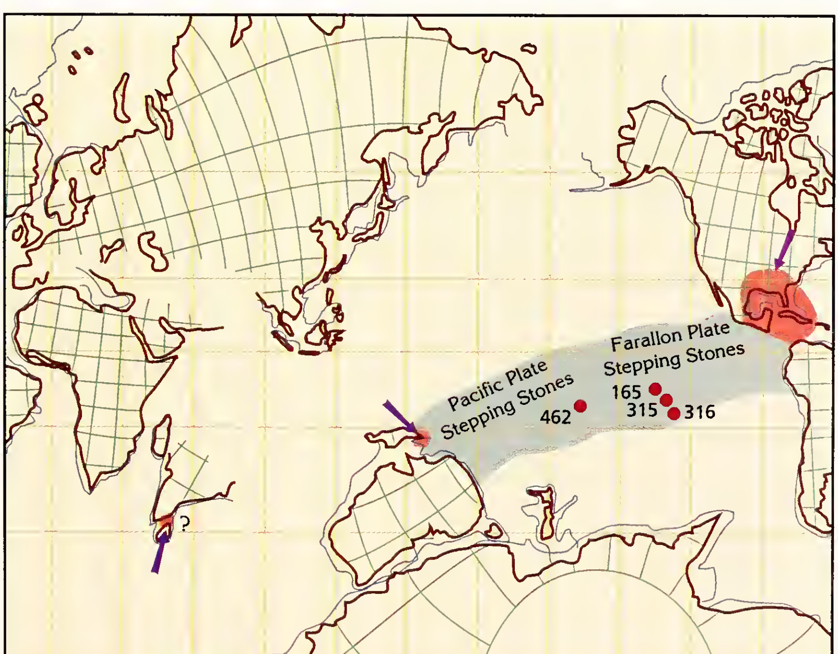

View of the Cretaceous Pacific, indicating the presence of volcanic pedestals or stepping stones across which reef-associated faunas could migrate westwards from the Caribbean. Numbers refer to drilling sites where redeposited shallow-water faunas of Caribbean affinity have been found in deep-sea sands. Arrows indicate areas where these faunas are known from outcrops on land. In tectonic terms, the ancestral Pacific was made up of the Pacific and Farallon plates and several others.

It has been suggested that the profuse volcanic activity characteristic of the Cretaceous globe would have increased the content of atmospheric carbon dioxide, thereby increasing global temperatures. One effect would have been a decrease in the amount of oxygen dissolved in marine waters, which could have helped preserve planktonic organic matter in marine sediments by protecting it from oxidation. Is there evidence for burial of anomalously large amounts of organic matter in Cretaceous oceans? The answer is yes, but higher global temperatures are but one of the mechanisms used to explain this phenomenon.

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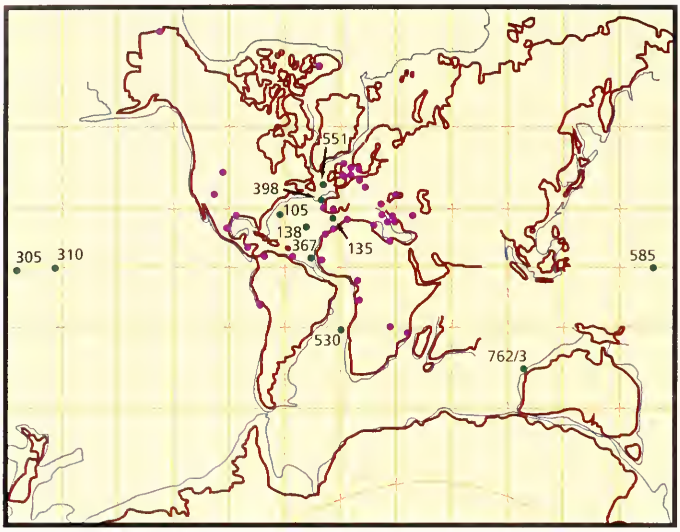


Location of carbon-rich black shales from numbered DSDP and ODP sites restored to their position some 90 million years ago (late Cretaceous) and from outcrops on land. All shales are of identical age, dated exactly at 93 million years ago, and probably record a period of elevated plankton productivity operating on a global scale.

Cretaceous carbon-rich black shales were cored in the Atlantic during DSDP Leg 1 as well as during several subsequent legs in the same ocean. As long as these carbon-rich black shales were seen as a uniquely Atlantic phenomenon they could be viewed as the product of a relatively narrow and restricted ocean, possibly stagnant and oxygen-depleted like the present-day Black Sea. But during Legs 32, 33, and 62, such sediments were cored on topographic highs in the ancestral Pacific super-ocean. Moreover, detailed dating of these sediments from all oceans, and from outcrops on land, showed that they were confined to discrete intervals of geological time, for example, about 120 and 93 million years ago. The balance has now swung to investigating anomalously high rates of plankton productivity as the proximal cause of these black shale "events." But what caused the elevated productivity? There are no definite answers yet, but if the ocean-atmosphere system is in steady state, one response to the production of excessive amounts of volcanogenic carbon dioxide could be to fix it as organic carbon in marine sediments. That most of the world's petroleum source rocks were formed during this period spotlights the economic importance of understanding the processes involved.

Hugh Jenkyns did his thesis work on deep-sea Mesozoic carbonates in Sicily from 1966 to 1969, working close to the village of Corleone, and has since seen the area depicted in a number of well-known movies. He was almost blown up in Palermo only once. He then went to the University of Basel in Switzerland, followed by a two-year spell at Oxford, but continued his love affair with Italy, particularly the less turbulent north Alpine region. The fact that the sediments exposed there were similar to those cored in the Atlantic introduced him to the Deep Sea Drilling Project, and he has since participated in three Pacific legs. He taught at the universities of Cambridge and Durham before returning to Oxford in 1977, where he has remained ever since.

The Central Mystery of the Quaternary Ice Age

A View From the South Pacific

Wolfgang Berger, Torsten Bickert, Eystein Jansen, Gerold Wefer, and Memorie Yasuda

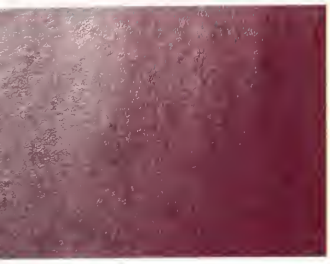
We live in an ice age: current sea level is some 70 meters below where it would be if the polar regions were warm. However, we live in a warm interval of this ice age—sea level is 120 meters higher than it was at the last glacial maximum 20,000 years ago. As large continental ice sheets wax and wane in the Northern Hemisphere, sea level fluctuates. Water locked in the ice is depleted in heavy stable isotopes of both hydrogen and oxygen; thus, a buildup of ice enriches the ocean's water with oxygen- 18 relative to oxygen- 16. The enrichment (and its cancellation during melting) can be measured as changes in oxygen isotope ratios within the calceous shells of marine organisms (as shown by University of Miami paleontologist-physicist Cesare Emiliani in 1955).

Certain planktonic foraminifera are well suited as recorders of isotopic ratios. However, in addition to recording the ice budget, the oxygen-18 to oxygen-16 ratio of their shells reflects changes of surface water temperatures. The best places to obtain unadulterated records of ice mass, therefore, are tropical regions that show little change in temperature from glacial maxima to glacial minima. Such a place is the Ontong Java Plateau in the western equatorial Pacific. The plateau is roughly the size of Texas and rises from the surrounding abyss to 1.6 kilometers below the water surface; it accumulates well-preserved shells of foraminifers.

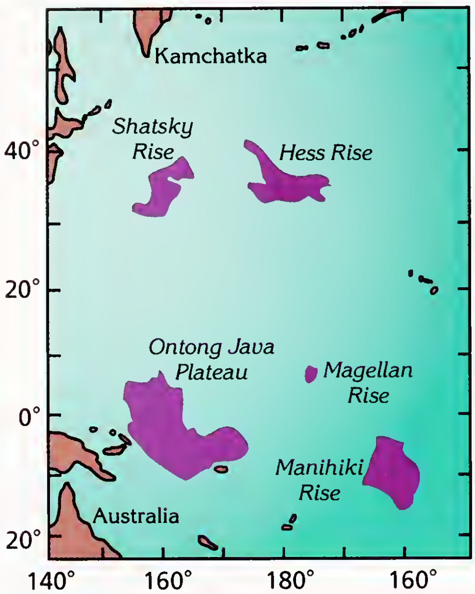
Five cores collected on ODP Leg 130 provide an excellent record of ice-mass fluctuations over the last two million years.

The Ice Age Record from the Ontong Java Plateau

Five cores collected on ODP Leg 130 (in 1990) at Site 806 provide an excellent record of ice-mass fluctuations over the last two million years (the Quaternary period). We base our interpretation of this record on the theory of the Serbian astronomer Milutin Milankovitch (1879– 1958). He proposed that periodic changes in the tilt of Earth's axis and in the



eccentricity (deviation from a circle) of Earth's orbit translate into growth and decay of ice mass through changes in summer insolation (the amount of sunlight reaching Earth's surface) in high northern latitudes (say, at 65°N). The formulation and step-wise confirmation of the Milankovitch theory is one of the great scientific success stories of our century (see Nicklas G. Pisias and John Imbrie, *Oceanus*, 29:4, 1987). In essence, the theory solves the mystery of why ice ages occur in cycles. The study of deep-sea sediments (and especially of oxygen isotopes) was of crucial importance in this context.



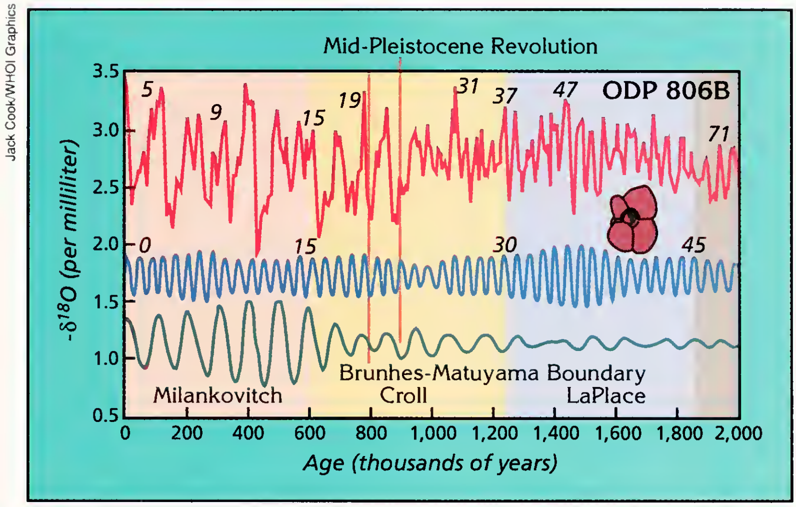
Location of Ontong Java Plateau where Site 806 was drilled. The plateau is one of the great basaltic edifices in the western Pacific created by enormous volcanic outpourings in the Mesozoic.

There is evidence in the Site 806 oxygen-isotope record for ice-mass control by both eccentricity and obliquity (figure opposite). Three subdivisions regarding climatic state are readily distinguished. The oldest third is dominated by 41,000-year axial-tilt cycles, the youngest third by roughly 100,000-year eccentricity-related cycles. The central third shows the transition from one regime to the other. The three regimes are labeled "Milankovitch" chron, "Croll" chron, and "Laplace" chron after the scientists who introduced the fundamental ideas underlying orbital dating. The Scot James Croll made the first attempt at template-dating of ice ages, while French astronomer Pierre Simon de Laplace's calculations provided a firm base for celestial mechanics, which allow extrapolation of orbital conditions into the distant past. Boundaries between the chrons are set according to the strength of the eccentricity cycle present. For simplicity, they are put precisely at the crests of obliquity-driven cycles 15, 30, and 45. The single most striking feature of the Site 806 ice-mass record (beyond the cyclicity itself) is that the nature of the cyclicity changes at the center of the Quaternary, about 900,000 years ago. We call this the "Mid-Pleistocene Revolution" (MPR).

An Orbital Template for the Ontong Java Plateau

Can simulation of the ice-record from orbital data help us understand the nature of the mid-Pleistocene climate shift? An early attempt to provide a match between target and template using data from the Ontong Java Plateau (by science journalist Nigel Calder, in 1974, with data from Nick J. Shackleton of Cambridge University and Neil D. Opdyke of Lamont-Doherty Geological Observatory) provided a good match back to about 600,000 years. We repeated the exercise using the longer (and less disturbed) oxygen-isotope record of Site 806, and a more efficient template-making model.

To generate the template we use the July insolation at 65°N, following the arguments of Milankovitch. Also, heeding his advice that cold winters do not necessarily have more snow than warm ones, we assume the same potential ice-growth year after year, regardless of the seasonal insolation distribution. The change in sea level at any time is then provided by the difference between steady ice growth and insolation-dependent melting. The record indicates that strong melting events follow maximum buildup. This effect can be achieved in the model by introducing negative feedback on ice growth in such a fashion that it



Oxygen isotope record of the planktonic foraminifer Globigerinoides sacculifer *at Site 806 (top curve). Numbers are isotope stages. Middle and bottom curves are cycles extracted by Fourier expansion of the record, centered on 41,000-year and 100,000-year periods, respectively. The right-hand orange line shows the mid-Pleistocene Revolution and the left-hand orange line the Brunhes-Matuyama boundary. See text for tripartite subdivision.*

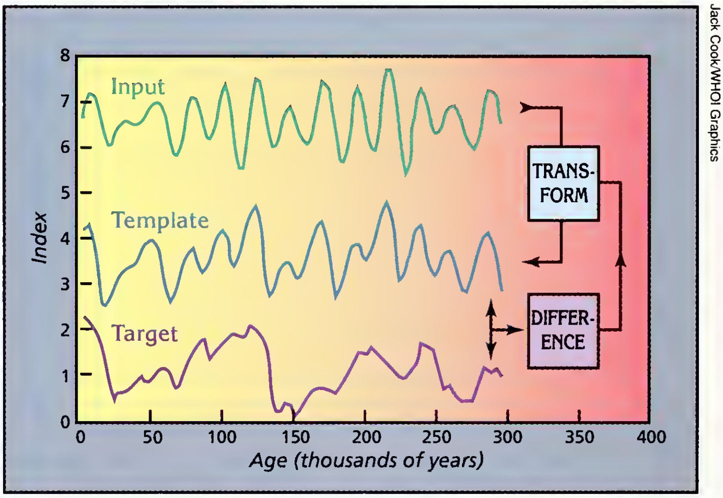
becomes important only when large ice masses are present for some considerable time, and when insolation values are high.

The transform algorithm resulting from fitting the last 300,000 years (figure below) is next used to "postdict" the record for the million years preceding 300,000 years. Although some ill-fitting portions remain, the quality of the match is remarkable.

Nature of the Climate Shift at 900,000 Years

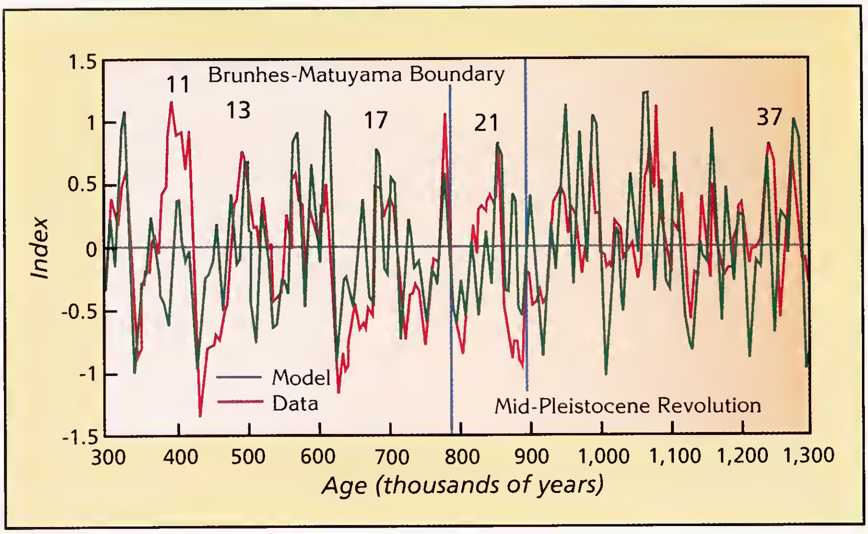
One striking result of the template matching is that the fit between template and record is no longer very good before the time of the climate shift: The rules of response have changed. The decisive change 900,000 years ago is the buildup of "surplus" ice, as is evident from comparing template and record. Apparently it is this additional ice (about 15 percent of the total active ice mass) that turns on the mechanisms responsible for the change in response.

The expansion of the maximum ice mass has two opposing effects: 1) It provokes additional cooling, thus stabilizing glacial conditions, so that little ice is removed except during periods of extreme summer insolation; and 2) the expansion increases instability by building ice on marine shelves and thus providing the potential for inland invasion of seawater below ice, when



Tuning the transform algorithm by minimizing the mismatch of template and target. Here the template is built from a model using input calculated by astronomers André Berger and M.F. Loutre. The target is the record of 806B-1H. The model is given by the equation $\Delta SL = -IGR + INS^a \cdot ICE^b \cdot MEM^c$, *which describes sea-level change (ΔSL) as a function of constant ice growth (IGR) opposed by melting, with variable insolation (INS), ice mass (ICE), and average ice mass over the last 40,000 years (MEM). Calculations are in normalized space (0 to 1). IGR is set to 0.14, and exponents are set to 3, 2, and 2, for a good fit to the last 300,000 years.*

Comparison of orbital templates (based on the fit shown in the figure at the bottom of page 55) and isotope record of 806B, for the time span from 300,000 to 1,300,000 years ago. Note the distinct misfit appearing before the mid-Pleistocene climate shift.



sea level rises. The process called "marine downdraw," which involves collapse of marine-based ice-sheets (for example, on the Barents Sea shelf) is thought to be of special importance. In addition, increased pressure at the bottom of an ice cap favors melting after maximum ice buildup.

Increased maximum ice mass is not the only change at the Mid-Pleistocene Revolution event. Melting tends to go further after the shift than before it. The role of the ocean in providing heat to high latitudes during deglacial and interglacial times may be crucial in prolonging interglacials and making them more extreme. From piston cores we know that periods of strong heat influx to the arctic realm are characterized by high foraminifer content in Norwegian Sea sediments. Deep drilling on the Vøring Plateau has shown that the onset of strong pulses of foraminifer accumulation coincides with the MPR event 900,000 years ago.

We do not know exactly why buildup of "surplus" ice and pulsed northern heat delivery are coupled and why they were initiated some 900,000 years ago. Many processes must be considered in addition to those mentioned above: changes in North Atlantic Deep Water formation (and the possible influence of Mediterranean outflow and bottom water production in the Barents Sea), effects on atmospheric carbon dioxide from greatly accelerated growth of the Great Barrier Reef during interglacials of the Milankovitch chron, uplift of mountain ranges from erosion and tectonic forces, and volcanism. Given these complexities, it is likely that the mid-Quaternary climate shift shall remain a mystery yet for some time. ■

Among many scientific honors, Wolf Berger received the Bigelow Medal in Oceanography from WHOI in 1979. He obtained his Ph.D. from the Scripps Institution of Oceanography (SIO), University of California, San Diego, in 1968. Finding that opportunities for interaction with the ocean are abundant and pleasurable in La Jolla, he has stayed on since, except for (sometimes extended) visits to the old country. Graduate student Memorie Yasuda helps hold the fort at the SIO Foram Lab during such visits. Eystein Jansen studies ice-age history at the University of Bergen, ready to clear his office should the ice advance again. Gerold Wefer heads the marine geology group at Bremen University, of which Torsten Bickert is a member. All the authors are indebted to Monika Segl, who is in charge of the isotope laboratory in Bremen.

From the Greenhouse to the Icehouse

A Southern Ocean Perspective of Paleogene Climate

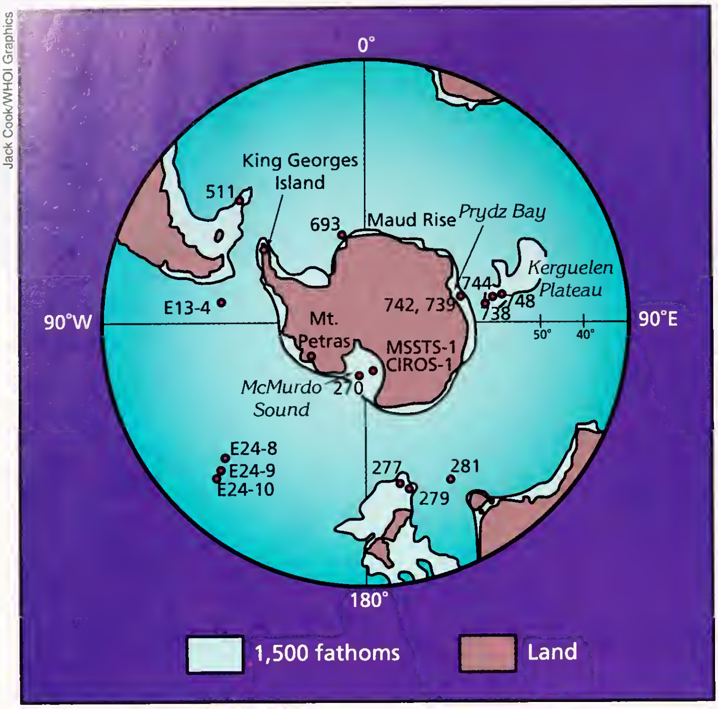
James C. Zachos

Glomar Challenger's retirement in 1983 marked the end of a highly successful 15-year international scientific drilling program that radically altered our understanding of the geologic and climatic evolution of the oceans. Among the many achievements was a new understanding of the early Cenozoic period of climate change known as the Paleogene era, which is further subdivided into three epochs, the Paleocene (57 to 65 million years ago), Eocene (35 to 57 million years ago), and Oligocene (25 to 35 million years ago). Paleontological and geochemical investigations of deep sea cores revealed that the Paleogene was a time of dramatic earth climate transition from warm, equable conditions of the "hothouse" or "greenhouse" mode, to cooler, glacial-like conditions of the "icehouse mode." Although the "greenhouse" mode prevailed during much of the Paleocene and early Eocene, the warmest conditions existed during the early Eocene, some 55 million years ago.

Temperatures of the deep sea at that time were some 10°C warmer than the present, as were temperatures of higher latitude surface waters, which were inhabited mainly by warm-water species of marine plankton. The warmer conditions found in marine environments seemed to conform with reconstructions of climate on the continents, where high-latitude regions were inhabited by temperate to subtropical species of vertebrates and plants, such

Jody Forster

Huge tabular icebergs float in the Southern Ocean. This one was photographed along the Antarctic peninsula.



Locations of ODP drill sites near Antarctica. Drilling at many of the sites penetrated sediments deposited during the early Paleogene (60 million years ago).

as alligators and palms. This episode of early Eocene global warmth lasted for several million years before the onset of cooling and a 20-to-30-million-year gradual transition to the "icehouse" mode. By Oligocene time, polar regions had cooled substantially, although it remained unclear whether or not ice sheets had existed.

As the details of this global-climate transformation emerged in the late 1970s, it began to draw the attention of paleoclimatologists who wondered why Earth's climate changed as it did. Was the early Eocene warmer and the Oligocene cooler because of a decline in the concentration of atmospheric carbon dioxide, a greenhouse gas, or were other factors responsible, such as rearrangement of oceanic passages and currents by slowly drifting continents? These questions grew in importance, especially with concern increasing over the future climatic impact of recent high carbon-dioxide levels. However, despite the great interest, the questions remained unanswered, partly because many critical details about the character of the Paleogene climate were still vague. In particular, the absence of sediment cores from the climatically sensitive high latitudes had left a crucial gap in the paleoclimatic record. Attempts to obtain deep sea sediments from polar regions during the initial drilling program were limited by persistent harsh, icy weather. As a result, little was learned about the pre-Pleistocene climate history of the high-latitude oceans.

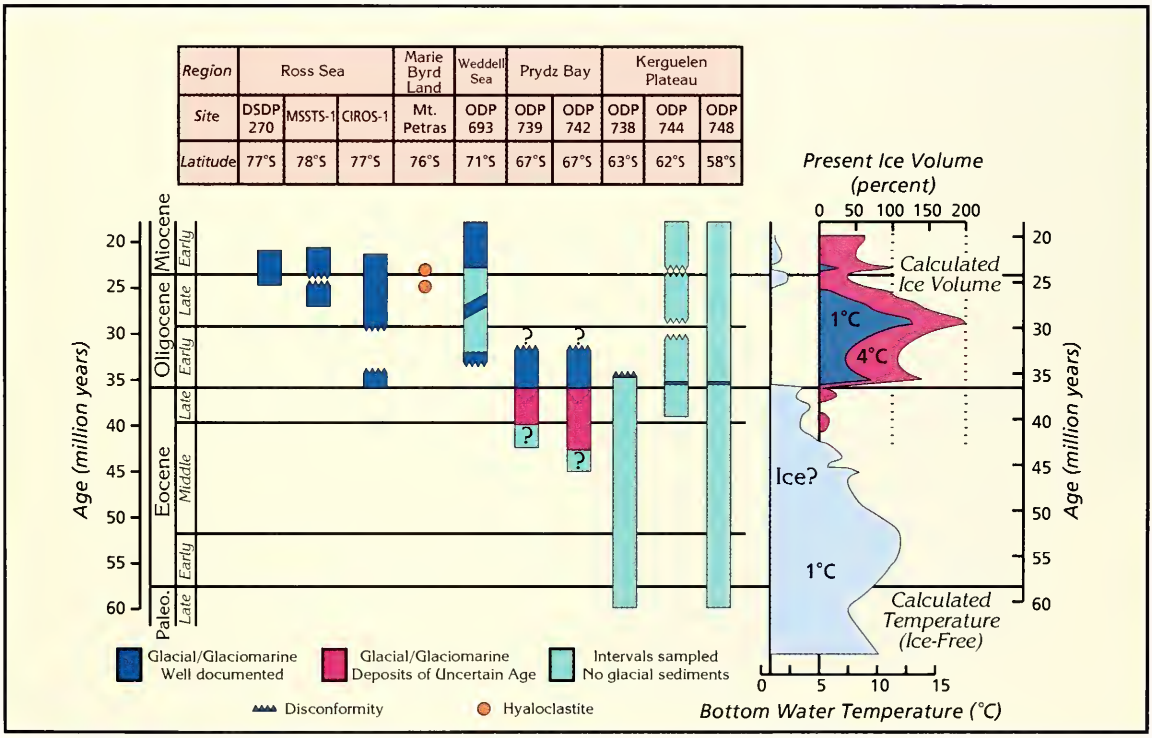
A New Perspective From the Bottom: Southern Ocean Paleoceanography

In 1985, with the initiation of *JOIDES Resolution* and the second phase of scientific drilling, scientists gained the capacity to drill in some of the more remote and inhospitable reaches of the world oceans, including the polar oceans. One immediate regional target was the Southern Ocean, where nearly 10 kilometers of sediment were recovered at more than 25 sites during four legs of drilling (Legs 113, 114, 119, and 120). In the years since, shore-based investigations of these cores have provided new insight into the Paleogene climate. Some of these findings are beginning to have profound effects on our understanding of the forces that altered Paleogene climate, as well as on climate-change dynamics in general.

Long- and Short-Term Warming in the Eocene

One of the more unexpected findings from high-latitude drilling resulted from high-resolution geochemical and paleontologic investigations of cores recovered from atop Maud Rise, and later Kerguelen Plateau, which revealed that the long-term climatic transitions were much more complicated than previously recognized. In reconstructing the sea-surface temperature records from the late Paleocene to the early Eocene, geologists found that Southern Ocean sea-surface temperatures (SST) first warmed from 4°C to 5°C, from 59 to 55 million years ago, reached a maximum of 14°C to 16°C in the early Eocene, and then began to decline. This was expected since the already available record of deep ocean temperature showed a similar trend.

A completely unforeseen result was the discovery of a brief but exceptional episode of high-latitude and deep-ocean warming midway through the longer-term trend, near the end of the Paleocene at roughly 57 million years ago. This unprecedented "event" was marked by an abrupt (less than 10,000 years) increase in high-latitude Southern Ocean SST with peak values in excess of 20°C, and deep sea temperatures as high as 16°C, conditions that were sustained for only a few tens of thousands of years. Moreover, this abrupt warm episode coincided with the demise of many species of bottom-dwelling, deep sea organisms, as well as increases in rainfall and chemical weathering rates on the antarctic continent.



Jack Cook/WHOI Graphics

Rock debris deposited by ice sheets as "glacial till" is very distinct, and thus serves as the most direct evidence of continental glaciations. This figure shows the age range and location of ice-rafted debris recovered from sites on and around Antarctica. The red area represents deposits whose exact age is uncertain. Many shallow and some deep sites show significant accumulation of ice-rafted debris throughout the Oligocene, indicating widespread glaciation. An indirect measure of ice-volume is obtained by reconstructing changes over time in seawater's mean oxygen-isotopic composition, which is sensitive to changes in global ice volume. Although this method provides only the lower limit on ice volume, it is currently the only semi-quantitative means to estimate ancient ice volume. The record shows that global ice volume was roughly 50 percent of present day volume by the earliest Oligocene.

Discovery of this short-term event immediately prompted several reinvestigations of other pelagic sequences from all ocean basins that eventually proved the event was global in scale.

The Onset of Antarctic Glaciation

In addition to documenting early Eocene global warming, the Southern Ocean investigations also provided critical evidence on the magnitude and timing of subsequent high-latitude cooling and continental glaciation. SST reconstructions showed a long-term, 8°C gradual cooling of the Southern Ocean over the middle and late Eocene from about 54 to 36 million years ago. As observed during the late Paleocene–early Eocene warming trend, a number of more abrupt steps were found in the record, times when Southern Ocean temperatures appeared to decrease rapidly in tens of thousands of years. Several short-term excursions toward warmer conditions—reversals of the long-term cooling trend—were also noted in the middle and late Eocene.

Until high-latitude drilling began, timing of antarctic glaciation was an extremely controversial subject.

By the late Eocene and early Oligocene, high-latitude climate had cooled sufficiently that conditions seemed frigid enough for continental glaciation. However, until high-latitude drilling began, timing of antarctic glaciation was an extremely controversial subject, with many geologists doubting the existence of continental ice sheets on Antarctica prior to the middle Miocene, some 15 million years ago. This perception was based mainly on the lack of significant physical evidence for earlier glacial activity. As a result of Antarctic drilling, however, it became evident that ice sheets were present on Antarctica as long ago as the earliest Oligocene. Thick sequences of glacially deposited debris found in Prydz Bay, together with similar deposits found earlier in McMurdo Sound on the opposite side of the continent, indicated widespread glacial activity, not atypical of continental ice sheets. Some of the oldest glacial sediments, however, were deposited in the late Eocene, suggesting that the very first ice sheets, albeit small, formed nearly 40 million years ago. Thus, it appears that glacial activity was limited regionally to portions of east Antarctica until about the earliest Oligocene (about 35 million years ago) when ice rafting became more widespread with occurrences even in distant offshore locations, indicating a permanent transition to full-scale continental glaciation.

Additional evidence for these continental ice sheets has come from oxygen-isotope geochemistry. This technique is based on the observation that the ratio of two naturally occurring isotopes of oxygen, $^{18}O:^{16}O$, is higher in ocean water than in ice sheets. The difference results from evaporation and condensation because these processes transfer relatively more ^{16}O-enriched water into precipitation, including snow. During glaciations enough of this ^{16}O water is locked up in ice sheets to increase the $^{18}O:^{16}O$ ratio of water remaining in the ocean.

Because changes in the ratio of seawater $^{18}O:^{16}O$ are imprinted in the calcareous shells of microscopic marine organisms, past variations in global ice volume can be reconstructed by measuring fossil shells from sediments of different ages. Analyses of microfossils from early Oligocene sediments deposited at roughly the same time as the glacial debris in Antarctica and the Southern Ocean yielded high $^{18}O:^{16}O$ ratios for seawater, indicative of large ice sheets, by at least 35 million years ago. This is tens of millions of years earlier than previously thought. Moreover, the oxygen-isotope records indicate that the ice sheets formed very suddenly, and briefly attained volumes close to those of present day ice sheets, before settling into a smaller, but more stable configuration.

Rapid Transitions and Transient Climates: Ramifications of Global Change

Not surprisingly, these recent discoveries of more rapid, and sometimes brief, excursions in early Cenozoic climate have influenced thinking about climatic driving forces. Can large-scale climate-forcing mechanisms behave episodically? For example, can carbon-dioxide outgassing due to volcanic activity along subducting margins or at mid-ocean ridges increase rapidly enough to produce the kind of abrupt, episodic warming that occurred near the Paleocene/Eocene boundary? Or does the global climate system respond episodically to gradual forcing due to the existence of physical thresholds in the climate continuum?

Some climatologists have suggested that even with gradual changes in boundary conditions, the ocean/atmosphere system is capable of shifting rapidly between two equilibrium modes, and in the process may temporarily overshoot equilibrium with the help of physical and chemical feedbacks in the ocean/atmosphere system. While there are many potential feedbacks, the exact source(s) of such nonlinear behavior in the climate system remains unclear. Nevertheless, these past excursions in global climate illustrate that climatic processes and forcing mechanisms can sometimes behave in unexpected ways. Although the Paleogene excursions were long by human time scales, such feedback-driven instability might exist at a variety of time scales, including the human. At the very least, the Paleogene climate excursions should serve as reminders of the climate system's unpredictable nature.

James Zachos is an Assistant Professor of Earth Sciences at the University of California, Santa Cruz. After obtaining his Ph.D. in oceanography from the University of Rhode Island in 1988, he spent four productive years at the University of Michigan before realizing that Ann Arbor is very far from the ocean. His current research interests range from early Cenozoic paleoceanography to horse diets.

The Challenge of High-Latitude Deep Sea Drilling

Jörn Thiede

Contrary to all older glacial episodes in earth history, the most recent development of cold polar climate was bipolar because of the peculiar Cenozoic plate tectonic subdivision of Earth's crust into relatively small ocean basins and continents. This ultimately resulted in an isolated continent over the South Pole, and a very restricted ocean basin over the North Pole. To learn more about these conditions, the deep sea drilling programs have collected cores in high southern and northern latitudes. The technique for drilling in ice-infested, high-latitude waters was first proven in the Southern Ocean on DSDP Leg 28. Since then, several DSDP and ODP legs have been devoted to unraveling the exciting story of the onset of Southern Hemisphere glaciations as early as Eocene/Oligocene times (see "From the Greenhouse to the Icehouse," page 57). In several instances the drill vessel required the assistance of ice picket (patrol) boats. The rather dry *Initial Reports* published do not reflect the reality of the harsh Southern Ocean environment—only by unearthing the "gray operational reports" can one read the stories of picket boats being "towed" by the icy giants and the dramatic experiences of scientists and crews during fierce storms and near-encounters with icebergs, either of which could force the drill ships to abandon sites.

Bipolar distribution of ice shields during the last glacial maximum. The drilling programs have collected cores in high southern and northern latitudes for studies of these conditions.

Jayne Doucette/WHOI Graphics

The Arctic Challenge

Giant floating ice fields keep the surface of the Arctic Ocean in constant motion, gyrating clockwise around a hidden western center (the Beaufort gyre), and moving straight across the eastern Arctic Ocean (transpolar drift) along a strange, narrow structural feature, the Lomonosov Ridge, between the Siberian and Canadian continental margins. It is only here that the world ocean reaches true high latitudes and its sediments hide the history of the most poorly known element of the global paleoenvironment's evolution. Sea ice is most common here, with icebergs as rare exceptions. The ice here is young because of the high, seasonally dependent rate of melting and freezing, and it is, therefore, not thick (generally only 3 to 5 meters). But

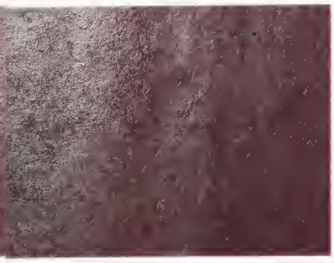
DSDP (Deep Sea Drilling Project) ▲ ODP (Ocean Drilling Program) it is hard and dense, so that most platforms available to scientific deep-sea drilling cannot penetrate it. The presence and movements of the ice cover have prevented collection of any long, stratigraphically undisturbed sediment sequences or underlying basement rocks. Therefore we know less about the Arctic Ocean's plate-tectonic and environmental history than we know about other oceans.

While seeking ways to circumvent the technical problems of drilling in permanently ice-infested waters, drilling engineers and geoscientists have conceived a whole new drilling program, the Nansen Arctic Drilling Program, which is associated with ODP but must employ a platform different from the vessels presently available for scientific deep sea drilling. Potential platform designs range from subsea installations and dynamically positioned nuclear submarines to ice-strengthened drill ships and semisubmersibles to powerful derrick-equipped icebreakers with the potential for station keeping even against the mighty pack ice. The necessary site surveys—detailed bathymetric data and networks of seismic reflection profiles—are lacking in most areas, and pose an additional intricate and expensive methodological challenge. However, the changing political arctic winds have also brought new possibilities for using unconventional research platforms such as formidable nuclear submarines for reaching regions hitherto closed to the international geoscience community.

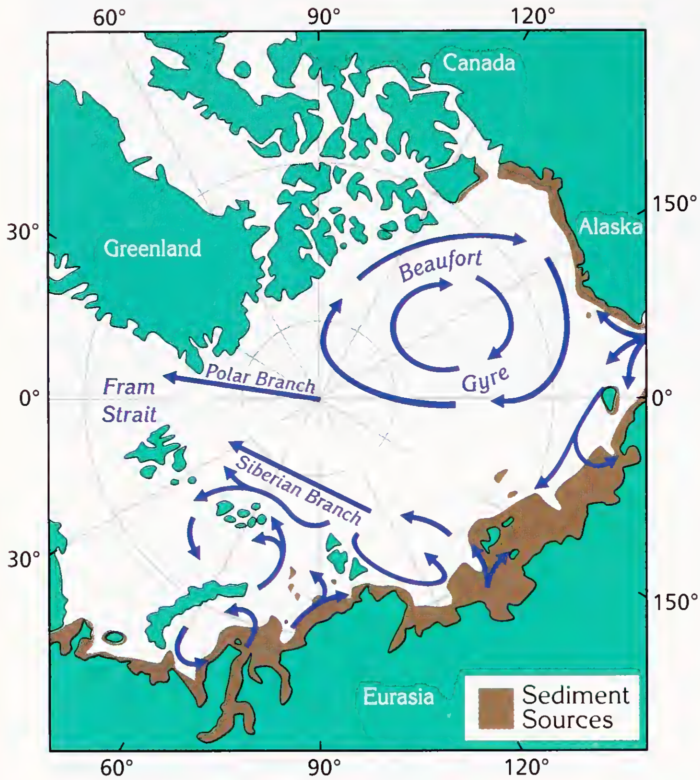
This photo was taken as JOIDES Resolution *confronted northwest Atlantic icebergs during ODP Leg 105.*

Seafloor exploration in the Arctic began with the famous Norwegian explorer Fridtjof Nansen, who was seeking to explain why a few pieces of equipment from the American arctic research vessel *Jeannette* were found off eastern Greenland in 1884 although the ship was wrecked off the coast of Siberia in 1881. Nansen embarked in 1893 on an arctic survey in his newly built research vessel *Fram*, specially designed to be frozen in the arctic ice for a drift of unknown duration across the top of the world. Though he did not reach the North Pole, Nansen proved the transpolar drift theory, took the first bottom samples from the arctic abyss, and learned that the arctic sea ice covered a deep sea basin rather than the shelf area he had imagined. Many high arctic expeditions that followed Nansen were heroic and successful, but there are also many histories of tragic loss by expeditions unprepared for the hostile arctic environment.

In modern times, however, advanced technology has opened fascinating new opportunities for geoscience research in the Arctic. American and Russian ice-island station crews made important progress in arctic deep-sea geology, especially by sampling near the seafloor surface. Further progress in determining the geological properties of the arctic deep seafloor now



requires penetration through the sediment cover into basement rock. Fossil hydrocarbon exploration has led to the discovery of large exploitable oil and gas accumulations whose origins are related to peculiar high concentrations of organic carbon in arctic and subarctic marine sediments, to their tectonic fate after burial, and to the poorly understood Mesozoic paleogeography of the Arctic Ocean and its surrounding shelf seas. Modern research in paleoceanography and climatology has shown that the Arctic Ocean and surrounding seas have experienced rapid, dramatic environmental changes—and their impact on the climate of now densely populated North America and Europe is recognized: An ice-free Arctic could result from future environmental changes in response to the greenhouse effect.



Several current systems that move the arctic ice pack make drill ship research in this area a challenge.

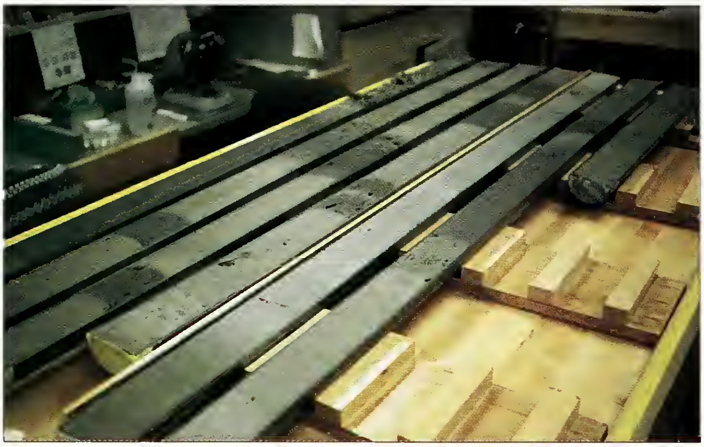
Jayne Doucette/WHOI Graphics

Possibilities for scientific drilling in the arctic abyss have been discussed in the deep sea drilling community since the mid 1970s. However, it was only after several successful *Glomar Challenger* and *JOIDES Resolution* legs to the iceberg-infested Southern Ocean, Norwegian and Greenland Sea, and Labrador Sea/Baffin Bay waters that *JOIDES Resolution* undertook true arctic drilling. Accompanied by the hypermodern Finnish icebreaker *Fennica*, the drill ship visited the northernmost Norwegian and Greenland seas as part of the North Atlantic Arctic Gateways Program during late summer 1993. Drilling sites included Fram Strait, the deep passage between the Arctic Ocean and the northern extension of the Norwegian and Greenland seas area, and Yermak Plateau, which is thought to be a true marginal arctic environment.

Data from the older DSDP and ODP legs combined with more recent evidence suggest a middle-to-late Miocene onset of Northern Hemisphere glaciations, first in the form of small glaciers and intermittent sea-ice covers. The occurrence of large proportions of ice-rafted, coarse, terrigenous debris increases substantially to the south of Greenland later, at approximately 4 million years ago, while in other areas it only increases at about 3.5 to 2.5 million years ago. Cyclical Milankovitch changes in sediment properties (the result of variations in Earth-Sun orbital geometry), a common characteristic of presently available sediment sections, suggest a close linkage between deep ocean sedimentation and paleoclimate. The search for the place and time of the oldest Northern Hemisphere glaciations continues, posing a great challenge to the scientific drilling community. It probably requires unconventional platforms that can withstand the onslaught of the arctic ice pack.

The Bipolar Challenge

Bipolar glaciation resulting from late Mesozoic and Cenozoic cooling has caused steep gradients in tropical-to-polar oceanic water-mass and atmosphere properties. The ultimate glaciation in both hemispheres' polar regions has forced terrestrial and marine biota to adapt to generally slow but sometimes catastrophically fast changes in their habitats, both on land and in the sea. The highly specialized arctic and antarctic marine biota have responded to this change by developing, gradually in the Southern Ocean and very late in Arctic Ocean populations, faunas and floras whose characteristics coincide in many instances, but also diverge in a wide range of examples. Today's Earth has reached an extreme environmental evolution; it has no analog in the geological past but can only be understood through studying long time series of sediments from the climatically most sensitive regions of our earth, the high-latitude, deep sea basins of both hemispheres.



Sub-arctic deep sea drill core (ODP Leg 104) showing alternations between glacial (dark) and interglacial (light) periods.

Jörn Thiede was Germany's first professor in paleoceanography. After studying geology in Kiel, Vienna, and Buenos Aires and after having jobs in Denmark, USA, Norway, and Germany, he is now working at the young GEOMAR in Kiel. He has participated in studies of coastal upwelling systems and their geological record and in DSDP and ODP legs in all major ocean basins, but his recent interest is centered around polar and subpolar deep sea basins and their paleoenvironmental record.

LITHOSPHERE

Oceanic Crust and Mantle Structure

Catherine Mével and Mathilde Cannat

Seven legs of drilling in Hole 504B brought a wealth of data on the structure and composition of the upper oceanic crust.

The ocean drilling programs have provided us with a wealth of new information about the nature of the oceanic crust, a 5- to 10-kilometer-thick layer of rock that covers more than two-thirds of our planet. Our knowledge of the oceanic lithosphere has traditionally been limited to indirect observations, such as bathymetric, gravity, and magnetic maps, or various kinds of seismic experiments made through the vast water column. Ocean drilling allows validation of these indirect methods through direct studies of rock samples. While it is possible to observe and sample oceanic rocks using submersibles and dredging, only drilling can provide long, vertically continuous sections of rock, and drill holes for logging experiments. Long rock sections are critical to identify the magmatic and tectonic relationships between the various rock types, and logging experiments provide data on the rocks' physical properties, allowing comparison with surface geophysical data, and providing ways to fill gaps in recovered cores. Through logging we can also relate tectonic or magmatic structures observed in the cores to their surroundings in the crust and sediment.

The Architecture of Oceanic Lithosphere: Fast- Versus Slow-Spreading Ridges

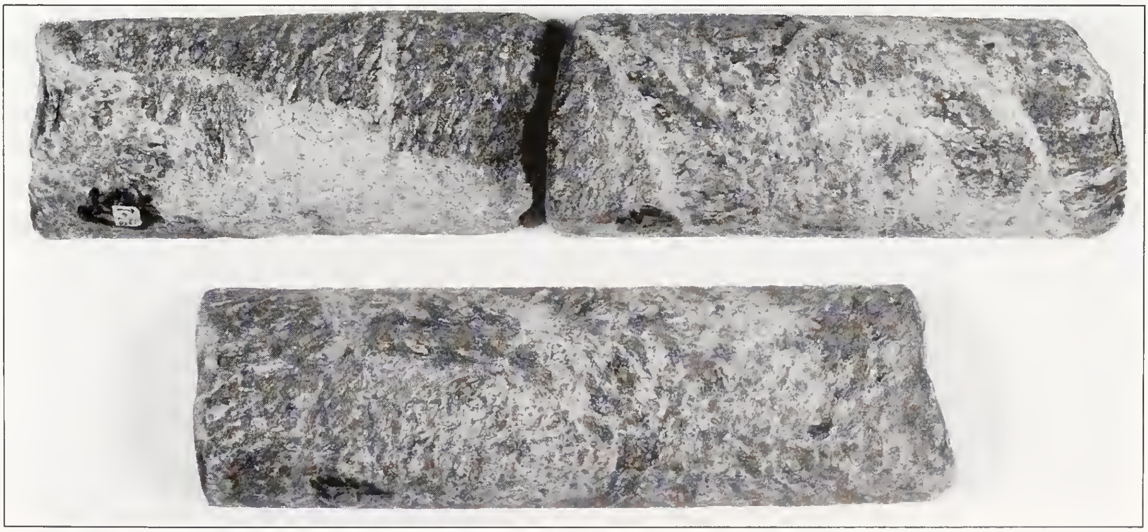
A multilayered model for oceanic lithosphere emerged in the 1970s from comparisons of oceanic seismic data with the stratigraphy of ophiolites (sequences of rocks found on land, usually incorporated in mountain belts, but believed to be pieces of oceanic lithosphere). The uppermost layer, composed of sediment, is called Layer 1. Layers 2 and 3 follow, bounded by increases in seismic velocities that may be either sharp or gradual. The model suggests that Layer 2 is made of fine-grained basaltic rocks, erupted as pillow lavas or intruded as dikes (pathways for upward movement of magma), and that Layer 3 is made of gabbros, coarse-grained rocks crystallized at depth from the same basaltic magma that feeds Layer 2. The Mohorovicic discontinuity, or Moho, defines a sharp increase in seismic velocities that usually lies 6 to 8 kilometers below the seafloor. In the layered model, it is interpreted as a petrological boundary between the gabbros of Layer 3 and the residual upper-mantle peridotites.

Validating the interpretation of seismic layering in terms of lithologies is not easy. Drilling through the Moho would require a hole several kilometers deep, which is still beyond the technological capability of the drilling community. Presently the deepest hole in the oceanic crust is located at Hole 504B, south of the Costa Rica rift, a ridge spreading at an intermediate rate. Seven legs of drilling have extended this hole to 2,111 meters and brought a wealth of data on the structure and composition of the upper oceanic crust. Beneath a sediment cover, the magmatic crust consists of 571 meters of basalts that erupted on the seafloor as pillow lavas or flows, then 200 meters of basalt breccias with crosscutting dikes that overlie a sequence of steep, sheeted dikes at least 1,100 meters thick. This is similar to the layered-model predictions, except that the dike/gabbro transition has not yet been crossed, although samples cored in the lowest part of the borehole exhibit Layer-3-type seismic velocities. In fast-spreading environments, seismic imaging shows a thin, narrow magma lens at the ridge axis, 1 to 3 kilometers below the seafloor. Gabbros must have crystallized in this thin magma lens, which appears to be permanently located at about the depth of the Layer 2/Layer 3 transition. The lithosphere of fast and intermediate spreading oceans is likely to be similar to the ophiolitic and seismic layered model.

The first indications that this layered model does not adequately describe the lithosphere composition of the slow-spreading Mid-Atlantic Ridge came in the 1970s with a series of holes several hundreds of meters deep, drilled near the ridge (Legs 37, 45, and 82). While most of these drill holes produced "normal" sections of extrusive basalts occurring as pillow lavas and flows, a few holes crossed peridotites or gabbros, either just beneath the sediment cover or within the lava sequence. According to the layered model, these rocks should only be found deep in the crust (Layer-3 gabbros) or below the Moho (mantle peridotites): Here, however, they were found in the uppermost crustal levels.

These drilling results were largely ignored, because nobody quite knew what to do with them. Then in the late 1980s and early 1990s, detailed bathymetric and gravity maps of the Mid-Atlantic Ridge became available, providing some explanation for the surprising results of earlier drilling legs.

Late magmatic liquid (white) intrudes a foliated gabbro. This core was retrieved from ODP Hole 735B.



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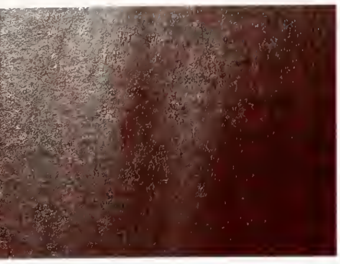


These maps suggest that magma supply to the slow-spreading Mid-Atlantic Ridge is variable in both time and space, causing the oceanic lithosphere to be segmented into magma-rich and magma-poor portions. Ridge segments receiving large volumes of magma should have a thick magmatic crust, possibly with a permanent magma lens favoring a layered structure similar to that of faster spreading oceans. By contrast, in ridge segments receiving very little magma, there should be no permanent magma lens at the axis, and spreading should be largely due to tectonic extension, causing the uplifting of gabbros and mantle peridotites to the seafloor.

Some evidence from recent drilling at Hole 735B in the Southwest Indian Ocean favors this interpretation, linking low magma supplies with a highly tectonized and lithologically discontinuous lithosphere structure. Another example is given by the mantle peridotites drilled at Site 670 in the wall of the Mid-Atlantic Ridge axial valley, which display evidence of high-temperature ductile deformation that is consistent with the highly tectonized structure this new model predicts for magma-poor oceanic lithosphere. These peridotites have interacted with seawater and recrystallized to serpentinites; however, their texture suggests that the recrystallization was not associated with the deformation, and it probably occurred after their emplacement.

Offset drilling sites holes where tectonic processes have exposed rocks of deep origin at the seafloor.

One consequence of this new nonlayered model is that the seismically defined Moho does not systematically correspond to the petrological transition between magmatic crust (consisting of rocks crystallized from magma) and residual mantle. Since residual peridotites outcrop, the seismic discontinuity must reflect another type of boundary. The most likely interpretation correlates the transition to the depth of seawater penetration, as the serpentinites are much less dense than freshwater peridotites.

Building the Lower Crust: How Do Magma Chambers Function?

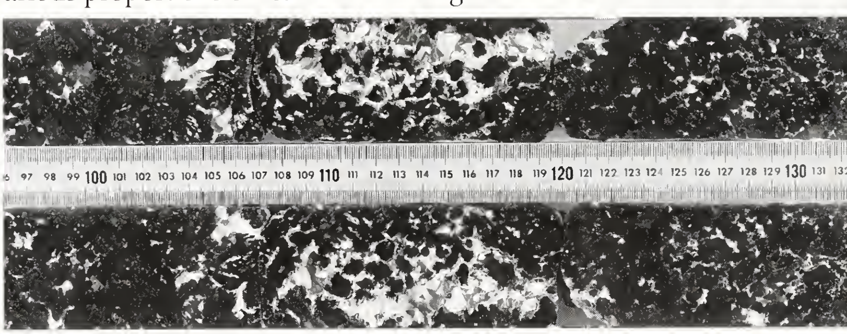
Gabbros and other coarse-grained magmatic rocks must crystallize at some depth beneath the ridge axis, presumably in some sort of magma reservoir. Most of our knowledge of how this chamber functions comes from indirect assessments, such as studying the composition of the erupted lavas or geophysical images of the crust. A major step toward understanding magmatic processes in magma-starved, slow-spreading ridges was taken at Hole 735B, where drilling initiated in outcropped seafloor gabbros produced a 500-meter section with few gaps.

Detailed core studies revealed that magmatic and deformational processes were strongly intermingled: Deformation started before the rocks were completely cooled, and therefore the crystals were oriented in preferential planes, creating a planar fabric called magmatic foliation. Formation of shear zones facilitated early seawater penetration in the deep crust and consequent reaction with rocks at high temperature. Several low-dipping normal shear zones were encountered. These were interpreted as resulting from the lithospheric stretching that was ultimately responsible for the deep crust's exposure. A conjugate network of fractures facilitated the seawater's penetration.

It is, however, beyond our present technological capability to reach the lower crust by drilling through the thick, layered oceanic lithosphere formed at fast- and intermediate-spreading rates. This technological limitation has led the ocean drilling program to design a new approach for drilling the lower crust and mantle: the offset drilling strategy, siting holes where tectonic processes have exposed rocks of deep origin at the seafloor.

Offset drilling was first applied during Leg 147 (December 1992 to January 1993) at the fast-spreading East Pacific Rise, in Hess Deep, a rift opened in the crust by propagation of the Cocos-Nazca Ridge. Here gabbros and peridotites outcrop in the walls and on the flanks of an intrarift ridge. Hole 894G provided a 150-meter gabbro section of heterogeneous texture with coarse-grained pockets, similar to the upper part of the gabbro sequence in ophiolite complexes. The section drilled displays no evidence of high-temperature deformation such as in slow-spreading ridges, but a spectacular magmatic foliation characterizes many cores. Its magnetic inclination tends approximately north to south, parallel to the East Pacific Rise ridge axis.

Similar steep magmatic foliation has been observed in the upper gabbros of the Oman ophiolites, and could correspond to the roots of the dike complex. At Site 895, several holes were drilled in mantle peridotites, yielding invaluable information about the percolation of magmatic liquids within the mantle. The residual mantle rocks were deformed at high temperature, then subsequently impregnated by magmatic liquids. They segregate to form small dikes that may react with the enclosing peridotites. By analogy with ophiolites, this zone is interpreted as the transition between the mantle and the lower crust. An important observation made at Site 895 was that three holes drilled a few hundred meters apart produced various proportions of residual and magmatic rocks, suggesting that the liquids feeding the crust are channeled along preferential pathways.



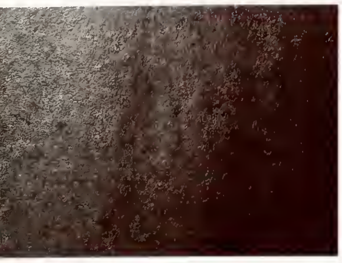
ODP

On ODP Leg 147, core retrieved from Hole 895C reveals black peridotite impregnated with white magmatic liquid.

A drawback to the offset drilling strategy is that the mechanisms leading to the exposure of normally deep rocks overprints the processes occurring at the axis. At Hess Deep, for instance, structural observations show that the opening of the rift is responsible for the formation of an east-to-west oriented fracture network. However, it is possible to decipher the successive episodes, and therefore better understand the evolution of the oceanic lithosphere.

Catherine Mével is a Senior Scientist working as a CNRS researcher at the Université Pierre et Marie Curie in Paris. Her research interest is to understand the processes of interaction between seawater and the lower oceanic crust and mantle.

Mathilde Cannat obtained her thesis in ophiolite studies at the Université de Nantes, then moved seaward to the coast of Brittany (Université de Brest) and mid-ocean ridges studies. She is now a CNRS researcher at the Université Pierre et Marie Curie, Paris.



Oceanic Crust Composition and Structure

Peter S. Meyer and Kathryn M. Gillis

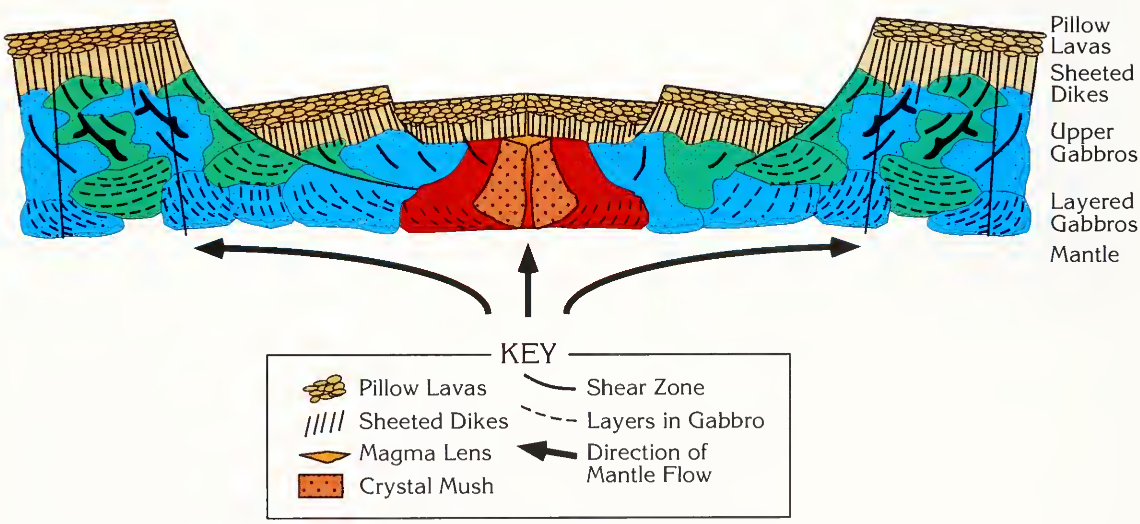
Drilling has recovered most parts of the crust by drilling deep and by taking advantage of lower crustal rocks exposed on the seafloor.

Magmatic and volcanic activity that creates oceanic crust plays an important role in controlling the fluxes of elements and heat in the oceans, and it was the degassing of magmas on Earth's surface that gave rise to the oceans and atmosphere in the first place. Heat from cooling magmas drives hydrothermal systems that underlie hot springs and black smokers on the seafloor, initiate ore-deposit formations, and support seafloor ecosystems in the absence of light. It is also possible that volcanic heating of the ocean leads to periodic events such as El Niños, warm-water currents off Peru that cause major changes in global weather patterns every four to seven years. To further examine these phenomena, however, we need to know more about how magma is generated in the mantle, how it crystallizes to form oceanic crust, and how the crust is disrupted by faults and altered by the circulation of heated seawater.

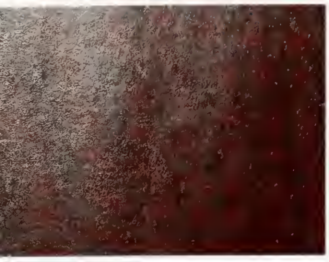
Oceanic crust is created at mid-ocean ridges where magma is continuously supplied from the mantle below, generated by the rise of hot, solid material from deep in the earth, followed by its partial melting at shallow depths. Three main crustal formations result from different rates of magma cooling and crystallization: fossil magma chambers, sheeted dikes, and pillow lavas. Fossil magma chambers are composed of gabbroic rocks with large crystals (1 to 10 millimeters in diameter) that form by slow cooling of magma within the crust. The crust acts like a Thermos bottle, insulating magma from cold seawater, and allowing crystallization and solidification to proceed over tens of thousands of years. Sheeted dikes are "frozen" channels where magma once flowed up toward the seafloor. When flow in these channels ceased, magma crystallized rapidly, perhaps within hours, to form basalts with small crystals (most less than 1 millimeter in diameter and many too small to see without the aid of a microscope). Pillow lavas form by the eruption and "quenching" of magma on the seafloor—cooling is so fast that volcanic glass forms on the rims of pillows. Slightly slower cooling within pillows produces crystalline basalt.

The amount of magma generated and the proportion of it that erupts varies along mid-ocean ridges, leading to significant variations in total crustal thickness and in the relative proportions of gabbroic rocks, sheeted dikes, and pillow lavas. High magma supply, high eruption rates, and a thick crust are typical of rapid spreading rates at mid-ocean ridges such as the East Pacific Rise. Low magma supply, low eruption rates, and a thin crust are typical of mid-ocean ridges where spreading rates are low, such as the Southwest Indian Ridge. Theoretically, high magma-supply rates should also result in slower cooling rates and a higher proportion of gabbroic rocks in the crust, but this remains to be proven.

To fully characterize the oceanic crust's composition and to understand how its composition is influenced by magmatic and hydrothermal processes requires a scale of sampling that can only be achieved by drilling. DSDP and ODP have successfully recovered most parts of the crust by drilling deep at a few sites and by taking advantage of lower crustal rocks exposed on the seafloor. A complete section of upper crust, including the lava and sheeted dike complex, has been sampled in a hole about 2,200 meters deep drilled during seven legs in the eastern equatorial Pacific at Site 504. Leg 118 recovered 500 meters of gabbroic rocks that formed in a magma chamber beneath the very slow-spreading Southwest Indian Ridge. Leg 147 recovered a sequence of gabbros that formed at the magma-rich East Pacific Rise, as well as the complex transition zone between the crust and upper mantle, revealing the



Schematic representation of ocean crust at a mid-ocean ridge. In an active ridge, magma rises out of the mantle and into the overlying crust where it feeds a magmatic system comprised of a crystal mush zone (85 percent crystals and 15 percent melt) and a magma lens at the base of sheeted dikes. Magma is also channeled through dikes to the seafloor. On both sides of the crystal mush zone are gabbroic cumulates, the fossil remains of earlier magmatic systems. The gabbros are divided into upper gabbros where there is no significant crystal layering, and layered gabbros, where crystal layering (dashed lines in the figure) is well developed. The upper gabbros are further characterized by shear zones oriented parallel to the high-angle normal faults. These provide channels for the migration of late, evolved melts. The sheeted dikes and pillow lavas are composed of basaltic rocks formed, respectively, by the rapid cooling of magma near the seafloor and the quenching of magma on the seafloor.



trapping and crystallization of magma within a previously melted piece of mantle. Investigation of these and other cores has significantly changed our view of how oceanic crust is built.

Variations in magma supply imply variations in the average degree of melting in the mantle, which affects the composition of primary magmas coming out of the mantle and therefore the average composition of the oceanic crust. At one extreme, low magma-supply rates result in infrequent intrusion of magma into the crust and "freezing" of the magma to form dikes whose basaltic composition is nearly the same as the melt initially generated in the mantle. With greater magma supply, more magma is intruded into the crust, its cooling rate decreases, and it is subject to the process of fractional crystallization prior to solidification. Just as evaporation of seawater leads to removal of pure water and concentration of salt in the water, the fractional crystallization of magma leads to the removal of some elements in crystal form and the concentration of others in the residual liquid. Dikes and lavas formed after fractional crystallization are significantly different in chemical composition than the melts originally generated in the mantle. This is because the first crystals to form in a basaltic magma, olivine and plagioclase, are chemically very different from the initial magma. Extensive crystallization and the addition of iron-titanium oxide minerals to the crystallizing assemblage may lead to the generation of melts that are very rich in silica (trondhjemite in the table opposite).

Leg 139 investigated a hydrothermal system that extends from the basaltic basement into an overlying sequence of marine sediments.

As magmas cool, crystals may accumulate on the floors, walls, and roofs of magma chambers and form crystal mushes that initially contain 40 percent melt, but prior to solidification contain less than 15 percent trapped melt. Melt may be expelled from a mush by such processes as compositional convection, compaction, and deformation. Solidification of mushes produces cumulate gabbros (troctolite and iron-titanium oxide gabbro in the table) with compositions that are significantly different from magma compositions (basalts). Troctolites are primitive cumulates, assemblages of olivine and plagioclase crystals together with a small fraction of crystallized trapped liquid, that formed during the early stages of magma crystallization. Iron-titanium oxide gabbros, on the other hand, are evolved cumulates that formed after extensive crystallization of basaltic magma at mid-ocean ridges.

Crystallization models and magmatic intrusions exposed on land suggest a simple crustal stratigraphy for the lower ocean crust, with primitive gabbros at the base displaying well-developed crystal layering and evolved gabbros toward the top characterized by the absence of layering. So far, we have yet to observe well-developed layering in drilled sequences of oceanic gabbros, and at Site 735 we found evolved gabbros interdigitated with primitive olivine gabbros and troctolites. Detailed chemical mapping of contacts between iron-titanium oxide gabbros and olivine gabbros at Site 735B indicates that evolved melts are sometimes mobilized in response to crustal deformation, and that melt flow may be either diffused through intergranular networks or focused along centimeter-scale channels. Depending on magma supply and cooling rates, crystal mushes may be invaded with new magma prior to solidification, modifying the bulk composition of the mush in addition to the composition of the invading magma.

The composition of the oceanic crust that results from magmatic processes is the starting point for a complex history of chemical exchange with seawater that leads to the formation of ore deposits and influences

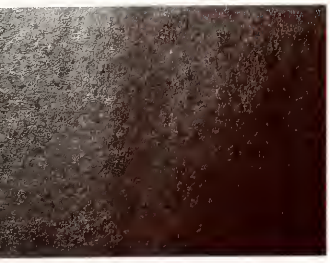
Composition of Common Rocks Found in Oceanic Crust

	Magma Compositions			Products of Crystallization	
	Basalt	Iron-titanium oxide basalt	Trondhjemite	Troctolite	Iron-titanium oxide gabbro
Silicon dioxide	48.00	49.47	70.82	44.87	42.53
Aluminum oxide	16.44	14.02	17.28	17.42	10.93
Titanium oxide	1.90	3.21	0.22	0.14	6.89
Iron oxide	10.45	12.88	1.12	7.20	20.67
Magnesium oxide	9.71	5.22	0.17	17.69	5.50
Manganese oxide	0.17	0.16	0.02	0.12	0.3
Calcium oxide	9.24	9.21	1.93	8.64	9.21
Sodium oxide	3.26	3.84	6.95	1.95	2.70
Potassium oxide	0.13	0.39	1.48	0.06	0.04
Phosphorus oxide	0.28	0.43	0.01	0.0	0.0

All compounds are given in percent by weight.

the composition of the world's oceans, arc volcanics, and the mantle. When erupted on the seafloor, volcanics immediately begin to react with the surrounding seawater. Within a hydrothermal system, seawater flows downward through cracks, fissures, and faults and may penetrate to depths as great as 5 or 6 kilometers. It reacts with rocks all along its path, resulting in exchanges of elements and the chemical modification of both seawater and crust. The extent of this exchange depends primarily on temperature and the abundance of seawater passing through a volume of rock, or, in other words, the water/rock ratio. Seawater heats as it migrates down into the crust toward an active magma chamber, and resulting hydration reactions enrich crustal rocks in magnesium and sodium and depletes them of calcium. By the time seawater makes it to just above the magma chamber, its composition has been significantly modified and low water/rock ratios and high temperatures (about 400°C) lead to leaching of metals from the rocks. These buoyant, hot, metal-enriched fluids rise to the seafloor where they mix with the ambient seawater and precipitate sulfides that accumulate in chimneylike structures and mounds. Leg 139 investigated the structure and composition of a hydrothermal system that extends from the basaltic basement into an overlying sequence of marine sediments. In fall, 1994, Leg 158 will drill into an unsedimented deposit. Chemical exchange within the deep root-zones of hydrothermal systems has been documented at Hole 504B where the base of a sheeted dike complex was found to be depleted in copper and zinc.

Although it is not known whether or not seawater-derived fluids actually enter into active magma chambers, the gabbroic core recovered at Hole 735B demonstrates that seawater did penetrate the lower crust very early in its history. Alteration of gabbroic rocks was initiated at temperatures greater than 600°C and focused within zones of ductile deformation. These zones show very little change in composition because the fluids had become strongly enriched in basaltic components by the time they reached this depth (3 to 4 kilometers). Lower-crust hydration may not be a significant process at ridges where there is a high rate of magma supply, simply because the crust is too hot to deform in a way



that provides pathways for fluids to flow deep into it. In fact, East Pacific Rise gabbroic rocks recovered during Leg 147 show that ductile deformation is not prevalent at this magma-rich ridge.

Modification of oceanic crust composition does not stop when a section of crust moves away from a mid-ocean ridge and off-axis. Seawater continues to circulate in and out of the crust until fluid pathways are sealed by the precipitation of minerals, or until sediment accumulation prevents penetration into the crust. As a crustal section ages and moves away from the mid-ocean ridge, the most significant compositional change occurs in the upper volcanic carapace, as fluid pathways deeper in the crust are thought to become sealed by the time it leaves the ridge. Within 5 to 10 million years, the volcanics are enriched in elements such as magnesium and potassium, and much of the basaltic iron has been oxidized. Although isotopic age dating of carbonates shows that mineral precipitation ceases within 20 million years, heat-flow data indicate that seawater may well continue to circulate beyond this time frame. The chemical consequences of such prolonged seawater circulation are not known.

Drilling the oceanic crust has proven to be an essential step in furthering our understanding of global geochemical cycles.

Most of our knowledge of crustal aging processes comes from the recovery of shallow oceanic crust that ranges from essentially zero age (such as at Site 649) to as old as the Jurassic, about 160 million years ago (Hole 801C). Core from more than 150 basement sites demonstrates that interaction between seawater or seawater-derived fluids and rock has a significant impact on crustal composition. Downhole compositional trends at Hole 504B show that different elements are mobile in different parts of the crust. Differences in chemical fluxes found in cores from Sites 417 and 418, drilled only 500 meters apart, show that the composition of the uppermost crust may be quite heterogeneous. Comparing cores of varying ages from all ocean basins suggests that the rate of chemical exchange is not simply a function of age, and that the greatest change in composition may occur in young crust. Chemical exchange within the oceanic crust plays an important role in world-ocean water composition by contributing to the delicate balance of sources and sinks that include the continents (through river input), the atmosphere, ocean sediments, and the ocean itself. Drilling the oceanic crust has proven to be an essential step in furthering our understanding of global geochemical cycles.

Peter S. Meyer is an Associate Professor at Rhode Island College and an Adjunct Scientist in the Department of Geology and Geophysics at the Woods Hole Oceanographic Institution. He developed an interest in geology while writing a career notebook in the eighth grade and visiting marble quarries in Vermont, then became hooked while scrambling up volcanos in Central America as an undergraduate at Dartmouth College. His current research interests include magma chamber dynamics, crystal-melt equilibria, and the evolution of the lower oceanic crust.

Kathryn M. Gillis is an Associate Scientist in the Department of Geology and Geophysics at the Woods Hole Oceanographic Institution. She developed an interest in geology during a family vacation across the US and Canada where she encountered a thoughtful observer of the earth, her cousin Jack. Over the years this interest became linked with her roots in eastern Canada and she eventually developed into a marine geologist. Her research interests revolve around the processes that shape the seafloor and the interaction between fluids and rocks.

Exploring Large Subsea Igneous Provinces

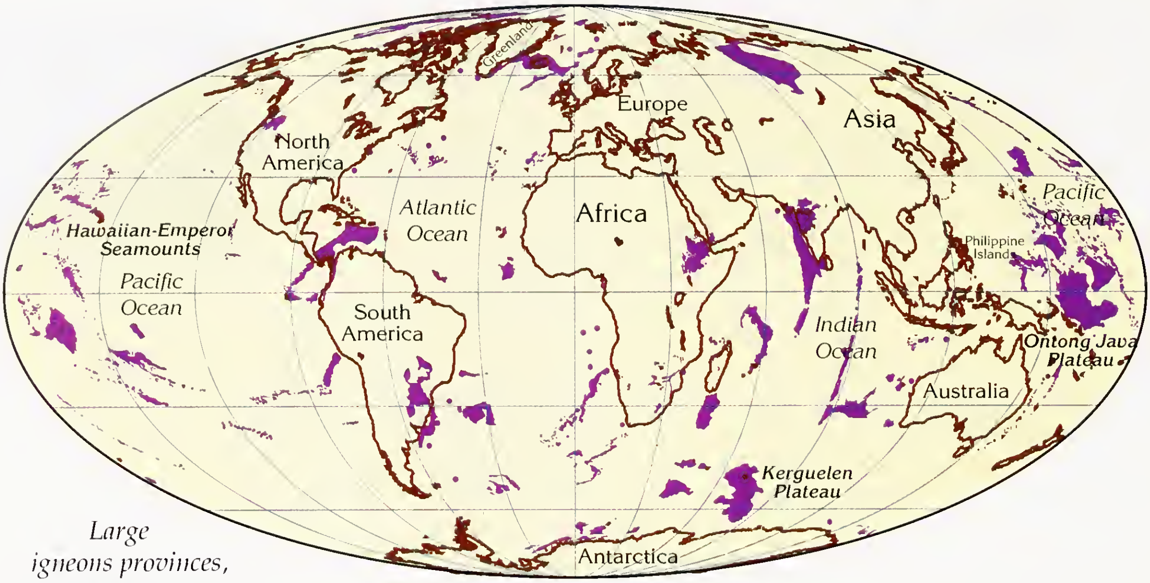
Millard F. Coffin and Olav Eldholm

Volcanic eruptions, such as the 1991 eruption of Mt. Pinatubo in the Philippines, can severely damage the local environment. Yet such events pale in comparison to the huge convulsions of magmatic activity during the undersea formation of large igneous provinces, or LIPs. Compared with other large geological features, most of these provinces were constructed very rapidly indeed.

Today LIPs (composed primarily of iron- and magnesium-rich rock) are found both on land, as continental "flood basalts," and under the sea, mostly as oceanic plateaus in the middle of oceans and as volcanic passive margins along the edges of continents. In fact, the two largest provinces, the Ontong Java and Kerguelen plateaus, now lie mostly below sea level. The construction of these two provinces, together with the volcanic passive margins between Greenland and Northwest Europe and in the South Atlantic, not only have profound implications for the regional and global environment, but also partially reveal the workings of the mantle, that part of Earth's interior between the outer crust and the molten core. Cores obtained from oceanic plateaus and volcanic passive margins by the Deep Sea Drilling Project and the Ocean Drilling Program, together with high-quality seismic reflection images

The onshore portion of the North Atlantic volcanic province on Greenland. The offshore portion, the volcanic continental margin, was recently drilled during Ocean Drilling Program Leg 152.

Courtesy Hans Christian Larsen/Greenland Geological Survey



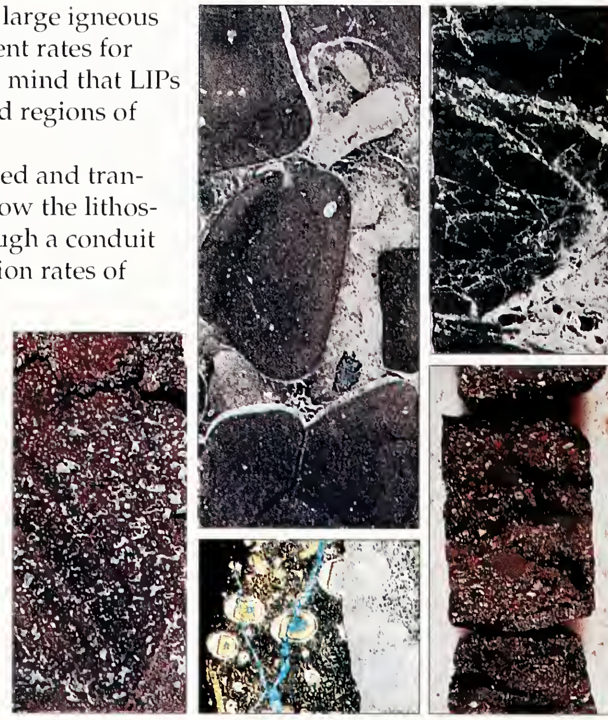
Large igneous provinces, shown in fuschia, appear in many geologic settings worldwide. Studies of these huge magmatic emplacements are adding to our understanding of how Earth's interior behaves, and how these features may affect conditions at Earth's surface.

have been instrumental in allowing scientists to understand the causes and effects of large igneous provinces.

While the theory of plate tectonics explains much of the geology we observe on Earth's surface, it does not readily explain large igneous provinces. These provinces are created neither by "normal" seafloor spreading, which occurs along the mid-ocean ridge system, nor by the subduction process, where one roughly 100-kilometer-thick lithospheric plate slides beneath another. On a geological time scale, both processes reflect persistent phenomena while LIP formation is transient. Although large igneous province rocks resemble those created by seafloor spreading, subtle differences suggest that they arise from deeper, hotter regions of the mantle. Early on in the development of plate tectonic theory, these regions were proposed to produce "hot spots" such as Hawaii, which somehow remain anchored in the mantle while the lithospheric plates above move horizontally. Most researchers believe that mantle hot spots account for large igneous provinces, although the details of how such hot spots work are poorly known.

How big are large igneous provinces? The volume of the biggest LIP, the Ontong Java Plateau and associated provinces in the western Pacific, would cover the contiguous US with 5 kilometers of basalt. Another large igneous province, the Columbia River continental flood basalt in the Pacific Northwest, encompasses only 3 percent of Ontong Java's volume. Individual lava flows of this lesser province, however, can be traced for over 750 kilometers. The enormous scale of these provinces is simply hard to grasp or even compare to historic eruptions. Their rapid emplacement is similarly difficult to comprehend. We know, for example, that the global mid-ocean ridge system has produced between 16 and 26 cubic kilometers of basaltic crust annually over the past 150 million years. By dating rocks from the Ontong Java Plateau, we calculate that the feature was constructed at a rate between 12 and 152 cubic kilometers per year over 0.5 to 3 million years. This considerable range in values expresses uncertainties about crustal structure and whether the LIP was created on a spreading axis or away from it. The minimum rates for Ontong Java and common rates for other large igneous provinces are thus comparable to emplacement rates for "normal" oceanic crust, but one must bear in mind that LIPs are produced only episodically within limited regions of Earth's surface.

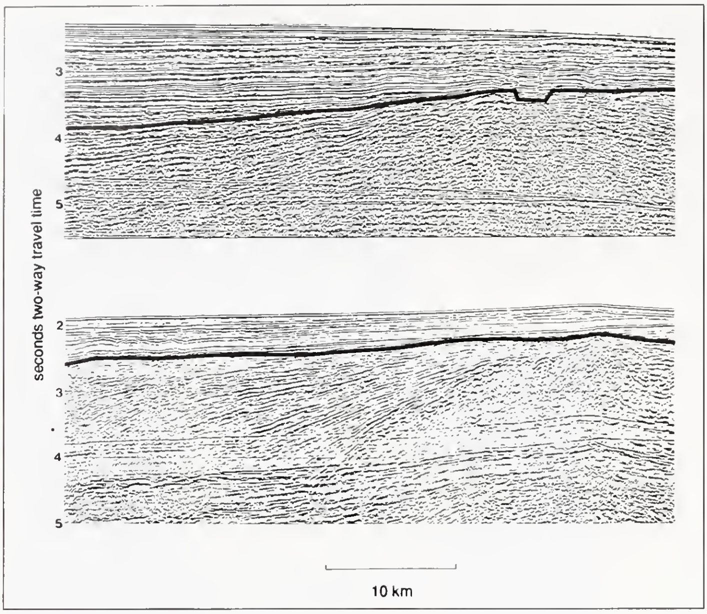
LIPs are surface manifestations of localized and transient increased melt potentials or plumes below the lithosphere that have reached Earth's surface through a conduit called a plume. Hence the size and construction rates of large igneous provinces reveal to some extent how the mantle works. In this way analysis of LIP parameters provides "hard facts" to the vigorous debate about such topics as scale of mantle circulation, origin of mantle plumes, and relations between hot spots and volcanic margins, to name a few. For example, if one knows the volume of rock contained in these provinces, one can estimate the dimensions of the hot mantle regions where they originated. We estimate that each large igneous province contains between 5 and 30 percent of the mantle plume's original volume, and use these numbers to calculate sizes of the thermal anomalies in the mantle that are responsible for the North Atlantic volcanic margins and the Ontong Java and Kerguelen oceanic plateaus. The analysis indicates that the largest plumes contain at least some material from the lower mantle more than 670 kilometers beneath Earth's surface, suggesting some interaction between the lower and upper mantles.



Courtesy of Kerry Kelts/University of Minnesota, and John Beck/ODP

These core samples from the Kerguelen oceanic plateau were acquired by scientists on ODP Leg 120. Left: subaerially weathered basalt; center: basalt conglomerate with mollusk and volcanic grain infill; middle bottom: thin section of basalt showing hematite weathering; right top: mud pebble conglomerate with volcanic sediment and coal; right bottom: weathered basalt.

The surfacing of a mantle plume leads to physical and chemical changes of the local, regional, and global environment, which in turn affect the conditions and evolution of life on Earth. The burst of submarine magmatic activity roughly 122 million years ago that created the Ontong Java Plateau coincided with increased biologic productivity, higher sea level, and a warmer climate than at present. In contrast, subaerial emplacement of the Kerguelen Plateau approximately 110 million years ago coincided with mass marine extinctions. Another significant change in the global environment took place about 55 million years ago, when many benthic plankton species and land mammals became extinct. Ocean temperatures were the warmest of the past 70 million years, and 55-million-year-old ash layers are found over large areas of northwestern Europe. These events coincided with emplacement of the North Atlantic volcanic margins and associated continental flood basalts. The temporal correlations among these three examples—Ontong Java, Kerguelen, and the North Atlantic provinces—as well as of continental flood basalt provinces, and global environmental changes, suggests some relationship must exist. Although the potential forcing functions and feedback mechanisms have yet to be refined, it appears that magmatic production rates, geological setting, and the environmental state during LIP formation are primary factors that determine environmental impact.



Scientific ocean drilling has only begun to scratch the surface of large igneous provinces; their crust is up to 40 kilometers thick with a cover of numerous basalt flows exceeding 5 kilometers. Most DSDP basement holes were quite shallow, whereas ODP Leg 104 volcanic margin drilling by *JOIDES Resolution* proved the feasibility of penetrating deeply into basement rocks. Presently, the deepest LIP hole has penetrated almost 1 kilometer into the igneous crust, but most other holes have only penetrated a few tens of meters into the basalts. The drill ship's capabilities were recently tested with success in late 1993 when scientists aboard *JOIDES Resolution* returned to drill the North Atlantic basalt off Greenland, with the ultimate objective of learning more about how plumes work.

Seismic reflection profiles show a cross-section (in seismic wave travel time) of Earth beneath the sea. Dipping reflector sequences (below the black lines) indicate basalt flows on the Norwegian volcanic passive margin (top) and the Kerguelen oceanic plateau (bottom).

The present LIP drilling data base is indeed sparse, but what we have learned from the existing holes and associated geophysical surveys is intriguing. Our current knowledge amply demonstrates that they contain crucial information about the internal behavior of Earth and about the natural causes of global change. The Ocean Drilling Program provides a unique tool for solving such fundamental problems in geoscience. ■

This is University of Texas Institute for Geophysics contribution number 1023.

The marine geoscientific career of Mike Coffin marks a return to the seafaring tradition of his Nantucket ancestors, although his more immediate forebears spent a few generations landlocked in Maine, New Brunswick, and France. A research scientist at the Institute for Geophysics, The University of Texas at Austin, he was educated at Dartmouth College and Columbia University. His interest in LIPs developed while amassing 6 months of "frequent floater" awards over the Kerguelen Plateau. When not studying tectonic problems, his diversions have included performing with the Royal Ballet, helicopter and cross-country skiing on several continents, and bareboat sailing in the Atlantic, Pacific, and Indian oceans.

Olav Eldholm grew up in western Norway and was educated in Bergen, but became "indoctrinated" at Lamont-Doherty Earth Observatory before returning to Norway where he is now a professor of marine geophysics at the University of Oslo. His Large Igneous Provinces interest was ignited as co-chief scientist during deep ODP drilling on the Vøring volcanic margin, and further stimulated by a sabbatical visit to the University of Texas Institute for Geophysics center of excellence. He keeps fit by climbing Norwegian glaciers and completing New York Times *crossword puzzles.*

DSDP/ODP Downhole Measurements in Hole 504B

Phillipe A. Pezard

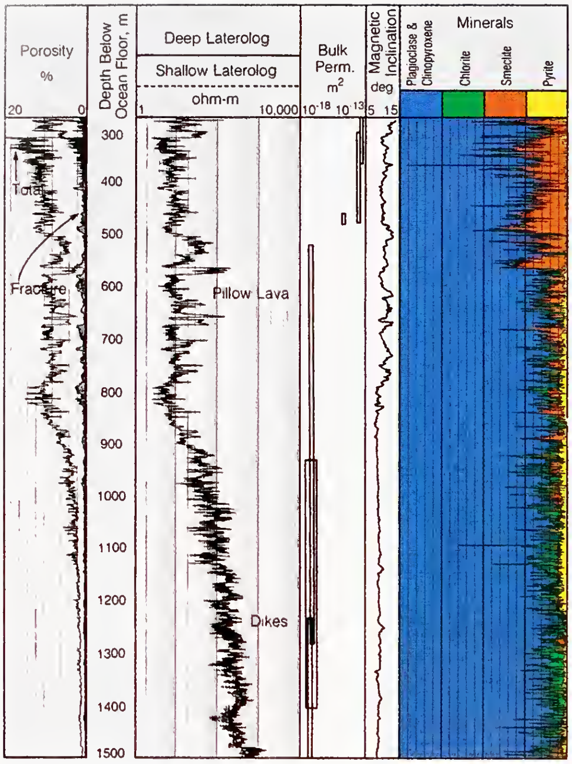
The Ocean Drilling Program's continuous downhole measurements have become essential to seafloor exploration. (See "Borehole Measurements Beneath the Seafloor," page 129 for a description of downhole measurements.) They supplement and verify information obtained from core studies and often provide data in sections where cores are not recovered. Over the past 10 years, these methods have steadily become more important to research on the structure and dynamics of Earth's upper crust.

DSDP/ODP Hole 504B, by far the deepest hole yet drilled into the oceanic basement, illustrates the importance of downhole measurements to earth science. The work done in 504B provides the scientific community with an excellent means for verifying models of the upper oceanic crust's structure and evolution.

The work done in 504B provides an excellent means for verifying models of the upper oceanic crust's structure and evolution.

Hole 504B is located beneath 3,475 meters of eastern equatorial Pacific water and penetrates ocean crust assembled on the southern flank of the Costa Rica rift. Beginning with DSDP Leg 69 in 1978, eight ocean drilling expeditions have been dedicated to drilling Hole 504B, to reach the present depth of 2,111 meters below the seafloor. Beneath 275 meters of sediments, including pelagic oozes and chert, 1,836 meters of basaltic basement has been cored, with recovery often less than 20 percent. The basaltic section comprises about 600 meters of pillow lavas and massive lava flows extruded 5.9 million years ago on the seafloor at the rift spreading center. Below the basalt layer lies a transition zone that leads to a 1,200-meter-thick section of sheeted dikes, solidified conduits from the magma chamber to the seafloor. As the gabbros (the prime objective of the last two drilling legs) were unfortunately not reached, downhole measurements covering the entire basement section were recorded.

The data collected from downhole measurements can generally be classified into two main categories associated, respectively, with the structure and the dynamics of the penetrated section. That related to structure reveals, either in terms of physical properties or lithostratigraphy,



Downhole measurements recorded during drilling on ODP Leg 111 into young oceanic basement created at the Costa Rica rift. The electrical resistivity profiles reveal, at the top of the basement, extremely porous and permeable pillow lava formed on the seafloor and, below, nearly nonporous and nonpermeable sheeted dikes of basalt formed by lava intrusion at the rift. The total and fracture porosity profiles were calculated from the analysis of resistivity data.

continuous data around the drillhole, generally at meter scale. From within the borehole, dynamic parameters reveal information at kilometer scale for mapping present or past fluxes, as well as force fields such as those associated with tectonic stresses.

Probably the most important finding in Hole 504B downhole measurements is a strong downflow of sea-bottom water into the upper basement. This vigorous flow was first discovered in 1979 as the hole was being re-entered during DSDP Leg 70. Scientists were surprised to observe a temperature profile showing 2° to 3°C water down to 300 meters, a few tens of meters into basement, where they expected to see water at 60°C. This was the clue for the downflow. Flow experiments with downhole packers, combined with geophysical measurements of electrical resistivity, revealed the presence of a 30-meter-thick, porous, permeable and underpressured aquifer located under a 14-meter-thick massive sheet flow of basalt at 300 meters. Since that time, temperature data are routinely recorded first whenever the hole is being re-entered for deepening and downhole experiments.

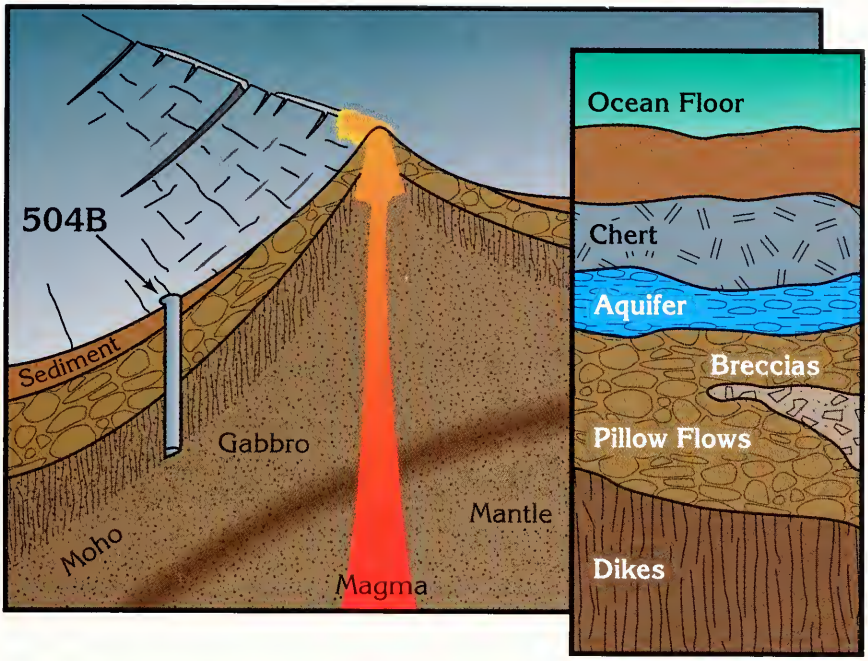
The temperature profile taken at the beginning of Leg 111 in 1986 showed that ocean-bottom water was still flowing into the aquifer, proving the large extent of this underpressured reservoir and, at the same time, the similarly large extent of its basalt seal.

The seal must have originated in a massive outpouring of basalt onto the seafloor near the ridge axis, an eruption different in many ways from somewhat more classic modes of volcanism that lead to emplacement of pillow lava. The pillows, characterized by low electrical resistivity (about 10 ohm·meter) appear to constitute more than 75 percent of the lava pile at Site 504 and are, consequently, considered to be the main mode of oceanic crust emplacement there.

Massive flows, on the other hand, have high electrical resistivity (above 300 ohm·meter) associated with low porosity and low permeability, so they are a limiting factor for upper crustal fluid circulation. A 5-meter-thick massive basalt flow at 580 meters appears to have played an even more important role in past fluid circulation near the ridge axis. Both the texture and thin sections from the recovered core show that nearly all of the basalts at 580 meters have been altered to some degree, while the geochemistry of the freshest rocks is remarkably uniform throughout the upper 1,500 meters of basement. Successive stages of near-axis hydrothermalism have produced three depth zones characterized by different mineral assemblages outlining the circulation of:

- seawater and oxygenated fluids at low temperature down to 580 meters,
- more evolved fluids that imply anoxic conditions at higher temperature below that depth, and
- fluids leading to the development, at even higher temperatures, of

Jack Cook/WHOI Graphics



DSDP/ODP Hole 504B, near the Costa Rica Rift. At the rift axis, magma forces its way from the upper mantle to the ocean floor, creating pillow lava and massive flows on top of vertical "feeder" dikes. Hole 504B was drilled in 3,475 meters of water to a depth of 2,111 meters below the seafloor during several visits of the drillships Glomar Challenger *and* JOIDES Resolution. *As the overall core recovery is under 20 percent, the hole was extensively logged.*

greenschist-facies minerals through the transition zone and into the sheeted dikes.

While the upper section is dominated by smectite and potassium-rich phases, pyrite abruptly appears at 580 meters. The extremely different chemical nature of these two regions proves here again the large lateral extent of the permeability barrier located between them. Downhole measurements may, then, not only reveal the presence of static structures such as basalt flows, but also help to understand their role in the dynamic evolution of the crust.

While these observations were mostly derived from measurements performed in the hole at meter-scale, centimeter-scale electrical images have recently been recorded throughout the hole and are still being analyzed. So far, this analysis has lead to a finer description of upper-basement structures. Also, a continuous vertical seismic profile obtained down to 2,000 meters will help to characterize the seismic nature of basement features located below the present bottom of the hole, as well as in the close vicinity of the borehole such as a fault at 825 meters that was revealed in ODP Leg 111 data.

Much has been learned over the past 15 years from downhole measurements in deep scientific holes such as 504B. The reliability and precision of the recording techniques have evolved substantially, to the point that they now constitute additional research tools specially suited to continuous observation of crustal processes along the length of the drillhole. ■

Philippe A. Pezard was initially educated in France, but soon ran away to the Middle East and Africa where he worked as a field logging engineer. After this, he somehow felt ready to face New York City and the Lamont-Doherty Earth Observatory, where he obtained his Ph.D. in borehole geophysics. Now emigrated back home at the Institut Méditerranéen de Technologie in Marseille, his research is focused on the analysis of borehole data and images, with a particular emphasis on electrical methods and implications for the structure and evolution of the upper oceanic crust.

TECTONICS

Studying Crustal Fluid Flow With ODP Borehole Observatories

Earl Davis and Keir Becker

Water circulating in the igneous crust dominates the heat budget at seafloor spreading centers, and rapidly quenches magma.

If you depend on a well for your water, chances are good that you have some notion about groundwater flow. The level of water in the ground, referred to as the water table, rises and falls (but never below the bottom of your well, you hope) with variations in supply from season to season. Water flow is often confined to discrete layers or fracture zones in the earth or rock (providing employment for countless diviners and a handful of geophysicists). The geometry of these zones, and the degree to which they are connected to one another and to other forms of porosity defines the ease with which water can flow through the rock (and hopefully to your well). In some cases, the combination of topography and the confinement of permeability can produce artesian or natural upward flow (the well owner's dream).

Most people are not aware, however, that many of these principles apply to fluid flow beneath the seafloor as well. Beneath the oceans, the water supply is unlimited, and the concept of a "water table" must be revised, but the sediments and rocks beneath the seafloor are porous and variably permeable, and the general rules for "groundwater" flow are the same. As beneath continents, water is driven through rock at rates that are established by a combination of the permeability and pressure gradients.

Instances of topographically driven flow, the most common type on land, are found beneath continental shelves, where water can be forced along permeable rock strata by the "loading" imposed by the above-sea-level water table in the adjacent continent. Elsewhere, the primary driving forces for sub-seafloor groundwater flow are different; they result from sedimentation and associated compaction in deep ocean basins, tectonic thickening and compaction in subduction-zone accretionary prisms, and thermal buoyancy at volcanically active seafloor spreading centers.

The consequences of fluid flow within the igneous and sedimentary parts of the oceanic crust, and of fluid exchange between the crust and the water column, are profound. Water circulating in the igneous crust dominates the heat budget at seafloor spreading centers, and rapidly quenches magma erupted and intruded at these locations. High-temperature hydrothermal fluids are extremely effective at dissolving and transporting large quantities of sulfur and base metals from the igneous crust to the seafloor and forming large polymetallic sulfide deposits. Long-term circulation of lower-temperature crustal fluids is responsible for widespread mineralogical alteration and mechanical consolidation of the upper igneous crust. Fluid pressures generated in subduction-zone accretionary prisms modify the mechanical behavior of the deforming sediment section, and the resultant fluid flow is believed to be responsible for hydrocarbon migration, the formation of methane hydrates, and major diagenetic changes in the sediments. In all instances, the seawater that circulates into the crust is modified substantially before it returns to the ocean, and this exerts a strong influence on the chemical composition of the oceans.

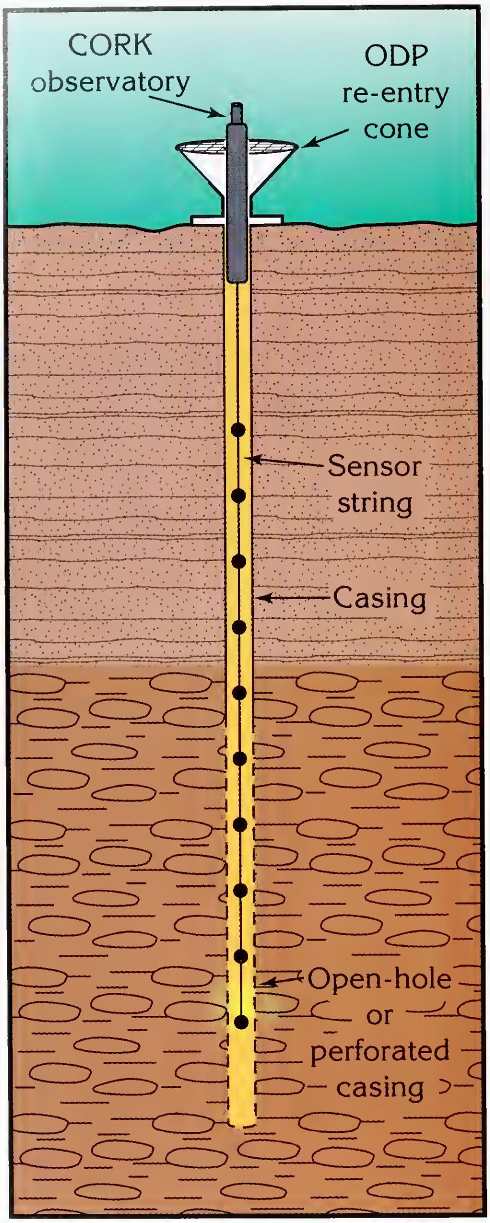
K. Becker

A Circulation Obviation Retrofit Kit (CORK) observatory installation assembled for deployment at the rig floor of JOIDES Resolution.

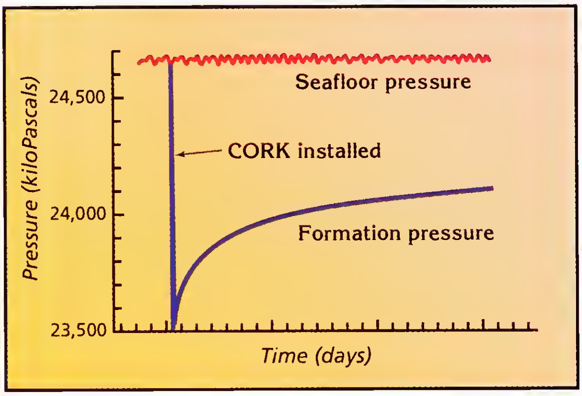
Observing Crustal Fluid Flow

To a limited extent, fluid flow regimes at depth can be inferred from seafloor observations. Variations in measured heat flow, geochemical anomalies detected in sediment cores, and observations of focused flow through the seafloor all provide valuable information. The best information about the physical and chemical nature of crustal fluid flow within the sediments and rocks beneath the seafloor, however, comes from observations that have been made in boreholes drilled by the Deep Sea Drilling Project (DSDP) and the Ocean Drilling Program (ODP). Downhole temperature measurements, logging, hydrologic experiments, and observations of pore-fluid chemistry and rock alteration have provided invaluable information about flow rates and directions, the crustal permeability structure, and the history and long-term consequences of fluid flow.

Unfortunately, hydrologic disturbances caused by drilling are large and relatively long lived, making accurate determinations of pressure and temperature, and samples of pristine pore fluids, difficult to obtain. Considerable quantities of heat are transferred conductively from the rock to the borehole, where cold seawater is circulated continuously to remove drilled-rock fragments. In zones of high permeability, the heat exchange can be even greater, because the cold drilling fluid can invade a large volume of rock. If the crustal formation is sufficiently permeable and the borehole sufficiently deep, this can lead to a runaway situation in which the cold, dense seawater in the hole displaces the warm, buoyant water in the formation. Left unchecked, this downhole flow can severely disturb the natural thermal, chemical, and hydrologic regime, thus rendering observations in the borehole meaningless. In formations that are naturally over pressured (artesian), up-hole flow can result. This creates different (but equally difficult) problems.



Schematic cross section of an ODP CORK installation, and records of pressures measured above and beneath the seafloor. In this hole, the pressure had only begun to recover from the drilling disturbance. The magnitude of the initial disturbance was equivalent to a 100-meter loss of head. The daily tidal signal, roughly 2 meters in amplitude at the seafloor, is highly attenuated but still present in the rock over 500 meters below the seafloor.



New Instrumentation for Long-Term Borehole Observations

With the goal of accurately determining the hydrologic conditions in deep ocean boreholes, a new device (dubbed the Circulation Obviation Retrofit Kit, or CORK) has been developed through a cooperative project among the authors, Tom Pettigrew (Ocean Drilling Program), Bobb Carson (Lehigh University), and Bob Macdonald (Pacific Geoscience Centre). This device provides a means to stop formation-fluid flow into seafloor boreholes in order to minimize the thermal and chemical effects on the formation from drilling-induced disturbances, and a means to monitor the in situ thermal and hydrological conditions and sample fluids long after holes are drilled and drilling disturbances have dissipated. The CORKs include:

- a hydrologic seal that is compatible with existing ODP reentry cones and slightly modified ODP casing hangers,
- a data logger with a 2- to 3-year recording capacity,
- a downhole string of 10 thermistors,
- a pressure sensor situated below the reentry cone seal, and
- plumbing through which fluids can pass from the formation through the seal for sampling by a submersible or a remotely operated vehicle (ROV).

Instruments constructed most recently include orthogonal pairs of tilt sensors for monitoring tectonic deformation. Future instruments may incorporate other seafloor and downhole sensors, such as ion-sensitive electrodes for detecting changes in borehole fluid composition, strain gauges for identifying motion on faults, and accelerometers for revealing local seismic events.

The seal comprises two parts. The outer part, deployed and recovered by the drill ship, provides a seal to the standard (30-centimeter inside diameter) casing that lines the upper part of each hole. This outer seal also serves as a landing collar for an inner seal that is part of a slim (6-centimeter inside diameter) pressure case containing the data logger. This part can be recovered with the drill ship, a submersible, a wire line, or an ROV. All seals and latches are designed to be capable of containing either positive or negative differential pressures of up to 10 megapascals. The data from the instrument are recovered via an electrical connection that can be mated by submersible, ROV, or wire line. A newly developed acoustic telemetry module, first deployed in 1993, now provides a way of communicating with the observatories and recovering data with only a surface vessel.

Recent Observations and Future Installations

Four holes have been sealed and instrumented with CORKs to date. Two were drilled in Middle Valley, a sedimented rift valley of the northern Juan de Fuca Ridge seafloor spreading center. One of these penetrated to a total depth of nearly 1 kilometer, through the relatively impermeable sediments that fill the valley, and into highly permeable rocks beneath, where 300°C hydrothermal fluids reside in a hydrothermal "reservoir." The second CORKed hole in the valley was drilled in the middle of a hydrothermal vent field, where fluids from the regional reservoir discharge through the seafloor, and, in one case, through a shallow exploratory borehole!

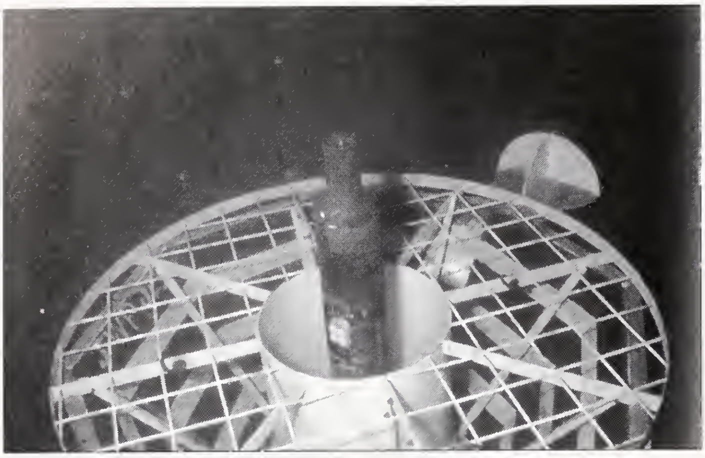
These holes have been visited three times since the CORKs were installed, the first time about three weeks after installation with DSV *Alvin* from the Woods Hole Oceanographic Institution, the second about ten months later with ROV *ROPOS* from the Canadian Institute of Ocean Sciences, and the third again with *Alvin*, just over two years after installation. Large drilling disturbances were seen in the records from both holes. A pressure offset equivalent to 100 meters of head was observed at the time the deeper hole was sealed. Virtually all of this negative differential pressure was caused by the tendency for the cold, dense water, unavoidably injected into the hole during drilling, to sink into the hot formation. (A similar suction is created when liquid is held in a soda straw with a finger on the top.) The initial drilling disturbance had decayed by only 50 percent during the first three weeks of recording. Large thermal and pressure disturbances were also observed in the hole drilled into the vent field. Pressures in this borehole eventually became positive, but only after a full year of waiting! Data from both holes clearly demonstrate the need for long-term measurements.

A second pair of holes has been drilled into the Cascadia accretionary prism, where over 2 kilometers of sediments are being scraped off the subducting Juan de Fuca plate along the west coast of North America, and slowly compressed into rock. One hole, located off the

The "business-end" of a borehole seal is prepared for deployment from the ODP drill ship JOIDES Resolution.

E. Davis

E. Davis



Photograph taken from the research submersible Alvin showing an ODP reentry cone in Middle Valley, Northern Juan de Fuca Ridge, fitted with an instrumented seal that filters through the hole. A submersible landing grid covers the top of the 5-meter-diameter cone. The observatory instrumentation includes a pressure sensor below the seal, tilt sensors, a chain of 10 thermistors, and a port through which formation fluids can be sampled. Holes up to 1 kilometer deep have been fitted with these instruments in the Pacific Ocean; four more are planned for the Atlantic.

coast of Oregon, penetrates through a shallow thrust fault within the prism. The other was drilled off Vancouver Island in an area where seismic reflection profiles indicate the presence of frozen methane hydrate in the accreted sediments. Observations in these holes are helping to define the relative importance of focused and diffuse fluid-flow pathways, and are showing that water may be expelled in an episodic manner. The observations will also answer questions about the seismic rupture potential of the deep thrust fault that lies beneath the prism and separates the sedimentary rocks accreted to the North American continent from the oceanic crust that slides beneath.

In 1994, four additional CORK installations are scheduled. In the spring, three holes will be drilled and instrumented in the Barbados accretionary prism. These holes will penetrate directly into the primary subduction thrust-fault zone that at this location lies at a depth that can be reached by drilling. One will penetrate an anomalously reflective part of the fault, where extremely high fluid pressures are believed to be present. Later in the year, another CORK will be placed in a hole that is to be drilled in the large TAG hydrothermal deposit. This hydrothermally active site is situated in the sediment-free rift valley of the Mid-Atlantic Ridge at 26°N. Information from this hole will complement the information gained from the Middle Valley sedimented-rift sites.

Hydrogeologic observations in deep ocean environments will never be as simple as equivalent observations on land. The consequences of porefluid pressures and "groundwater" flow beneath the seafloor are great, however, and the extra effort required to understand sub-seafloor fluid flow processes is well justified. Holes drilled by ODP provide unique opportunities for studying the surprisingly active hydrologic environments beneath the seafloor; the tools described here provide one way to take advantage of these opportunities. ■

Earl Davis is a senior research geophysicist at the Pacific Geoscience Centre, Geological Survey of Canada, where he spends most of his time either studying the signals and wrestling with the noise associated with crustal fluid flow, or dreaming up new ways to measure them. When asked privately, he reveals that he would rather be a diviner, but concedes that where he likes to work, even a good diviner would be in over his head.

Keir Becker is a professor at the Rosenstiel School of Marine and Atmospheric Science, University of Miami. His interests have been focused on the hydrogeology of oceanic crust for much of his career; he has spent nearly two years of his life on the drill ships of the Deep Sea Drilling Project and the Ocean Drilling Program, conducting downhole hydrogeologic experiments like those described here. He openly admits that he would rather be windsurfing, where his love for water can be realized more simply, and where being in over his head is just part of the fun.

Fluid Composition in Subduction Zones

Miriam Kastner and Jonathan B. Martin

Evidence for large-scale fluid flow and fluid expulsion at subduction zones includes several observations:

- the porosity of the originally water-rich sediments of accretionary complexes is rapidly reduced by tectonic forces,
- heat flow is regionally variable,
- depth profiles have characteristic temperature and pore-fluid chemical and isotopic anomalies that can only be maintained by rapid and rather recent fluid flow, and
- diffusive and/or channelized fluid venting is widespread.

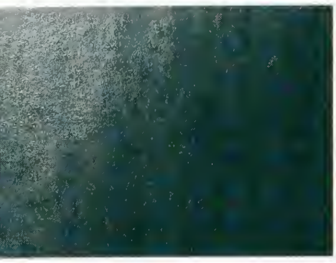
The latter occurs along sedimentary and structural-tectonic conduits such as unconformities, faults, and the décollement (the prominent boundary between the overriding and underthrusting plates shown in the figure on page 87) as well as through mud volcanoes.

These fluids sustain prolific benthic biological communities and cause widespread carbonate deposition as cement, vein filling, crusts, or chimneys, mostly from oxidation of microbially or thermogenically derived methane. The fluids also play an important role in the deformational, thermal, and chemical evolution of subduction zones, and enhance sediment diagenesis and rock metamorphism. Fluids released from these reactions transport dissolved components into the ocean, some of which may be important for global geochemical budgets. At greater depths (more than 80 kilometers), released fluids, especially water from the subducted sediments and altered oceanic basement and carbon dioxide from methane oxidation and decarbonation reactions, may expedite partial melting processes in the overlying mantle wedge, leading to arc volcanism.

An extensively fractured sediment core from the décollement at Nankai, retrieved during ODP Leg 131, Site 808, about 960 meters below the seafloor.

The presence of sediment-derived isotopes and trace elements, especially cosmogenic beryllium 10 (half life 1.5 million years) in arc lavas, provides evidence for sediment recycling in some subduction zones. Global estimates of sediment contribution to arc lavas range from a few to 20 percent of the subducted sediments.

The total volume of the internally available fluid sources in subduction zones through steady-state processes has been estimated to be 1 to 2

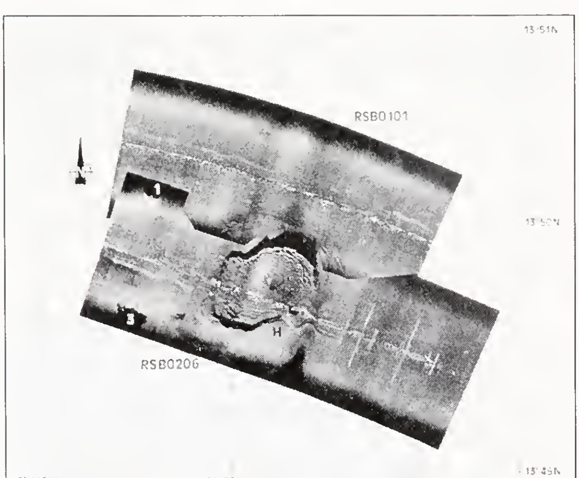


cubic kilometers per year. These estimates, however, do not account for the 2 to 6 order of magnitude larger than predicted fluid-flow rates measured at numerous channelized fluid venting sites, for example, at the Barbados, Nankai, and Cascadia accretionary complexes. This discrepancy in fluid volumes suggests either that the channelized fluid flow is transient in nature and/or that a major external fluid source exists. Meteoric water (rain or snow) is the most likely external source, but how it might be transported to the subduction zones is yet unknown.

Geochemistry of the Fluids

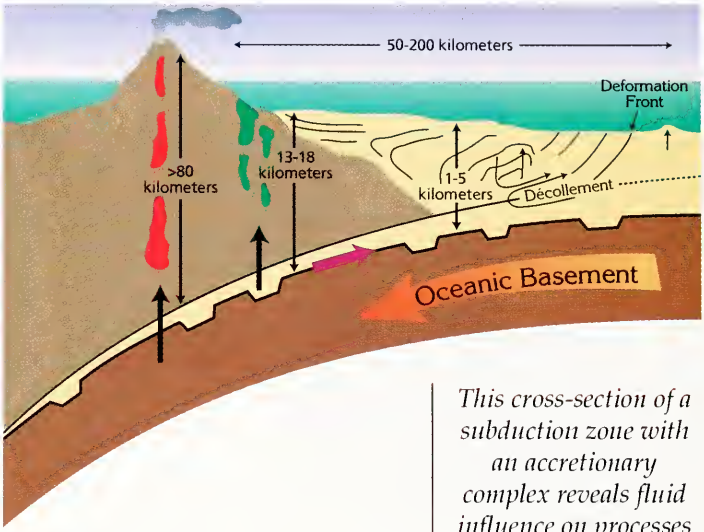
Detailed studies of the chemical and isotopic compositions, mostly of the pore fluids obtained through drilling and of the channelized venting fluids obtained with submersibles and conventional coring, indicate that the chemical and isotopic characteristics of the expelled fluids differ markedly from seawater, the original pore fluid (see the figures on page 88). Of particular interest are the ubiquitous fresher-than-seawater fluids often found in accretionary complexes and associated with fluid conduits such as faults, the décollement, or mud volcanoes. Seawater chloride dilution of 10 to 64 percent has been recorded. Unraveling the origin of fresher-than-seawater fluids is of great importance to understanding subduction zone hydrogeochemistry. The only internal sources and processes that may provide water for the formation of the low-chloride fluids are: 1) Dehydration or breakdown of hydrous minerals, particularly clay minerals, amorphous opal (opal-A), and zeolites in the accretionary complex and of minerals such as talc, phengite, serpentine, and amphiboles in the oceanic basement, 2) Dissociation of gas hydrates (clathrates), ice-like crystalline compounds whose expanded ice-lattice forms cages that contain gas molecules (mostly methane hydrate has been recovered from several accretionary complexes, and geochemical and geophysical evidence for the presence of gas hydrateshas been observed at most of them), and 3) Clay membrane ion filtration: Geochemical evidence for the occurrence or importance of the latter process in clay-rich subduction zones is yet unavailable.

Deep-towed side-scan sonar image of a mud volcano, located about 20 kilometers east of the deformation front at the Barbados convergent margin. The swath width of the image is 1,500 meters and the height of the mud volcano (above the surrounding sediments) is about 50 meters.



These overall dilute and fresher-than seawater fluids are often characterized by other chemical and isotopic anomalies. They are generally enriched in alkalinity, lithium, sodium, silica, beryllium, boron, iodine, methane (ethane, propane), carbon dioxide, and hydrogen sulfide; in contrast, they are depleted in potassium, magnesium, and sulfate. Concentrations of calcium and strontium vary, influenced by carbonate recrystallization and, at greater depths, by decarbonation. Strontium isotopic ratios that vary from highly radiogenic continental crustal to nonradiogenic oceanic basement values suggest communication with various deep-seated basement sources. This is also supported by the presence of mantle-derived helium; for example, based on helium isotopic analyses, at Nankai below the décollement, about 25 percent of the helium is mantle-derived. Helium, like chloride, is an excellent geochemical tracer because it is conservative and unaffected by chemical or biological reactions; its isotopic composition uniquely defines its source. Trace amounts of magmatic methane and carbon dioxide may be present as well. If so, they would be masked by the abundant microbially and thermogenically-derived biogenic methane and carbon dioxide.

Unusually high pH (alkaline) and chloride-depleted (57 percent seawater dilution) fluids that are rich in methane, ethane, and propane as well as in hydrogen sulfide, carbonate alkalinity, and ammonia, have been recovered from the Conical Seamount, an active low-density serpentinite mud volcano in the Mariana forearc, and in the Chile convergent margin adjacent to the triple junction. This suggests a rather deep (greater than or equal to 10-kilometers) source for these fluids. The global flux of these unusual fluids is as yet unknown. The Mariana subduction zone lacks an accretionary complex; here all the sediment is being subducted.



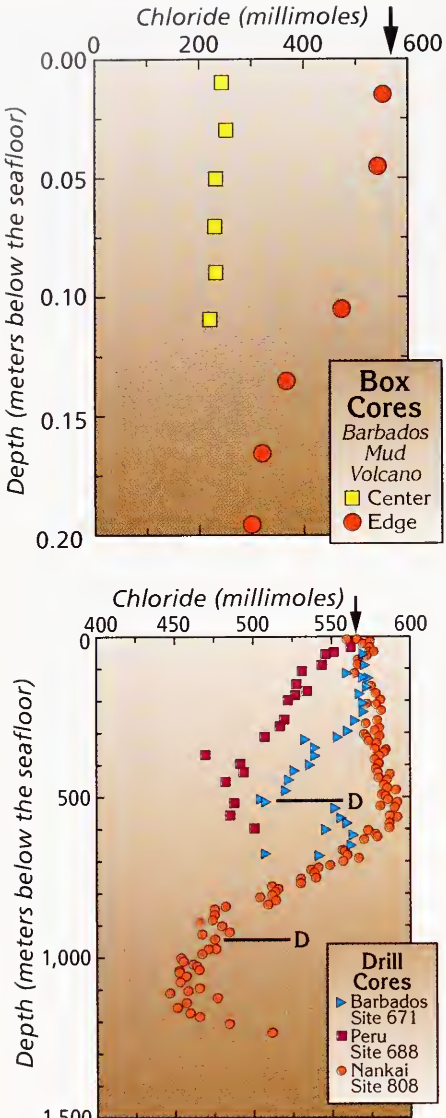
Jack Cook/WHOI Graphics

This cross-section of a subduction zone with an accretionary complex reveals fluid influence on processes at various depths of the zone. At depths of 1 to 5 kilometers, fluids flow through accreted sediments (small arrows) either along conduits such as faults, stratigraphic horizons, and mud volcanoes, or by porous flow. At depths of 13 to 18 kilometers, water from the subducting slab forms serpentinite within the overlying mantle wedge. It erupts because its density is lower than that of the surrounding peridotite (large arrow at green blobs). At depths of about 80 kilometers, water evolves from the slab and initiates mantle wedge melting, causing arc volcanism (large arrow at red blobs).

Mud Volcanoes

A variety of seafloor bathymetric features known as mud volcanoes typify sites of focused fluid venting. Their shapes range from conical, with diameters of a few meters to about 1 kilometer, to linear ridges that are occasionally greater than 10 kilometers long. These features are common at subduction zones; they have been found at every convergent plate margin surveyed at the appropriate resolution. One of the most extensively studied mud-volcano fields occurs at the Barbados convergent margin. Here the surface area of the mud volcanoes covers nearly 45 percent of an approximately 1,600-square-kilometer region. About 30 square kilometers of this mud-volcano field, situated on the oceanic side of the deformation front, has been extensively surveyed using geophysical and coring techniques.

Deep-towed side-scan sonar images of the Barbados margin show a variety of mud volcano features. These images allow us to record temperature gradients in detail and recover cores from individual mud volcanoes. One of the larger mud volcanoes is shown in the figure at left. In its center, temperatures of about 20°C were measured at only 1 meter below the seafloor (mbsf); the surrounding bottom water temperature is about 2°C. The venting fluid is characterized by chloride concentrations of 211 millimoles, about 40 percent of seawater's value. These temperatures and chloride concentrations reflect extraordinarily rapid, focused, vertical flow of fluid from the mud volcano. Numerical calculations based on the temperature gradients indicate flow rates of 17 meters per year. The temperature gradients and chloride dilution decrease closer to the edge of the volcano, indicating that flow is most rapid in its center.



Jayne Doucette/WHOI Graphics

Chloride concentration versus depth profiles, in pore fluids extracted from sediments recovered with piston cores from the Barbados mud volcano, in pore fluids extracted from sediments recovered with drill cores in the accretionary complexes at Barbados and Nankai, and from slope sediments at the Peru subduction zone.

Saline Fluids in Subduction Zones

The residual fluids from gas hydrate formation and clay membrane ion filtration are brines, fluids of high solute concentrations and of high density. However, brines have not been observed in association with the ubiquitous gas hydrates in accretionary complexes. This is best explained by loss of solutes through diffusion or fluid advection at the sites of hydrate formation.

In addition to precipitation or dissolution of evaporite minerals such as halite or sylvite, brines with more than twice seawater chloride concentrations result from the hydration of volcanogenic sediments or of oceanic basement rocks to hydrous minerals such as clay minerals and zeolites. An excellent example of a brine formation from seawater evaporation has been observed in the Peru forearc basins; brines from volcanic ash alteration occur in the New Hebrides intra-arc Aoba basin and in an Izu-Bonin forearc basin. At all the previously drilled accretionary complexes, however, the fresher-than-seawater fluids dominate. Saline fluids should, however, be present in accretionary complexes associated with evaporites, for example in the Mediterranean Sea. The only fluids with somewhat (less than 15 percent) higher chloride concentrations than seawater were observed in association with volcanogenic sediments in the Nankai and New Hebrides accretionary complexes. Similar to submarine hydrothermal fluids, the elevated chloride fluids associated with volcanogenic sediments or oceanic basement could evolve into calcium-chloride brines. Saline fluid inclusions have been observed in mineralized veins in metamorphic rocks of accretionary complexes. Because of the scarcity of geochemical data on these fluid inclusions, it is premature to speculate on their origin or quantitative importance. ■

Miriam Kastner, the first woman professor at Scripps Institution of Oceanography, gradually migrated westward from Harvard University where she received her Ph.D., through the University of Chicago at which she spent a year as a post doctoral fellow. During her first summer as a Harvard graduate student, she became interested in oceanography, and worked with a prominent conservative scientist on the geochemistry and mineralogy of sediments recovered from the flanks of the Mid-Atlantic Ridge. She is interested in natural-fluid rock processes, especially between seawater and marine sediments and oceanic basement. Her finite "spare" time is mostly dedicated to music.

Jonathan B. Martin came to Scripps Institution of Oceanography to work on fluids after graduating with a master's degree in geology from Duke University, where he worked on rocks. During the past year, he has completed his Ph.D. dissertation and produced a son, Peter. He is grateful to his wife, Ellen, for her help in both endeavors. After graduation, he will continue to work on convergent margin processes, both modern and ancient, at the University of California, Santa Cruz, and at the US Geological Survey.

Scientific Ocean Drilling and Continental Margins

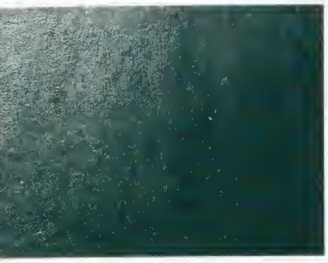
Understanding the Fundamental Transition from Continent to Ocean

James A. Austin, Jr.

Extending from the beach to the base of the continental rise, continental margin waters are the "ocean" most familiar to Earth's human population. They are a popular recreational site, and fish from these waters sustain much of the global population. Most of the remaining hydrocarbons that fuel modern civilization's activities are expected to be found beneath these waters, associated with the thick sediments that line many continental edges. Climate researchers are now concentrating on continental margins, because their sediments hold vital historical clues for helping us unravel global temperature changes and associated sea-level fluctuations. However, we still know little about the most fundamental crustal transition on the earth's surface: that from continent to ocean. The study of plate tectonics has rewritten Earth's geological history as a story of continents moving across the surface of a (presumed) rigid sphere through time, but it has not yet provided details of their interactions, the critical link in understanding the nature of ocean-continent boundaries (OCBs). Drilling, along with detailed geological and geophysical surveys, must fill that gap.

We still know little about the most fundamental crustal transition on the earth's surface: that from continent to ocean.

Ascertaining the geological history of continental margins has been a priority of scientific ocean drilling for many years. Drilling transects across margin pairs are now recognized as critical to properly describe the competing models of intracontinental extension, in particular the roles of throughgoing crustal detachment faults in margin formation and subsidence. The Atlantic Ocean is an obvious place for ODP to attack this important theme, because conjugate "passive" continental margins (defined as those where continental and oceanic crusts are fused together) are better



developed and more accessible around the Atlantic than anywhere else. The birth of various Atlantic margin pairs has occurred at different times: about 50 million years ago north of Iceland, 130 million years ago between southern South America and Africa, 180 million years ago between North America and Africa, and 110 million years ago for eastern Canada and the Iberian Peninsula. (Even younger margin pairs, for example in the Red Sea, may be addressed in the future.) ODP has chosen two of these pairs as prime examples of volcanic and nonvolcanic end-members of continental fragmentation and ocean-basin formation: southeast Greenland-Norway (see "Exploring Large Subsea Igneous Provinces," page 75) and Iberia Abyssal Plain–eastern Canada, respectively.

Jack Cook/WHOI Graphics

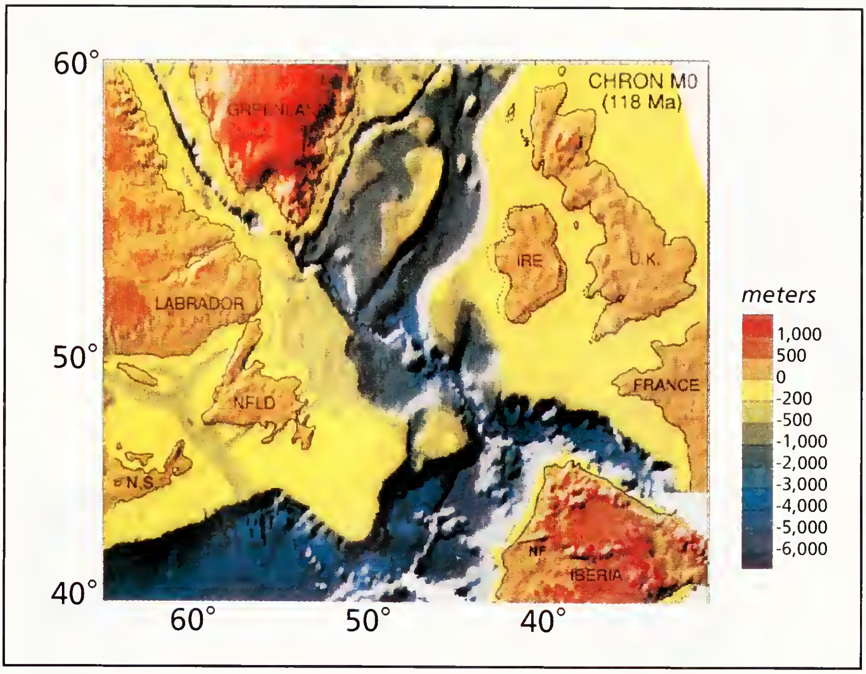
A reconstruction of the Atlantic and adjacent seas approximately 180 million years ago. A number of conjugate margin pairs with widely differing estimated ages of formation are available for study. The black lines near the colored coastlines are presumed ocean-continent boundaries, based upon available geological and geophysical data.

The Eastern Canada–Iberia "Nonvolcanic" Transect

The margins off the Grand Banks and Iberia are logical drilling candidates for several reasons. They have been intensively studied using a variety of marine geophysical and geological techniques, including coring, dredging, bottom and subbottom sound profiling, and submersible diving. As a result, their prebreakup reconstruction is well understood. Breakup-related crustal structures, the key to these margins' early history, are buried under just 2 to 3 kilometers of sediments, making basement rock accessible to ocean drilling. In addition, their locations relative to other thematically important ODP study sites allow convenient repeated access by *JOIDES Resolution*, and return visits of the drill ship are essential for successful margin drilling, because the research targets are deep and technically challenging.

ODP has just commenced a systematic approach to drilling in passive margins in the North Atlantic with Leg 149 (March to May 1993), which included a transect across part of the Iberia Abyssal Plain (IAP) west of Portugal. The shipboard scientific party encountered faulted blocks composed of rocks of continental affinity separated from normal Atlantic Ocean seafloor basaltic volcanic crust by a broad zone containing both exhumed, faulted oceanic crust and altered plutonic igneous rock known as peridotite. The peridotite forms a ridge that extends for more than 100 kilometers and delimits the approximate ocean-continent boundary along this margin.

The northern Newfoundland Basin (NB) is the conjugate to the Iberia Abyssal Plain. Available geophysical data suggest that the Newfoundland Basin contains a zone approximately 150 kilometers wide of thinned continental crust separating known Grand Banks continental crust from known oceanic crust seaward of a mid-Cretaceous period (about 118 million years ago) isochron, a magnetic anomaly known as MO. This crustal transition is much like that postulated for the Iberia Abyssal



Jack Cook/WHOI Graphics

Illuminated from the northwest, this shaded relief bathymetry map shows the positions of Iberia, eastern Canada, and adjacent plates at magnetic anomaly MO time, approximately 118 million years ago. This paleo-reconstruction is extraordinarily well constrained, which is one of the reasons that ODP has decided to concentrate on the Iberia–eastern Canada margin pair.

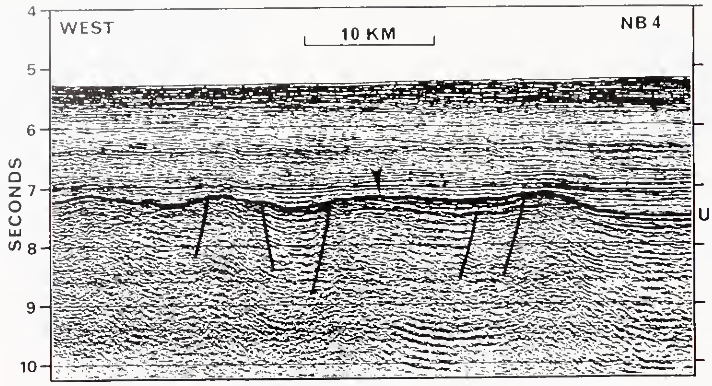
Data courtesy S. Srivastava, Bedford Institute of Oceanography

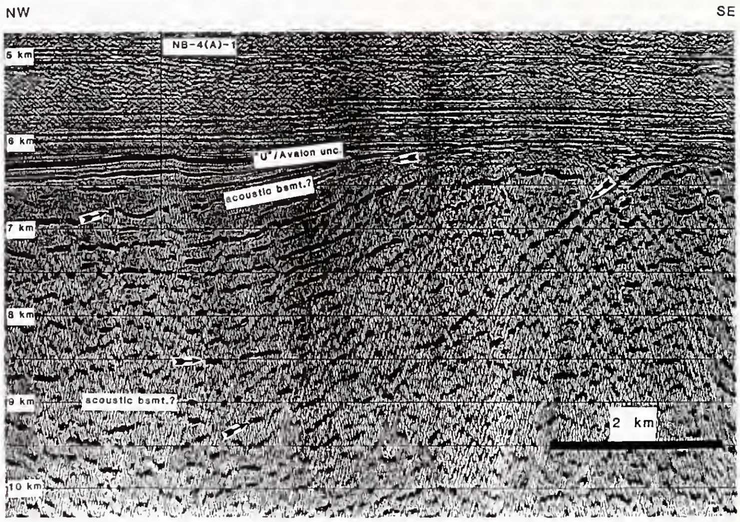
Plain. This zone constitutes one of the largest areas of enigmatic seafloor in the North Atlantic. The Newfoundland Basin may also be characterized by a peridotite ridge. However, the Newfoundland Basin differs significantly in one major way—it exhibits a well-defined geological unconformity ("U"/Avalon, in the figure on page 94) that caps and occasionally truncates underlying crust out to the interpreted ocean-continent boundary 20 to 40 kilometers west of magnetic anomaly MO. The strong development, relative flatness, and wide areal extent of "U" suggest that it was eroded at or near sea level during the Iberia–Grand Banks breakup.

The first-priority issue for proposed ODP drilling in the Newfoundland Basin is to ascertain the origin of the "U" unconformity and the nature of underlying crust. If the wide transition zone in the Newfoundland Basin proves to be floored by continental crust that has thinned, faulted, and eroded in a subaerial environment, a *fundamental new class of crust* will be documented that must be accounted for in future models of continental breakup. Drilling in the Newfoundland Basin will also provide the crucial geological control for understanding the early history of this part of the North Atlantic, particularly when used in conjunction with results from the Iberia Abyssal Plain, the other half of the conjugate pair.

What the Future Holds

Continental margin drilling represents a long-term, multinational commitment. Completing the volcanic and nonvolcanic transects as presently defined will take multiple drill ship expeditions over a period of years. This will cost tens of millions of dollars, because continental margin holes require multiple nested metal liners to promote stability for deep penetration. Furthermore, thick sediments present safety hazards because of their potential to contain overpressured fluids and gases. *JOIDES Resolution* or her successor will eventually need to be equipped





Sound profiles near ODP Site NB-4 illustrate geology characteristics of the Newfoundland Basin. The recording above is in reflection time, and the recording at right is of actual depth (relative to the sea surface). The nature of the prominent "U"/Avalon unconformity, and its relationship to underlying basement, is clear. Basement rock may be thinned continent, part of North America affected profoundly during its separation from Iberia. ODP plans to drill to and sample both the "U"/Avalon unconformity and basement rock.

with complicated and expensive blowout-prevention capabilities, similar to those now used in the oil and gas industry. Despite these inherent costs and the remaining engineering difficulties, ODP must meet the margin challenge if we are ever to understand the essence of the global jigsaw puzzle that we call home. ■

This is University of Texas Institute for Geophysics Contribution #1016.

James A. Austin, Jr., first recollects seeing the Woods Hole Oceanographic Institution as a toddler, staring through the railing of the ferry bound for his parents' summer home on Martha's Vineyard. About 18 years later, he was admitted to the MIT/WHOI Joint Program in Oceanography, from which he emerged (relatively unscathed) with his doctorate at the end of 1978. Since that time, he has been a research scientist at the University of Texas at Austin. However, New England still calls, that summer home on the Vineyard still exists, and the ferries from Woods Hole still run, so with luck he will never get too far from his oceanographic roots.

When Plates Collide

Convergent-Margin Geology

Asahiko Taira

On the modern globe, Earth's tectonic plates mostly converge in deep sea trenches or collisional troughs. (See *Oceanus* Winter 1992/93 for a discussion of "Island Arcs, Deep-Sea Trenches, and Back-Arc Basins.) Ocean drilling has provided fundamental information about colliding-plate processes, including accretion of sediments and volcanic edifices from underthrusting to overriding plates, emplacement of rocks that have been altered by the forces at work in colliding-plate zones, and the nature of continental collisions. It has opened new avenues for comparative studies of modern and ancient earth processes. Recent plate-tectonic models indicate that many areas known as "orogenic belts," where Earth's crust has been deformed by such mountain-building phenomena as thrusting, folding, and faulting, have evolved through convergent-plate-margin processes such as formation of accretionary prisms, accretion of various exotic terranes, and the collision of arcs and continents.

Drilling results show that sediments from the descending plate are underplated onto the overriding plate.

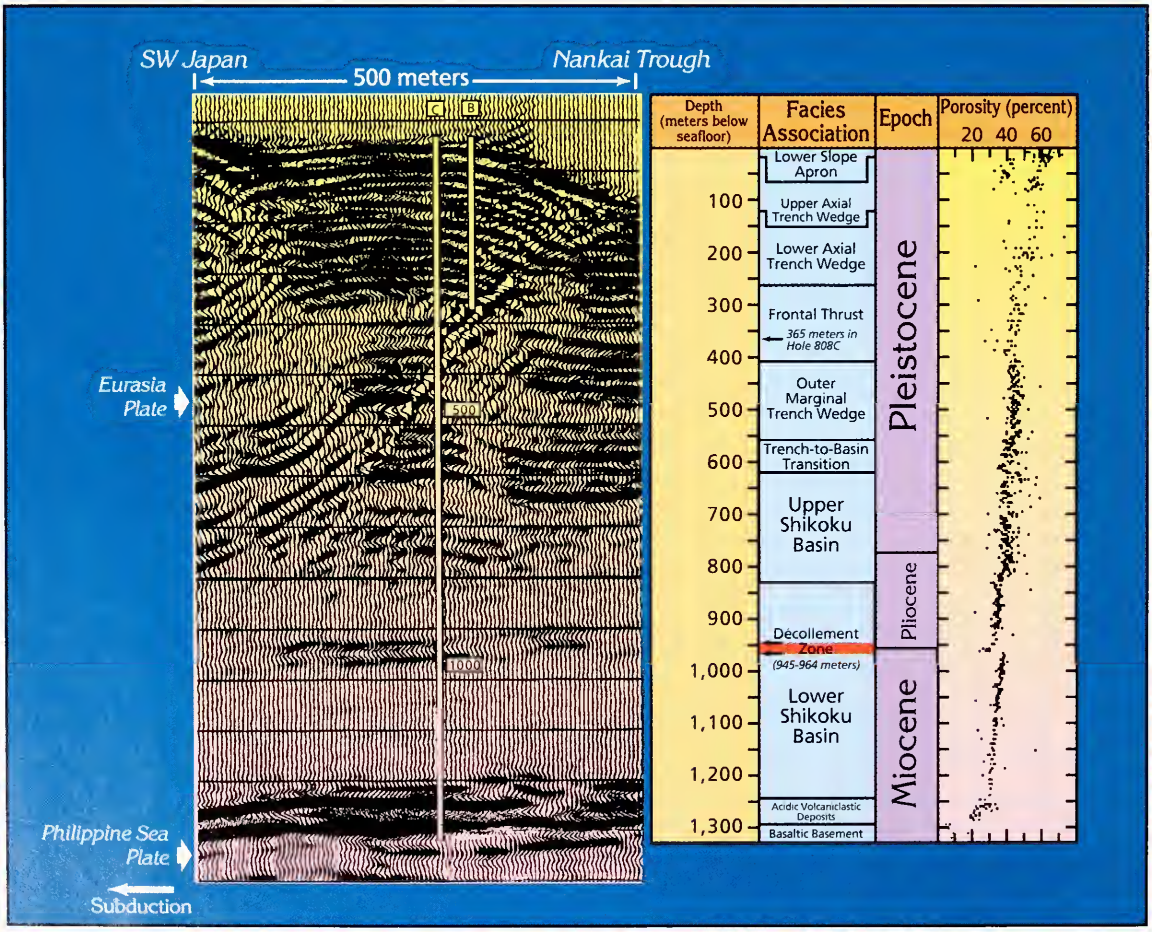
Accretionary Prisms

The seafloor-spreading concept posed the question of the fate of sediments on descending oceanic plates, and the ocean drilling program offered an opportunity to study the nature of sediment deformation in the deep trenches. DSDP investigations demonstrated that oceanic plate sediments progressively adhere to the leading edge of the overriding continental plate, forming an "accretionary prism." Drilling results also show that sediments from the descending plate are underplated onto the overriding plate, apparently thickening and lifting the prism. The figure on page 96 shows seismic reflection and drilling data for the Nankai accretionary prism, where coring penetrated the incoming sedimentary sequence completely, transecting the frontal thrust, the décollement zone (zone of detachment that separates accreted and underthrust sediments), and underthrust deposits to the ocean basement. The Nankai drilling provided basic trench stratigraphy, including small-scale structural features that develop during initial deformation, and it allowed measurement of frontal thrust displacement and décollement zone thickness. In addition to clarifying the geology of initial deformation, the deep coring shows a sharp increase in porosity of mudstone across the décollement, indicating that the décollement is a zone of overpressured pore fluid.

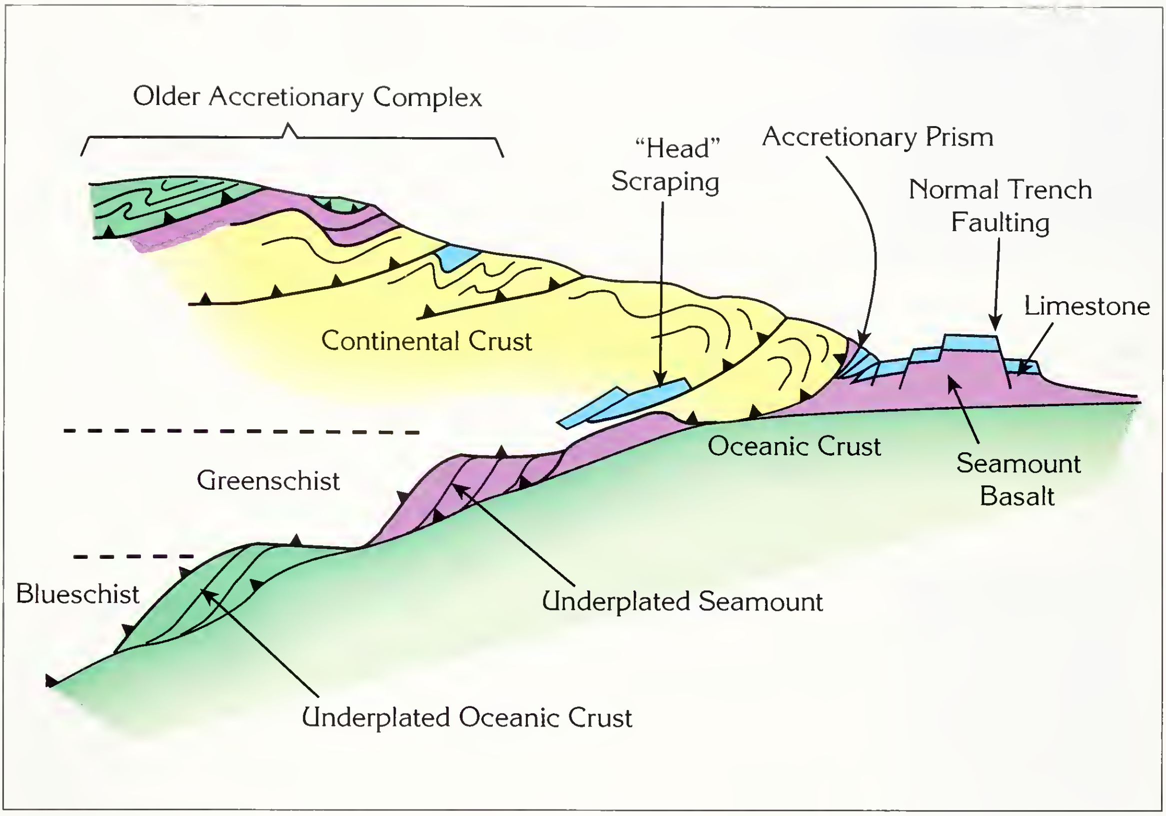
We know from studies of orogenic belts on land that they contain large volumes of highly disrupted and deformed clastic sediments (mostly turbidites) with minor amounts of apparently interlayered basalts, cherts, and tuffs. Detailed stratigraphic work in the Shimanto belt of Japan, for example, showed an orderly sequence before disruption: oceanic basement (basalts), pelagic sediments, hemipelagic sediments with silicic tephras and muddy turbidites, and coarser grained turbidites, basically similar to that found in the Nankai Trough. Identification of such stratigraphy in the orogenic belts is a key to the recognition of ancient accretionary prisms.

Analysis of small-scale structures in the Nankai cores showed that they faithfully recorded the geophysically determined direction of plate convergence. This verification of the connection between small-scale structural development and plate motions lends a whole new level of credibility to studies that claim this correlation in ancient rocks.

ODP drilling results from the Nankai accretionary prism, offshore of southwest Japan. The seismic reflection image on the left was correlated with ocean-drilling data, revealing the information on the right, including the presence of accreted sediments above and underthrust sediments below the overriding plate.



Jack Cook/WHOI Graphics



Summary of seamount and oceanic crust accretion at and under the leading edge of an overriding plate. Parts of an incoming seamount can be accreted at the "toe" and also underplated to several kilometers deep, and a part of the oceanic crust can be underplated 10 to 30 kilometers beneath the seafloor.

Exotic Terrane Accretion and Blueschist Emplacement

Recent advances in the study of orogenic belts include discovery of many exotic geologic bodies such as fragments of oceanic plateaus or island arcs that have traveled great distances to their present position. Recent drilling in the Vanuatu forearc of the southwest Pacific (the leading edge of Fiji microplate) unequivocally demonstrates the accretion of sediments and mid-ocean ridge volcanic rocks as discrete thrust sheets that form a frontal accretionary prism.

Many orogenic belts are characterized by metamorphic rocks called blueschists that have been formed under high-pressure and low-temperature conditions. The frequent mixing of such "high-grade" metamorphic blocks with materials of lower metamorphic grade (greenschists) presents a perennial problem in accretionary tectonics. Recent ocean drilling penetration of serpentine diapirs and volcanoes in the Mariana forearc (leading edge of the Eurasian plate, in the Philippine Sea) documents intermixed blocks of mid-ocean ridge basalt and blueschist. The metamorphic grade indicates transport of the blueschists from sources 13 to 18 kilometers below the serpentine volcano and suggests accretionary processes are at work in deeper parts of the forearc. These drilling results strongly support field observations in many orogenic belts that accretion and underplating of seamounts and parts of oceanic crust occur over a range of depths (see the figure above).

Ridge Subduction

The effect of the collision or subduction of an active spreading center has been controversial. One can argue that oceanic highs such as spreading ridges provide a principal mechanism of ophiolite emplacement in forearc regions. It can also be inferred that forearcs record unusual thermal events. Ocean drilling in the Chile triple junction penetrated a site previously interpreted as an emplaced ophiolite and discovered, instead, evidence for near-trench in situ volcanism.

Shikoku Basin basalts recovered during Nankai Trough drilling are covered by a thick submarine pyroclastic deposit that dates to about 15 million years ago. This correlates with land geology in southwest Japan, where there is evidence of several contemporary unusual thermal events: near-trench igneous activity including gabbro and granitic rock intrusions, as well as high-temperature metamorphism. The combination of ocean-drilling results and orogenic-belt studies shows the geologic events in the forearc that are associated with the subduction of an active spreading center.

Drilling in the Chile triple junction penetrated a site previously interpreted as an emplaced ophiolite and discovered, instead... in situ volcanism.

Collision Processes

Collision of major crustal features such as continents and island arcs is considered to be a principal cause of orogenesis that normally results in building mountain chains and thickening the crust. Mountain-building processes, however, are poorly understood. One approach to this problem is to study the eroded sediments that are deposited in the ocean, such as Leg 116 drilling in the Indian Ocean's Bengal fan, which was formed by Himalaya Mountain erosion as perhaps the largest sedimentary deposit in all earth history. Detailed study of heavy mineral assemblages suggests a two-phase uplift of the higher Himalayas, one during the period from 11 to 8 million years ago and the other less than 1 million years ago. Compilation of DSDP and ODP data from various places in the Indian Ocean also reveals a similar two-phase uplift pattern. The general inference of such studies is that mountain-building processes are episodic, and considerably swifter than previously thought.

Ocean Drilling Contributions to Continental Evolution

Accretion of various materials from one plate to the other is a part of the global material cycle. In early earth history, igneous rocks derived from the mantle were progressively assembled and accreted to form continental crusts. Subsequent collision of continental blocks and arcs produced mountains and yielded new sediments. As a result, sedimentary accretionary prisms became a major part of modified continental blocks. Thus ocean drilling should continue to be important not only to marine geoscientists but also to those who study continental geology. ■

Asahiko Taira went from Japan to Texas where, to his astonishment, everything was flat. After receiving his Ph.D. from the University of Texas at Dallas in sedimentology, he went to Kochi University in Japan, where he encountered the vertically dipping, highly deformed Shimanto accretionary prism. The Shimanto belt research led him further into the study of the deep sea. Since 1985, when he moved to the University of Tokyo, he has been in charge of Japanese ODP operations. He was co-chief scientist for the drilling he describes in Nankai Trough. His current research interest lies in the evolution of arcs and continents.

From the Superchron to the Microchron

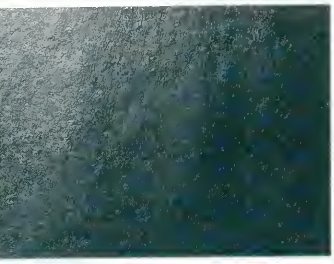
Magnetic Stratigraphy in Deep Sea Sediments

Yves Gallet and Jean-Pierre Valet

Recent new methods in chronology considerably improve the time resolution of marine sediment magnetic records.

Sediments acquire the signature of Earth's prevailing magnetic field at the time of their deposition. Because the polarity of the geomagnetic field has reversed repeatedly in the geological past, the successive polarity changes imprinted in sedimentary sequences provide the physical basis for magnetic polarity stratigraphy. This "magnetostratigraphy" can be used as a correlation and dating method. A general outline of the magnetic polarity time scale has emerged from scientific studies over the past 30 years; the ultimate goal is to extend and date the record over even older periods. Recent new methods in chronology considerably improve the time resolution of marine sediment magnetic records and provide the first opportunity to resolve fine-scale features of Earth's magnetic field.

We consider the present-day polarity field to be normal: Magnetic lines of force are directed toward the north magnetic pole, and the north-seeking pole of a compass needle points north. However, when the field has the opposite polarity, the lines of force are directed south and a compass needle points south. Until the mid 1960s, magnetic polarity time scales were calibrated using only continental volcanic rocks younger than 5 million years old. Study of marine sections became possible in the mid 1960s with the development of more sensitive magnetometers that could measure the weak magnetization of sediments. Correlation of magnetic records from various deep-sea cores and with paleomagnetic and radiometric studies of on-land lava flows followed and verified the value of sedimentary sequences as records of polarity changes in Earth's geomagnetic field. With succeeding work on much longer time series,



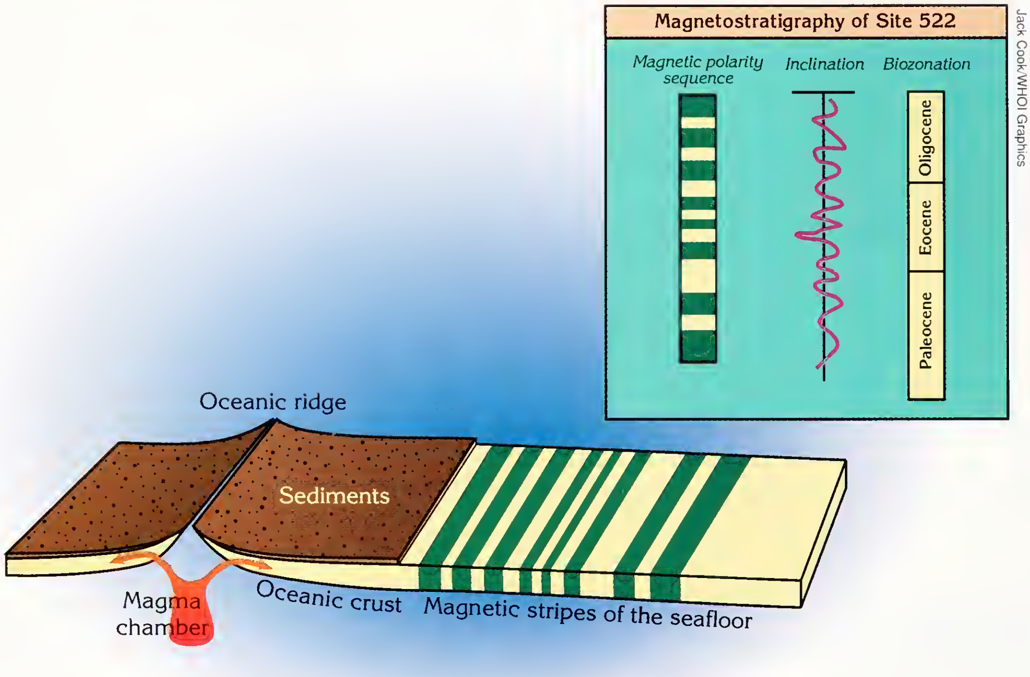
magnetostratigraphy has become a very accurate method of dating sedimentary sequences.

The first long (pre-Pliocene) magnetic polarity time scale was proposed by geophysicists from the Lamont-Doherty Geological Observatory of Columbia University in 1968. Covering the last 80 million years, the scale was constructed from profiles of marine magnetic anomalies of the South Atlantic Ocean. A few years later, this scale was extended to the Lower Cretaceous and late Jurassic periods, with the first continuous sequence of reversals for the last 160 million years, using magnetic surveys from the Pacific Ocean. In the meantime, some authors cautioned against uncritical acceptance of sediment magnetostratigraphy because the record may be complicated by several factors, such as post-depositional overprinting of the signal due to chemical changes in the sediment. The situation then greatly improved with the development of extremely sensitive (cryogenic) magnetometers, making it possible to measure large numbers of weakly magnetized samples.

During the 1970s, magnetostratigraphic studies from pelagic limestone sections of land and deep sea sediments drilled during DSDP confirmed most of the magnetic polarity intervals (or chrons) determined from profiles of marine magnetic anomalies. Magnetostratigraphic results were also used to calibrate the polarity time scale. This was achieved by cross-correlating biostratigraphic zonations deduced from paleontological studies with the magnetic polarity sequences observed in sedimentary sections and revealed from the magnetic stripes of the seafloor. This research has advanced significantly through the work of the ocean drilling programs. For example, coring on DSDP Leg 73 in the South Atlantic yielded a tight calibration between bio- and magnetic-polarity time scales for the Paleogene. Magnetostratigraphic and paleontological data are now available for most of the geological boundaries since the late Jurassic, the age of the oldest oceanic crust. Among these boundaries, the Tertiary-Cretaceous time boundary, which is important because of its signature faunal extinctions, is particularly well documented. The relationship to biostratigraphic zones is in general well established, but it is not yet possible to relate the zones to isotopic ages with the same precision. Magnetic polarity intervals that are directly dated by isotopic methods are rare. There are two possibilities to obtain this absolute calibration. The first is to date one or several interstratified lava flows in sections where a magnetostratigraphic sequence has been identified. The second possibility is to drill the ocean floor beneath a well-defined magnetic anomaly and determine the age of the basalt layer using isotopic dating. After 20 years of detailed studies, the paleontological calibration of the magnetic polarity time scale is now in good shape, though there is work to be done to obtain detailed absolute datings.

Magnetic Reversals

Earth's magnetic field is generated in the iron-rich outer core through a dynamo process, by which the mechanical energy released from fluid motions is converted to magnetic energy. The geomagnetic field is dominated by a dipolar geometry with either a normal (north pole of the magnetic needle pointing toward the north geographic pole) or a reversed (north pole pointing toward the south geographic pole) polarity. The brief periods of a few thousand years of switch between the two polarity states are called reversals. Reasons for the reversals are still unknown. However, the magnetization of rocks as they are formed provides records, like a tape recorder, of the succession of the magnetic reversals through time, ultimately yielding the definition of the magnetic polarity time scale with more than 300 reversals over the last 160 million years.



Typical magnetostratigraphy obtained at Site 522 from Leg 73 in the South Atlantic. The magnetic polarity sequence is deduced from changes in inclinations. Green shows normal polarity intervals, white reversed poles. These intervals, which are easily correlated to the magnetic oceanic anomalies, are well calibrated to the geological stages. Therefore, these results provided a tight calibration of the magnetic polarity time scale since the late Eocene. (After Tauxe et al., 1984.)

A High-Resolution Stratigraphic Method

The frequency of reversals appears to have changed markedly since the late Jurassic. Indeed, if the reversal sequence is observed over several million-year periods, the character of the polarity time scale shows successive periods of low and high frequency. The rate of reversals gradually decreased from about 4 reversals per million years at 155 million years to zero reversals at 118 million years when a 35-million-year-long normal period occurred, the so-called Cretaceous Long Normal Superchron. From 83 million years onward, the mean frequency of reversal increases more or less regularly, up to about 5 reversals per million years for the recent period.

The Cretaceous Superchron is not unique in geomagnetic history. Another long polarity interval has been identified during Permo-Carboniferous times from land sequences. At the other extreme of the time scale are very short intervals of a few tens of thousands of years. The minimum polarity interval that can be resolved on individual marine magnetic profiles is about 20,000 years; it requires that high spreading-rate profiles be available. Magnetostratigraphic records from sedimentary sequences with high deposition rates can provide sufficient resolution to detect shorter intervals, in the range of a few thousand years. No less than 10 short magnetic polarity features lasting less than 30,000 years (microchrons) have been proposed for the last 3 million years. Microchrons observed at a single location remain speculative, while others appear to be relatively well documented by distinct records from various geographic locations. Among these, events known as Cobb Mountain at about 1.1 million years and the Gilsa at about 1.7 million years could be studied in detail from Hole 609B (Leg 94) sediments in the North Atlantic.

One of the current major objectives of research in magnetostratigraphy is to confirm the existence of the short magnetic polarity events. So far, none of the events reported during the Brunhes epoch (from 780,000 years ago to the present) appear to be sufficiently worldwide for inclusion in the polarity time scale. Their existence is critical for statistical analyses based on the distribution and frequency of reversals, which in turn have important implications for the mechanisms that generate the magnetic field. Short events could also be used for detailed calibration and high-resolution stratigraphic correlations between sites.

The new technologies developed by the Ocean Drilling Program represent a significant step toward the acquisition of very detailed magnetic records from sediments. Several techniques (X-ray, magnetic susceptibility, color reflectance) allow detailed between-hole correlation and the construction of continuous composite sequences from multiple holes drilled at the same site, such as during Leg 138 in the equatorial Pacific. Improvements in drilling technology have significantly reduced the physical disturbance of sediment collected in cores. Continuous measurements of very weak magnetization intensities are now routinely made with the horizontal pass-through cryogenic magnetometer aboard *JOIDES Resolution*, and most techniques required for detailed magnetic analyses can also be used in ship laboratories. All these factors have contributed to the acquisition of very long and detailed paleomagnetic records.

One of the current major objectives of research in magnetostratigraphy is to confirm the existence of the short magnetic polarity events.

After many years of analyzing the directional changes of the field, scientists are now trying to obtain records of geomagnetic field intensity. Since the intensity changes are synchronous over the entire globe, their record should provide a powerful new stratigraphic tool and new constraints on the process. Recently, during ODP Leg 138, a detailed record of geomagnetic field intensity was obtained by Laura Meynadier and Jean Pierre Valet (Institut de Physique du Globe de Paris) for the last 4 million years from sediments of the equatorial Pacific. The typical pattern of the curve and the similarity to results from other geographic areas indicate the promise of this new approach for future studies. ■

Yves Gallet completed a Ph.D. on fundamental and practical aspects of magnetostratigraphy in the Paleomagnetism and Geodynamic Laboratory at the Institut de Physique du Globe de Paris. His research interests include the magnetic polarity time scale for pre-oceanic periods and changes in magnetic reversal frequency since the Paleozoic Era.

Jean-Pierre Valet completed his Ph.D. thesis at the Centre des Faibles Radioactivités at Gif/Yvette by trying to extract information from the magnetization of tiny specimens of sediment, hoping that they would tell him something about geomagnetic reversals. He is now working at the Institut de Physique du Globe de Paris, looking at various kinds of materials, sediments and basalts, that record geomagnetic field variations.

Terrigenous Sediments in the Pelagic Realm

Sedimentary Processes

David K. Rea

The composition, mass accumulation rate, and grain size of the terrigenous component of deep-sea sediment provide records of both the sediment's continental source region and of transport and depositional processes. By volume, most terrigenous material arrives in the deep ocean through the deposition of turbidites (see "Turbidite Sedimentation," page 107). Here I will review the other three pertinent processes and outline how 25 years of ocean drilling has allowed marine geologists to understand the earth history thus recorded. The three processes provide the following kinds of sediment to the deep sea:

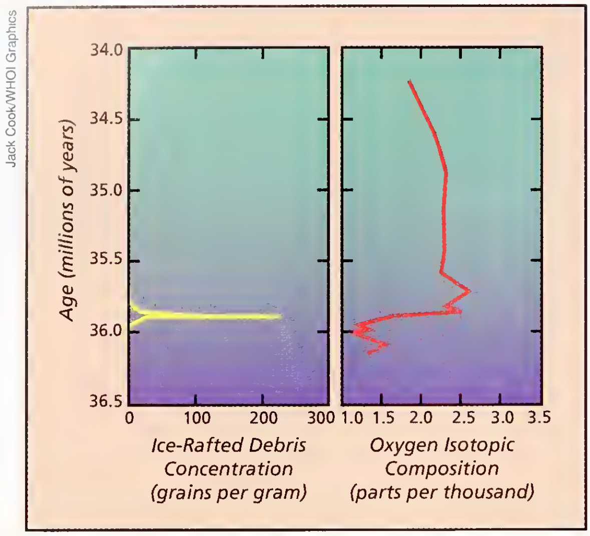
- ice-rafted debris, which gives direct physical evidence of glaciers at sea level;
- aeolian (wind-borne) dust, which offers information about the climate of the dust-source region and the intensity of the transporting winds; and
- hemipelagic muds, which record continental erosion and runoff in their flux data.

There is no way to obtain long, relatively continuous records of these processes other than ocean drilling. The resulting cores contain information that spans extended time periods so that geologists may track global change through many tens of millions of years. The hydraulic advanced piston core (APC) technology developed by the drilling program also permits recovery of undisturbed cores containing very high-resolution sequences of the climate cycles of the past few hundred thousand years. Finally, a quarter of a century of ocean drilling has resulted in nearly global coverage; samples are available from most parts of the world's oceans with the exception of the Arctic and the central Pacific south of about 20°S latitude.

There is no way to obtain long, relatively continuous records of these processes other than ocean drilling.

Ice-Rafted Debris

The geological history of glaciation has been a subject of lively debate ever since Swiss naturalist and geologist Louis Agassiz (1807–1873) convinced the scientific public that his idea of vast continental glaciers was correct. Discussions of the timing of glacial onset centered first on



Ice-rafted debris (IRD) distributions and oxygen-isotope values for benthic foraminifera from ODP Site 748 on Kerguelen Plateau. The IRD pulse matches the timing of the early Oligocene rapid increase in oxygen isotope values, linking this physical and chemical evidence for the onset of antarctic glaciation.

the Northern Hemisphere, and then the Southern. Early in the history of DSDP, Legs 12 to the North Atlantic and 18 and 19 to the North Pacific had among their major objectives the determination of the timing of Northern Hemisphere glaciation, especially the age of glacial onset. Cores from all three of these cruises clearly showed that ice-rafted debris became an important component of the sediment at a time then estimated to be in the middle to late Pliocene. Later, North Atlantic Legs 38 and 49 confirmed the original results of Leg 12.

The ice-rafted debris stratigraphy was reasonably clear in these regions, but use of the hydraulic piston corer in the late 1970s along with improved resolution of the biostratigraphy, oxygen-isotope stratigraphy, and magnetic-reversal stratigraphy were needed before the timing of glacial onset could be determined precisely. These improved stratigraphies were provided for the North Atlantic by the scientists of Leg 81, and by the mid 1980s it became clear that Northern Hemisphere ice rafting began in both the North Atlantic and North Pacific almost exactly at the time of the Matuyama-Gauss magnetic reversal, recently dated at 2.6 million years ago.

The details of high northern latitude glaciation were an important objective of DSDP Leg 94 and ODP Legs 104, 105, 151, and 152 to the North Atlantic and DSDP Leg 86 and ODP Leg 145 to the North Pacific. In addition to further defining the Plio-Pleistocene glaciation 0 to 2.6 million years ago, these cruises found evidence for a latest-Miocene to earliest-Pliocene ice advance: 4- to 6-million-year-old glacial dropstones have been recovered from both the North Atlantic and North Pacific oceans.

The drilling history of the high southern latitudes is similar. Legs 28 and 35 recovered ice-rafted debris as old as the Oligocene with large numbers of such grains occurring in Miocene and younger sediments. ODP has made high southern latitudes a special target. A major objective of legs 113 to the Weddell Sea and 119 and 120 to the Kerguelen Plateau and the margin of Antarctica was articulation of this history. As a result, scientists have been able to link the onset of significant ice rafting with the shift in oxygen isotopes at the Eocene/Oligocene boundary that signifies the buildup of ice on the southern continent.

Aeolian Dust

Although some aeolian studies arose from Pacific Leg 62, the first DSDP cruise to specifically target accumulations of aeolian dust was Leg 86 to the Northwest Pacific. That cruise cored the area's well-known red clay sediments and recovered one of the first whole Cenozoic records of aeolian deposition. It showed very low dust fluxes through most of the latest Cretaceous and Cenozoic, with an order of magnitude increase in dust input beginning about 3 million years ago, corresponding to the drying of Asia and the beginning Northern Hemisphere glaciation.

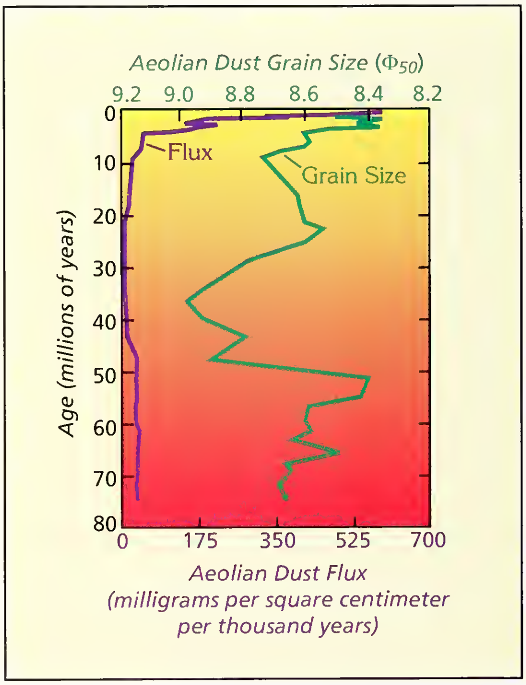
Dust-grain size provides a record of wind intensity. In the North Pacific the Leg 86 data confirmed a large reduction in aeolian grain size found to occur once before at the Paleocene/Eocene boundary, suggesting that atmospheric circulation in the early Eocene was much more sluggish than in the late Paleocene. Samples from that same cruise were later used to demonstrate that this grain-size change was one of several significant paleoclimatic changes that occur at the Paleocene/Eocene boundary. Refining the aeolian history of the Northern Hemisphere was among the objectives of North Pacific Leg 145 in 1992.

Leg 108 in 1986 investigated the late Cenozoic record of dust transported from the Sahara to the eastern North Atlantic and documented the history of north African drying over the past several million years. Leg 117 in 1987 to the Arabian Sea demonstrated a strong monsoonal influence in the aeolian-grainsize wind-strength record and that dust fluxes from Arabia to the Indian Ocean increase severalfold during glacial times.

Unraveling the history of Southern Hemisphere atmospheric circulation from the aeolian dust record was one among several paleoclimatic objectives of Legs 92 to the South Pacific, 121 to the Indian Ocean, and 130 to the western Pacific. Those cruises found very low flux values of dust to these areas for the past 60 million years, suggesting among other things that Australia has been essentially deflated for most of the Cenozoic (all the fine-grained dust has blown away). Grain-size data suggest that an increase in zonal wind intensity of the Southern Hemisphere trade winds occurred in the early part of the late Miocene, the only significant change found in those Neogene records. Finally, there is little or no indication of any Southern Hemisphere response to the late-Pliocene onset of Northern Hemisphere glaciation.

Comparing the aeolian records from the two hemispheres suggests that they may vary independently, a concept termed "hemispherical asymmetry." Such asymmetry should be strongest during the 30 million years beginning in the early Oligocene when the earth was characterized by one glaciated pole and one warm pole. Leg 138 to the eastern Equatorial Pacific allowed an explicit test of this idea, using aeolian dust to construct a history of the past locations of the Intertropical Convergence Zone, which has been in its present latitude only for the past 4 million years. Prior to that time it lay well to the north, consistent with the idea of the Southern Hemisphere being more energetic than the Northern Hemisphere before the late Pliocene.

Grain and flux of aeolian dust from DSDP Site 576 in the northwest Pacific Ocean. Micrometer equivalents of the logarithmic phi-units of size are about 9.0Φ = 2 micrometers, 8.4Φ = 3 micrometers; lower phi numbers correspond to larger grains.



Jack Cook/WHOI Graphics

Hemipelagic Mud

The hemipelagic muds that may extend many hundreds to a thousand kilometers offshore are one of the last major unknowns of the several kinds of deep sea sediment. These deposits have been hard to date, but should provide an important payoff because they may contain records of climate, particularly continental runoff, in their mass accumulation rate and compositional data. Though no DSDP or ODP cruise has had this kind of deposit and the paleoclimatic record it might contain among its major objectives, combined terrigenous flux data from the several legs to the northern Indian Ocean—Legs 22 and 23, 116 and 117, and 121—allow the history of sediment delivery to that ocean from the rising Himalayas to the north to be constructed. That record shows uniformly low deposition rates before 11 or 12 million years ago, and high rates of terrigenous clastic deposition since about 9 million years ago. This is interpreted to represent rapid uplift and erosion of the Himalayas beginning in late Miocene time.

Leg 146 recovered advanced piston cores from a basin in the California borderland that is characterized by a very high deposition rate of hemipelagic sediment. Cores from these kinds of settings will play an increasingly important role as we turn our attention to climatic and environmental changes on short oceanic or societal time scales. The abrupt climatic changes found in ice cores and lake cores should also be present in the hemipelagic sediments of the marginal basins, allowing the development of a direct link between continental and oceanic climatic regimes in the sedimentary record.

Drift deposits formed from a mixture of hemipelagic mud and pelagic sediment are the result of contour-following deep-ocean currents adhering to the sides of bathymetric features, often the lower continental slope or continental rise. Their depositional history provides a record of bottom-water formation and flow that can be obtained in no other manner. Although drift deposits have been identified in the South Atlantic and South Pacific, nearly all of our information on drifts is from the North Atlantic, Legs 12, 49, 93, and 94, and 104 and 105, where such current-controlled deposition began in the early Oligocene and increased in rate in the Miocene. Leg 145 to the North Pacific showed that the thick sediment deposit along the northeast side of the Emperor Seamounts, called the Meiji Tongue, is a drift deposit similar in character and geometry to those of the North Atlantic. This recent finding in the North Pacific means that there has been bottom water flowing south out of the Bering Sea into the North Pacific since early Oligocene time. The similar response of the North Atlantic and Bering Sea to climate change in the early Oligocene provides new insight into the degree of Northern Hemisphere cooling that occurred at the same time as the onset of glaciation in the Southern Hemisphere.

Since the early days of the ocean drilling programs, an important objective has been to provide the means to decipher the record of terrigenous material in pelagic and hemipelagic sediment accumulations. The global coring operations have resulted in information essential to our understanding of continental climate and atmospheric and oceanic circulation during the Cretaceous period and Cenozoic era, information that is not present on the continents but only beneath the oceans and which can be recovered only by ocean drilling.

David K. Rea is one of those people who was not really convinced that in 1970 we knew more about the back side of the moon than the deep sea, but, after a quick reality check, he entered graduate school in oceanography and not the space program. After finishing a Ph.D. in marine geophysics and plate tectonics at Oregon State in 1974, he moved to Ann Arbor where he immediately set up a sedimentology lab and began studies of the paleoclimatic record of terrigenous, especially aeolian, and other sediments. He is now Professor of Geology and Oceanography in the Department of Geological Sciences at the University of Michigan, working on projects ranging from the climatic records preserved in the sediments of the Great Lakes to the geological history of the North Pacific as based on the results of Leg 145.

Turbidite Sedimentation

William R. Normark and David J.W. Piper

Turbidity currents are the fastest and most destructive currents in the ocean. The most powerful of them, which can carry hundreds of cubic kilometers of sediment as coarse as gravel, are commonly initiated when earthquakes or storm waves cause submarine landsliding that dislodges sediment on the slopes of continental margins. Hurricane storm surges can initiate turbidity currents from otherwise peaceful atoll and oceanic-island coral reefs. Another important turbidity-current environment lies offshore from Earth's largest rivers, where sediment-laden river water can generate turbidity currents through hyperpycnal flow in which some of the suspended sediment of the river discharge flows along the seafloor and continues downslope as a turbidity current. In addition, the rapidly deposited deltas of these rivers are prone to periodic failure and landsliding.

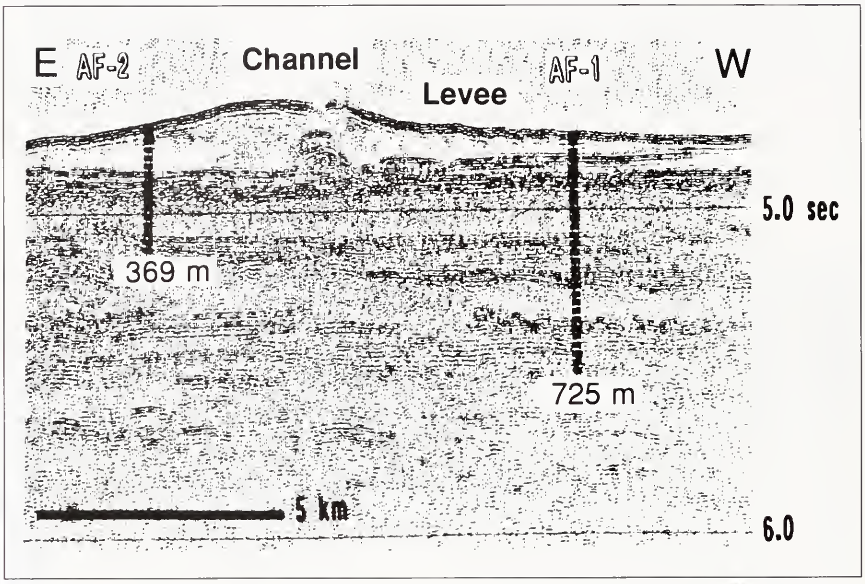
Rare, very large turbidity currents periodically deposit thick sequences of sediment on oceanic abyssal plains, but their return periods span many thousands of years. However, in some high-discharge fan deltas, several turbidity currents may occur in a single year. Turbidity currents often damage and even destroy human structures, especially submarine telecommunications cables. In fact, our best "observations" of turbidity current velocities are drawn from records of the time elapsed between progressive down-slope cutting of a series of submarine telecommunication cables as a current flows. Velocities of 10 to 20 meters per second are not uncommon. Our understanding of turbidite sediments comes principally from conventional marine-geologic sampling of near-surface sediment and three-dimensional studies of the sediment sequences using seismic-reflection profiling. Ocean drilling allows us to verify this data by sampling the sediment sequences revealed by seismic profiles.

The most fascinating attributes of turbidity currents, their high speeds and their ability to transport coarse sediment into deep water, are also those that make them difficult to study with ocean-drilling techniques. Standard HPC (hydraulic piston core) coring techniques normally

JOIDES/ODP

Photo of turbidite layer recovered during ODP Leg 146, Santa Barbara Basin, California.

used to recover the upper, softer sediment cannot penetrate the thick sand layers left by large turbidity currents. Older, deeply buried sand deposits are easily penetrated by standard rotary drilling, but the sand layers generally are not consolidated (unlike the interbedded mud layers); as a consequence, the sand outside the drill string begins to flow down the hole eventually wedging the drilling pipe in the hole and sometimes causing pipe loss.



Modified after R.D. Flood

A seismic-reflection profile from the Amazon Fan shows channel and levee turbidite elements and two of the proposed drill site objectives for Leg 155.

Many ocean-drilling scientific objectives require the recovery of continuous and uniform records of deposits for studies of biostratigraphy, past ocean environments, and subsurface geochemical processes. Turbidite deposits typically represent discontinuous or episodic sedimentation and the inclusion of many microfossils transported from shallower water. In thick sediment sequences, turbidite sands commonly comprise hydrocarbon reservoirs and thus must be avoided for safety reasons. As a consequence, many ocean-drilling legs are deliberately planned to avoid turbidite deposits.

Nevertheless, turbidite sediment deposits do provide important information on ocean history. They are the most direct record of rapid mountain-belt erosion and provide a high-resolution record of the supply of terrigenous detritus to the ocean. Turbidite sediment derived from volcanic seamounts or oceanic-carbonate platforms provides evidence of the timing of tectonic and volcanic events or faulting on the ocean floor and eruptive activity of seamounts. Predominantly muddy turbidite sediment has been drilled successfully, with high rates of sample recovery on several ocean-drilling legs, with the objective of obtaining continuous stratigraphic sections for interpreting both ocean history and tectonic history of surrounding land areas. Examples of such sections include the Weddell Abyssal Plain (Leg 113) for the glacial history of West Antarctica, the Lau Basin (Leg 135) for volcanic history of adjacent islands, and the Argo Abyssal Plain (Leg 123) for the erosional history of the adjacent continents. Leg 116 drilled the abyssal plain south of the Bengal deep-sea fan, primarily to understand the erosional history of the Himalayas and the character of oceanic-floor tectonism in the area.

In addition to revealing information on oceanic events and tectonic history of the adjacent land areas, the turbidite layers also provide information about some of the flow characteristics of the turbidity currents themselves. Because the precise source area for turbidite-sediment grains can commonly be determined, the Deep Sea Drilling Program and Ocean Drilling Program cores have shown, for example, that sediment from the Columbia River off the Pacific Northwest has been carried by turbidity currents more than 700 kilometers south, then moved west about 150 kilometers before being carried north into an axial valley of a spreading ridge (Leg 5). Turbidity currents generated by large landslides on the flanks of the Hawaiian volcanoes have traveled at least 250 kilometers seaward and moved up and over topographic barriers some 500 meters high (Leg 136).

Ocean-drilling targets selected primarily for stratigraphic or tectonic significance also provide opportunities to determine what turbidite sequences are typical of particular submarine environments. However, many of the fundamental questions concerning the processes of turbidite deposition cannot be addressed on basin floors, reached only by occasional turbidity currents. Cores from deep-sea fans that are crossed by channel/natural levee complexes offer the most continuous record of turbidite deposition and allow us to unravel the complex interplay between seabed morphology and turbidity-current processes.

Glomar Challenger's last cruise (Leg 96) drilled the Mississippi Fan, one of the largest modern turbidite deposits, with the express purpose of learning about the history and processes of deep-water sedimentation in an area where the paleoclimatic effects on sediment supply were relatively well known. The Leg 96 program confirmed extremely rapid rates of deposition on the mid fan (11 meters per thousand years at a distance of nearly 500 kilometers from the river mouth) and that large-scale landsliding also provides major contributions to deep-sea fan sequences. Core samples from the major fan-valley areas further demonstrated a marked change in sedimentation (rate and type of sediment) as sea level rose after the last glacial period.

Exposed in northern Italy, this typical turbidite sediment outcrop is a tens-of-meters-thick section of flat-lying turbidite sand and mud beds. The Santa Barbara turbidite beds may look like this in a few million years if they are exposed above sea level by tectonic activity.

The next major program for turbidite study will be in early 1994 on the Amazon Fan, which is even larger than the Mississippi Fan. The Amazon Fan exhibits a complex series of meandering channels built by basinward-flowing turbidity currents. A lobe-like deposit of sediment builds up from turbidity currents flowing through and exiting the channels. The channels periodically change course and build new lobes. The Amazon Fan leg aims to further define the sediment types and ages of deposits that have been identified by seismic-reflection profiling, and to relate this information to controls on sediment supply for turbidity currents, such as sea-level change and river discharge.

The thick turbidite sequences on the Mississippi and Bengal submarine fans and other abyssal plains drilled by the Deep Sea Drilling Program and the Ocean Drilling Program are in areas underlain by oceanic crust. The closing of ocean basins through subduction means that the ultimate fate of these turbidite sequences is to be highly fragmented and deformed in subduction zone accretionary wedges and eventually to form part of collisional orogenic belts, and become welded into the crystalline metamorphic fabric of continental crust. Indeed, many of the accretionary wedges drilled on the ocean margin contain a high proportion of turbidite deposits.

The relationship between sea-level change and turbidite deposition is one of the major objectives of the forthcoming Amazon Fan leg.

The stratigraphic record provided by ocean drilling has brought better understanding of some of the external controls on the accumulation of turbidite deposits. For example, turbidite deposits are more common when sea levels are low worldwide, particularly at mid and high latitudes, and there is a marked increase in turbidite abundance with the onset of extensive continental glaciation in the late Tertiary (during the last 5 million years). The detailed relationship between sea-level change and turbidite deposition remains unclear and is one of the major objectives of the Amazon Fan leg planned for spring 1994.

Being reared near Ocean Lake, Wyoming, is one of the more plausible excuses for Bill Normark's keen desire to go to sea whenever possible. He has been a loyal fan of deep-sea turbidite fans ever since his thesis advisor at Scripps Institution of Oceanography suggested that he choose between global marine excursions and a career in research. When he is not actively involved in the study of modern turbidites or doing his duty as Assistant Chief Geologist for the US Geological Survey, he dreams about continuing his other research interests, including the submerged parts of the Hawaiian volcanoes where humongous submarine landslides dominate the seafloor.

David Piper was educated as a traditional land geologist at Cambridge University. During his Ph.D. studies, he spent a sabbatical year at Scripps Institution of Oceanography, where he met Bill Normark, and has enjoyed working at sea ever since. His interests are in using marine geology to understand the processes involved in depositing rocks seen on land. He is a Research Scientist with the Geological Survey of Canada at Bedford Institute of Oceanography.

Shallow Carbonates Drilled by DSDP and ODP

Oceanic Benchmarks and Dipsticks for Continental Margins and Volcanic Aseismic Ridges

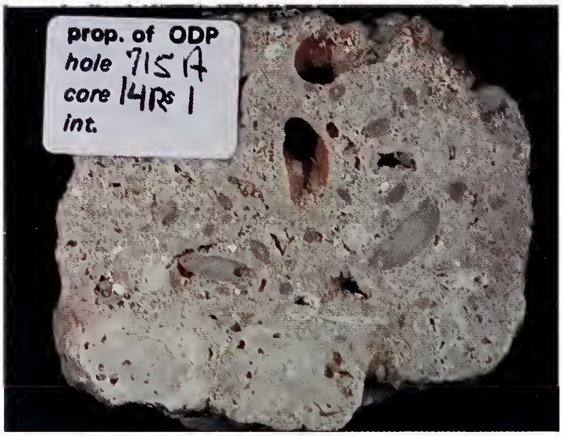
André W. Droxler

Shallow carbonates, mostly marine and biogenic in origin, originate within the ocean, instead of being transported there from land as are siliciclastic sediments. Individual carbonate-secreting fauna and flora produce shells, micro- to macroscopic in size, to protect themselves from predators and adverse physical conditions. The bulk of the carbonate production, related to benthic carbonate-secreting flora and fauna living in symbiosis with micro-algae, is limited to the upper 100 meters of the water column where sunlight penetrates. Furthermore, the optimum carbonate production is restricted to relatively warm waters (subtropical and tropical regions) within a narrow range of water depths between low-tide depth and 20 meters. These basic parameters, in addition to the general evolution of oceanic carbonate-secreting biota, have greatly influenced the development of thick carbonate platforms and shelves, usually characterized by successive phases of growth, reduction, recovery, and ultimate demise or "drowning."

Taken together, billions of individual carbonate-secreting fauna and flora produce huge volumes of carbonates, indirectly compensating for the sinking of the substratum and/or the rising of sea level and thus unconsciously attempting to remain within the light. In addition to being relatively accurate indicators or "dipsticks" of

Bottom of ODP Hole 627B, core 60X, from Leg 101 in the Bahamas. From the late Albian (abont 100 million years ago) these bioturbated skeletal dolostones with small benthic foraminifers (miliolids), shell molds (such as gastropods), and gypsum inclusions, indicate they were deposited in a shallow subtidal lagoon in a very shallow tidal to supratidal evaporitic environment (sabkas).

(left) *Recovered from Hole 812B on the Queensland Plateau, this mold of faviid scleratinian coral (presumably* Platygyra*) offers evidence for tropical shallow carbonate during the middle Miocene.*



(right) Molds of coral pieces such as this (species undetermined) were recovered from Hole 715A through drilling the far eastern edge of an early Eocene (some 50 million year old) shallow carbonate platform that was established briefly on a volcanic basement.

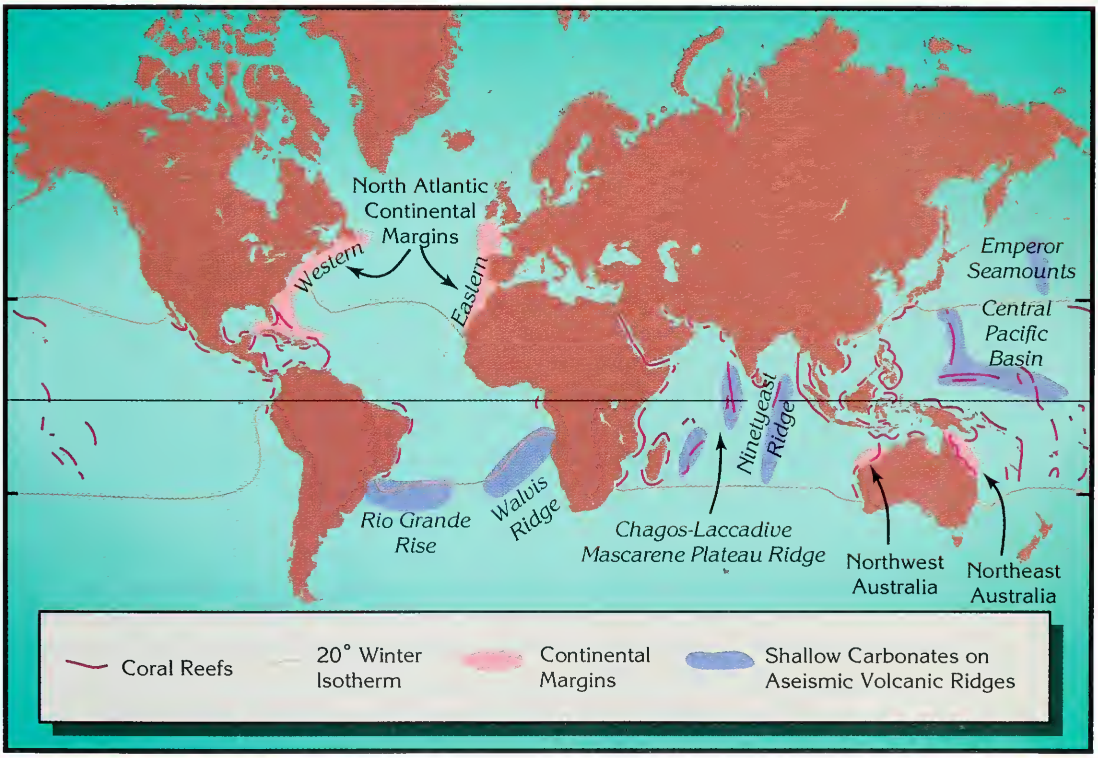
sea-level fluctuation, shallow carbonates become also excellent benchmarks for quantifying the magnitude and rate of vertical motion (subsidence and uplift) characteristic of passive continental margins and intraplate volcanic ridges in the context of plate tectonics. Finally, because of the temperature limitation of most carbonate-secreting biota, shallow carbonates are rather precise recorders of latitudinal plate movement (horizontal translation) and climatic and biochemical changes.

During the past 25 years, the ocean drilling programs have recovered numerous shallow carbonate sequences, ranging in age from the late Triassic (230 million years ago) to the Quaternary period (the last 1.6 million years), along continental passive margins and aseismic volcanic ridges in intra-oceanic basins (see map). Several ODP legs have been drilled specifically to address questions about the evolution of shallow carbonate systems. For instance, Leg 101 in the Bahamas, the ODP maiden voyage in spring 1985, was the first drilling leg fully dedicated to a single carbonate system.

Shallow Water Carbonates on Continental Margins

Triassic Development of the Northwest Australian Continental Margin. On the Wombat Plateau, Triassic (230 to 205 million year old) shallow carbonate rocks, so far the oldest sediments recovered by ocean drilling, were first deposited in association with deltaic sediments and then as shelf-lagoon limestone/marlstone and more than 200-meter-thick coral/sponge reef. The reef complex has some close similarities to the spectacular reefs of the Northern Calcareous Alps in the Dolomites that developed at the same time.

Late Jurassic/Early Cretaceous Development of the North Atlantic's Conjugate Continental Margins. In addition to dredging and seismic profiling, drilling on the Blake Plateau, in the Bahamas, and in the southeastern Gulf of Mexico, has helped to constrain the early evolution of the western North Atlantic passive margin. A Mesozoic shallow carbonate shelf or "giga-bank" at some point surrounded the Gulf of Mexico and stretched from the northern part of Cuba and the Bahamas to the Grand Banks off Newfoundland. In the southeastern Gulf of Mexico, the first shallow water limestones encountered by drilling are late Jurassic (about 140 million years old). Drilling in the Bahamas and on the edge of the Blake Plateau showed that the Mesozoic carbonate giga-bank, though segmented by several deep reentrant basins, already existed in the late Jurassic and early Cretaceous periods (approximately 125 million years ago). Drilled in several sites, this giga-bank is characterized by limestones typically deposited along a shelf edge, on tidal flats, and on very restricted platform interiors. The "drowning" of the mega-bank occurred earlier in the northern part of the Blake Plateau/ Grand Banks (in Barremian time, about 115 million years ago) than the southern part (late Albian, about 100 million years ago). On the eastern North Atlantic margin, another carbonate platform evolved from an Early Jurassic (about 190 million year old) carbonate ramp to a Middle Jurassic (some 165 million years old) platform, that is, a phase of vertical buildup followed by a phase of mostly lateral growth. Based on drilling along the Moroccan continental shelf, high energy oolitic shoals and scattered coral-sponge reefs, similar to those observed on the conjugate Scotian Shelf margin, colonized the edge of the Late Jurassic platform. The early Cretaceous demise of the Moroccan platform was constrained by sudden change in the composition of limestone turbidite beds in the deep Moroccan basin.



Jack Cook/WHOI Graphics

The main continental passive margins and aseismic volcanic ridges where shallow water carbonates have been drilled in the past 25 years by DSDP and ODP are indicated. The global distribution of modern coral reefs and the 20°C winter isotherm are also shown.

Cenozoic Development of the Northeastern Australian Margin. Recent drilling during Leg 133 on the Queensland and Marion plateaus illustrated a rather sudden transition from temperate bryozoan-rich shallow water limestones (middle Eocene to late Oligocene, approximately from 40 to 25 million years old) to tropical coral and green algae-rich shallow water limestones (early/middle Miocene, some 20 to 11 million years old). This sharp transition is better explained by an abrupt onset of the tropical surface water convergence off Northeast Australia than the steady northward drift of the Australian Plate at that time. The Miocene shallow-water carbonate systems on the Queensland and Marion plateaus, drowned during the late Miocene and early Pliocene (an interval between 10 and 3.0 million years), only partially recovered during a global lowering of sea level 2.9 million years ago when parts of the plateaus reentered the photic zone. Results from drilling offshore of the Great Barrier Reef clearly show that the largest modern barrier reef on Earth was established only very recently, possibly less than a million years ago!

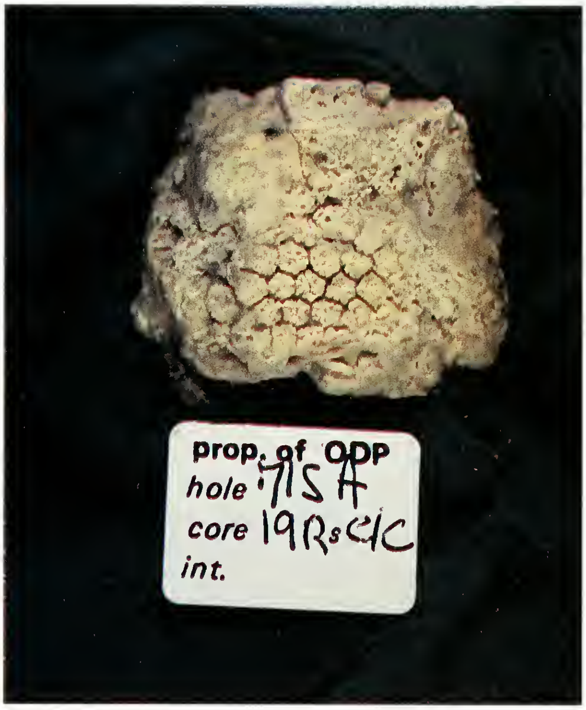
Results from drilling offshore of the Great Barrier Reef clearly show that the largest modern barrier reef on Earth was established only very recently.

Shallow-Water Carbonates on Aseismic Volcanic Ridges

Central and North Pacific Basins. Guyots (flat-topped volcanic seamounts currently at water depths exceeding 1,000 meters) within the Mid-Pacific Mountains, the Line and Marshall islands, and east of the Izu-Ogasawara-Mariana Trenches, have been visited several times during the past 25 years of ocean drilling. Recently ODP Legs 143 and 144 focused on drilling the shallow carbonate caps and the upper part of the underlying volcanic pedestals of seven guyots. The shallow carbonate systems found atop the guyots surprisingly more resemble carbonate banks than the modern Pacific atolls, which are characterized by a solid rim built of a coral-algal-reef framework surrounding a lagoon. The interiors of the shallow Cretaceous and Eocene carbonate caps range from shallow subtidal environments characterized by oolite shoals, occasionally deepening into depths of perhaps 10 to 20 meters with rudist banks, to supratidal depositional environments. Their edges consist mainly of poorly cemented bioclastic sands, deposited along beaches and shoals and interbedded with muddy lagoonal deposits. On their very edges, drilling revealed only thin constructions of abundant rudists, sponges, and some corals, implying that these organisms flourished in water depths to 30 meters below sea level; therefore, evidence is lacking for a physiographic wave resistant reef characterized by a cemented framework at sea level. (Rudists were bivalves that grew up to 1.5 meters in length. During the Cretaceous period they proliferated, then disappeared.) The irregular patterns of subsidence and the discovery of late-stage eruptive phases in some guyots make our theoretical models for thermal rejuvenation and seamount subsidence less predictable. Even though sea-level fluctuations seem to have played a role in the demise of the Pacific shallow-carbonate systems, the preferential drowning of four of the seven Pacific guyots during the mid-Cretaceous (Albian time, approximately 100 million years ago), though a relatively warm time, could have been caused by changes in ocean circulation and nutrient cycling. The Paleogene (approximately 60 million year old) shallow carbonates atop four of the seamounts along the Emperor Chain in the North Pacific Basin are rich in skeletal debris of bryozoans, echinoids, mollusks, and red algae with pervasive red algal encrustations and only rare coral. This bryozoan-algal limestone, typically deposited today between 24°N and 30°N, contrasts with the tropical coral-algal calcareous sediment characteristic of the modern Hawaiian sub littoral deposits, under which a hot spot is currently located (at 19.5°N). The latitudinal difference in sediment reinforces 7 degrees of true polar wander for the Hawaiian hot spot estimated from paleomagnetic data.

Ninetyeast Ridge and Laccadive-Chagos-Mascarene Plateau Ridge in the Indian Ocean. Shallow carbonates recovered from several sites along the Ninetyeast Ridge evolved from Campanian (approximately 80 million year old) algae and coral-rich limestones at the most northern site, Maestrichtian (about 70 million year old) shallow carbonates farther south, Paleocene (some 63 million year old) gastropods, bivalves, and echinoderms at a more southern site, and, finally, at the most southern site, a middle/upper Eocene to lower Oligocene (52 to 30 million year old) faunal assemblage. This progressive decrease in age from north to south illustrates that the ridge formed gradually as an island-seamount chain related to a hot spot. By drilling some limestones, characterized by typical shallow reef (right-hand photo on page 112) assemblages with small and age-diagnostic larger benthic foraminifers (photo above), and radiogenicly dating the volcanic basement in several sites (such as the early Eocene, about 55 million years ago, in the Maldives), the Chagos-Laccadive Ridge, along with the Mascarene Plateau, was also found to be part of the volcanic track for a hot spot located today under the island of Réunion. Contrary to the main carbonate system of the Maldives Archipelago that has been thriving from the early Eocene (55 million years ago) until today, the carbonate platform drilled during leg 115 on the far eastern edge of the archipelago rapidly sank below the photic zone after a very short life (a few hundred thousand years) toward its current depth of 2,400 meters.

Study over the past 25 years of cores from the sites described, along with many others, has brought understanding of shallow carbonate systems that could be accomplished only through ocean drilling.



Bioclastic limestones with abundant larger foraminifers (including alveolinids and nummulites), small foraminifers (miliolids), and rhodoliths (algal balls) are also characteristic of an early Eocene (some 50 million year old) shallow-carbonate platform drilled in Hole 715A on Leg 115.

First introduced to Jurassic carbonates in the Jura Mountains of Switzerland, his native country, André Droxler pursued graduate studies at the Rosenstiel School of Marine and Atmospheric Science of the University of Miami, studying the slope and basin carbonate sediments offshore of the Great Bahama Bank. He has been a Rice University faculty member for the past seven years, currently as an Associate Professor of Geology and Geophysics. His current and past research has lead him to conduct research in the Bahamas, in the Caribbean Sea on the Nicaragua Rise, and along the Belize Barrier Reef, in the Maldives (Central Indian Ocean), and on the Queensland Plateau/Great Barrier Reef (Coral Sea). In addition to spending many months at sea on more than 10 research cruises, he participated as sedimentologist on ODP Legs 101, 115, and 133, and has been involved at different levels within the JOIDES advisory panel structure.

Sea Level

Drilling for Sea-Level History on the New Jersey Transect

Gregory S. Mountain and Kenneth G. Miller

Studies focus on the global sea-level signal locked in the sedimentary record of the coastal plain, shelf, and slope.

Sediments deposited along ancient continental margins represent a significant portion of the geological record and comprise a sensitive and lengthy record of environmental change, not the least of which is a position change of the sea itself. Sea level is a complex interaction of processes that operate both locally and globally. Variations in sediment supply and adjustments to stress placed on the underlying crust are two local processes that can temporarily overwhelm global sea-level controls. For example, as the crust beneath Scandinavia continues to rebound from the weight of its last glacier, the shoreline is retreating and local sea level is falling as fast as several meters per century. Elsewhere, tide gauges detect inexorable shoreline flooding at the rate of tens of millimeters per century, and though the cause is uncertain, a strong candidate is polar ice melting.

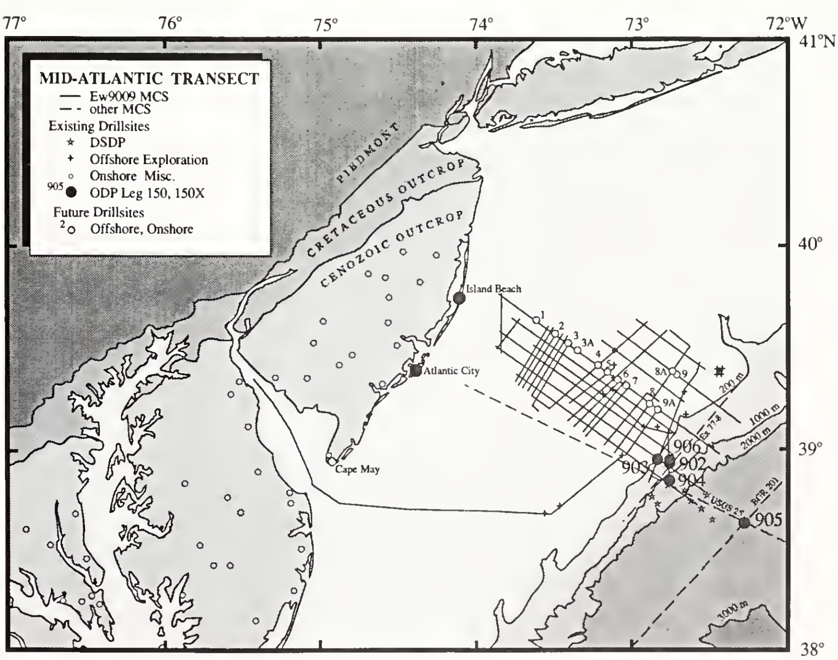
Many researchers in the academic community are striving to understand the history of sea-level change on geological time scales (10,000 to 10,000,000 years) because of its profound influence on fundamental elements of the earth system, such as: particle, chemical, and nutrient flux into the ocean; distribution and character of near-shore ecosystems; and air-sea-land interactions and their relationship to global climate. Consequently, studies are focused on extracting the global sea-level signal that is locked in the sedimentary record of the coastal plain, shelf, and slope in key regions of the world.

The industrial community has long had an interest in understanding what controls the character and distribution of sediment deposited in shallow water (less than 200 meters deep), particularly as this understanding helps to predict the occurrence of hydrocarbons. Peter Vail and his colleagues at the Exxon Production Research Company published a watershed monograph in 1977 that described how to read the history of local sea-level change in seismic reflection profiles collected along continental margins. They argued that angular relationships between reflectors are the key to identifying times of local sea-level change, and that when profiles are compared around the world, common signals emerge to form a truly global sea-level record. The work met with immediate controversy that was based, in part, on the challenging argument that the effects of local processes typically swamp the sedimentary record.

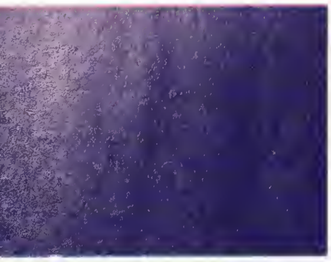
The Deep Sea Drilling Project entered into the conflict by conducting three legs in search of the imprint of sea-level changes along continental margins: Leg 80 drilled on the Irish continental slope, and Legs 93 and 95 drilled on the New Jersey slope and rise. The results of all three programs provided tantalizing support for the times of sea-level change Vail and his associates had proposed back several tens of millions of years into the past. Unfortunately, all drill cores encountered long stratigraphic gaps and were located in relatively deep water (more than 1,000 meters), where the record of sea-level change is indirect at best. The results swayed few opinions, and the "Vail curve" remained controversial.

Beginning in 1987, Exxon again revolutionized the search for a record of global sea level. This advance was achieved in part by improved technologies, and in part by improved insight into how these technologies can be integrated. A series of publications described the use of outcrops, cores, wireline logs, and seismic profiles for detailing sedimentary histories at previously unattainable spatial and temporal scales. Ironically, a continuously cored hole is rare in the oil industry, so the potential of this technique cannot always be achieved with commercial data.

The academic community soon realized that it had in *JOIDES Resolution* a unique and valuable tool to probe continental margins for evidence of sea-level changes. Continuously cored and logged boreholes are routinely collected by this vessel, though to date it has not drilled in typical continental shelf water depths. In a series of meetings between 1987 and 1991, the scientific drilling community developed the strategy



Map of the middle-Atlantic coast, showing the locations of geologic samples and seismic reflection profiles. In 1993, ODP Leg 150 (offshore) recovered 4,034 meters of cores from Sites 902 to 906, and Leg 150X (onshore) recovered 816 meters at Island Beach and Atlantic City. Cape May drilling is scheduled for early 1994. The authors hope to gain permission to complete the New Jersey Sea Level Transect by drilling most of the additional sites on the continental shelf, which are located here on a grid of multichannel seismic data collected on a 1990 R/V Maurice Ewing *cruise.*



The ages of many falling sea-level trends match the oxygen-isotopic record assumed to be a proxy indicator of glacial ice growth.

needed to address sea-level change based on transects of boreholes extending from the coastal plain to the continental slope. To build on the success of Legs 93 and 95, we proposed a transect of the New Jersey margin. The first two of three steps in this effort began in 1993: 1) during Leg 150, sponsored by the Ocean Drilling Program, four boreholes on the continental slope and one on the rise were completed; and 2) the National Science Foundation Continental Dynamics Program along with ODP funded the drilling of two boreholes on the onshore coastal plain. Step three requires drilling on the continental shelf, but has been postponed until sufficient data are collected to evaluate risks posed by the chance of encountering hydrocarbons.

Several characteristics make New Jersey an ideal margin for this transect: We know there have been few local tectonic disturbances in this well-studied region; its mid-latitude setting maximizes the chance for excellent age control built on the integration of biostratigraphy and chemical isotopic and paleomagnetic stratigraphies; and high sedimentation rates over the last 30 million years promise a record with especially high resolution. We focus on this time interval for an important reason: Oscillations in the marine-oxygen isotopic record detail a 30-million-year history of glacial ice growth and decay. This geological interval represents a starting point for a detailed study of the stratigraphic response to known changes in global sea level. Conclusions about the mixed local/global record along the New Jersey margin will be evaluated by future studies on other margins that focus on this same time interval in places where local conditions such as the age of continental rifting are different, and the global signal can be more confidently extracted.

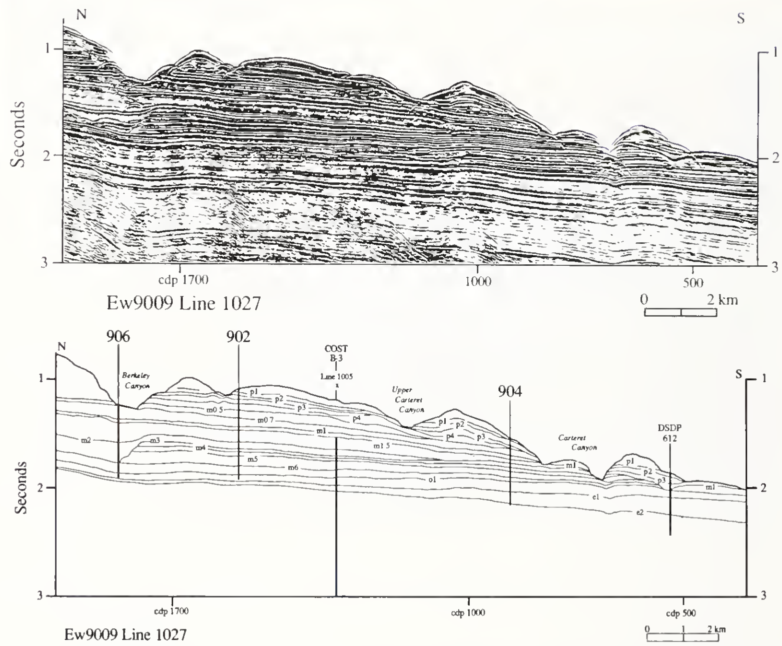
We began our study in fall 1990 by collecting a grid of seismic reflection profiles across the New Jersey margin. Based on these data and background information provided by Exxon Production Research, we laid out a transect of drill sites needed to document the age and character of discontinuities recognized in these profiles. We anticipated that the most dramatic discontinuities would have formed when local sea level fell rapidly and little sediment could be retained on the shelf. By contrast, intervals of widespread shelf deposition would indicate times of rapid sea-level rise.

We led ODP Leg 150 last summer and drilled four sites on the slope and another site several tens of kilometers out on the continental rise. Water depth at the slope sites ranges from 450 to 1,130 meters. We are able to trace over a dozen reflectors to all four sites and correlate each to the rock record. In most cases the reflectors match debris swept off the adjacent shelf; in others they match especially well-cemented intervals that developed during times of especially slow sediment accumulation. We conclude that the former occurrences mark times when local sea level fell, and the latter, times of local sea-level rise, when a wide continental shelf—not the slope—was the primary depository for sediment washed in by rivers. Preliminary analyses suggest that the ages of many falling sea-level trends that we found match the oxygen-isotopic record that is assumed to be a proxy indicator of glacial ice growth and, consequently, of global sea-level minima.

Two more holes were drilled onshore of the New Jersey shelf in 1993 to sample shallow-water (less than 200-meter) marine environments now beneath the coastal plain. Another hole is planned for 1994. The onshore boreholes recovered an excellent record of sedimentary environments that are especially sensitive to sea-level changes. With this sensitivity, however, comes a challenge: These sediments typically lack the fossils found in deep-water sediments, and biostratigraphic control is often too coarse to be useful for sea-level studies. Fortunately, we have recovered numerous shell beds that can be dated with strontium isotope techniques. As a result, we are confident that we will be able to establish time planes that tie the continental slope record to the coastal plain record.

We have thus continued a transect begun by DSDP Legs 93 and 95. We are completing the onshore drilling and integrating the results with those of the five continental slope and rise boreholes. Our most challenging work awaits us: determining that drilling can be done safely on the shelf, completing this bold effort, and integrating these results with existing data. ■

After two years of describing cores at the Woods Hole Oceanographic Institution as a Research Assistant, Greg Mountain concluded that most cores are cylindrical and full of mud. With that foundation he enrolled in graduate school in 1974 at Columbia University's Lamont-Doherty Earth Observatory; he is still there, now as a Research Scientist studying the effects of sea-level change. He has learned that one such effect—rarely mentioned—is a rising tide of planning documents, meetings, and ancillary activities that accompany such interdisciplinary efforts. When not treading in this sea of paperwork, Greg makes his home in Westwood, New Jersey, where he and his wife are raising two boys at 176 meters above sea level.



(Top) Multichannel seismic line 1027 down the continental slope offshore of New Jersey. The vertical scale is seconds of two-way travel time (1 second in sediment is approximately 950 meters), and the horizontal scales are shown. Sound generated by airguns towed at the sea surface reflects off surfaces of discontinuity in the sediments beneath the seafloor; the authors are investigating how sea-level changes contribute to generating these discontinuities. (Bottom) Line drawing interpretation of line 1027 crossing ODP Leg 150 Sites 906, 902, and 904 drilled in summer 1993. Numerous reflectors were traced across this line and throughout the grid of the seismic data. Leg 150 data allowed matching of reflectors to surfaces in the cores for age determination: p = Pleistocene, m = Miocene, o = Oligocene, and e = Eocene.

Ken Miller is a Professor at Rutgers, the State University of New Jersey, an Adjunct Scientist at Lamont-Doherty Earth Observatory, and a 1982 graduate of the MIT/WHOI Joint Program. When not teaching, going to sea, or attending meetings, he can be located somewhere on the New Jersey Turnpike, caught in traffic during one of his frequent commutes to Lamont-Doherty. Otherwise, Ken can be found at the Jersey shore, keeping a diligent watch on the inexorable rise in sea level from the deck of his house at 4 meters above sea level.

Spinoffs for Oil Exploration

ODP Leg 122 off Northwest Australia

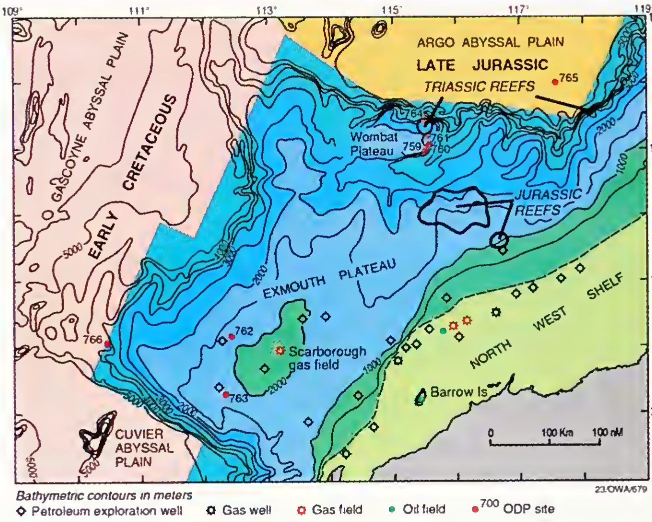
Neville F. Exon

ODP cores revealed when the Tethys Ocean lapped a united Gondwana continent as a shallow sea in Triassic and Jurassic times.

I first heard of the Exmouth Plateau in 1974 when, as a geologist at the Australian Bureau of Mineral Resources, I was transferred to a geophysical group that was studying the plateau's geology and petroleum prospects for the first time. This work was being done as part of the large-scale Continental Margins Survey: 222,000 kilometers of continuous geophysical profiles recorded at 4-kilometer intervals around Australia, from close inshore to the abyssal plain—a survey far ahead of its time in scope and imagination. The Exmouth Plateau is a deep-water extension of the Australian continent northwestward under the Indian Ocean. With a total area of about 263,559 square kilometers, it is almost half the size of Texas. Much of the plateau is in water shallower than 2,000 meters, but it is surrounded on three sides by abyssal plains more than 4,500 meters deep.

We studied 18,000 kilometers of seismic-reflection profiles recorded by the Bureau of Mineral Resources, Gulf Oil, and Shell Oil (which provided cross sections through Earth's crust as deep as 15 kilometers) and any other relevant geophysical and geological information we could lay our hands on. The result was a positive assessment of petroleum prospects that was published in several different forms, including in the widely read *Bulletin of the American Association of Petroleum Geologists*. The area's main attraction was huge buried fault blocks of Triassic deltaic sediments, similar to those of the giant North Rankin gas field, east of the plateau. We had reason to speculate that more valuable oil, rather than gas, might be trapped in these fault blocks. A secondary attraction was the overlying early Cretaceous Barrow delta, the reservoir of a giant oil field at Barrow Island, southeast of the plateau. When five large lease areas were made available, they were taken by consortia of exploration companies, including several of the world's largest.

In 1977 to 1980, an unprecedented deep-water petroleum exploration program commenced with detailed seismic reflection surveys, and ended with the drilling of 11 wells on the plateau in water as deep as 1,354 meters. The deepest well, Phillips Saturn No. 1, was 4,000 meters deep and was drilled in water 1,177 meters deep. At that time there was much excitement around the world about deep-water oil potential, and huge, dynamically positioned drill ships were being built especially for exploring it. No oil fields had ever been found or exploited in the prevailing water depths of 800 to 2,000 meters, but the consortia assured us that new exploitation technology could be developed if large fields were discovered. The total exploration cost was about $150 million (US), and the result was the discovery of the giant Scarborough Gas Field in the Barrow delta (which is still not developed) and whiffs of gas and oil elsewhere.



Although the results of this round of exploration were disappointing, we still believed the plateau had oil potential and we set out to gather new information for another assessment. For this we needed a geoscience research vessel. Fortunately the German Bundesanstalt für Geowissenschaften und Rohstoffe was studying passive continental margins like Australia's, and in 1979 their R/V *Sonne* came to the virtually unexplored northern Exmouth Plateau for a joint survey. The *Sonne* dredging and coring program returned tons of rocks, including potential oil source and reservoir rocks. Since then our own R/V *Rig Seismic* has carried out three more geoscience cruises over the plateau, providing more data and a better understanding of the plateau's origin and evolution.

Location of ODP drill sites. Leg 122 Sites 759-764 were drilled on the Exmouth Plateau and Leg 123 Sites 765 and 766 were in deeper water nearby. Triassic and Jurassic reefs grew in the Tethys Ocean, and were discovered for the first time in Australia as a result of the ODP work. The abyssal plains formed later as the supercontinent Gondwana broke up in two stages, in the late Jurassic and early Cretaceous (160 and 130 million years ago).

In 1985, Ulrich von Rad (Bundesanstalt für Geowissenschaften und Rohstoffe) and I realized the vital role that deep drill holes with continuous core could play in understanding the plateau's geology and the Mesozoic Tethys Ocean's history. This ocean lapped over the region before the plateau came into existence as a topographic feature. It was a warm ocean, extending many thousands of kilometers east and west, flanked by broad shelf seas where thick limestones were laid down. Many of the limestones that extend from southeast Asia to the Pyrenees are Tethyan rocks, and the most valuable of them host the oil of the Middle East. We marshalled all our information and submitted a proposal to the Ocean Drilling Program.

In 1988, ODP Legs 122 and 123 were drilled on and near the plateau. Vital new information gleaned from the resulting cores revealed more about the region's history:

- when Tethys lapped a united Gondwana continent as a shallow sea in Triassic and Jurassic times,
- when a small part of Gondwana broke away to the north in the late Jurassic and the Argo abyssal plain formed from upwelling basalt

behind the departing fragment,

- when west Gondwana broke away and moved westward in the early Cretaceous, leaving the basalts of the Gascoyne and Cuvier abyssal plains behind, and
- when the plateau subsided to its present depth and moved steadily northward with Australia in Cretaceous and Cenozoic times.

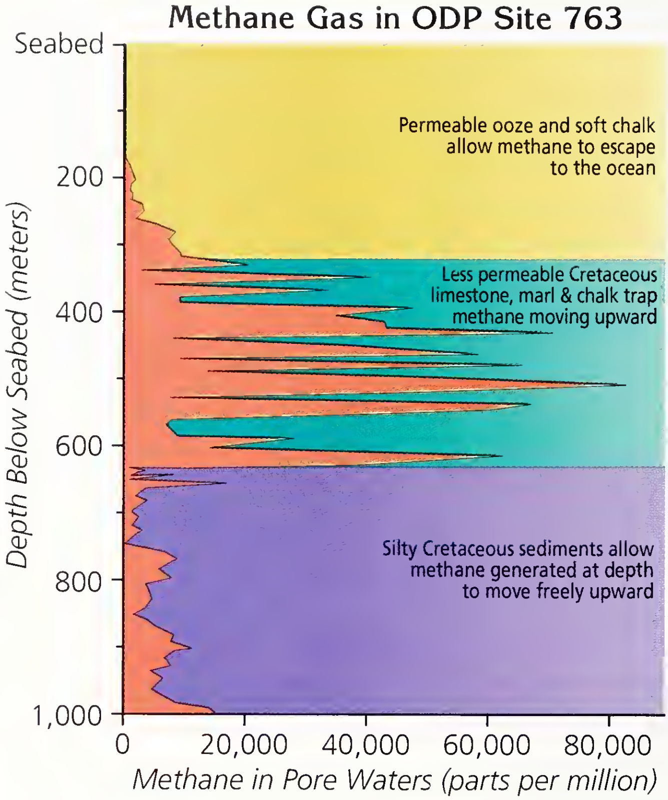
ODP was concerned about the danger of striking gas during Leg 122, especially in the Cretaceous strata of the central plateau, because the drill ship *JOIDES Resolution* (which, coincidentally, had once drilled for oil on the plateau before it was converted to a research vessel) had been modified to simplify deep water drilling in a way that prevented it from controlling a gas "blowout" at the sea bed. So the exploration geologists on the ODP Safety Panel turned their minds to the novel problem of *not* finding large accumulations of gas. They decided that the safest procedure would be to drill near existing exploration wells where gas had been monitored continually and had been shown to be incapable of blowing out. (As these wells were not cored at our levels of interest, there was little duplication of effort.) While the ODP holes were drilled, gas was continuously monitored by geochemists and a petroleum geologist; any unexpected rise in core gas content would lead to that hole being plugged with concrete and abandoned. One hole was, in fact, terminated 50 meters above its planned depth. Abundant gas is constantly being generated at depth and trapped beneath impermeable limestones. Although the concentrations we measured could not cause a blowout, they were high enough for gas to stream from the cores at surface air pressure, bulging the plastic core liners and dislodging their end caps. Geochemical studies revealed that the gas was not generated in

Strata Drilled on ODP Leg 122

Stratigraphic Age	Absolute Age (million years)	Maximum Thickness (meters)	Sediments Deposited
Cenozoic	0 to 65	550	Deep water limestone, chalk, and ooze
Cretaceous	65 to 140	850	Shallow marine mudstone and limestone deposited as the continental margin sank
Late Jurassic	140 to 160	none	Shallow marine mudstone deposited after continental break up and during initial subsidence
Early & Middle Jurassic	160 to 205	none	Shallow marine limestone and coal measures deposited in rift valleys before continental break up
Late Triassic	205 to 230	700	Deltaic sediment and shallow water limestone deposited during rifting before continental breakup

Cretaceous strata, but probably in the Triassic sediments.

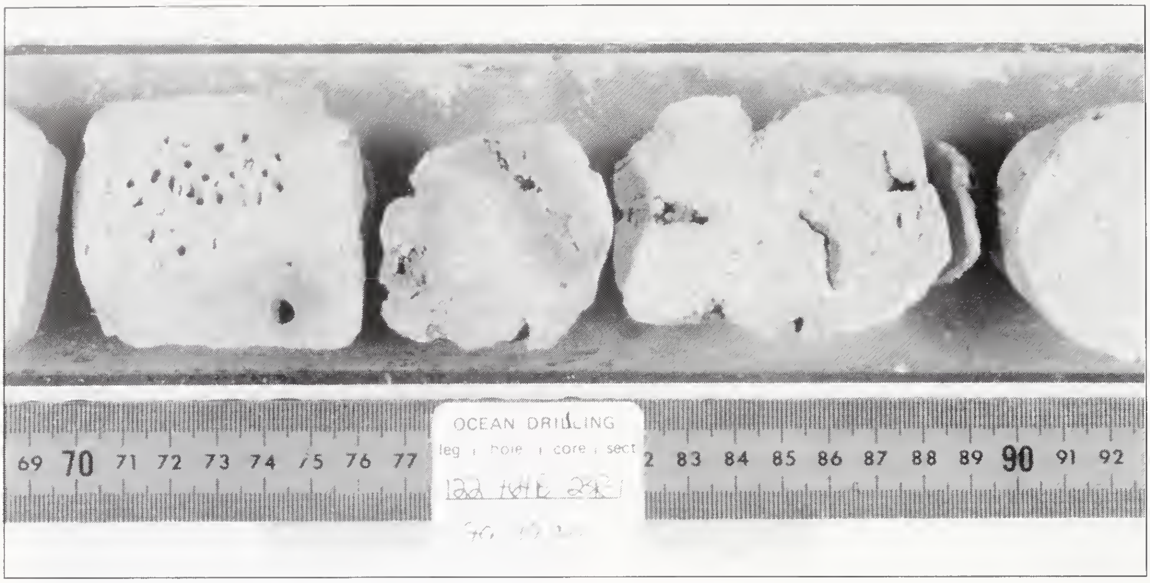
Like all good scientific work, the ODP drilling had its surprises. The greatest of these was the coring of several hundred meters of late Triassic limestones containing reefs very similar to those in the Alps, above deltaic Triassic sediments on the northernmost part of the plateau, nearly 3,000 meters below sea level. Such deltaic sediments provide the main petroleum reservoirs of the Northwest Shelf, now a major producer of both gas and oil. Late Triassic and early Jurassic limestones were known from the Exmouth Plateau and some other areas on the outer Northwest Shelf, but these were the first reefs of this age ever found in Australia. This was of considerable scientific interest, but also of commercial interest because limestones provide more than half the world's oil. The reasons for this are many and complicated, but two are significant: Certain lagoonal sediments are rich in organic matter that is capable of producing oil when it is deeply buried and thermally "cracked," and many buried reef complexes contain highly porous beds that are excellent oil reservoirs. We publicized the results in oil industry journals to encourage exploration companies to take another look at their seismic sections, in case potential reefs have not been seen because of the mind-set "they don't occur in Australia."



Gas was routinely extracted from rock core and then analyzed aboard JOIDES Resolution. *On the central Exmouth Plateau, abundant gas was known to be present, and it was monitored closely to ensure that levels did not become high enough to cause a "blowout" at the hole. The plot shows the variation of methane, the most abundant gas, with depth at Site 763. Gas generated at depth migrates upward through the strata, accumulating beneath impermeable beds. Its chemistry shows that it formed below the Cretaceous sequence, probably in Triassic deltaic rocks.*

Jayne Doucette/WHOI Graphics

Furthermore, we at the Bureau of Mineral Resources decided to do what we could to help companies in their assessments. First we defined the seismic character of the newly discovered reefs, and then we took a new look at existing seismic profiles farther inshore. To our great pleasure, we discovered several very large bodies that looked like Jurassic (not Triassic) reef complexes sitting on uplifted fault blocks, in water depths as shallow as 1,000 meters (therefore, economically feasible to drill). Although most of the bodies were deeply buried beneath younger sediments, one rose above the seabed and was dredged. The rocks recovered proved to be identical to Early Jurassic limestones from the Alps, where they occur as mounds formed by calcareous organisms. We also recorded new seismic profiles linking exploration wells (with their



Porous late Triassic limestones, like these from a core taken 250 meters below the seabed at Site 764, prove that reefs existed here in the warm waters of the southern Tethys Ocean. Some of the pores have formed where coral branches have weathered out. Such reefs are now potential targets for oil drilling further inshore.

known geology) to the lower continental slope, not only of the plateau but also farther northeast in the Canning Basin. We then dredged the continental slope along the profiles and recovered late Triassic reef limestones in two areas of the Canning Basin, providing hard evidence that fossil reefs are indeed widespread.

Only time, and the economics of exploration, will tell whether oil exists in Mesozoic reefs on the Northwest Shelf. However, ODP drilling that was originally performed for purely scientific purposes has presented us with new, potentially valuable information for the petroleum exploration industry, and ultimately for Australia as well.

Neville Exon is a Senior Principal Research Scientist at the Australian Geological Survey Organisation (AGSO, formerly the Bureau of Mineral Resources) who started his career in regional geological mapping of onshore sedimentary basins. After seven enjoyable years he decided to study recent marine sedimentation in the epicontinental Baltic Sea, a modern analogue for the marine Cretaceous sequences of the Australian Great Artesian Basin, and went off to Kiel University in Germany to earn a Ph.D. Since then he has worked largely in studies of offshore sedimentary basins around Australia, but did have a spell in the South Pacific as a United Nations marine geologist based in Fiji, which led to an ongoing interest in deep sea manganese nodules. He has thoroughly enjoyed his association with ODP—planning, participating in, and writing up the results of the Exmouth Plateau drilling. He publishes this article with the permission of the Director of AGSO.

Technology Developments in Scientific Ocean Drilling

Barry W. Harding

Engineering technology and drilling operations advancements have been preeminent since the Ocean Drilling Program (ODP) began in 1984. Engineering and drilling challenges identified at COSOD I (Conference on Scientific Ocean Drilling) in 1981 and met in the first two years of operation include carbonate reefal sequencing (Bahamas, Leg 101), high-latitude drilling (Baffin Bay, Leg 105), ridge-crest drilling (Mid-Atlantic Ridge, Leg 106), and accretionary prism sequencing (Barbados Transect, Leg 110). In addition to converting an oil/gas industry drillship and outfitting it for scientific coring, the Ocean Drilling Program's Engineering and Operations team began in 1984 to plan for the difficult and wide range of lithologies and conditions to be encountered.

Planning how to best drill a hole on an unsedimented ridge crest of the Mid-Atlantic Ridge was ODP's first major technical challenge.

Diamond Coring System (DCS)

Planning how to best drill a hole on an unsedimented ridge crest of the Mid-Atlantic Ridge was ODP's first major technical challenge; known rock-drilling techniques required 50 to 100 meters of sediment for drill-string stabilization before rock could be cored. Completely new systems were required, and industry contracts were awarded for the design and development of:

- a hard-rock guide-base system (including deployment on the seafloor),
- a real-time subsea TV system for reentry operations,
- positive displacement coring motors,
- a cementing system for both guidebase anchoring and hole stabilization, and
- improved roller-cone drill bit design for basement lithologies.

While ODP's results from coring unsedimented ridge crests have not been totally successful, they are, however, encouraging. With each successive leg dedicated to either ridge-crest or crystalline rock drilling, ODP has gained better understanding of the problems posed by bare rock and fractured formations. The results from Legs 106, 109, 118, and

Major ODP Development Engineering Projects

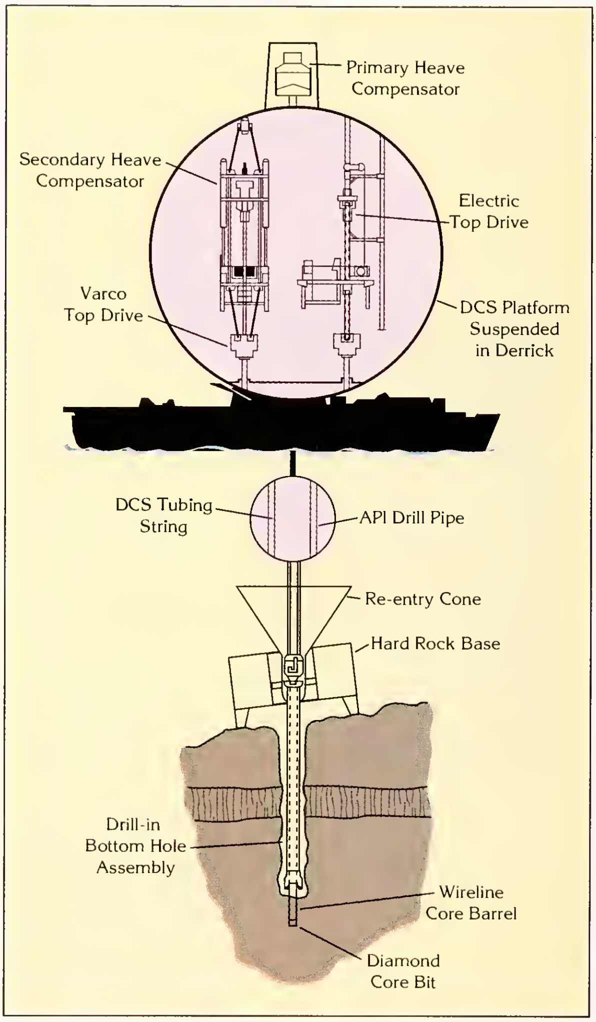
Project	Initiated	Current Status
XCB: Extended core barrel system	DSDP	Operational for ODP since Leg 101
• Incorporated first venturi vent system (v.108)	11/85	Did not pass sea trials during Leg 108; alterations made to later XCB versions
• Added improved cutting shoes (v.121)	1/88	Successful upgrade modified to v.124E
• Improved cutting shoe flow (v.124E)	8/88	Operational XCB through Leg 101
• Extended core-barrel flow control system (XCB/FC)	4/91	Prototype versions tested; results inconclusive; further testing planned
APC: Advanced piston corer system	DSDP	Operational for ODP since Leg 101
• Minor upgrades over DSDP models (v.101)	4/84	Used successfully for Legs 101 to 103
• General design overhaul (v.129)	1/90	Upgraded versions used for Legs 129 to 149
• Modification of v.129 (v.150)	1/93	Successfully introduced for Leg 150
DIC: Drill-in casing system	DSDP	Used several times since, with success
Core bit development roller cone, PDC, hybrid	DSDP	Continuous development and testing
Hard rock spud systems (for Legs 106, 109, and 118)	3/84	Successfully used for assigned legs, then made obsolete in favor of mini guidebases
APC core orientation system	5/84	Used and upgraded since Leg 101
Colmek underwater TV system	6/84	Used since Leg 106
NCB: "Navidrill" core barrel	6/84	Tested until Leg 124E, then made obsolete
Reentry cone redesign	10/84	Continuous ODP upgrade since Leg 106
VIT: TV vibration isolation frame	2/85	In use with upgrades since Leg 106
PDCM: Positive displacement coring motor	2/85	Developed and used for Legs 106, 109, and 118; still operational
LFV: Lockable flapper float valve	3/86	Developed and used since Leg 113
Line cutter/crimper (Kinley)	11/86	Developed and used since Leg 113
PCS: Pressure core sampler	7/87	Developed and operational
VPC: Vibro-corer	4/88	Initial design failed; under redevelopment
CSES: Conical side entry sub	4/89	Developed and used since Leg 133
HRO: Hard rock orientation system	6/89	Overall system still unproven
Mini-HRB: Hard rock guide bases	8/89	Successfully deployed on four legs
CORK: Reentry cone plug and instrument feedthrough	10/89	Successfully developed and tested; four installations emplaced to date
Commandable-retrievable beacons	10/90	Developed and used since Leg 138

DSDP (Deep Sea Drilling Project) ▲ ODP (Ocean Drilling Program)

147, together with advice from the mining drilling industry, led ODP to develop a slimhole high-speed coring system, named the Diamond Coring System or "DCS."

The DCS prototype (demonstrated on Leg 124E in 1989, offshore of the Philippines) had a tubing length limited to 2,000 meters, while the DCS currently under development will have 4,500 meters of total tubing length. The DCS encompasses several primary subsystems: a tubing/drill-rod string for offshore deep water slimhole drilling and coring operations; special slimhole (less than 15 centimeters outside diameter) diamond core bits to function in a variety of operating environments; a modified wireline retrievable core barrel, modeled after a mining-style design; an electric top drive, secondary compensation system, mud-pump controls, hydraulic power unit, and other ancillary support functions; and a specially designed, tapered stress joint, for modulating American Petroleum Institute drill-string bending stress at the hard-rock base.

The DCS system is expected to solve several high-priority objectives identified in 1987 by COSOD II working groups, especially for deeper drilling in difficult lithologies. In the last five years the oil and gas industry has begun using slimhole technology and rigs in their exploratory drilling. Because of the technological progress amid environmental and budget constraints in the oil field, slimhole drilling has been pushed to the forefront. Slimhole drilling is advantageous both economically and environmentally: It costs less per foot to drill as it requires a smaller rig, and less area is cleared for the drill site, which translates to less clean-up once drilling is complete. A combined industry project entitled DEA-67 (Drilling Engineering Association, study number 67), which has 55 industry participants and nearly $2 million in funding, is under way to study the drilling and equipment-related problems of slimhole drilling. ODP is part of the DEA-67 study.



Jack Cook/WHOI Graphics

The Diamond Coring System (DCS) is a slimhole high-speed coring system. The original system had a tubing length of 2,000 meters. A new system (now being developed) will go to 4,500 meters.

Coring Tool Development

In the 23-plus years of ocean drilling operations, the DSDP/ODP development engineering groups have initiated a total of 65 projects, ranging from minor tool upgrades to entire coring system development. Currently 48 projects have been successfully completed, 10 projects are under development, and 7 have been dropped or were unsuccessful.

The table on page 126 lists the higher profile coring-tool development projects to date and their current status. During the 15 years of DSDP, *Glomar Challenger* drilled 1,092 holes at 624 sites worldwide, and recovered 96 kilometers of core. The first 50 legs of ODP operation have resulted in 719 holes at 293 sites, and 83.3 kilometers of recovered core.

Because the geological challenges presented at COSOD I and II and in the ODP Long Range Plan (1990) have become increasingly difficult, technology developments for scientific ocean drilling are critical. For example, geological challenges presented at COSOD II include drilling hot-spot traces and fractured oceanic crust to study plate motion through time, and drilling crustal holes 5,000 meters below the seafloor to define crustal compostion. The Long Range Plan purposely divided the scientific goals into three phases, with Phase I requiring more near-term technologies (such as drilling very deep sites in both igneous rocks and unconsolidated sediments, and overall improved sample recovery) and progressing from there.

To develop economically viable technology with low-risk methods, the oil and gas offshore industry has initiated cost-sharing consortia to drill and obtain hydrocarbons from deep water tracts. ODP has always looked at ways to adapt or modify existing technologies before initiating development of any tool or system. In addition to numerous subcontractors and industry consultants, ODP receives technical advice and assistance from many companies and corporations within the oil and gas, mining, geothermal, and scientific drilling industries, both in the US and abroad. The ambitious scientific goals stated in the Long Range Plan can be achieved, but only with the proper commitments of funding and manpower, and the reservation of ship time for the development process.

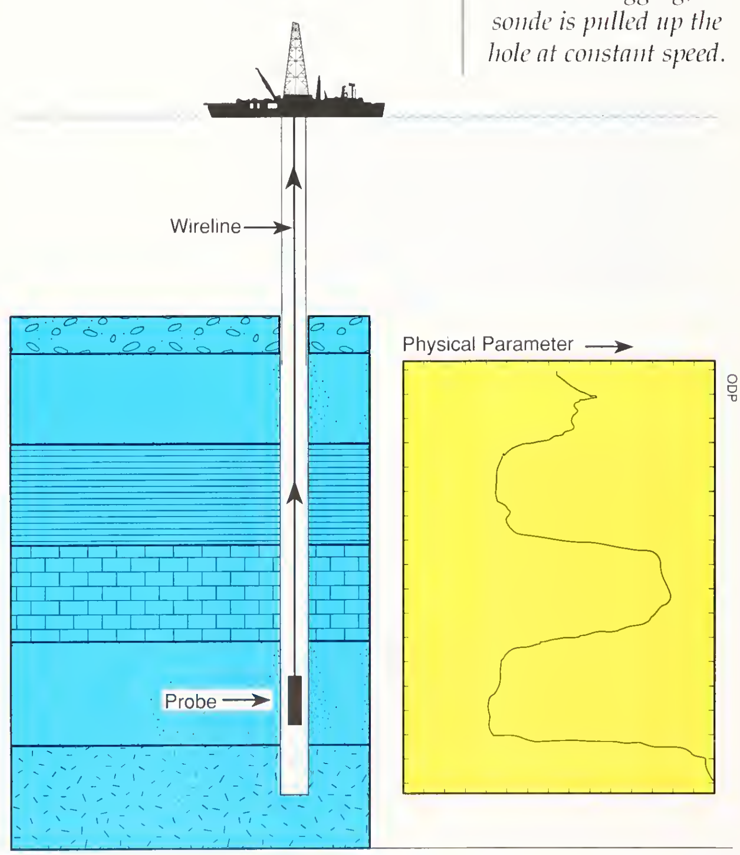
Barry W. Harding has been the ODP Manager of Development Engineering and Drilling Operations, based at Texas A&M University, for eight years. As an engineer who has never been averse to taking risks, he started a land-drilling company partnership in early 1981, after 13 years of experience in the offshore drilling industry. The diverse and challenging work at ODP aside, he found time in 1992 to pursue his original dream—attending a "Major League Fantasy Baseball Camp."

Borehole Measurements Beneath the Seafloor

Paul F. Worthington

When a scientific borehole is drilled beneath the seafloor, there is an opportunity to measure rock properties in an environment that would otherwise have remained totally inaccessible to us. Although physicochemical rock properties of recovered cores have been measured routinely in shipboard laboratories, it is desirable for several reasons to complement these data with measurements in the borehole, which constitutes a natural laboratory. First, core recovery can be erratic, leaving substantial sections of the borehole column unsampled, especially in hard sediments and basement rocks, which fragment easily and are too hard for piston-coring. Second, core measurements are usually made at surface conditions, whereas borehole measurements are necessarily made at in situ conditions of temperature and pressure, thereby leading to a more realistic database of physicochemical rock properties. Third, downhole measurements are usually made at a scale that is many times greater than the core scale, and this attribute provides an important linkage between laboratory studies and surface geophysical surveys.

In borehole logging, the sonde is pulled up the hole at constant speed.



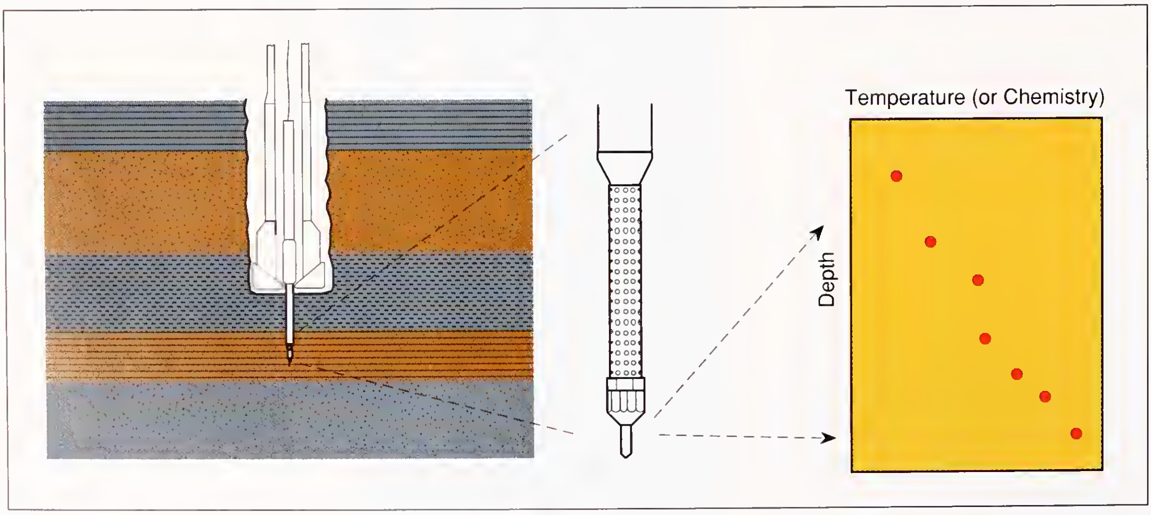
The Nature of Downhole Measurements

Downhole measurements used in scientific ocean drilling programs can be grouped into three categories. The most common are wireline logs, spatially continuous records of the physical and chemical properties of the formations penetrated by a borehole. The wireline is a cable that extends from a ship down to a probe or sonde in the borehole; it comprises one or more conductors that allow real-time communication between the probe and the surface. Logs or depth records are made as the probe is pulled up the length of the hole at constant speed to provide continuous measurements of the surrounding formation. Some tools are lowered on a mechanical line, or slickline, that provides no digital communication with the surface: These are known as memory tools, and they are deployed where cable specifications would be inadequate, for example, in very hot holes where temperatures are greater than 400°C. Logging tools are available for measuring a wide range of formation properties, including electrical resistivity (laterologs and induction logs), sonic velocity, natural radioactivity (gamma-ray log), porosity (neutron log), density, susceptibility, magnetic field orientation and strength, and temperature. The primary sources of tool technology have been the oil-field well-logging service companies, which have provided and run the majority of drilling program logging tools on a contractual basis.

The second category of downhole tools includes formation testers and fluid samplers, which provide spatially discrete data. These tools are designed to respond to formation-behavior-induced mechanical disturbance, such as an applied stress or a pressure drawdown in the wellbore. They can be deployed on a wireline, a slickline, or as part of the drill string. Primary objectives of such tools are the in situ measurement of dynamic parameters such as permeability, temperature, and pressure; determination of stress distributions; and the acquisition of pristine pore-fluid samples.

The third type of downhole tool is a long-term sensor placed in a drill hole to record natural data over a period of time. In this case, the borehole is used not as a laboratory but rather as an observatory. Sensors can be designed to record variations in local microseismic activity or in

Downhole probes sample fluids and measure temperature and pressure ahead of the drill bit: ODP has developed a probe capable of measuring up to 200°C.

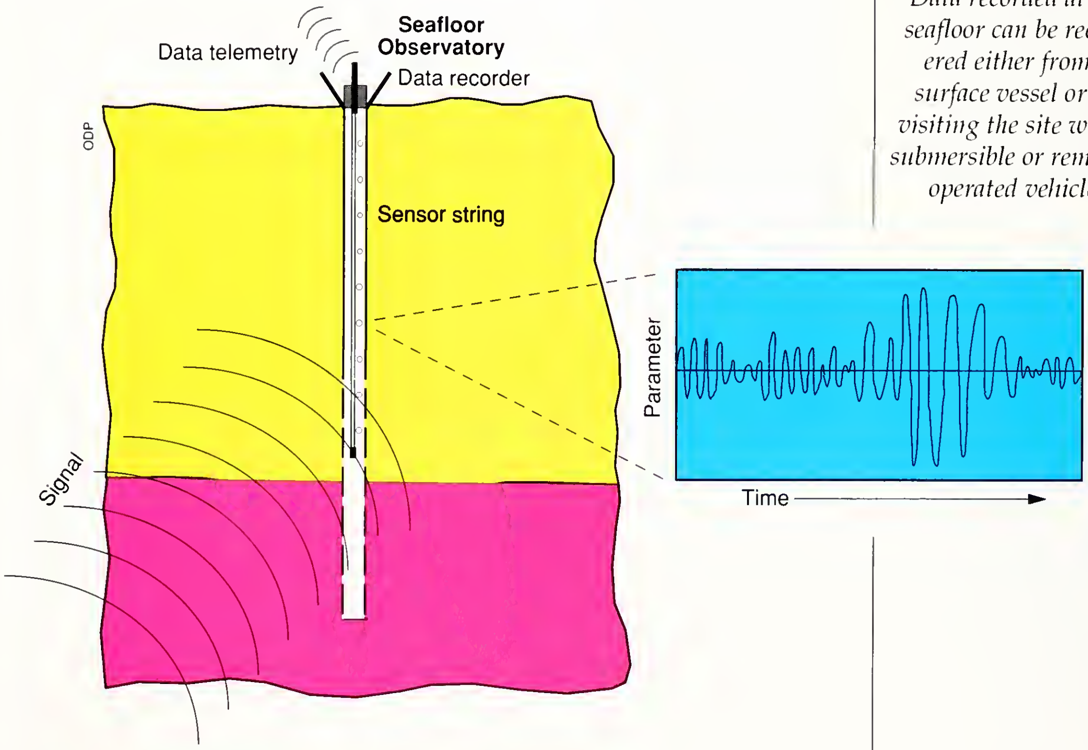


ODP

fluid properties such as temperature, pressure, or chemistry. In some cases, the long-term measurement of fluid properties requires that the borehole observatory be sealed to prevent direct flow between the deeper pore fluids and the sea above.

The History of Downhole Measurements in Scientific Ocean Drilling

Although logs had been run in offshore wells in established petroleum sedimentary provinces such as the Gulf of Mexico for many years, the deep water sites and basement rocks encountered by the scientific drilling programs presented new operational and technological challenges that once again made borehole measurements a pioneering venture. The first DSDP borehole logs were run northwest of Bermuda in September 1968. These used natural gamma-ray and neutron-porosity tools run in the drill pipe. From this point the use of borehole logs increased erratically, drawing eventually on most of the branches of classical physics, but there were extended periods when no logs were run at all. Two basic open-hole tool suites gradually emerged. These can



A downhole observatory beneath the sea. Data recorded at the seafloor can be recovered either from a surface vessel or by visiting the site with a submersible or remotely operated vehicle.

be described retrospectively as a seismic-stratigraphic tool suite (to make resistivity, sonic, and gamma-ray measurements) and a lithology-porosity tool suite (for density, neutron porosity, and gamma-ray measurements). The gamma-ray log is run with all tool combinations to facilitate reconciliation of depth scales between logging runs.

When DSDP was succeeded by ODP in 1985, the logging program became more formalized. The standard logging suite encompassed the seismic-stratigraphic and lithology-porosity tool sets from DSDP days, but also took advantage of subsequent developments in tool technology by oil-field service companies. A geochemical tool set was added to provide the elemental concentrations of formations surrounding a borehole. In 1988 the formation microscanner was added to the standard suite. This is a high-spatial-resolution microresistivity tool that provides an electrical image of the borehole wall. The formation microscanner allows matching of cores and logs in terms of both depth and orientation.

In addition to the standard tools, several other oil-field tools have been deployed from time to time. These essentially comprise in-hole seismic tools for vertical seismic profiling, a borehole televiewer for obtaining an acoustic image of the borehole wall (analogous to the formation microscanner), and, more recently, a susceptibility/magnetometer tool for resolving magnetic reversals in sediments, which are weakly magnetized compared to basement rocks. All of these are examples of technology originally developed for oil-field applications. However, several downhole tools have been built by scientists in the DSDP/ODP community specifically for scientific use. They include an ultra-deep-sensing resistivity tool for hydrogeological studies of rock porosity; a high-resolution temperature tool for heat-flow studies; a probe tool for taking water samples and measuring temperature and pressure in sediments ahead of the drill bit; and a thermistor string for long-term deployment in a borehole observatory.

ODP

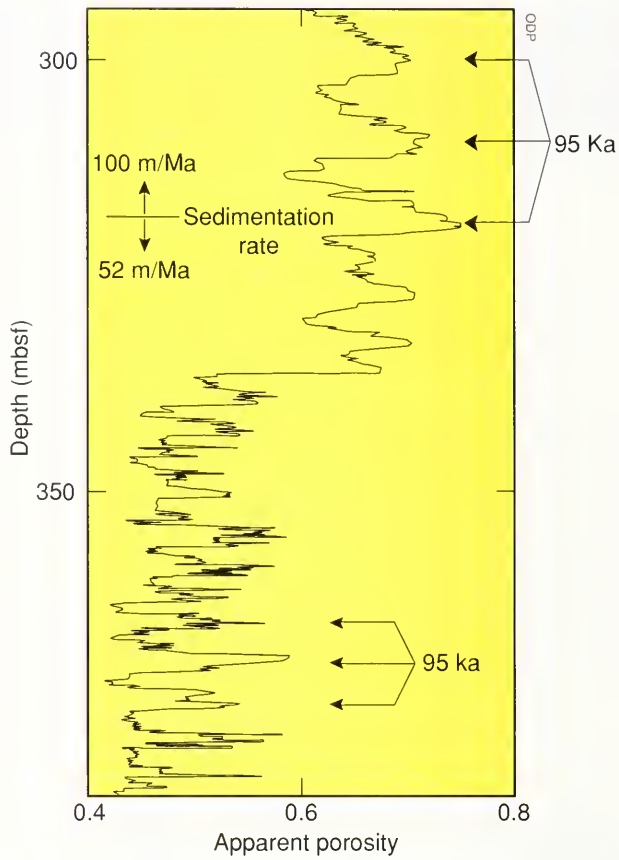
Downhole Measurement \ Principal Applications	Economic Geology	Geochemistry	Geothermics	Hydrogeology	Paleoclimatology	Petrology/Sedimentology	Seismology	Stratigraphy	Structural Geology	Tectonics
Stress probing									●	●
Acoustic imaging						●			●	●
Electrical imaging					●	●			●	●
Acoustic waveform					●	●	●	●	●	
Natural acoustic energy							●		●	
Spectral density					●	●		●	●	
Electrical resistivity				●	●	●		●	●	
Neutron porosity				●	●	●		●		
Temperature			●	●						
Fluid pressure			●	●						
Fluid sampling		●		●						
Natural radioactivity	●	●			●	●		●		
Geochemical	●	●			●	●		●		
Susceptibility					●	●		●		
Magnetization								●		

The contributions of downhole measurements to classical geological subdisciplines.

Scientific Applications of Downhole Measurements

Downhole measurements have made a major contribution to all the principal scientific themes of DSDP and ODP. The first key area is that of global environmental change. Logs are especially well suited to addressing these problems because the solutions require a continuous depth record so that cyclic variations in sediment composition and texture can be evaluated in terms of paleoclimate and ocean circulation. The second area is crustal composition and structure, which must be known in order to understand the origin and evolution of oceanic lithosphere. For example, the sharper spatial resolution of logs relative to surface seismic data has led to a better understanding of the acoustic characteristics of different layers of Earth's crust. The third area is hydrogeology, with all its implications for the global geochemical budget. The two key parameters are porosity and permeability. Porosity can be evaluated from density, neutron, sonic and (in the absence of hydrocarbons) resistivity logs. Permeability is determined from downhole pressure tests over an interval of the borehole that has been isolated using packers or seals. The fourth key area is the global stress regime. Our understanding of the forces that drive tectonic plates and determine their motions can be advanced through knowledge of in situ stresses. Stress orientations can be inferred from failures of the borehole wall, known as "breakouts," which can be imaged using the borehole televiewer or formation microscanner. Changes in stress orientation can be depicted with depth or mapped regionally.

Scientific borehole logging is entering a new era. It is no longer sufficient to rely on oil-field technology to meet ODP logging needs. A major ODP objective is to drill in the young brittle crust near spreading centers. This will require high-temperature tools that are less than 5 centimeters in diameter and rated to 400°C. Since these specifications exceed the capabilities of commercial logging tools, ODP will have to develop its own tools, possibly in conjunction with other scientific programs in order to share the considerable engineering costs. At present, resistivity, temperature, and fluid sampling tools are being developed for high-temperature slimhole deployment. In this respect, scientific borehole logging is at a watershed. The scientific community is responding to the technical challenges positively so that the downhole measurements of the future will constitute as effective a scientific legacy as their present counterparts.



Porosity logs from ODP Site 646 in the Labrador Sea show cyclic properties that can be attributed to astronomically governed climatic variations. The spacing of peaks is related to the post-compaction sedimentation rate, which changes from 52 to 100 meters per million years at 335 meters below the seafloor.

Paul F. Worthington served as Chairman of the ODP Downhole Measurements Panel from 1987 to 1992. He is an environmental and resource evaluation consultant, based in Ascot, Great Britain, and a visiting research professor at the Lamont-Doherty Earth Observatory of Columbia University.

Book Reviews

Polar Day Nine

By Kyle Donner, 1993. Diamond Books; New York, NY. 353 pp. - $5.50.

"The second Ice Age begins in nine days," warns the book's cover. The back cover adds, "Dr. Cliff Lorenz knew the dangers of tampering with the environment. He had seen first-hand the disastrous results of an experiment with climate control."

After my wife gave me this paperback science fiction novel for light weekend reading, I flipped through the pages on the way to pour a cup of coffee and happened upon this passage: "Dive number two thousand fifty-one is on behalf of the Department of the Interior and the Environmental Protection Agency. The three man crew will consist of pilot Bill Bates, chief scientist Cliff Lorenz, and our nuts-and-volts master mechanic Fritz Hoffmeister." It went on to describe a dive of DSV *Alvin* from R/V *Atlantis II*. More page flipping turned up R/V *Knorr*, the drillships *Glomar Challenger* and *Glomar Explorer*, and a discussion of deep ocean drilling. The book had my attention!

The author (real name Ubaldo DiBenendetto) is a Professor of Foreign Languages at Harvard University and lives south of Boston, according to the exceedingly brief biography in the book. He has woven together a fascinating mix of climate modification research, oceanography, cold-war-type competition between the US and Russia, science advising, national decision making, internal science competition, and the culture of ocean science research and ocean engineering technology. In addition, there are nearly perfect descriptions of research operations at sea, believable characters, whale stranding, a love story complete with dual careers, and even a "sleeper" spy on a Woods Hole oceanographic research vessel.

I admire the author's ability to describe the geographic setting. One passage, for example, where Cliff Lorenz gazes across the docks from aboard R/V *Knorr*, instantly transported me back to a view of the same scene as I departed Woods Hole on a *Knorr* voyage several years ago.

I highly recommend this enjoyable book for all readers, but especially for ocean science fans, oceanographers, and ocean engineers. Scientists, engineers, officers, and crew who have sailed on Woods Hole ships or worked at the Woods Hole Oceanographic Institution will enjoy the challenge of identifying models for some of the main characters.

—John W. Farrington
Associate Director for Education
& Dean of Graduate Studies
Woods Hole Oceanographic Institution

The Woman Scientist:
Meeting the Challenges for a Successful Career

By Clarice M. Yentsch and Carl J. Sindermann, 1992. Plenum Press; New York, NY. 271 pp. - $24.95.

Lately, when a student or young colleague asks me about being a woman scientist, I don't just tell my stories. I also recommend this book. Yentsch and Sindermann have described with clarity and simplicity the multiple facets of surviving and ultimately succeeding in academia and research science. Unlike many other books and essays treating the woman scientist, this one does not lead to debilitating anger about past or continuing inequities or, alternatively, resignation. Instead we are graced with advice about coping with the present and suggestions for change. Mostly, I like the thoughtful analysis that is both honest and hopeful; my women students and young colleagues will still want to be scientists when they finish this book!

I very much like the format of the book. Yentsch and Sindermann present a sequence of issues that face women as they enter and pursue success in science. Information from their own questionnaire and from other publications, including helpful statistical analyses, clarify the issues. They often then present vignettes to illustrate their themes. As I read, I filled the margins with exclamation marks as I remembered my own and colleagues' incidents—some as recent as last week (!) on these very same themes. A pithy action list follows, with survival techniques and both short- and long-term action agendas. The authors then summarize the themes, reiterating their key points.

I found some aspects of the book particularly enlightening and intriguing. With the book's introductory discussions, I was reminded of a well-known quote from Sigmund Freud: "The great question...which I have not been able to answer despite my thirty years of research into the feminine soul is 'what does a woman want?'" The answers are clear for women scientists. (You will have to read the book for them, however!) The authors deal with some of the most personal dilemmas women often discuss: marriage, children, the timing of these and the "costs" they may incur. They find that successful career women have no single strategy, but there do appear to be some important ancillary factors. Particularly fascinating to me were the different daily "menus" for time use by male and female scientists. Their discussions give compassionate insights into our perennial guilt and often frazzled condition. The authors clearly spell out the hazards of the research assistant, describe the many faces of sexual harassment, and give insider information about how to become initiates of the "clubs" and "fraternities" found in the inner circles of science. I was very pleased with the authors' "generational perspective:" They clearly map both the changes that occur over the time course of a woman's professional career and they show the (mostly) positive changes that have occurred in the conditions for women scientists over the last two decades or so. Again and again the authors validated my own personal experience and that of the many women friends I have made in science: They were telling "our story."

—**Mary Wilcox Silver**
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Saving the Oceans

Joseph MacInnis (general editor), 1992. Key Porter Books; Toronto, Canada. 180 pp. - $50.

First let me say that this book has some of the most spectacular pictures you will ever see of ocean life—absolutely superb. It will make an excellent addition to anybody's coffee table.

The text, actually a series of 11 articles written by various authors, is a little more variable in quality, but all are interesting (I mention a few below). The underlying premise of this book is the great peril that the ocean is or will soon be facing. The beautiful photographs almost seem to be in contradiction to this premise. None would question that parts of the ocean, especially many coastal-zone regions, are in trouble, but the more vast and open ocean is really not in such jeopardy—nevertheless, some concern is appropriate.

The story starts with the editor making a 13,000-foot dive in the Soviet *Mir 1* submarine. Some hydraulic oil has leaked from the support ship and we are reminded about "the suffocation and death of the great waters" (i.e., *Exxon Valdez* and the Persian Gulf). The implication is that we have lost touch with nature.

Hillary Hauser follows with a compelling article ("The Meeting Place") based on his experience as a journalist and diver. He discusses estuaries, their use and misuse, and coral reefs, as well as pollution from ocean dumping, offshore oil activities, and the impacts of global warming.

Marie Tharp writes a lovely article entitled "Origins." A well-known cartographer, Tharp was the co-drafter (with the late Bruce Heezen) of the well-known physiographic chart of the ocean that is still found in many oceanographers' offices. A smaller version covers two pages of this book. She discusses the work she did with Heezen that led to the discovery of the world-encircling ocean ridge system, which in turn was one of the cornerstones to the then-developing concept of seafloor spreading.

"The Planet's Lifebelt" by T.R. Parsons emphasizes the resilience of the ocean but wonders what we are doing to it. He notes that only 27 years after its discovery the Stellar's sea cow became extinct, and ponders whether other species, such as some turtles, will suffer a similar fate.

In "The Twilight Zone" by Sylvia Earle we share her now-famous dives as deep as 1,250 feet in a one-person, hard-shell diving suit (frequently called Jim for Jim Jarrett, the first person willing to try an early version of the suit). Earle says "there are no words to describe the blueness" of the oceans—but she does quite well.

In "The Dynamic Abyss," Peter A. Rona writes of his many discoveries. He does get a little lost, however, in his explanation of the Law of the Sea Conference and a 1982 convention for mining deep-sea nodules.

John Lythgoe, in "The Sensory World of the Deep," writes about light and sound in the ocean and how various organisms see and hear, and Mike Donoghue, in "Protecting the Oceans," describes some of the harmful effects of pollution, such as PCB poisoning of beluga whales in the St. Lawrence River of Canada. He also mentions several recent treaties to restrict or reduce pollution, and what one can do as an individual.

After reading this pleasant and well-edited book, I still remain somewhat skeptical about its premise. Rather than the ocean being in serious danger at this moment, I feel that our recent concern and efforts toward the marine environment have had some impact. Perhaps it's just that a beautiful book like this makes me see the positive.

—David A. Ross
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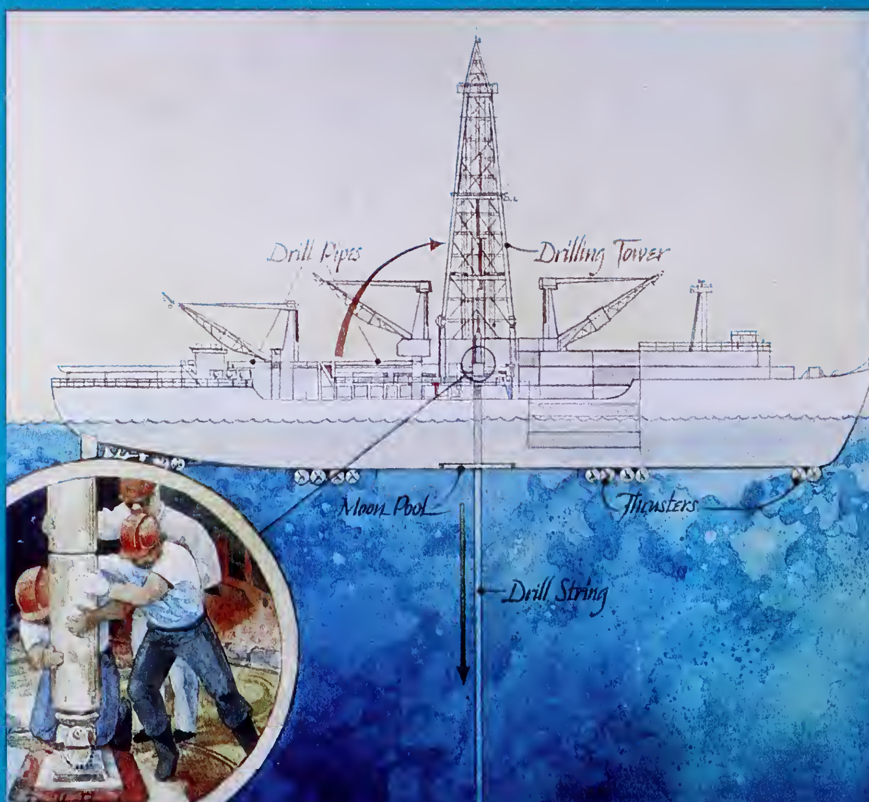
Back cover: The seven-member *JOIDES Resolution* drill floor crew uses a variety of mechanical and hydraulic devices to extend the drill string to the seafloor. Lengths of pipe exceeding 28 meters and weighing 874 kilos are lifted by the drawworks at the base of the drilling tower, threaded onto the drill string, and lowered through the moonpool in the bottom of the ship. In 5,500 meters of water, it takes 12 hours for the drill bit to reach the seafloor where drilling can begin.


Drill Pipes
Drilling Tower
Moon Pool
Thrusters
Drill String