Ocean Drilling Program

Long Range Plan

1989 - 2002

May 1990

Joint Oceanographic Institutions
INCORPORATED

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Credits:

Cover Design: Trish Crowe
Photography: ODP, Texas A&M University

Additional copies of this document are available from:

Joint Oceanographic Institutions, Inc.
1755 Massachusetts Avenue, NW, Suite 800
Washington, DC 20036-2102 USA
Phone: 202/232-3900
Fax: 202/232-8203
Telemail: JOI.INC

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ACRONYMS

APC	Advanced Piston Corer
COSOD	Conference on Scientific Ocean Drilling
DCS	Diamond Coring System
DSDP	Deep Sea Drilling Project
EXCOM	JOIDES Executive Committee
GOFS	Global Ocean Flux Study
HPC	Hydraulic Piston Corer
HRGB	Hard Rock Guide Base
IGBP	International Geosphere-Biosphere Program
IPOD	International Phase of Ocean Drilling
JOIDES	Joint Oceanographic Institutions for Deep Earth Sampling
JOI, Inc.	Joint Oceangraphic Institutions, Inc.
LDGO	Lamont-Doherty Geological Observatory
MBSF	Meters Below Sea Floor
ODP	Ocean Drilling Program
PCOM	JOIDES Planning Committee
RIDGE	Ridge Inter-Disciplinary Global Experiments
TAMU	Texas A&M University
WCRP	World Climate Research Program
WOCE	World Ocean Circulation Experiment
XCB	Extended Core Barrel

EXECUTIVE SUMMARY

This is the science plan for the future of the Ocean Drilling Program (ODP). It reflects the consensus of an international consortium of scientists concerned about the future of the largest and most visible ocean science research program. The plan discusses the Program's scientific objectives and accomplishments, technological developments, plans for the future and the stages for implementing these plans. It shows how scientific ocean drilling is critical not only to basic research in earth sciences but also to the oil and mining industries, which use the results of scientific ocean drilling to develop better exploration strategies.

Coring operations of ODP's forerunner, the Deep Sea Drilling Project (DSDP), produced supporting evidence critical to the 1960s plate tectonic revolution in the earth sciences. DSDP scientists used biostratigraphic dating of sediments that directly overlie the basaltic basement to show that the seafloor gets older away from midocean ridges. This "seafloor spreading" explained the observation that sediment cover thickens away from the ridge crest, which had puzzled marine scientists for many years. Deep drilling also proved that the oldest seafloor is only about 170 m.y., a fraction of the earth's age, supporting the theory that oceanic crust is "consumed" at subduction zones.

At first, DSDP was solely a U.S. venture. Over time, the Federal Republic of Germany, France, Japan, the United Kingdom and the Soviet Union joined the drilling program. The period of this joint effort was called the International Phase of Ocean Drilling (IPOD).

Plate tectonic theory was well established by the early 1980s, but many important elements of plate motions, oceanic crustal generation and coincident climatic change remained poorly understood. In 1981, scientists convened at an international conference in Texas to identify the scientific goals of further drilling and to establish drilling objectives for the next decade (Conference on Scientific Ocean Drilling, COSOD I). To meet these objectives and test the theories on which they were based, ODP was launched with several technical mandates, such as to drill deeper, drill in higher latitudes, drill into newly created

ODP Member Countries:

Federal Republic of Germany
France
Japan
United Kingdom
Canada/Australia Consortium
European Science Foundation Consortium for Ocean Drilling
  - *Belgium*
  - *Denmark*
  - *Finland*
  - *Greece*
  - *Iceland*
  - *Italy*
  - *The Netherlands*
  - *Norway*
  - *Spain*
  - *Sweden*
  - *Switzerland*
  - *Turkey*

United States

crust at ocean ridge crests, and make physical and chemical measurements in the boreholes. ODP leased one of the most advanced drill ships in the world, the *JOIDES Resolution,* to be the platform for the enterprise. The scientists who met in Texas also strongly recommended that better geophysical surveying be completed well in advance of drilling, and stressed the importance of international cooperation in these endeavors.

Now five years old, ODP comprises the United States and six international partners: the Federal Republic of Germany, France, Japan, the United Kingdom, the Canada/Australia Consortium and the European Science Foundation Consortium for Ocean Drilling (Belgium, Denmark, Finland, Greece, Iceland, Italy, the Netherlands, Norway, Spain, Sweden, Switzerland and Turkey). The member nations provide ODP with an array of scientific, engineering and other technical resources and expertise, as well as the critical financial support to run one of the largest international earth science programs. Member nations also advance ODP's mission by funding geophysical surveys of potential drill sites and the drilling-related research projects of individual scientists.

WHY DRILL?

A long-term program of scientific ocean drilling is essential to research in the earth sciences. The ODP facility—its drill ship, laboratories, core and data repositories, wireline logging center, and the publications that have resulted from the program—have been used by over a thousand scientists and engineers from all over the world. Ocean drilling is the only technique for:

- obtaining detailed records of the last few million years of earth's climatic history. These data are critical to scientists modeling future global climate change.
- directly sampling most of the oceanic crustal column. Cores, logs and downhole sensors provide ground-truth data to refine models in disciplines of earth sciences from seismology to paleoceanography.

- obtaining *in situ* data related to fluid circulation in ocean sediments and hard rock. These data are vital to scientists who study the geochemical and thermal balance of the oceans and lithosphere, as well as those who develop strategies for issues ranging from waste disposal in the oceans to petroleum exploration.

- studying ore-forming processes that occur at depth. It is a surprising fact that drilling data are necessary to improve the predictive framework for mineral exploration on land.

- providing deep boreholes in oceanic crust so that instruments may be emplaced for long-term geophysical and geochemical experiments. Data from these experiments tie ODP to other geoscience programs, which will significantly enhance understanding of earth structure and composition.

PROGRESS

Since its first operational leg in January 1985, ODP has contributed to our understanding of a number of geological processes of global significance. This document summarizes seven major contributions of ODP to studies of:

(1) evolution of global climate;

(2) fluids in accretionary complexes;

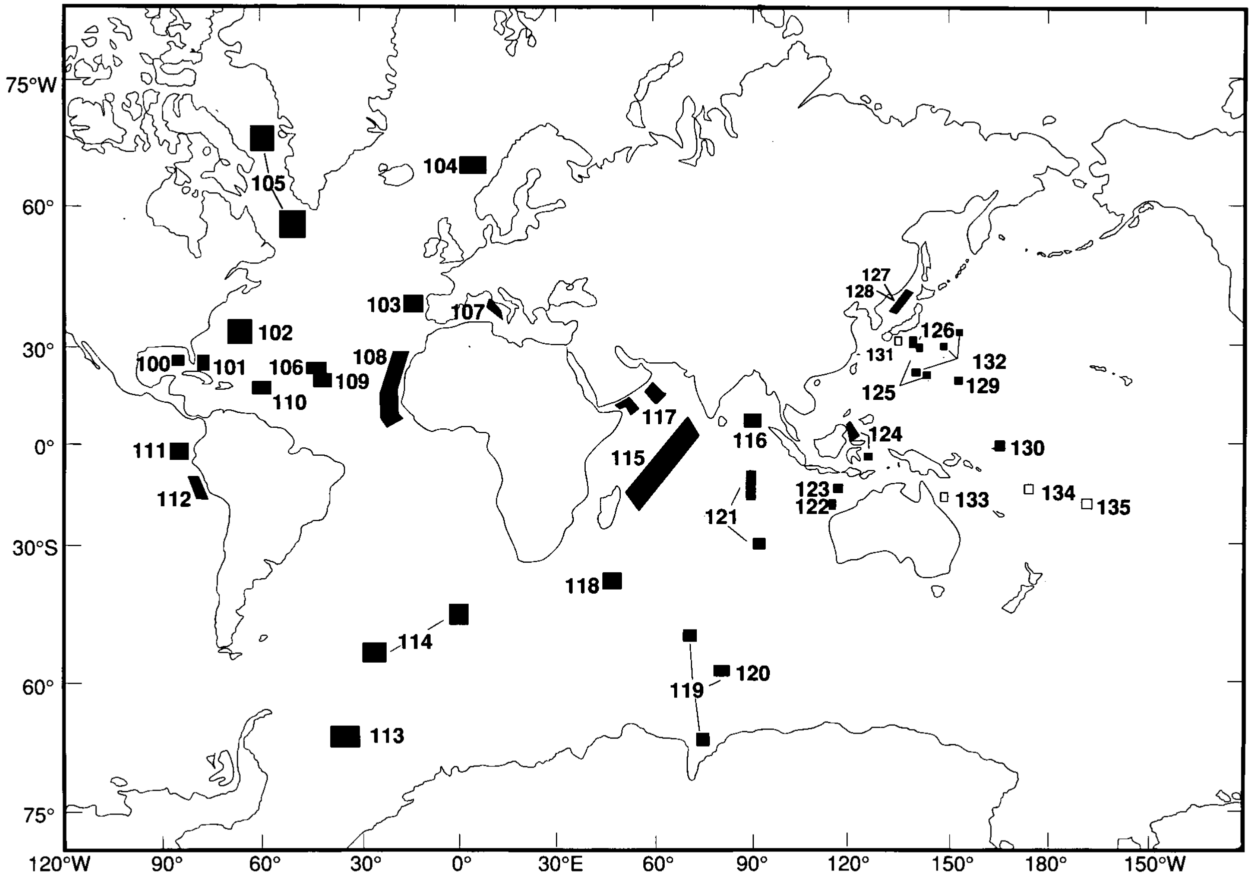
(3) exploration of the oceanic crust;

(4) hotspot evolution and true polar wander;

(5) plate divergence;

(6) drilling and coring technology; and

(7) downhole measurements.

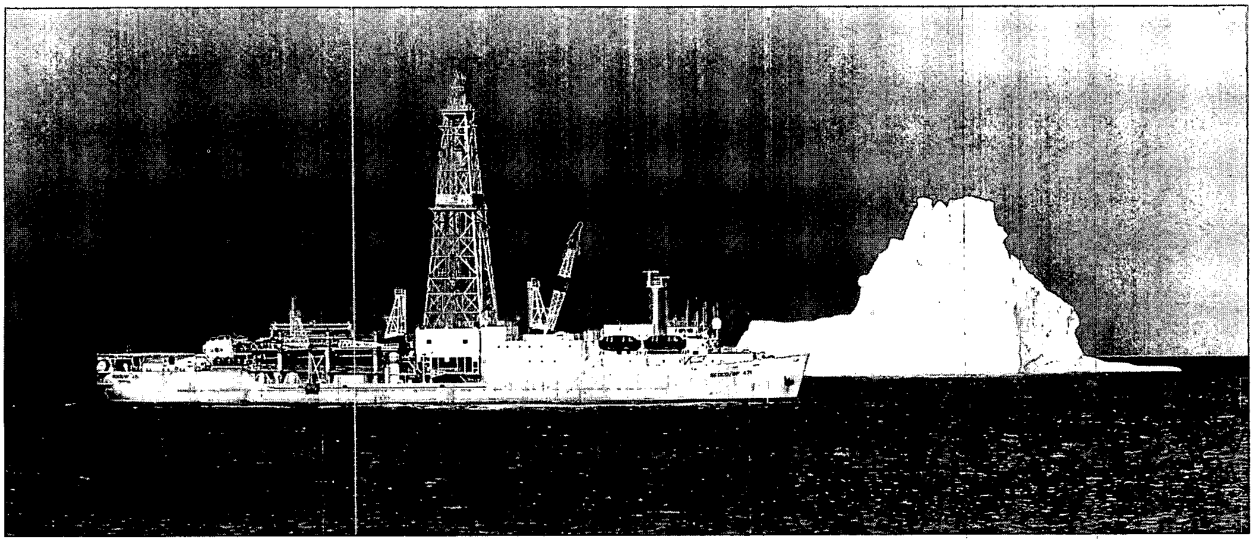


Dark areas indicate sites that have already been drilled; unfilled boxes are legs planned for future drilling.

Evolution of global climate

One ODP mandate is to drill in high latitudes, regions that play a major role in affecting both the short- and long-term evolution of global climate and the oceans. Climate change at high latitudes can both drive the global climatic system and amplify change through complex feedback mechanisms. Oscillations in ice accumulation in polar regions effect changes in sea level.

ODP drilling in the Antarctic and Subantarctic (Legs 113, 114, 119, and 120) has provided much new evidence about the environmental evolution at high latitudes, including climate. The Antarctic as we know it today has undergone radical changes in climate during the last several tens of millions of years. Numerous major steps were involved, some of which



The JOIDES Resolution *in Baffiin Bay*

occurred rapidly. ODP drilling has clearly defined the major steps, from the temperate, forested Antarctic continent in the Eocene, through initial glacial conditions in the early Oligocene, to the accumulation of major and, perhaps, permanent ice sheets in the Cenozoic. The drilling evidence supports ideas of the initial development of the East Antarctic ice sheet followed by later development of the ice sheet covering West Antarctica. Drilling during Legs 104 and 105 at high North Atlantic latitudes confirm the much younger (~2.5 million years old) initial development of the ice sheets that have periodically covered North America and Europe. These high-latitude drilling results are critical to our understanding of the history of global environmental evolution, the processes involved in this change, and our ability to predict future change.

ODP has also provided the first high-resolution records of tropical climates and circulation covering the last several million years in the Atlantic and Indian Oceans (Legs 108 and 117). The records provide direct evidence of the onset and evolution of monsoonal circulation, which plays a critical role in controlling climate over large areas of the tropics. These data assist modeling efforts to better understand the mechanisms controlling past climatic conditions and our ability to predict future global climate change.

Leg 118, along the Southwest Indian Ridge, obtained the first continuous section of lower oceanic crust.

Fluids in accretionary complexes

ODP drilling on Legs 110 and 112 on the Barbados and Peru margins, respectively, demonstrated for the first time that fluids move through and flow out of modern accretionary complexes. Accretionary complexes are formed where sediment is scraped off as the oceanic crust is consumed beneath the overriding margin. This newly discovered mode of fluid transport contributes to the geochemical fluxes within the lithosphere, hydrosphere and biosphere, which influences oceanic and atmospheric chemistry. Recent ODP drilling in convergent margin settings has also revealed the complexity of the thermal regimes and indicated the importance of advective heat flow, at least on a local scale. To date, the models of thermal maturation used in the oil industry rarely include consideration of advective heat transport; as a result, some prospective areas may have been unduly excluded from exploration.

Exploration of the oceanic crust

On Leg 106, ODP took a major step in a long-term investigation of oceanic spreading centers by successfully spudding a drill hole into "zero-age" crust in the rift valley of the Mid-Atlantic Ridge. Leg 118, along the Southwest Indian Ridge, used this same technology to obtain the first continuous section of lower oceanic crust. Shipboard analyses performed on Leg 118 show these lower oceanic crustal rocks to have an unusually high magnetization, which, if demonstrated to be of regional extent, has major implications for our understanding of how the earth's magnetic field is recorded in the oceanic crust.

On Legs 102 and 109 in the Atlantic Ocean and Leg 111 in the Pacific, scientists used an extensive suite of state-of-the-art logging tools and conducted borehole experiments by reentering the three deepest crustal holes drilled during DSDP. The data from these experiments indicate that the oceanic crust 100-200 meters below the seafloor ("Layer 2") has a uniformly low permeability, too low to permit hydrothermal circulation in the lower crust. These unexpected results are extremely important for modeling hydrothermal processes at midocean ridges and understanding the alteration history of the oceanic crust.

Hotspot evolution and true polar wander

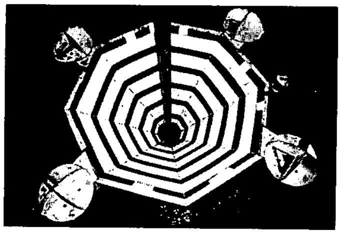
New paleomagnetic data collected by ODP on Leg 115 in the Indian Ocean address the controversial hypothesis of "true polar wander," which states that the earth's spin axis changes through time with respect to the mantle reference frame, as represented by hotspots, perhaps in response to changes in its principal moments of inertia. These provocative, and as yet unpublished, results have fundamental implications for research ranging from dynamics of the mantle to plate tectonic reconstructions.

Plate divergence

DSDP drilling helped confirm that seafloor is created at midocean ridges, but left unexplained how and why continents fragment. ODP Legs 119-123 in the Indian Ocean explored why the lithosphere extends; Legs 103-104 in the Atlantic looked at how continents fragment. Indian Ocean drilling showed that in some regions the lithosphere may extend because of far-field stresses, rather than local stress caused by mantle convection processes. This surprising result displaced an earlier hypothesis that lithospheric bulging associated with mantle upwelling *always* occurs prior to continental breakup. Indeed, the sediments drilled during Leg 121 revealed no shoaling of Broken Ridge, a rifted fragment of an oceanic platform (Kerguelen Plateau is the conjugate rifted platform) which would indicate mantle convection.

ODP drilling on Legs 103 (Galicia margin off the Iberian Peninsula) and 104 (Voring Plateau off Norway) resolved an outstanding controversy regarding the evolution of rifted continental margins. Of the two prior rifting hypotheses, one held that during early rifting of the continent prior to seafloor spreading there is extensive stretching and thinning of the continental lithosphere with virtually no associated magmatism. The other held that the continental lithosphere undergoes a small amount of extension with voluminous magmatism. Drilling on Legs 103 and 104 showed that both hypotheses may be correct. Drilling on the Voring Plateau proved that at least some seaward-dipping reflector sequences noted on multichannel seismic records are large accumulations of volcanic rocks, while drilling on the Galicia margin showed that continents can also rift apart with little to no magmatic input.

Drilling and coring technology



Reentry Cone

ODP and DSDP have generated and benefited from many technological developments specifically required for scientific ocean drilling. DSDP was based primarily on standard oil industry technology such as rotary drilling, wireline coring and dynamic positioning. To collect more scientifically useful data, however, technology had to be advanced. Deeper drilling required reentering holes to replace old, worn-out drill bits. Two years after DSDP began, it achieved the first hole reentry on the deep seafloor. DSDP engineers and scientists also realized that standard rotary drilling destroys much of the fine structure of unconsolidated sediments. After ten years of effort, the hydraulic piston core (HPC) was successfully deployed. Development of the HPC led to the advanced piston core (APC) and ODP's current ability to sample unconsolidated sediments with minimal disturbance.

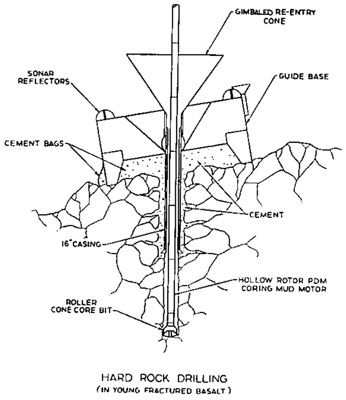


Illustration of Hard Rock Guide Base

ODP's other mandates, such as drilling into zero-age crust, led to further technological achievements. To stabilize the drill string when spudding into sediment-free basalt, a hard-rock guide base (HRGB) was developed. Three successful deployments of the HRGB have proved the feasibility of drilling into bare rock at the seafloor. This new technology soon will be used again to drill the East Pacific Rise crest for further studies of ocean crust generation and hydrothermal circulation. ODP has also collaborated with industry on the potentially revolutionary adaptation of land mining coring systems to ocean drilling by developing a diamond coring system to improve recovery in "difficult formations" such as fractured basalts, loose and broken rocks, unconsolidated sands, chert, and sloughing clays and shales. Diamond coring technology developed by the mining industry uses smaller diameter core bits and much higher bit rotation speeds. The diamond coring system has been tried once on the *JOIDES Resolution,* with encouraging results, and will be tested again, in deeper water, during 1990.

Downhole measurements

ODP now fields the most sophisticated array of logging and sampling downhole tools in the world that are available for routine use.

A major thrust of the Ocean Drilling Program has been its downhole measurements program. ODP now fields the most sophisticated array of logging and sampling downhole tools in the world that are available for routine use. These tools have provided new data on the nature of climate variability in the global ocean and the first *in situ* measurements of the physical properties of the deep ocean crust. They also permit measurement of the state of stress in the lithosphere, as well as changes in fluid composition. Logs are an invaluable resource to ocean drilling because they record continuously downhole. Their continuity often allows resolution of complex cycles of deposition, which discontinuous core data often miss. Unlike measurements on core material, which are irreversibly changed by acquisition, *in situ* measurements record properties of the broader environment around the borehole and lead to better, more representative determination of chemical and physical properties of that environment. In addition to the challenges already imposed by taking measurements downhole, ODP will soon test the limits of technology by trying to log in high-temperature holes (about 350°C) near the crest of the midocean ridge.

IMPACT

Oil industry

Scientific ocean drilling has had an impact on the exploration for natural resources. In particular, DSDP and ODP drilling have made significant contributions to the testing of marine depositional models. Verifying these models is important to the oil industry because they can be extremely useful tools in predicting the distribution of reservoir deposits, source rocks, and sealing shales within a basin. While these models can be tested on land by careful geologic field work, models of marine deposition are best tested at sea. Scientific ocean drilling programs enhance the database collected by drilling for oil exploration because:

(1) the sites can be located to test specific scientific hypotheses concerning the nature of depositional sequences (not to find reservoir oil), and

(2) the sites are both continuously cored and logged so that a full suite of data on the section is available for study.

ODP results have provided definitive data on evolutionary trends of marine organisms and the consequent temporal and stratigraphic standards on which the petroleum industry relies for much of the geological column.

Additionally, ODP results have provided definitive data on evolutionary trends of marine organisms and the consequent temporal and stratigraphic standards on which the petroleum industry relies for much of the geological column.

While the scientific database provided by ODP has clearly benefitted the oil industry, ODP technological developments also have applications beyond scientific ocean drilling. A few of these ODP engineering developments are:

- Measurement of actual stress during deployment and while drilling with long drill strings. These measurements are important for the design of slimline risers for deep water oil field drilling.
- Development of the wireline-retrievable Motor-Driven Core Barrel and positive displacement coring motors. The 24 centimeter (9-1/2 inch) positive displacement coring motors should serve both science and industry as the downhole coring motors that are best suited for coring in crustal lithologies. ODP has been developing these coring motors with Eastman Christensen (located in the Federal Republic of Germany).
- Deep-water, real-time TV reentry systems. This remote viewing system, which can be used by industry in oil field and ocean engineering applications, has proved to be both rugged and reliable for deep water reentries or ocean bottom surveying.

Mining industry

ODP research may also assist discovery of new base- and precious-metal resources on land, which requires increasingly more precise geological targeting of sites for intensive exploration effort. Geological models of ore formation must be based on knowledge of three-dimensional attributes of ore-bearing areas. Seafloor exploration by deep-sea cameras and submersibles suggests that some of the most important ore-forming processes operate in submarine environments, but little is known about the ore-forming processes that occur at depths beyond which conventional piston coring methods reach (about 20 meters, but usually less in hydrothermal zones). Deep ocean drilling in regions from continental margins to ridge crests yields vital information on the structural, petrogenic and stratigraphic controls, as well as the sequence of events and the sources of metals for ore formation.

Education

ODP provides educational opportunities for the scientist, student, and layperson. Over seven hundred scientists from all over the world have participated in studies aboard the drill ship and many more have used ODP's shorebased facilities (e.g., Site Survey Data Bank, core repositories, log analysis center) to further their research. Lamont-Doherty's Borehole Research Group has held logging schools in most ODP member countries to educate university and industry scientists about the benefits of downhole logging, the tools available on the drill ship, and the facilities at Lamont-Doherty's log analysis center.

Japanese visitors tour the JOIDES Resolution *during a port call in Tokyo.*

Each ODP member country has its own programs to promote drilling-related opportunities for students. The JOI/U.S. Science Support Program, for example, has a graduate fellowship program to encourage student participation on the drill ship and ODP-related research. In the U.K. similar opportunities exist and, because the National Environment Research Council (NERC) is the sponsor of may of the research students, arrangements to extend studentships to allow for the additional commitments of ODP participation are often made. In this way, and others, many doctoral students have served as shipboard scientists where they have been exposed to "cutting-edge" geoscience and technology equivalent to that found in a first-rank university.

Citizens of many nations have been introduced to the unique capabilities of the *JOIDES Resolution* while they toured the ship during port calls. Highlights of ODP's history, achievements, and objectives have been presented at meetings of civic groups, industry professionals, and elementary, secondary, and college-level students around the world.

Other major earth science programs

The existence of ODP is vital for other major earth science initiatives to achieve their goals.

It has become clear recently that the existence of ODP is vital for other major earth science initiatives to achieve their goals. Deployment of downhole seismometers in ODP holes has the potential to expand coverage of the Global Seismic Network and enhance the resolution of this powerful new array. New initiatives such as the Ridge Interdisciplinary Global Experiment (RIDGE) in the U.S. and BRIDGE in the U.K. depend in part on ODP's ability to drill and emplace instruments in young oceanic crust. Cooperation between the Nansen Arctic Drilling Program and ODP has recently been initiated to promote the retrieval of long cores from this largely unexplored ocean basin. New ties between ODP and continental drilling have also been initiated to facilitate the exchange of technology and ideas among the marine and terrestrial geoscience disciplines.

FUTURE

What is next for ocean drilling? This plan presents 16 major scientific ocean drilling objectives, representing a distillation of workshop and panel discussions over the last 4 years and the conclusions of 2 major international conferences (COSOD I and COSOD II). The 16 objectives fall into 4 thematic categories:

Structure and Composition of the Crust and Upper Mantle

- Exploring the Structure of the Lower Oceanic Crust and Upper Mantle
- Magmatic Processes Associated with Crustal Accretion
- Intraplate Volcanism
- Magmatism and Geochemical Fluxes at Convergent Margins

Dynamics, Kinematics and Deformation of the Lithosphere

- Dynamics of Oceanic Crust and Upper Mantle
- Plate Kinematics
- Deformation Processes at Divergent Margins
- Deformation Processes at Convergent Margins
- Intraplate Deformation

Fluid Circulation in the Lithosphere

- Hydrothermal Processes Associated with Crustal Accretion
- Fluid Processes at Plate Margins

Cause and Effect of Oceanic and Climatic Variability

- Short Period Climate Change
- Longer Period Changes
- History of Sea Level
- The Carbon Cycle and Paleoproductivity
- Evolutionary Biology

These future drilling objectives are summarized below. A unifying goal is to obtain data concerning the complex relationship among the oceanic crust, overlying sediments, and seawater in order to better understand the dynamics of the earth system.

Structure and composition of the crust and upper mantle

Knowledge of the structure and composition of the oceanic crust and underlying mantle is critical to an understanding of how the solid earth has evolved through time, and the processes that have shaped its evolution. While plate tectonics has provided a basic kinematic framework for these studies, over the past decade there has been increasing interest in quantifying and modeling the actual physical and chemical processes involved in this solid-earth geochemical system. The objectives of these studies can be divided into three general areas:

(1) quantifying the global geochemical fluxes between the crust and mantle;

(2) investigating the magmatic and tectonic processes that control these fluxes at spreading centers, in intraplate settings and at convergent margins; and

(3) determining the composition and heterogeneity of the underlying mantle.

This process-oriented approach to lithospheric studies has spawned new initiatives like the Ridge Interdisciplinary Global Experiment (RIDGE) program and promises to revolutionize our understanding of geodynamics in the coming decade.

In some instances, ocean drilling is the only method by which some critical data can be obtained.

ODP can make important contributions to these lithospheric studies and, in some instances, ocean drilling is the only method by which some critical data can be obtained. Information provided by deep drilling, for example, is the only way of determining the bulk composition and *in situ* physical properties of the oceanic crust, interpreting the geological significance of seismically defined crustal layering, and constraining the alteration history and aging of the oceanic crust. Thus, one key goal of crustal drilling in the next decade is to develop the capability for deep crustal penetration, with the ultimate objective of drilling through an entire 6-kilometer-thick oceanic crustal section. In order to investigate crustal accretion processes, a "natural laboratory" approach is favored in which arrays of relatively closely spaced holes are drilled (some shallow, others relatively deep), and used for a variety of short-term and long-term borehole experiments and observations. This type of drilling can provide unique constraints on the complex and interrelated magmatic, tectonic and hydrothermal processes occurring at oceanic spreading centers. The capability to establish at least one permanently instrumented seafloor "volcano observatory" along an actively accreting plate boundary is another major objective of ODP. Achieving these long-term goals will require major advances in crustal drilling technology, logging equipment and long-term borehole instrumentation, as well as close coordination between scientific planning and engineering development. Extra effort at coordination with other programs such as RIDGE will also be required.

Dynamics, kinematics and deformation of the lithosphere

In the 12 years beginning in 1989, ODP will be in a position to make new and unique contributions to knowledge of the dynamics and kinematics of the lithosphere and the processes of lithospheric deformation. These developments will be made possible by a new and more technologically advanced approach to scientific ocean drilling as well as the ability to drill deeper holes in unstable environments. *In situ* stress measurements in consolidated sediments and basement will permit evaluation of models of plate driving forces and reveal the dynamics of transform faults and ridge systems. Deployment of long-term geophysical observatories should provide a unique oceanic component to improve global seismic tomography of the deeper mantle and core, as well as detailed studies of dynamic processes in specific tectonic environments such as ridge crests and transform faults. Measurements of *in situ* stresses and long-term

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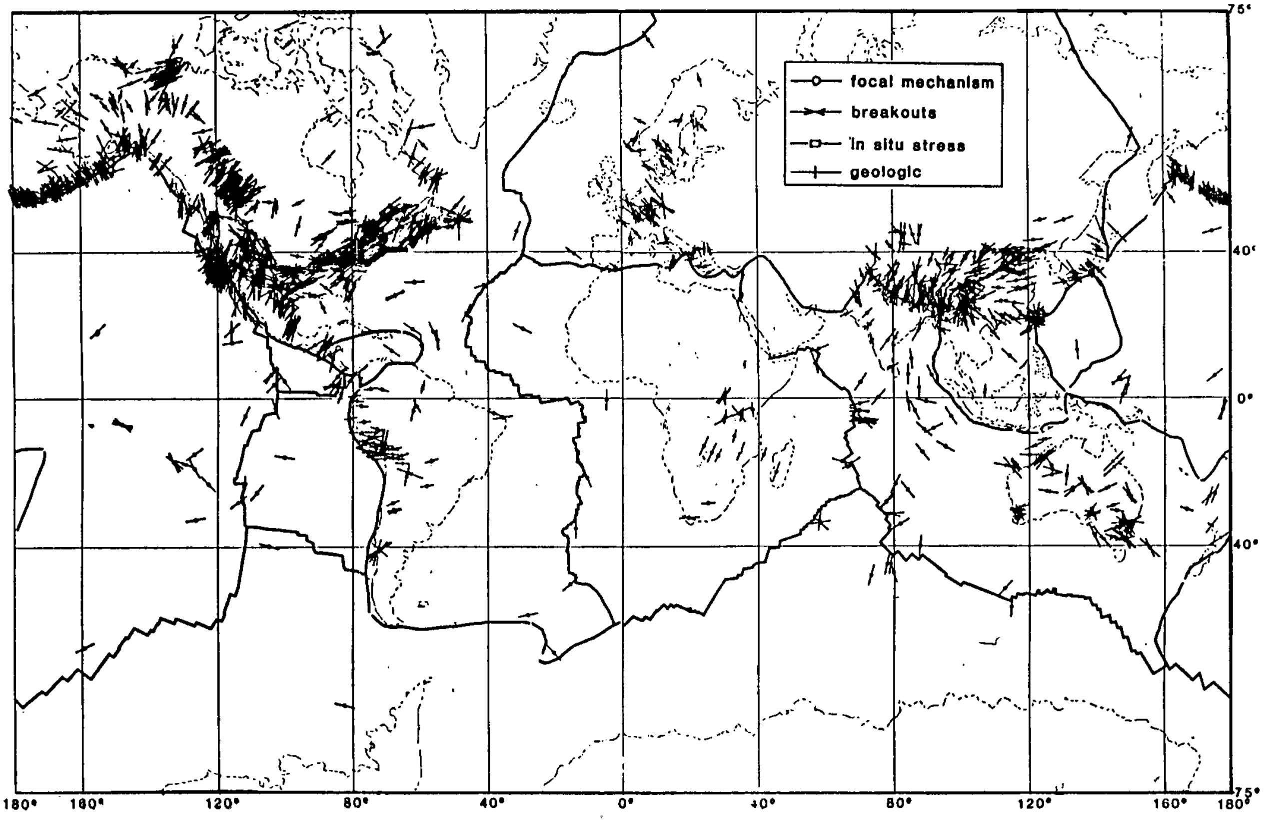


World stress map—S_{HMAX} orientations. This map contains estimates of the direction of maximum compressional stress within the plates derived from earthquake focal mechanisms, borehole breakouts, hydraulic fracture measurements and contemporary surface folding. Huge gaps exist in Asia and on all oceanic plates (Courtesy of M.L. Zoback).

monitoring of earthquakes and physical and chemical parameters at lithospheric plate boundaries will provide new insight into orogenic processes. The study of lithospheric deformation increasingly will emphasize active processes and measuring such parameters as permeability, pore-fluid pressure and geochemistry. This research should improve understanding of the rheologic behavior of the lithosphere under stress and fluid flow at plate boundaries.

Under the theme of dynamics, kinematics and deformation of the lithosphere, ODP will emphasize concentrated drilling campaigns aimed at testing models of important tectonic processes. ODP will cooperate with other geoscience programs to devote more time to instrumenting drillholes and taking downhole measurements in order to characterize the environmental and physical conditions of the rocks being deformed. These efforts will require much more detailed site surveys to integrate the drill-hole data with regional geology and maximize the value of the drilling results. In this way, and others, the entire program will coordinate more closely with other global geosciences initiatives.

Fluid circulation in the lithosphere

The role of fluids in the lithosphere is a new frontier of current marine research. Temperature-driven hydrothermal flow is ubiquitous in the global framework of ocean plate accretion at midocean ridges and backarc spreading centers. Tectonically driven hydrologic flow determines the style of sediment accretion and mechanism of lithification at convergent margins. Ultimately, subducted fluids, escaping dewatering in accretionary complexes, may control the distribution of deep-focus earthquakes. Gravity-driven subsurface flow is increasingly recognized as a major process in chemical redistribution and alteration within the sedimentary regime of passive margins. Ocean drilling is the leading scientific effort for advancing understanding of these fluid regimes.

Another set of objectives involves the poorly understood movement of fluids in marine sedimentary sections, whether driven by gravity, mechanical stress or heat. The transport of heat and material by these fluids affects the rates of geochemical cycling and is vital to understanding the oceanic and atmospheric abundances and variability of materials such as CO_2. In addition, fluid compositions are diagnostic of the chemical reactions occurring in these environments and illuminate the conditions at depths and temperatures beyond our ability to sample. In those regions that can be reached by the drill, the study of the changes in composition and mineralogy outlines the history of temperature, pressure and chemical reactivity which have brought marine sediments and the associated oceanic crust to their present condition. Some fluid-flow regimes lead to accumulations of metalliferous deposits which are analogous to ore occurrences of economic importance on land. ODP drilling presents a unique opportunity to sample and study these processes as they occur.

The interaction of fluids with sediment and oceanic basalt is a first-order process affecting the global cycling of elements. Drilling helps to identify sinks and sources in the mass transfer of these elements among the earth's reservoirs. A definition of geochemical budgets and an identification of reaction fluids, source depths and pathways of dewatering are the overall objectives in ODP's research intitiatives concerning the role of fluids in the lithosphere.

Cause and effect of oceanic and climatic variability

Paleoceanographic records obtained through ocean drilling are essential to reconstructions of past temperature, chemical composition and circulation of the atmosphere.

ODP also greatly contributes to efforts to understand the causes and consequences of global climatic and environmental change. Understanding complex interactions in the earth climate system is essential for dealing with the consequences of future change. Paleoceanographic records obtained through ocean drilling are essential to reconstructions of past temperature, chemical composition and circulation of the atmosphere; ocean sea-surface temperatures and salinity; the changing wind- and water-borne flux of material from the continents; and the level of productivity of different regions of the ocean. Ocean drilling information permits reconstruction of the positions of the continents, the gateways from one ocean basin to another, the

More than any other aspect of ODP, paleoceanographic research has evolved to the point where global systems models can be tested.

topographic barriers to deep circulation and the degree of flooding of the adjacent land masses. These data also assist derivation of the history of geochemical fluxes of the earth's system caused by processes at the ridge crests and subduction zones and by volcanic activity. Thus, drilling facilitates access to both the historical record of past climate over a range of time scales, and to the processes acting to control and change the climate system.

Advances in conceptual and mathematical modeling (the latter benefiting from the computer revolution) make ODP uniquely well-placed to apply focused deep-sea drilling to solving key questions about the fundamental controls of change in the global environment. The program has firmly established its ability to obtain remarkable records of the last few million years of earth history. These records provide a wealth of information about the interactions among earth orbital geometry, atmospheric circulation and carbon dioxide level, ocean chemistry and circulation, the cryosphere and the biosphere. ODP's objective is to extend this ability in order to obtain equally good sequences covering longer intervals during which continental position, ocean circulation, sea level, and changing chemical fluxes played critical roles in changing the global environment.

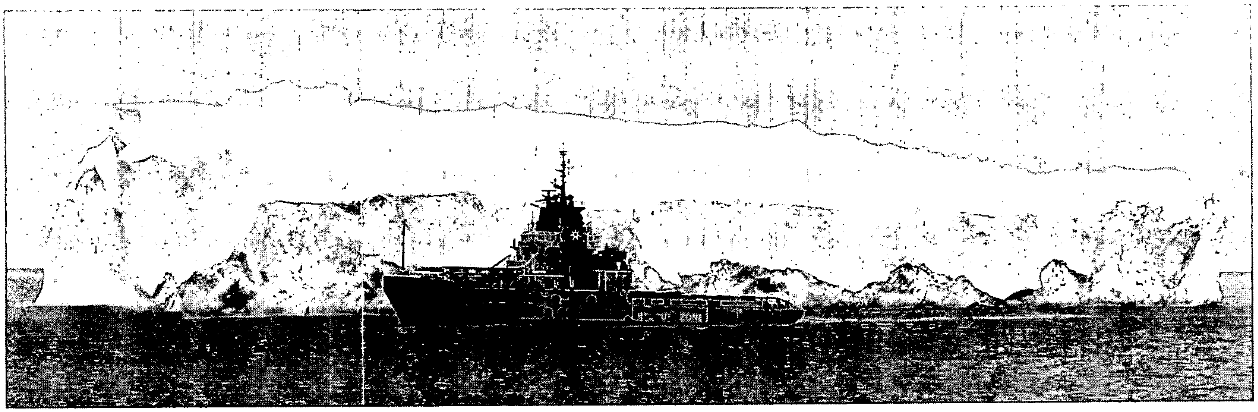
More than any other aspect of ODP, paleoceanographic research has evolved to the point where global systems models can be tested. A major objective of the next phase of the drilling program will be developing better high-resolution recovery techniques and high-resolution downhole measurements. These techniques will be applied to the systematic collection of the critical temporal and spatial data necessary to test existing models and, inevitably, to develop new ones.

PROGRAM REQUIREMENTS

The annual funding levels presented in Table 1 are the best available cost estimates for maintaining a scientific ocean drilling program that is on the leading edge of ocean research and technology. The budget is separated into two main categories: standard operations and special requirements. Standard operating funds enable drilling and logging to continue year-round, *ODP Proceedings* to be published, modest engineering development to continue, and allow the ODP Site Survey Data Bank, JOIDES Office, and administrative offices to maintain operations. Support for geophysical surveys of potential drill sites and scientists' participation in ODP would continue through separate programs in each member country.

To meet many of ODP's scientific goals over the next ten years, there are also special program requirements. Some of these include:

- development of drilling and logging technology for high-temperature drilling, sampling and measurement in highly corrosive environments;
- further development of the diamond coring system as well as slimline logging tools in order to improve ODP's capability to core and log in fractured, hot and brecciated rocks;
- purchase or rental of slimline risers and blow-out preventers so that ODP can drill into initial rifting sequences where organic-rich sequences may be found, and drill deeply into accretionary complexes for fluid and tectonic deformation studies where complete circulation and safety control will be necessary;
- rental of ice-support vessels so that the drill ship can operate safely in high latitudes;



Ice Support Vessel, Maersk Master, *hired by ODP to protect the* JOIDES Resolution *from icebergs during high-latitude legs.*

- rental of a jack-up rig so that ODP can drill shallow-water atolls; and
- further development of packers, fluid samplers and other tools so that the *in situ* properties of the rocks and fluids in the boreholes may be properly measured.

Other special requirements include replacing drill pipe, dry dock expenses, replacing shipboard laboratory equipment, increasing the number of staff scientists and marine technicians, computer and curatorial improvements, and increasing publications staff to speed up production of *ODP Proceedings* volumes. The feasibility of using a light drilling vessel in tandem with the *JOIDES Resolution* is also being explored.

CONCLUDING REMARKS

ODP is an international university where a multi-national group of scientists pool technical resources to tackle earth science problems of global concern. The drill ship provides a unique environment where scientists can discuss new ideas together as data is acquired and analyzed. ODP has been very successful in fostering international cooperation so that drilling proposals are now more often authored by scientists from several nations rather than from one nation.

ODP provides the only ground-truth capability available to a large number of earth science disciplines ranging from evolutionary biology to rock physics to seismology. This unique capability and DSDP/ODP's long history of successes have led scientists from these disciplines to rely on drilling and to presume its continued existence as part of the background matrix of their science. Much of the new earth science planned for the 1990s and the next century requires ocean drilling as a provider of samples, geophysical experiments or observatory sites.

Ocean drilling has evolved from an exploratory coring program to a thematically driven coring and logging program. ODP now must evolve into a coring, logging and observatory-building program in partnership with other major global geoscience studies.

Table 1: Long Range Plan Budget Summary

(By fiscal year in millions of dollars)

Standard Operations	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
Science Operator														
Headquarters	1.66	1.77	1.89	1.97	2.06	2.15	2.25	2.35	2.46	2.58	2.70	2.83	2.97	3.11
Science Services	3.15	3.45	3.64	3.84	4.05	4.27	4.50	4.75	5.01	5.29	5.58	5.90	6.22	6.57
Drilling & Engineering	3.12	3.16	3.30	3.44	3.58	3.74	3.90	4.07	4.24	4.43	4.62	4.83	5.04	5.27
Technology & Logistics	3.04	3.49	3.65	3.82	4.01	4.20	4.40	4.62	4.84	5.08	5.32	5.59	5.86	6.15
Science Operations	.96	1.00	1.05	1.11	1.16	1.23	1.29	1.36	1.43	1.50	1.58	1.66	1.75	1.85
Subtotal	**11.93**	**12.87**	**13.53**	**14.18**	**14.86**	**15.59**	**16.34**	**17.15**	**17.98**	**18.88**	**19.80**	**20.81**	**21.84**	**22.95**
Ship Operations	18.57	19.02	19.59	20.18	20.78	21.40	22.05	22.71	23.39	24.09	24.82	25.56	26.33	27.12
Subtotal	**30.50**	**31.89**	**33.12**	**34.36**	**35.64**	**36.99**	**38.39**	**39.86**	**41.37**	**42.97**	**44.62**	**46.37**	**48.17**	**50.07**
Wireline Logging														
Operations	1.28	1.36	1.41	1.47	1.53	1.60	1.67	1.74	1.81	1.89	1.97	2.05	2.14	2.23
Schlumberger Subcontract	1.68	1.76	1.86	1.97	2.09	2.21	2.35	2.49	2.64	2.80	2.97	3.15	3.33	3.53
Other Subcontracts	.07	.03	.03	.03	.03	.03	.03	.03	.03	.03	.03	.03	.03	.03
Subtotal	**3.03**	**3.15**	**3.30**	**3.47**	**3.65**	**3.84**	**4.05**	**4.26**	**4.48**	**4.72**	**4.97**	**5.23**	**5.50**	**5.79**
Program Management														
Subtotal	**1.60**	**1.67**	**1.75**	**1.84**	**1.94**	**2.03**	**2.13**	**2.24**	**2.35**	**2.47**	**2.59**	**2.72**	**2.86**	**3.00**
Total Standard Operations	**35.13**	**36.71**	**38.17**	**39.67**	**41.23**	**42.86**	**44.57**	**46.36**	**48.20**	**50.16**	**52.18**	**54.32**	**56.53**	**58.86**
Special Requirements *														
Science Operator														
Science Services	.00	.00	.20	.20	.27	.27	.27	.27	.27	.23	.23	.23	.23	.23
Drilling & Engineering	.41	.98	1.94	1.94	2.90	2.40	2.90	2.40	1.34	.99	1.34	.99	.18	.18
Technology & Logistics	.00	.00	.20	.20	.20	.20	.20	.20	.20	.20	.20	.20	.20	.20
Science Operations	.02	.17	.34	.34	.34	.24	.24	.24	.24	.24	.24	.14	.14	.14
Ship Operations	.59	.00	.00	1.00	.00	2.00	2.50	1.00	.00	.00	1.00	.60	.00	.00
Wireline Logging														
Special Tools	.00	.08	.38	.28	.35	.35	.25	.20	.25	.25	.25	.25	.25	.25
Program Management														
Special Program Needs	.01	.06	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
Total Special Requirements	**1.02**	**1.29**	**3.06**	**3.96**	**4.06**	**5.46**	**6.36**	**4.31**	**2.30**	**1.91**	**3.26**	**2.41**	**1.00**	**1.00**
TOTAL PROGRAM	**36.15**	**38.00**	**41.23**	**43.63**	**45.29**	**48.32**	**50.93**	**50.67**	**50.50**	**52.07**	**55.44**	**56.73**	**57.53**	**59.86**

OVERVIEW: DISCOVERY AND NEW DIRECTIONS OF OCEAN DRILLING

A new view of earth

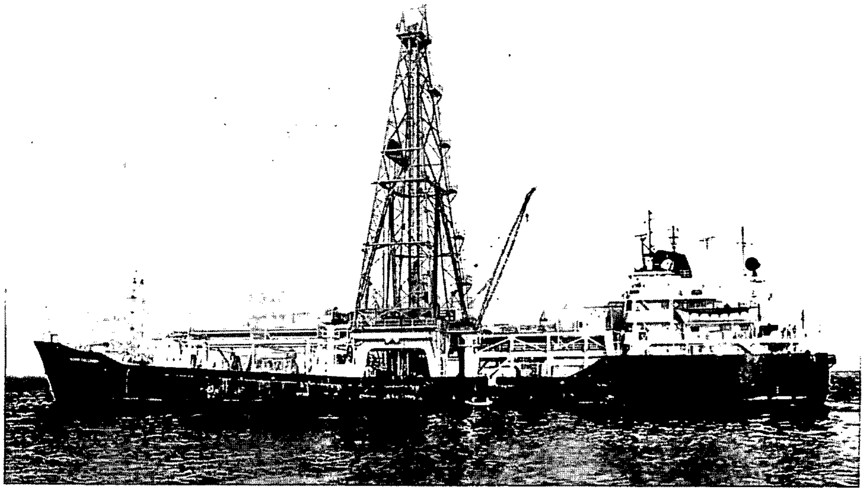
The Ocean Drilling Program (ODP), building on the success of its predecessor, the Deep Sea Drilling Project (DSDP), continues to provide the vital evidence upon which an increasingly comprehensive understanding of global processes and interactions are built. Cores of rock and sediment taken from the world's oceans over the last two decades have revealed the basic mechanisms by which ocean basins, island chains and mountain ranges are constructed ("plate tectonics") and has outlined the history of changes in global circulation, sea level and climate over the last hundred or so million years. The ongoing challenge is to further explore past and present changes in earth's complex interconnected systems: the oceans, atmosphere, biosphere and lithosphere in order to better monitor and manage mankind's increasing use of and pressure on our natural resources and environment.

THE DEEP SEA DRILLING PROJECT

A mission to the blue planet

DSDP was ocean science's first exploratory mission into the unknown region beneath our planet's seafloor. The *Glomar Challenger,* DSDP's research vessel, was used by DSDP scientists from 1968 to 1983. The ship was operated by Scripps Institution of Oceanography while the scientific activities were guided by the Joint Oceanographic Institutions for Deep Earth Sampling (JOIDES). The *Challenger* was dedicated to drilling the sediments and crust of the ocean floor and bringing back cores for detailed studies of sedimentation, crustal composition and physical properties.

DSDP work provided confirmation of seafloor spreading, the relationship of crustal age to magnetic anomalies, and plate tectonics—theories that emerged in the early 1960s as the unifying framework for understanding the creation and destruction of crustal materials. Geologic features on the continents, such as chains of active volcanos of the Pacific rim became much less baffling when placed into the new scheme of global tectonics.



Glomar Challenger

DSDP was, by nature, exploratory. The *Challenger* sailed to all ocean basins (except the Arctic) including the Mediterranean Sea, Red Sea, Black Sea, Gulf of Mexico and Caribbean. Sediments and oceanic crust were drilled in order to provide a global sampling of core and downhole logging data. Over 90 kilometers of core material at 624 sites were collected, analyzed and then reported on in the landmark *Initial Reports of the Deep Sea Drilling Project.* The results of these cruises truly changed our ways of looking at the planet and its history.

THE OCEAN DRILLING PROGRAM BEGINS

New data — more questions

The array of marine sediment cores from the Mesozoic to the Recent provided a whole new view of the geologic evolution of the earth's ocean and atmosphere.

In the early days of the drilling program, research in each new drilling environment achieved spectacular results. Drilling discoveries led to further questions and hypotheses, as well as to the birth of whole new disciplines in earth sciences such as the field of paleoceanography. The array of marine sediment cores from the Mesozoic to the Recent provided a whole new view of the geologic evolution of the earth's ocean and atmosphere. Though the early sediment sections were poorly sampled because of rotary drilling technology, these sediment records provided insights into how the ocean circulation patterns operated millions of years ago, as well as how the climate of the earth has evolved over the past 100 million years. These studies have now gone a step further—to quantify cycles of sedimentation in environments at times when little evidence of significant climate variability was available. A major goal of future drilling is to improve our understanding of how the ocean interacts with the other components of the climate system. This will lead to a better understanding of forcing mechanisms of global climate change.

Crustal drilling confirmed the hypothesis of deep chemical weathering of oceanic crust by hydrothermal fluids. These chemical reactions have important implications on the ultimate control of both the chemistry of the ocean crust and of the ocean itself. These discoveries raised many new questions in addition to demonstrating the importance of hydrothermal processes. A major goal of future drilling is to better define the chemical processes which alter oceanic crust by taking a more focused, integrated approach to the studies of ocean ridges.

More questions — more expertise

Along with an expanding number of problems that could be addressed by ocean drilling, the community involved in scientific drilling grew as well. In the mid-1970s, five countries formally joined with the U.S. JOIDES institutions and initiated the International Phase of Ocean Drilling (IPOD). With this heightened participation level, new directives for ocean drilling were established.

COSOD I

The experts assemble

An international Conference on Scientific Ocean Drilling (COSOD) was held in late 1981. The mandate of COSOD was to determine how ocean drilling and associated scientific programs could be organized and coordinated to attack the most pressing scientific problems in the most productive way. The organization of the COSOD working groups itself reflected the progress in ocean sciences, and the following high priorities areas of study were identified:

- origin and evolution of the oceanic crust
- tectonic evolution of continental margins and oceanic crust
- origin and evolution of marine sedimentary sequences
- causes and long-term changes in the atmosphere, oceans, cryosphere, biosphere and magnetic field
- tools, techniques and associated studies needed to carry out these objectives

With over a decade of experience in ocean drilling behind them, scientists realized the importance of new technology to further the goals of DSDP. The scientific blueprint for ten years of drilling was comprehensive, and focused on these objectives:

LITHOSPHERIC OBJECTIVES

- magma generation and crustal construction at midocean ridges
- fluid fluxes, chemistry and dynamics of hydrothermal systems in oceanic crust

TECTONIC OBJECTIVES

- early rifting history of passive margins
- dynamics of forearc evolution
- structure and volcanic history of island arcs

SEDIMENTARY HISTORY AND GLOBAL PROCESS OBJECTIVES

- response of marine sedimentation to fluctuations in sea level

- sedimentation in oxygen-deficient oceans
- global mass balancing of sediments
- history of ocean circulation
- response of atmosphere and oceans to variations in planetary orbits
- patterns of evolution of microorganisms
- history of the earth's magnetic field

In addition to global coverage for drilling, more focused investigations requiring higher technical demands were proposed, such as the drilling of deep crustal sections into Layers 2 and 3 of the oceanic crust. This required deep, stable holes in igneous rock as well as drilling on bare rock where a sediment cover is not available to stabilize the drill string.

ODP MEETS THE CHALLENGE

More theories — better tools

Thus, a new decade of drilling for scientific problems was outlined—and the Ocean Drilling Program was launched. The fitting of a new drilling vessel, *JOIDES Resolution,* had been commissioned and the first leg of the international Ocean Drilling Program (ODP) set sail in 1985.

The stability and dynamic positioning capabilities of the *JOIDES Resolution* allowed drilling under harsh sea and weather conditions. New regions could be drilled. More continuous core recovery allowed a refinement of global stratigraphy not possible with conventional drilling vessels.

The COSOD blueprint was ambitious, and like most building projects, was underbudgeted in time and money required to complete it. As in any structure, some elements took the load—in this case, the biggest share of budgetary resources. Bare-rock drilling (drilling into massive igneous rock without the support of sediments for the drill string) was recognized as a potentially expensive undertaking. Legs 106, 109 and 118, made possible with the hard rock guide base, were successfully drilled and showed that engineering challenges can be met if adequate development funds are available.

The new Science Operator at Texas A&M University made a commitment to drilling engineering, and improved bits and core barrels have pushed riserless drilling to new limits. Along with the Science Operator, the Borehole Research Group at Lamont-Doherty Geological Observatory commenced its efforts to exploit standard oil industry logging. New tools and techniques such as geochemical logging and borehole televiewer experiments are providing a continuous record of the borehole for correlation with the cores and new data on global stress conditions, respectively.

The early success of ODP has attracted new members. With the addition of the European Consortium for Ocean Drilling, 12 European nations were added to the program. Recently Australia has joined with Canada, bringing the total number of nations directly involved with planning and conducting the drilling program to 19.

What's the experiment?

ODP legs are like any application of the scientific method—a hypothesis is stated and attempts are made to test it. In the JOIDES process, the hypothesis is stated in a drilling proposal. These proposals outline a scientific problem and present supporting geophysical data and models. In practice, past ODP legs have often been combinations of several proposals in order to take advantage of multiple objectives achievable at a given drill site or region.

While this has been a practical approach, there has been a tendency to continue the reconnaissance mode of drilling based on a defined ship track in regions where specific geologic problems can be addressed. The ship track for the first phase of

ODP was determined by logistics more than "filling in the picture" of global geosciences. There was a recognition, however, that certain global themes are best covered in specific ocean basins. For example, the nature of backarc spreading and collisional tectonics, are best studied in the young basins of the Western Pacific.

COSOD II

The experts define experiments

A second international Conference on Scientific Ocean Drilling (COSOD II) was convened in the summer of 1987 to define a unified approach to thematic drilling. At COSOD II, the proposed drilling experiments focused on interconnected global systems and more interaction with other global initiatives. Again, the plans called for pushing ODP drilling capabilities to deeper, more unstable, hotter, and in general, more difficult conditions. Major COSOD II objectives and their technological demands included:

Again, the plans called for pushing ODP drilling capabilities to deeper, more unstable, hotter, and in general, more difficult conditions.

Objective	Technological Demands
Drilling a series of crustal holes to 5000 meters below seafloor to define crustal composition	Capability to drill deep into igneous crust; improved coring and bit life necessary
Drilling accretionary prisms to study deformational processes and mechanism of dewatering	Deep drilling capability in unstable, unconsolidated sediments
Drilling on sedimented ridges and sediment prisms to study diagenetic and deformational processes, geochemical cycling and origin of metal-rich deposits	Fluid sampling techniques to recover hot, corrosive fluids; instrumentation to withstand 300°C conditions

Drilling hotspot traces and fractured old oceanic crust to study plate motion through time	Improved recovery in crust; ability to extract core with magnetic orientation undisturbed

In addition to these programs requiring new technology, new constituencies of researchers have been introduced to ODP, some of whose objectives can be addressed with existing technology. Examples include:

- Scientists who study the evolution and extinction of oceanic biota: what can ocean drilling tell about mass extinctions and theories of speciation of the earth's biosphere?

- Scientists who view ODP boreholes as natural laboratories for instrumentation: downhole seismometers, long-term monitoring of stress and temperature; use of new wireline reentry techniques to deploy instrumentation and innovative data recovery techniques.

- Scientists who study global environmental change: detailed cycle stratigraphy made possible with new instrumentation and new methodology (especially in areas of environmental modeling). Cooperation with other global change studies to advance learning on carbon cycling and other atmospheric effects to which man's activities have contributed.

JOIDES SCIENCE PLANNING

From proposals to ODP programs

The JOIDES science advisory panels and committees looked at COSOD in three ways:

(1) Which COSOD I and II objectives have already been achieved by ODP?;

(2) How can we implement the recommendations for long-term drilling objectives within the existing technology? and;

(3) What developments will be needed for the more ambitious projects?

The JOIDES thematic panels were, in part, responsible for producing planning documents in response to and for refinement of COSOD goals. These panels outlined how ODP can implement broad scientific goals into drilling strategies. This long range plan is based on the high priority themes and provides a timeline and implementation schedule for achieving them.

It became evident that the JOIDES panel structure needed to be modified slightly in order to be responsive to COSOD II objectives, with its emphasis on process-oriented drilling, and to allow a rigorous review of drilling proposals. In ODP, the unsolicited drilling proposals from the international scientific community are the ultimate driving force for the program, providing testable experiments and specific drill sites. Proposals, and integration into unified drilling programs, allow tremendous access to the program for geoscientists from many disciplines and countries.

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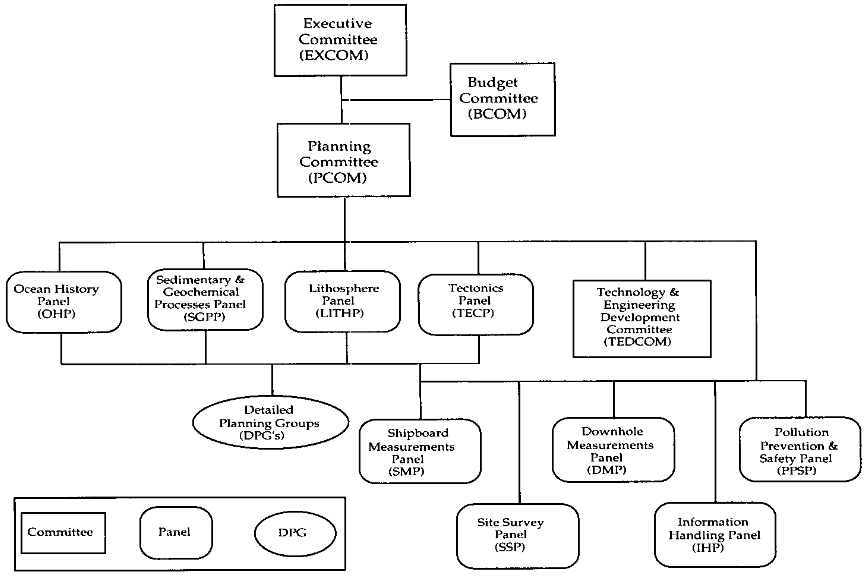


JOIDES Panel Structure

In the new panel structure, the former regional panels have been replaced with Detailed Planning Groups (DPG). The tasks of the DPGs are to present syntheses of high priority proposals and produce an optimal drilling strategy to be reviewed by thematic panels and ultimately PCOM. These approaches may require multiple legs to achieve a desired objective and may be built on progressive advances in drilling technology.

Futurism versus realism

The questions before the scientific community now are:

- **What experimental data are needed to build a more comprehensive understanding of global processes and interactions?**

- **How does this translate into a set of coherent and compelling themes for ocean drilling?**

- **How can these themes be effectively carried out?**

This document summarizes those broad themes, develops some detailed objectives and shows how deep ocean drilling can address them. The international scientific community has two fundamental challenges over the next two years. First, the community must continue to develop a still more efficient and effective strategy of ocean drilling that will markedly improve our understanding of Planet Earth. Second, the community must convince governments and funding agencies alike of the paramount importance of not only maintaining, but enhancing their investment in this key program of research. Ocean drilling provides vital information about how mankind can continue to utilize the earth, its natural resources and environment without destroying them.

ACHIEVEMENTS OF ODP TO DATE

Introduction

The predecessor of ODP, the Deep Sea Drilling Project, made a major impact on the way in which we view the evolution of the earth, its oceans, atmosphere and natural resources. By way of practical example, "plate tectonics"—strongly supported by ocean drilling—now provides the scientific framework within which the majority of modern petroleum and mineral exploration is carried out. As these natural resources become increasingly difficult to find, a still more comprehensive scientific framework will be required to guide exploration. The impact of human development upon the natural environment is also coming into sharper public focus and some of the broader interactions have already been defined by ocean drilling.

A more comprehensive understanding of earth systems and interactions is emerging from the current program. Within the first four years of ODP, the largest international geosciences program studying the ocean, major new contributions in our scientific understanding of the earth, in technical developments and in educational opportunities have been made. In this section some of these important successes are highlighted.

SCIENTIFIC ADVANCES OF ODP

In this section we identify some of the major new contributions made towards an improved understanding of important geologic processes rather than provide leg-by-leg results of the Ocean Drilling Program. Six major scientific topics have been selected to document major achievements made in ODP:

(1) evolution of global climate;

(2) fluids in accretionary complexes;

(3) exploration of the ocean crust;

(4) hotspot evolution and true polar wander;

(5) plate divergence; and

(6) scientific benefits of downhole measurements.

1. Evolution of global climate

On the earth today, glacial ice contains a volume of water equivalent to a 30 meter rise in sea level. With the exception of Greenland and small mountain glaciers, most of this ice is found on the Antarctic continent. The large ice mass on Antarctica is made up of two major ice sheets, the smaller West Antarctic ice sheet (with a volume equivalent to a sea level rise of only six meters) and the much larger East Antarctic ice sheet.

The presence of this large ice mass in the high southern latitudes has major implications for global climate. The ice affects the surface albedo, the surface elevation and the thermal gradient of the earth. Thus, understanding the history of this major feature of the ocean-atmosphere-cryosphere system is critical to our understanding of the global climate system during the Cenozoic.

Part of the scientific objectives of Legs 113 and 119 was to provide direct sedimentologic evidence on the evolution of both the West and East Antarctic ice sheets. Leg 113 drilled sites within the Weddell Sea where sedimentation is affected by the presence of both ice sheets. Drilling results showed that the West Antarctic ice sheet underwent its major development during the late Miocene (about six to eight million years ago). Drilling off the Antarctic Peninsula suggests that the early history of this ice mass was a time of major instability, with large fluctuations in the extent of glaciation. Drilling results suggest that much more stable conditions have existed since the Pliocene.

Initial interpretation of the Leg 113 results suggests that the major development of the East Antarctic ice sheet was slightly earlier than in West Antarctica and occurred during the middle Miocene. This age for development of major ice in Antarctica was consistent with previous interpretation of other geologic evidence. However, other interpretations of the marine stable isotopic records suggest that the major development of ice in Antarctica occurred much earlier. Leg 119 was sent to Prydz Bay off the Antarctic continent to recover sediment records of the East Antarctic ice sheet. Unlike the Weddell Sea, Prydz Bay in the southernmost Indian Ocean receives terrigenous sediments which originate only in East Antarctica and thus should have an unequivocal record of the history of glaciation of the East Antarctic ice sheet.

Sediments recovered in Prydz Bay provide the first direct evidence that the development of ice in Antarctica is much older than previously assumed. Glacial marine sediments of early Oligocene to Eocene in age were recovered and glacial sediments possibly as old as 42 million years were recovered. Other sediment evidence suggests that the East Antarctic ice sheet may have been considerably larger than at present during its early history. This new evidence clearly will cause much re-examination of our previous interpretation of the evolution of Cenozoic climates and will greatly add to our understanding of the evolution of global climate.

A major feature of atmospheric circulation in the tropics is the monsoon circulation of the eastern equatorial Atlantic and northern Indian Ocean. The geologic history of this important feature of the climate system reflects the changes in insolation of the tropics that result from changes in the earth orbital parameters and the evolution of the Himalayas. Today the high elevation of the Himalayas and its associated high albedo from snow cover results in a marked seasonal contrast in the heating of the Asian continent versus the Indian Ocean. This contrast results in a marked seasonal cycle in atmospheric circulation with very strong southwesterlies during the summer months and northeasterlies during the winter.

This complete reversal in winds has a profound effect on ocean circulation and oceanic productivity in the northern Indian Ocean. Drilling in the Indian Ocean was, in part, designed to examine a number of important aspects of the monsoon circulation. For example:

(1) how did the intensity of the monsoons change and how was this change related to the uplift of the Himalayas;

(2) how did the variability of the monsoons change with geologic time and how are these changes related to the known pattern of change in insolation that result from orbital changes in the earth; and

(3) how was the deposition of organically rich sediments, which result from the high biologic productivity in the coastal upwelling regions, affected by the monsoonal circulation?

Drilling results from Leg 116 on the Bengal Fan show that large quantities of coarse grained sediment were delivered to the distal part of the fan by the early Miocene. This suggests that major uplift of the Himalayan Mountains occurred earlier than the middle Miocene age often assigned to this event.

Leg 117 was specifically designed to test hypotheses about the origin and evolution of the Indian Ocean summer monsoon and its effect on global climate changes. The leg was a spectacular success in both the quantity (over 4,300 meters of recovery—a new record) and the quality of the sediments recovered. The outstanding achievement of the leg was acquisition of a unique, well-preserved record of monsoonal upwelling and eolian transport that is continuous, high-resolution and extends back over ten million years. The observed frequencies of variation in sedimentary parameters are those predicted by hypotheses that relate the strength of the monsoon to changes in the earth's orbit around the sun. The record also shows some long-term changes that are related to the onset of monsoonal upwelling, an event that may reflect the uplift of the Himalayas. Initial results indicate that upwelling faunas and floras appeared in the early late Miocene about ten million years ago. Detailed quantitative analysis of the plankton groups in this continuous section will establish the true date of the initiation of monsoonal upwelling.

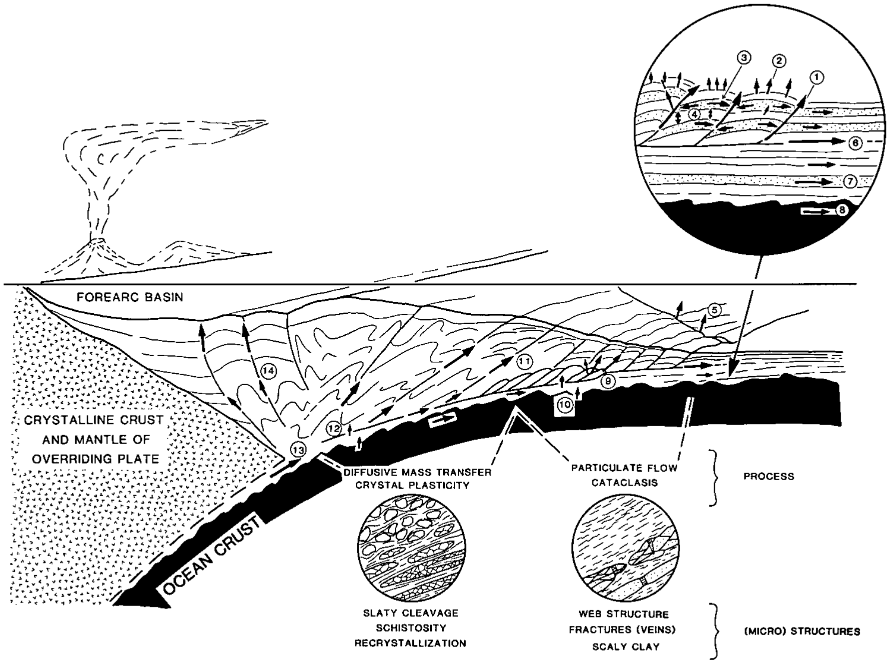
2. *Fluids in Accretionary Complexes*

The magnitude of flow and dissolved mass transport and its effect on the global geochemical balance are largely unknown and may rival that of midocean ridges.

Active margins are the sites where, by tectonic compaction, fluids return to the ocean from subducted and accreted sediments. The magnitude of flow and dissolved mass transport and its effect on the global geochemical balance are largely unknown and may rival that of midocean ridges. The cycle of water and volatile components is especially affected by this newly recognized mode and pathways of transport.

The interaction of fluids, fluid pressures and sediments within the accretionary prism controls deformation at convergent margins. For example, the accretionary wedge becomes lithified by cements precipitated from circulating fluids; the fluid pressure distribution is responsible for the partitioning of accreted and subducted sediments; ultimately, subducted fluids alter the strength of rocks and therefore the distribution of deep-focus earthquakes. The composition of subducted sediments, whether rich in organic matter, terrigenous clastics or oceanic volcanic components, imprints the fluid chemistry and controls the generation of fluid and gas pressures in forearc regions. There are two primary mechanisms for fluid flow in an accretionary prism. Gravity-driven flow of fluids seaward through aquifers is a hydrologic mechanism distinct in importance and source from those of tectonically-driven flow. Gravity-driven flow is typically developed in passive continental margins but also occurs in active margin settings and hence requires attention in the context of accretionary complexes. All of these processes can be uniquely addressed by ocean drilling.

Drilling during the last three years has provided important insights into the mechanisms by which the accretionary prism develops. The first hole ever drilled through an accretionary complex and into subducted sediments was completed on Leg 110 in the Lesser Antilles forearc. Data collected from this site defined two distinct hydrogeologic systems through which the Barbados accretionary prism dewaters. Pore water chemistry, temperature anomalies and structural observations from drilling indicate that fluids are moving principally through zones controlled by fracture permeability associated with faults, and



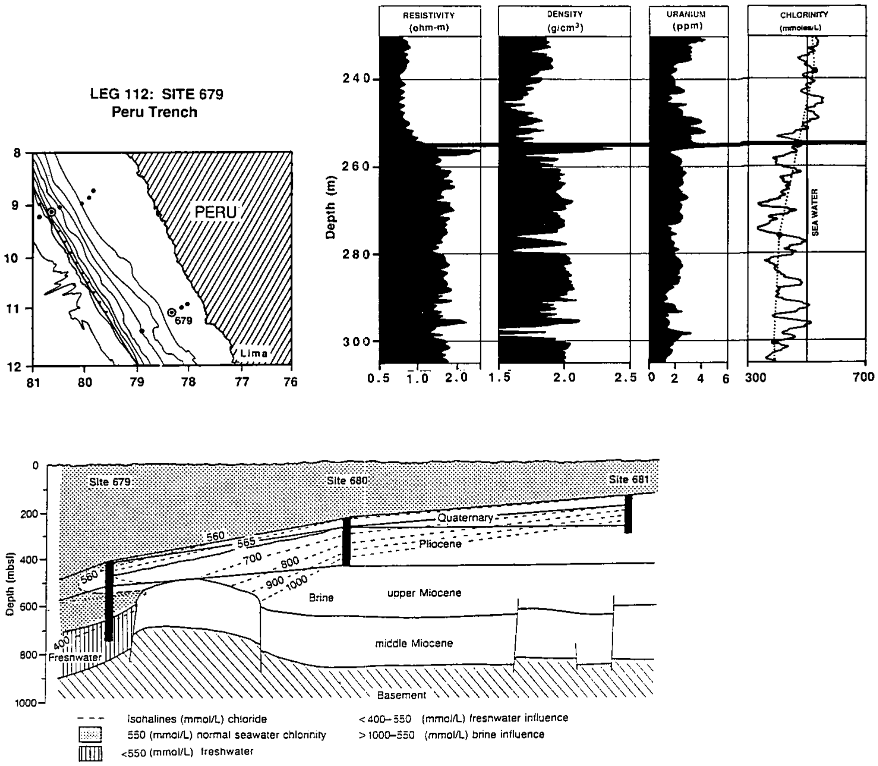
Fluid migration paths and deformation mechanisms in an accretionary prism. Circled numbers 1-8 show possible fluid flow paths in the zone of initial accretion. Paths 9-14 are possible routes of escape for fluids generated in or squeezed from rocks deep in the complex. Deformation mechanisms, illustrated in the two circles at the bottom of the figure can range from grain boundary sliding at shallower levels to diffusive or crystral-plastic processes at depth. Fluid pressure strongly influences the dominant operative mechanism, for example, by changing from particulate flow at lithostatic pore pressures to cataclastic as the fluid pressure drops. (Reprinted from Langseth, M.G., and Moore, J.C., 1990, Eos Transactions, vol. 71, no. 5, p. 245 by, the American Geophysical Union, Washington, DC).

secondarily along stratigraphic levels controlled by intergranular permeability. The accretionary wedge and underthrust sediments comprise distinct fluid reservoirs, separated by a permeability barrier paralleling the decollement zone.

Data from Legs 110 and 112 (Peru margin) show that fluids from sediments of active margins can be significantly "fresher" than normal seawater. This evidence supports previous observations from the DSDP and several concepts are being advanced as to their source: the break-down of water-rich methane gas hydrates, the ultrafiltration of seawater during flow through clay rich intervals and the dehydration from clay and other hydrous minerals. The flow of fluids from the subducting slab through the fractured leading edge of the continental crust is another intriguing phenomenon of the hydrology of convergent margins. Geochemical logging, in conjunction with other fluid chemistry measurements, for the first time documented "freshening" of subsurface fluids.

Drilling in the Peru accretionary prism, the Oman margin and off northwest Africa, also documented extensive subsurface brines. In these instances, upward diffusion of salt has created unusual geochemical environments in which sulfate-reducing

Salinity inversion in the continental shelf off Peru



In the forearc of the Peru Trench, geophysical logs in Hole 679 identified a major seismic impedence boundary that forms a prominent reflector throughout the area. The geochemical logs show that the pore waters below the reflector are fresher that those above. The likely source of the fresh waters is an aquifer being fed from land 100 kilometers to the east. (Anderson, R. and Greenberg, M., Proceedings of the Ocean Drilling Program, Scientific Results, 112, in press).

bacteria continue to degrade organic matter to several hundred meters depth in the sediment where otherwise carbonate-reducers would be active. Advective and density driven hydrologic flow in these margin settings thus impacts greatly on the geochemical and sediment facies of these deposits.

3. *Exploration of the Ocean Crust*

Drilling into deep layers of the oceanic crust is a high scientific priority of the Ocean Drilling Program. The overall thematic objective of lithospheric drilling is to understand the origin and evolution of the oceanic crust, lithosphere and underlying mantle. The two highest priorities for this drilling are:

(1) to determine the structure, composition and alteration history of the crust; and

(2) to characterize the processes of magma generation, crustal construction and hydrothermal circulation involved in the formation of oceanic crust.

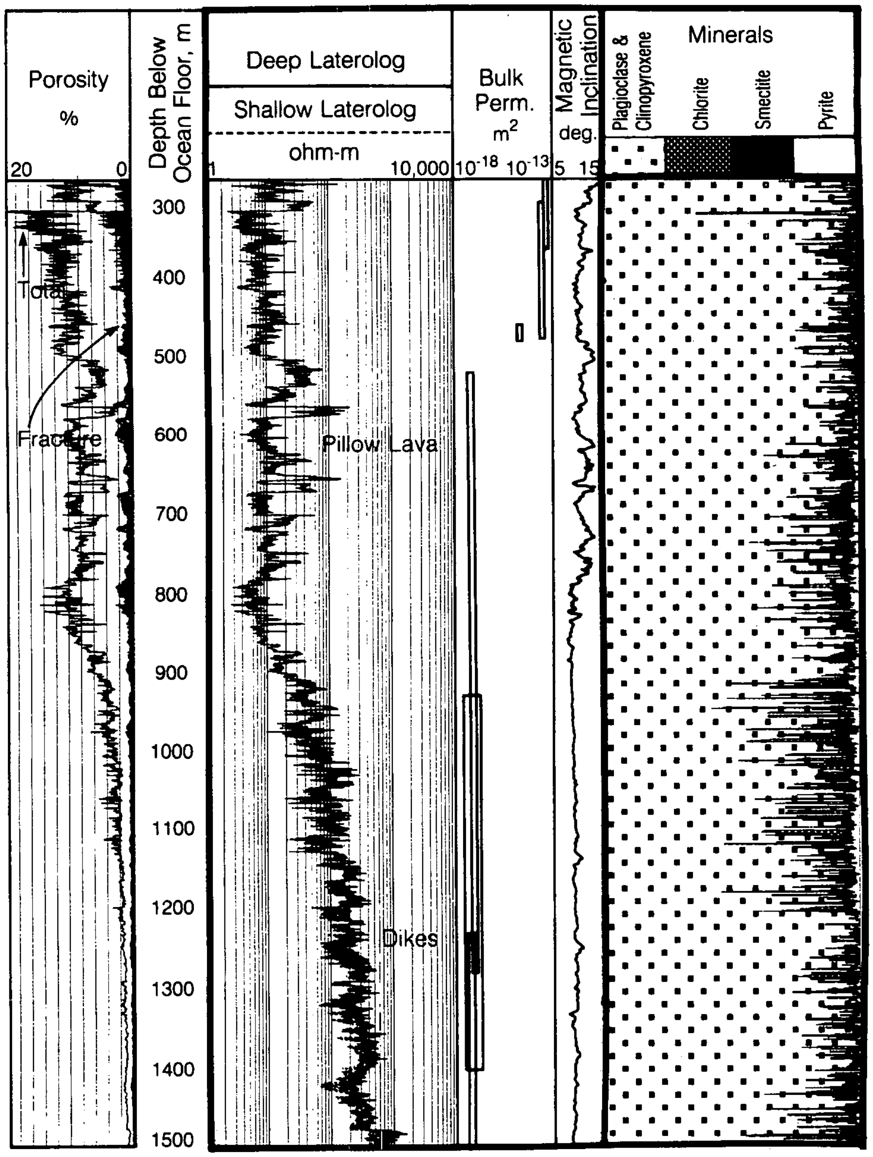
Drilling can also provide important insights into the magmatic processes associated with the onset of seafloor spreading, mid-plate volcanism, convergent margin processes, the physical properties of oceanic lithosphere, and the composition and dynamics of the underlying mantle.

To achieve these objectives we needed both to develop drilling technologies that allow initiation of a drill hole on bare rock (where sediment cover does not provide the necessary support of the drill string when starting a hole) as well as to improve drilling in fractured young crustal rocks. Legs 106, 109 and 118 were devoted to improving our ability to drill in the ocean crust and to extend our knowledge about how oceanic crust is generated. Drilling results from the Mid-Atlantic and Southwest Indian Ridges have provided important new constraints on the structure and composition of the oceanic crust and upper mantle along slowly accreting plate boundaries.

Leg 106 was the first attempt to deploy the hard rock guide base (HRGB) designed by ODP engineers to allow the spudding of holes at bare-rock sites. The leg succeeded in deploying the HRGB in the rift valley of the Mid-Atlantic Ridge and establishing a drill hole. Leg 109 returned to this site to continue operations. On Leg 109 serpentinites and partially serpentinized harzburgites were recovered in the Mid-Atlantic Ridge rift valley only a few kilometers from the spreading axis. The presence of these rocks, thought to be typical of the lower crust or upper mantle, at very shallow crustal levels away from any major fracture zone, indicates that slow spreading ridges must be characterized by periods of very low magma supply and/or extensive tectonic thinning. Studies of the peridotites themselves have been extremely useful in understanding the compositional variability and melting history of the upper mantle beneath a slow spreading ridge.

An important accomplishment of ODP to date was the completion of downhole logging programs on Legs 102, 109 and 111, at the three deepest crustal holes drilled during the Deep Sea

Drilling Project (Holes 395A, 418A, and 504B). The extensive suite of state-of-the-art logging measurements and specialized borehole experiments carried out in these holes has provided unique data on the physical properties of both young and old oceanic crust. At 504B it was found, somewhat unexpectedly, that the lower 1,000 meters of the hole, comprising the partially-sealed pillow lavas and sheeted dikes of Layer 2, has uniformly low permeability, too low to permit hydrothermal circulation in the lower crust. Thus the only highly permeable section of the crust in this hole is the upper 100-200 meters of pillow basalts.



Logs from ODP Hole 504B drilled into young crust created at the Costa Rica rift. The logs reveal, at top, porous pillow lava created as magma reaches the ocean in the Costa Rica rift, and below, nearly non-porous, sheeted dikes of basalt formed by intrusion at the rift. Not shown is an initial 275 meter section of sediments. (Anderson, R.N., J.C. Alt, and J. Malpas , 1989, Proceedings of the Ocean Drilling Program, Scientific Results, 111: College Station, TX, pages 119-132).

These results are extremely important for modeling hydrothermal processes at midocean ridges and understanding the alteration history of the oceanic crust.

The most exciting, and unexpected, lithospheric drilling achievement to date is unquestionably the recovery of 500 meters of gabbro at Hole 735B during Leg 118 on the Southwest Indian Ridge.

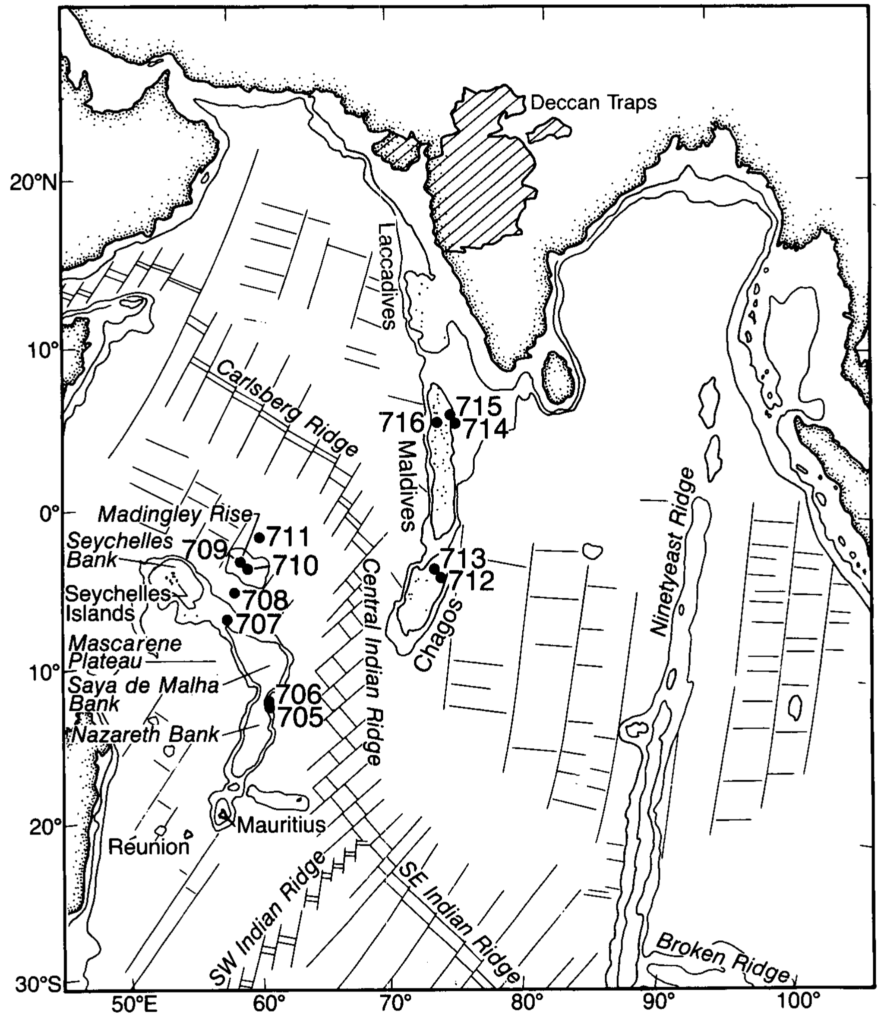
The most exciting, and unexpected, lithospheric drilling achievement to date is unquestionably the recovery 500 meters of gabbro at Hole 735B during Leg 118 on the Southwest Indian Ridge. Technically, this hole was a major triumph for the new bare-rock drilling techniques developed by ODP; it also set new records for both penetration (60 meters/day) and recovery rates (95% for the bottom 400 meters; 87% overall) in a crustal drill hole. The gabbros obtained at this site represent the first coherent section of *in situ* Layer 3-type material ever recovered from the ocean basins. Studies of the geochemical and petrologic variations in this section will allow the magmatic evolution of a fossil oceanic magma chamber to be investigated in its true stratigraphic context. The logging and borehole experiments carried out in Hole 735B have also provided the first *in situ* information on the physical properties (porosity, seismic velocity, and magnetism) of Layer 3.

4. Hotspot evolution and true polar wander

Hotspots are melting anomalies of the upper mantle which produce linear chains of volcanic islands, seamounts and ridges on overlying lithosphere. These hotspot-related volcanic lineaments are a feature of all the ocean basins. Their distinguishing characteristics are an orientation consistent with the direction of motion of the plate on which they are formed and a progression in age of volcanism away from the hotspot. Thus, drilling along hotspot lineaments can provide first-order data about the history of plate motions, which is fundamental to our understanding of global tectonics.

It is currently debated whether such hotspots are fixed in the mantle (and so constitute a useful reference frame for plate motions and reconstructions) or whether they move within some upper mantle convective flow regime. The objective of Indian Ocean drilling Leg 115 was to examine these alternate hypotheses.

Leg 115 investigated one of the two prominent hotspot lineaments in the Indian Ocean, that begins in western India as the Deccan flood basalts, continues south as the Laccadive, Maldive and Chagos Island chains, and culminate as the Mascarene Plateau and young volcanic islands of Mauritius and Reunion. This nearly north-south line parallels the Ninetyeast Ridge and the two together trace the northward motion of India away from the supercontinent of Gondwana over the last 100 million years. The results of this leg establish clearly that the age of eruption of the volcanoes increases to the north in keeping with the hotspot model. Furthermore, the geometry and ages along the parallel hotspot tracks support the idea that at least these hotspots are stationary features in the mantle over long periods.



Major bathymetric features of the central Indian Ocean are shown by 2- and 4-km depth contours. Leg 115 drilled into volcanic rocks at Sites 706 and 707 (Mascarene Plateau), Site 713 (Chagos Bank), and Site 715 (Maldives Ridge). These sites are part of a volcanic trail that links present-day hotspot activity near Reunion Island with the Deccan flood basalt volcanism erupted at the Cretaceous-Tertiary boundary. (Reprinted from Backman, J., Duncan, R.A., et al., 1988, <u>Proceedings of the Ocean Drilling Program</u>, Initial Reports, 115: College Station, Tx., Ocean Drilling Program; page 6, Fig. 1.).

The Deccan flood basalts, which have been correlated with the mass extinctions at the time of the Cretaceous-Tertiary transition, are now definitely linked to the catastrophic volcanic effects of the onset of Reunion hotspot activity.

Because hotspots appear to be fixed in the mantle, their volcanic traces provide a very convenient record of the motion of lithospheric plates passing over them. Paleomagnetic measurements also determine the motion of a site with respect to the geomagnetic dipole axis (assumed to coincide with the spin axis of the earth). Hence, every volcano that has erupted over a given hotspot should record the same magnetic latitude in the magnetized basalts. Leg 115 found, however, a systematic departure in paleolatitudes recorded along the hotspot trace. It appears that the Reunion hotspot was about 8 degrees south of its present position until 55 million years ago, and since then moved northward. Assuming a geocentric axial dipole model for the time-averaged geomagnetic field, this could be evidence that hotspots are not fixed except that all hotspots would have to move together in order to preserve the congruence of their traces. In addition, this result supports data from the Pacific basin that show a southward motion of the Hawaiian hotspot of a similar magnitude over the same period. Both studies are compatible with the old idea of "true polar wander"; that is, rotation of the entire figure of the earth with respect to the spin axis, perhaps in response to changes in its principal moment of inertia. Hence, in the paleomagnetic reference frame the Pacific mantle appears to head south at the same time the Indian mantle moves north.

5. Plate Divergence

New models of continental rifting have been formulated as a result of ODP drilling.

The effects of plate divergence, or rifting, are well known as they relate to the formation of ocean basins, but processes and styles of rifting remain controversial. The roles of pure shear versus simple shear processes attendant to continental and oceanic rifting are debated. Additionally, rifted margins may or may not be associated with large volcanic sections. A variety of drilling results have helped to characterize the nature of specific rifted margins, although results in several instances remain a topic of controversy.

ODP drilling on the Voring Plateau (off Norway) proved that seaward-dipping reflector sequences (SDRS) that characterize the outermost regions of some continental margins may indeed be large piles of volcanic material. However, the full range of composition of these volcanic rocks is still not known; drilling did not penetrate their full thickness so that the composition of the basement beneath these volcanic strata is not known, i.e., thinned continental or oceanic crust. Already, however, new models of continental rifting have been formulated as a result of ODP drilling.

Off the Galicia margin of the Iberian Peninsula, mantle-like ultramafic rock was found at shallow crustal levels, and elsewhere along this margin peridotite is known to crop out on the seafloor. To some geologists this is confirmation of the model of simple shear rifting involving low-angle detachments that cut the entire crust. An alternative interpretation however, holds that these peridotitic rocks are older remnants of accreted ophiolites from the late Paleozoic Hercynian orogeny. Mountains and crustal uplift are not restricted to convergent margin settings. Such prominent ranges as the Transantarctic Mountains and the Sierra Nevada of California are believed to be flaps of crust that were uplifted as a result of breaking from a larger piece of more depressed lithosphere. Recent drilling on Broken Ridge in the Indian Ocean has provided another possible example of this tectonic style. This rebound-style of tectonics is poorly understood, particularly as crustal subsidence normally follows a rifting event.

An important realization of the past several years is the way in which both divergent and convergent tectonics can occur simultaneously in a single orogen. Drilling in the Tyrrhenian Sea provided an example of this. Results there clearly documented the age of back-arc rifting to be post-Late Miocene and the formation of ocean crust to be Pliocene to Recent. These young ages correspond exactly to the age of thrusting in the Apennine fold belt that is trenchward of the Tyrrhenian Sea.

On the northern margin of the Exmouth Plateau (northwest Australia), ODP drilling recovered marine sediments with the oldest known nannofossils and discovered upper Triassic reef complexes on the edge of the pre-Indian ocean rift. As an important spin-off, this discovery is also likely to define a new regional objective for future petroleum exploration.

6. Scientific benefits of downhole measurements

Downhole measurement programs at sites with deep crustal penetration have provided new insights into the evolution of basaltic crust.

Downhole measurements are playing an ever increasing role within the scientific efforts of the Ocean Drilling Program. Downhole measurements have produced exciting new results in three key areas: the study of crustal properties and evolution; the study of paleoclimate and paleoceanography; and the change in composition of formation fluids.

Downhole measurement programs at sites with deep crustal penetration have provided new insights into the evolution of basaltic crust. Geophysical properties such as velocity, density, porosity and magnetization often have been estimated from measurements of dredge samples or sea-surface geophysical surveys. *In situ* downhole measurements provide continuous records not only of these properties, but also provide new insights as to their causes: flow morphology, fracturing, permeability and fracture filling by alteration. Measurements of principal stress directions on ODP boreholes show that it is feasible to test models for the relative importance of different plate driving forces, but many more measurements are needed in future holes of opportunity as well as specific experiments.

Downhole measurements have provided a level of resolution and continuity that allows paleoclimatic and paleoceanographic information to be derived in a manner which has previously been attainable only in the best of coring circumstances. Signal frequencies of the same character as the well-known climate frequencies have been seen at several sites consistent with the hypothesis of orbitally forced climate change. Many of these signals have been observed during times when evidence for orbital forcing was not well defined. This information is essential to a better understanding of how climate and the oceans have changed over geologic time. Geochemical logging, specifically the use of chlorine and hydrogen indices, for the first time has documented the "freshening" of subsurface fluids of a convergent margin. Such information is the highest priority for evaluating the role of fluids in accretionary complexes.

TECHNICAL DEVELOPMENTS AND OPPORTUNITIES

Introduction

The development of new drilling approaches and the ability to make downhole, *in situ* measurements have become integral parts of the Ocean Drilling Program. Many of the scientific objectives for drilling in oceanic crust could not be accomplished without the use of new drilling tools and techniques. The study of fluids in accretionary prisms cannot be accomplished without better instruments for sampling pore fluids or techniques for measuring *in situ* physical properties of the oceanic crust that interact with these fluids.

Drilling Developments

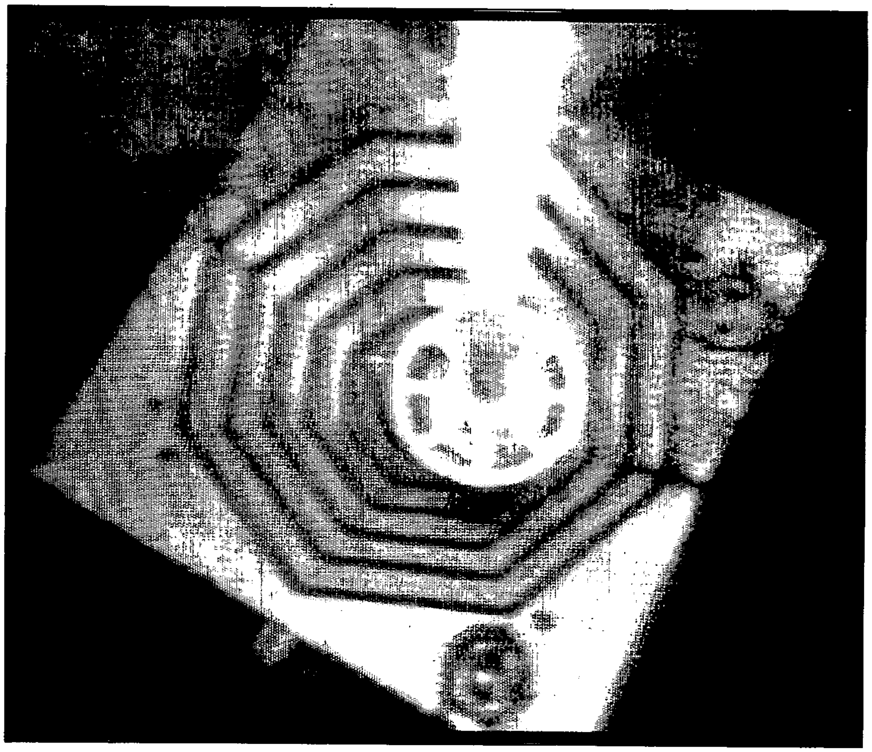
While Ocean Drilling Program engineering developments are specifically designed to address the scientific objectives of the program, many of these developments have applications beyond scientific ocean drilling. Examples of such developments are:

- Measurement of actual stresses during deployment and while drilling with long drill strings. These measurements are important for the design of slimline risers for deep water oil field drilling.

- Development of the wireline-retrievable NaviDrill Core Barrel and positive displacement coring motors. The 24 centimeter (9-1/2 inch) positive displacement coring motors should serve both science and industry as the downhole coring motors that are best suited for coring in crustal lithologies. ODP has been developing these coring motors with Eastman Christensen (located in Celle, Federal Republic of Germany) since 1985.

- Development of various types and designs of hard formation bits. ODP-designed bits will best be utilized to drill crystalline lithologies, both on the continents and in the oceans. ODP has worked with several major bit manufacturers to lengthen bit life and improve core recovery.

- Deep-water, real-time TV reentry systems. This remote viewing system, which can be used by industry in oil field and ocean engineering applications, has proved to be both rugged and reliable for deep water reentries or ocean bottom surveying.



View of hole reentry using underwater remote viewing system

- Development and deployment of the hard rock guide base. Along with developing the hardware to allow unsupported drilling, ODP has shown that large packages of equipment can be set on the ocean floor in deep water with a drill string. This operational procedure has definite application to both industry and science for earthquake monitoring and/or study of undersea habitats.

- High-speed diamond coring systems. On Leg 124E ODP successfully deployed for the first time a high-speed, narrow-kerf, top-driven diamond coring system (DCS) inside ODP's drill string. This system has worked extremely well for land-based use in both minerals and scientific drilling, but had never been used offshore. The use of a DCS from a drilling vessel is anticipated to greatly aid in the coring of highly-fractured crystalline rock as well as interbedded chert/chalk sequences. If the DCS can be demonstrated to be a feasible solution to the many technical problems faced by ODP, the oil industry will most probably look at a similar system for deep-water exploratory holes if a blow-out prevention system could be incorporated into the design.

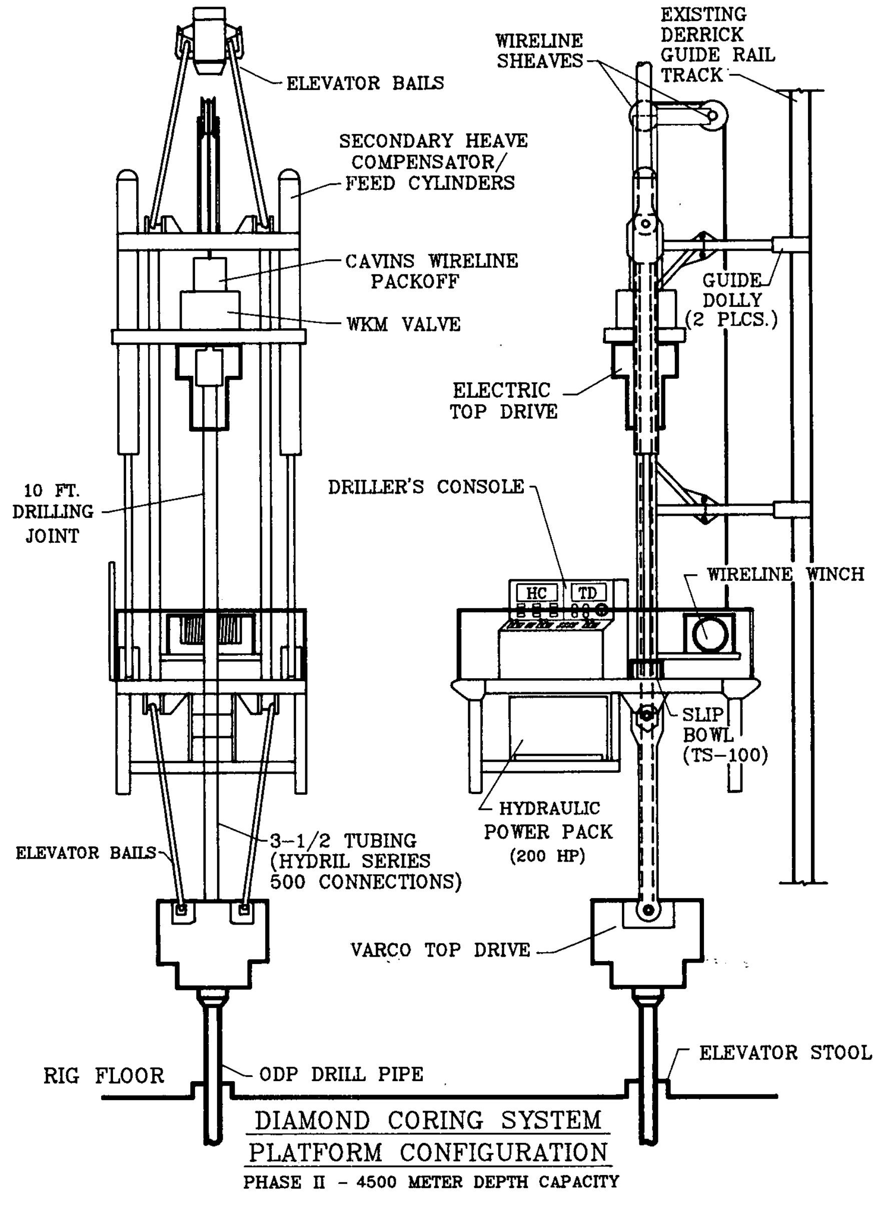


Illustration of the Diamond Coring System

Downhole Measurements Development

The Ocean Drilling Program now fields a state-of-the-art research effort that will become increasingly important as the major testing ground in the next decade for new technologies.

The wireline logging operations of the Ocean Drilling Program have taken on new importance for the development, testing and dissemination of new technologies to the world's largest single industry—the discovery, production and distribution of oil and gas. This important role came about from the collapse in oil prices in 1986 which resulted in a major reduction in workforces of the international oil companies (30% average reduction in major oil companies), elimination of more than one-half of the independent oil companies in the world, and consolidation of the oil field service industry into one dominated by four mega-companies (Balbei-Hughes, Haliburston, Schlumberger and Western-Atlas). Because of the collapse in prices, the research and development efforts of major oil companies have been necessarily redirected to near-term objectives, and that of the major service companies severely crippled (for example only 40% of those who worked for Schlumberger in 1980, still work for the company).

The Ocean Drilling Program now fields a state-of-the-art research effort that will become increasingly important as the major testing ground in the next decade for new technologies which will be reported in the open literature. Efforts in development of new technologies, calibration and interpretation techniques for dissemination to the oil industry are exemplified by on-going experiments with the sophisticated, new geochemical logging tool. This borehole tool measures the chemistry of rock and fluids *in situ* and in real-time. The chemical signals obtained with the geochemical tool are complementary to the present technology of measuring the geophysical signature of rocks and fluids (sound velocity, porosity, density and electrical resistivity). ODP has logged over 30 sites worldwide with this newly evolving technology whereas no oil company has logged more than four wells. The industry has been closely following the results of this effort and cooperation and collaboration in the interpretation of ODP results have led to significant improvements in this technology.

Future developments within ODP of high temperature cooling-techniques, borehole-fluid sampling, monitoring permeability and pore pressure by wireline instruments deployed from non-drilling research vessels, ultrasonic and electrical imaging, core orientation, and software integration will be followed closely by industry.

Industry and Scientific Cooperation

A large part of the Ocean Drilling Program's technical success can be attributed to its unique worldwide association with private industry and scientific research organizations. The program enjoys unprecedented cooperation with industry for developmental work. Also contributing to the program's technological base is the close association with U.S. government research labs such as Sandia and Los Alamos National Laboratories. In addition, ODP enjoys close liaison with such international research projects as the German Continental Drilling Program (KTB), the Swiss NAGRA drilling for nuclear waste disposal, Sweden's Vattenfall Project and France's Institute Français du Petrole (IFP).

A large part of the Ocean Drilling Program's technical success can be attributed to its unique worldwide association with private industry and scientific research organizations.

Oil companies, drilling technology and other firms that have been involved with ODP include: Amoco, Chevron, Eastman, Britoil, British Petroleum, Statoil, Norskhydro A/S, Christensen, Huddy, Christensen Mining Products, Tonto Drilling, Westech, Security, Rock Bit Industries, Diamant-Boart, Longyear, Exlog-Totco and Baker-Hughes.

In addition to this direct cooperation, industry has participated in the program in other ways. Many industry scientists have been involved in the planning process and have participated in many of the drilling cruises. Finally, the drilling program has provided a first-order data set on the sedimentation and history of the world's ocean which is fully available to industry scientists.

OPPORTUNITIES IN EDUCATION AND INTERNATIONAL RESEARCH

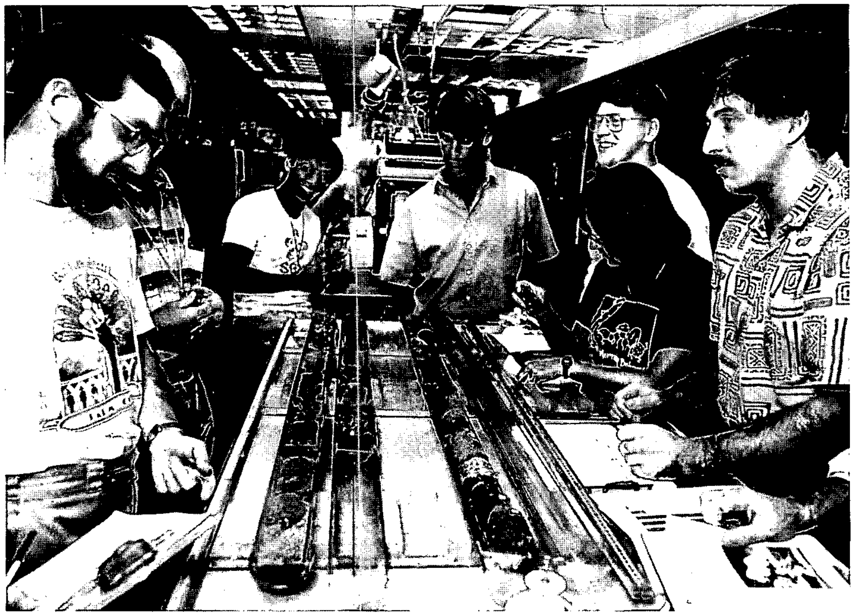
One of the major roles ODP plays in educating future earth scientists is through direct participation of graduate students.

Indeed, ODP can be regarded as a major international "university" for the training of undergraduate and graduate students in earth sciences. Graduate students can become involved in ODP, and have done so in considerable numbers, in the same ways as more senior scientists. Proposal submission within the JOIDES structure, participation as a member of a shipboard scientific party, and samples of DSDP/ODP cores are all available to graduate students, who may follow the same procedures as other members of the scientific community.

Proposal Submission: JOIDES accepts input by individuals or groups in the form of preliminary or mature proposals for drilling programs. Graduate students most often become involved in proposal submission through their faculty advisor. Topics for numerous theses, dissertations, and graduate research projects have evolved from the preparation of these proposals, as well as from ODP cruises based on proposals that successfully found their way into the drilling schedule.

Shipboard Participation: There is no minimum-education restriction upon shipboard scientific participation; 19% of the applications received for shipboard participation have been from graduate students, and 18% of all shipboard scientists were graduate students at the time of their participation. They successfully compete on an equal basis with more experienced scientists for shipboard positions corresponding to their area of expertise. This provides a unique opportunity in graduate education, to be able to interact in the intense scientific environment typical of long ocean drilling legs as well as being involved in the production of the important scientific contribution represented by the volumes published for each leg.

Shipboard participation exposes the student to as wide an array of frontier geoscience and technology as is found in a first-rank university, with the added advantages of intense interaction and cross-fertilization of ideas among workers in different specialties; opportunities to learn from some of the world's leading geoscientists; experience of organizing multidisciplinary work on a common set of materials; working to strict deadlines on an interdependent team; opportunities to observe and discuss discoveries in one's own and other disciplines, as they happen.



Graduate students on board the JOIDES Resolution.

Specific to the United States, the JOI/U.S. Science Support Program makes funds available to both faculty and students of U.S. academic institutions for cruise-related salary and travel, and for post-cruise science support. In addition, JOI/USSAC Ocean Drilling Fellowship Program awards are made periodically following a national competition among graduate students at the pre-doctoral level. These awards provide opportunities for Fellows to develop a high degree of proficiency in their research training and at the same time to advance the research of the Ocean Drilling Program by either participating on an ODP cruise as a member of the shipboard scientific party or studying DSDP/ODP samples recovered on a previous cruise. A total of 15 such fellowships have been awarded to date; over half have gone to students at non-JOIDES-associated institutions, an indication that this fellowship is known outside the immediate JOI community.

In the U.K., similar student opportunities exist and, because the Natural Environment Research Council (NERC) is the sponsor of many of the research students as well as being the U.K. national member of JOIDES, arrangements to extend studentships, to allow for the additional commitments of ODP participation, can often be made.

Also, graduate-level participation in ODP has come through direct affiliation with Texas A&M and Columbia Universities. These graduate assistants with ODP are a multi-national group, reflecting the large percentage of foreign nationals who come to TAMU and Columbia University for graduate studies. Many of these students, who work in ODP Borehole Research Group, Science Operations, Drilling Operations and Engineering, and Science Services, sail as members of the scientific party or as marine technicians at some point during their years with ODP.

Shore-based Research: Samples from ODP and DSDP cores can be requested for graduate students' research. Samples provided in conjunction with cruise participation or before one year post-cruise provide an opportunity for peer-reviewed publication of results in *ODP Proceedings* volumes. In addition the wealth of data contained within the volumes produced from ocean drilling provides a basis for many undergraduate senior theses studies as well as important reference material for graduate studies. The JOI/U.S. Science Support Program has funded the compilation of all digital DSDP data in Compact Disk-Read Only Memory (CD-ROM) format, which has made a vast amount of drilling data easily available for all students of earth science.

Other Educational Opportunities

Most earth science programs today have at their core, major geologic interpretations based fundamentally upon DSDP/ODP scientific achievements.

Samples can be and have been requested for educational purposes by classroom teachers. Most earth science programs today have at their core, major geologic interpretations based fundamentally upon DSDP/ODP scientific achievements. Students are able to actually work with the same materials that scientists used to document such important theories as seafloor spreading, continental drift, and global tectonics. The U.S. has also funded scientists to develop supplements to undergraduate curricula that use the results of DSDP and ODP. This is necessary because:

(1) most textbooks are several years behind the literature and have yet to incorporate important contributions from ODP; and

(2) material published in support of ODP, such as the *Initial Reports* volumes, are directed toward a research-oriented audience and are thus not generally utilized as reading material for undergraduates.

In addition to textbooks, drilling-related science also appears prominently in film series, educational television programs, and other teaching materials.

ODP frequently presents plans for future programs and preliminary results of current research at specialized scientific conferences such as those of the International Union of Geology and Geophysics (IUGG), the International Geological Congress, the American Geophysical Union and the Geological Society of America. Highlights of ODP's history, achievements, and objectives are presented at meetings of civic groups, industry professionals, and elementary, secondary and college-level students around the world. In the U.S., for example, informational displays at school "career days" are frequently provided. Tours of all three core repositories, and of the ship while in port, also are available to interested groups from nearby schools.

SCIENTIFIC OPPORTUNITIES AND OBJECTIVES FOR THE FUTURE

Introduction

The earth is a dynamic system. The most obvious geological manifestation of this is in the movement of the lithospheric plates. There are also other, equally important parts of the system that play a major role in controlling global climate. These include both the intricate exchange between ocean crust and overlying seawater through sedimentological, hydrothermal and biologic activity as well as circulation and gas exchange between the ocean and atmosphere. The earth system has evolved, through time: the heterogeneous mantle, the continents and the ocean basins, and the seawater in those basins. Understanding it fully requires a knowledge of the material and energy that are transferred among its different reservoirs. At the present time, however, there is a decided lack of data concerning the many integrated circulation cells. One of the major scientific goals of the Ocean Drilling Program is to examine these circulation cells to improve our understanding of the earth as a whole. Indeed, many of the scientific objectives which address this overall goal are best, or only, studied using ocean drilling.

The major scientific goals for ocean drilling have been defined by international conferences, the scientific community involved in ODP and others. In this section we outline our present understanding of the problems and synthesize the achievable goals. ODP clearly interacts with and compliments other major earth systems programs and these are identified where appropriate.

Overview

Two headings summarize the major scientific realms that can be studied by ocean drilling and highlight the overall view of an earth system:

(1) The composition, structure and dynamics of the earth's crust and upper mantle—lithosphere and athenosphere, and

(2) The evolution of the earth's environment—hydrosphere, cryosphere, atmosphere and biosphere.

THE COMPOSITION, STRUCTURE AND DYNAMICS OF THE EARTH'S CRUST AND UPPER MANTLE — LITHOSPHERE AND ASTHENOSPHERE

Through the study of these deep-sea cores we can obtain a view of the stability and variation of climate, the time scale and magnitude of variations in sea level, the rhythmic alteration of glacial advances and retreats during the past million years.

Because more than two-thirds of the earth's crust is made up of oceanic lithosphere, an understanding of the composition, structure and dynamics of this lithosphere is a key to our understanding of the earth as a whole. Circulation systems within the earth (Figure 1) include the movement of plates; sophisticated exchange mechanisms between ocean crust and seawater through hydrothermal, sedimentary and biologic activity; subduction and recycling of surface material at convergent plate margins; and redistribution of the mantle through convection. The oceanic lithosphere is directly linked to the continental land masses by the deposition of terrestrially derived sediments along continental margins and in ocean basins.

Ocean drilling provides two important ways to study solid-earth circulation. First, drilling is the only means of directly sampling crustal material *in situ* and is thus the only means of verifying measurements of crustal properties made from remote sensing techniques. Second, drilling can provide information about very deep earth structure through the use of downhole ocean seismometers, for example. **This latter use of ocean drilling provides a new direction for the Ocean Drilling Program and will allow a much wider scientific community to acquire important new information.**

THE EVOLUTION OF THE EARTH'S ENVIRONMENT—HYDROSPHERE, CRYOSPHERE, ATMOSPHERE AND BIOSPHERE

The earth's surface is constantly changing in response to forces acting on time scales from the daily alternation of light and dark to the billion year progression of biological evolution. The sediments of the ocean floor record many of these variations in a multitude of proxy indicators. Through the study of these records we can obtain a view of the stability and variation of climate, the time scale and magnitude of variations in sea level, the rhythmic alteration of glacial advances and retreats during the past million years, the pace and variety of the evolution of the marine biota, the fundamental controls on the circulation and chemistry of the ocean and much more (Figure 2).

In order to study and interpret this record, we must collect and analyze sediment sequences from sensitive environments, environments that can only be sampled by drilling and coring in the ocean.

Our improved ability to interpret the geologic record of past climates has been paralleled by our improved ability to model the global climate system. We are now poised to utilize and integrate this modeling ability with the geologic record of climate change both to improve our understanding of past climates and to model and predict present and future climates. The geologic past provides the testing ground for our efforts to describe and model present climate. Can we use these models to describe the past adequately? If not, the models may not contain a full understanding of the present climate. If we can, then we can begin to have confidence in our ability to predict the future.

The Ocean Drilling Program is now engaged in an effort to recover this information by systematically collecting samples from transects across important oceanographic boundaries. **This systematic approach to testing models and reconstruction of the history of the earth's environment represents a new focus for ODP.**

Definition of Major Themes

Each of these components represents major parts of the circulation cycles described by the COSOD II report. Their separation in this document is for convenience, and not to understate the important link between material circulation within the lithosphere and asthenosphere and the environment represented by the hydrosphere, cryosphere, atmosphere and biosphere.

Figure 1: The Composition, Structure and Dynamics of the

* STRUCTURE AND COMPOSITION OF THE CRUST AND UPPER MANTLE

. Exploring the Structure and Composition of the Lower Oceanic Crust and Upper Mantle

? Fate of subducted ore bodies

? Metal addition

2. Magmatic Processes Associated with Crustal Accretion

3. Intraplate Volcanism

? Fate of sediment

4. Magmatism and Geochemical Fluxed at Convergent Margins

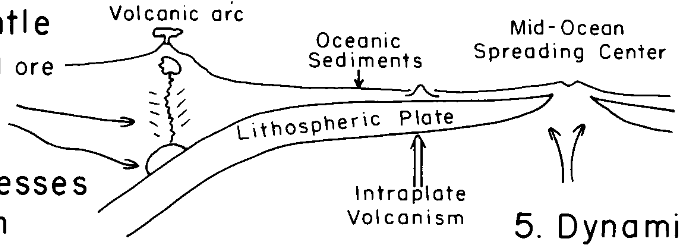
? Assimilation

? Metasomatism

? Melting

? Melting or dewatering

? Final fate of subducted plate



5. Dynamics of Oceanic Crust and Upper Mantle

* FLUID CIRCULATION IN THE LITHOSPHERE

10. Hydrothermal Processes Associated with Crustal Accretion

? Control of ocean chemistry

? Mineralization in sea water

? Fluid chemistry

? Controls of oceanic chemistry

? Crustal alteration

? High temperature alterations

? Origin of life from non-solar energy systems

11. Fluid Processes at Plate Margins

? Chemistry of fluids

? Reaction between fluids and crust

? Tectonic dewatering

? Fluids from subducting slab

? Cold seep venting

? Diapirism

? Effect on ocean chemistry

? Reflux of volatiles

* DYNAMICS, KINEMATICS AND DEFORMATION OF THE LITHOSPHERE

6. Plate Kinematics

? Relative and absolute direction and rate of one plate in motion

7. Deformation Processes at Passive Margins

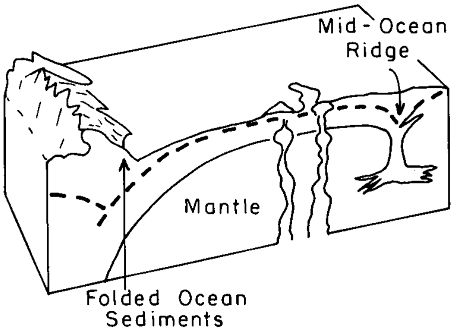
? Nature of initial breakup

? Volcanism

? Structures

? Subsidence history

? Controls of sedimentary facies



8. Deformation Processes at Convergent Plate Margins

9. Intraplate Deformation

? Lithospheric strength

? Driving force for plate tectonics

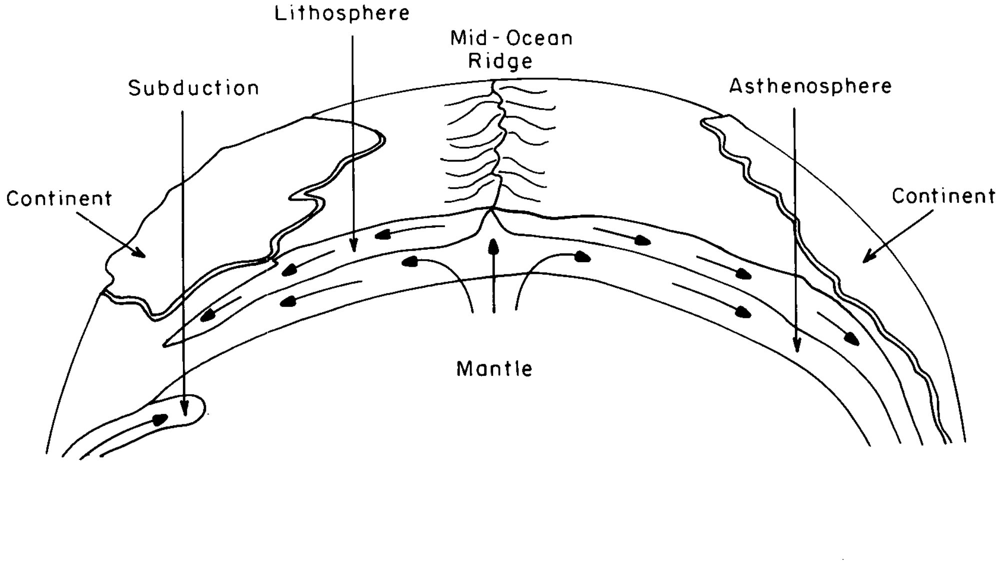
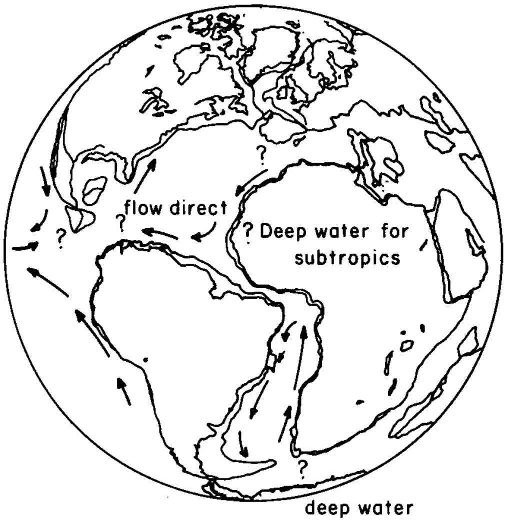
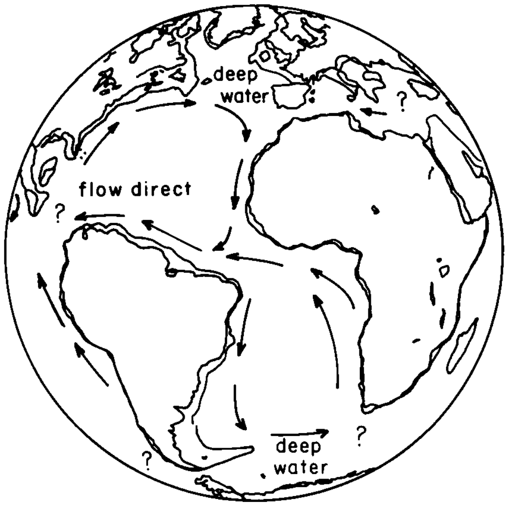


Figure 2: The Evolution of the Earth's Environment—
Cause and Effect of Oceanic



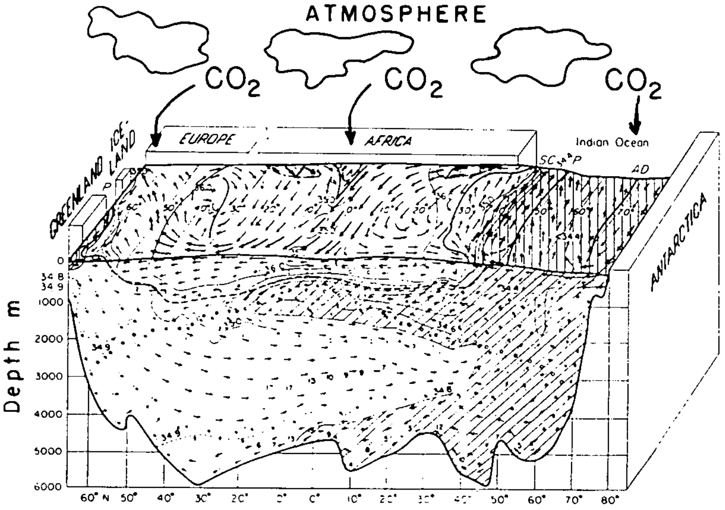
100 Ma



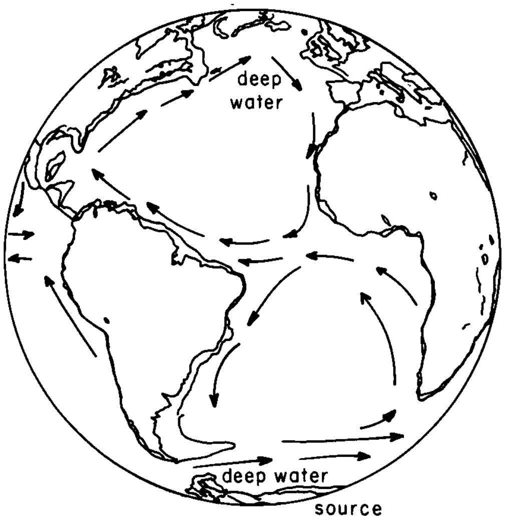
50 Ma

12. Short Period Climate Change

- ? Variability of climate on time scales of 10's to 100's of thousands of years
- ? Variability of surface-deep circulation (13)
- ? Range of possible climates at a given evolving boundary condition (13)
- ? Effect on biological evolution (12)
- ? Role of short term CO_2 changes in controlling climate variability (15)



Hydrosphere, Cryosphere, Atmosphere and Biosphere
and Climatic Variability



0 Ma

13. Longer Period Changes

? Ocean surface circulation through time global heat transport

? Deep ocean circulation – sources of bottom water

? Evolution of global environment

14. History of Sea Level

? Evolution of cryosphere (13)

? Relationship to ocean tectonics

? Controls on sedimentation

15. The Carbon Cycle and Paleoproductivity

? Cycling of carbon in ocean and sediments (12,13)

? Controls of atmospheric CO_2 (12,13)

? Depositional environment of organic rich sediments

16. Evolutionary Biology

? Response of the biology of the ocean

? Response to long period changes (13)

ODP, using new theoretical and technological approaches, will contribute in a unique way to our understanding of these components of the earth circulation system by addressing four major themes:

I. STRUCTURE AND COMPOSITION OF THE CRUST AND UPPER MANTLE

Deep crustal drilling is the only way of determining the bulk composition and in situ *physical properties of the oceanic crust, interpreting the geological significance of seismically defined crustal layering, and constraining the alteration history and aging of the oceanic crust.*

Knowledge of the structure and composition of the oceanic crust and underlying mantle is critical to an understanding of how the solid earth has evolved through time, and the processes that have shaped its evolution. While plate tectonics has provided a basic kinematic framework for these studies, over the past decade there has been increased interest in quantifying and modeling the actual physical and chemical processes involved in this solid-earth geochemical system. The objectives of these studies can be divided into three general areas:

(1) quantifying the global geochemical fluxes between the crust and mantle;

(2) investigating the magmatic and tectonic processes at spreading centers, in intraplate settings, and at convergent margins that control these fluxes; and

(3) determining the composition and heterogeneity of the underlying mantle. This process-oriented approach to lithospheric studies has spawned new initiatives like the RIDGE program and promises to revolutionize our understanding of geodynamics in the coming decade.

ODP can make important contributions to these studies, and in some instances can provide crucial data that can be obtained in no other way. Deep crustal drilling, for example, is the only way of determining the bulk composition and *in situ* physical properties of the oceanic crust, interpreting the geological significance of seismically defined crustal layering, and constraining the alteration history and aging of the oceanic crust. Thus, one key goal of crustal drilling in the next decade is to develop the capability of deep crustal penetration, with the ultimate objective of drilling through an entire 6-kilometer-thick oceanic crustal section. In order to investigate crustal accretion processes, a "natural laboratory" approach is favored in which arrays of relatively closely spaced holes are drilled, some shallow, others relatively deep, which can be used for a variety of short-term and long-term borehole experiments and observations. This type of drilling can provide unique constraints on the complex and interrelated magmatic, tectonic and hydrothermal processes occurring at oceanic spreading centers. The establishment by the year 2000 of at least one permanently instrumented seafloor "volcano observatory" along an active accreting plate boundary is another major objective of ODP. Achieving these long-term goals will require major advances in crustal drilling technology, logging equipment and long-term borehole instrumentation, as well as close coordination between scientific planning and engineering development.

II. DYNAMICS, KINEMATICS AND DEFORMATION OF THE LITHOSPHERE

In situ *stress measurements in consolidated sediments and basement will permit evaluation of models of plate driving forces and understanding of the dynamics of transform faults and ridge systems.*

In the 12 years beginning in 1989, the Ocean Drilling Program will be in a position to make new and unique contributions to our knowledge of the dynamics and kinematics of the lithosphere, and to our understanding of processes of lithospheric deformation. This will come with a new and more technologically advanced approach to scientific ocean drilling as well as the ability to drill deeper holes in unstable environments. *In situ* stress measurements in consolidated sediments and basement will permit evaluation of models of plate driving forces and understanding of the dynamics of transform faults and ridge systems. Deployment of long-term geophysical observatories should provide a unique oceanic component to improve global seismic tomography of the deeper mantle and core, as well as detailed studies of dynamic processes in specific tectonic environments such as ridge crests and transform faults. Measurements of *in situ* stresses and long-term monitoring of earthquakes and physical and chemical parameters at lithospheric plate boundaries will provide new insight into orogenic processes. The change in the study of lithospheric deformation will come with emphasis on active processes and measurement of such parameters as permeability, pore-fluid pressure and geochemistry. This should lead to a clearer understanding of the rheologic behavior of the lithosphere under stress as well as an improved understanding of fluid flow at plate boundaries as discussed under the next major theme.

Overall emphasis will be on concentrated drilling campaigns aimed at testing models of important tectonic processes. Much more time will be spent on instrumenting drill holes and taking downhole measurements in order to characterize the environmental and material conditions of the rocks being deformed. All of this effort will require much more detailed site surveys in order to integrate the drill-hole data with regional geology and maximize the value of the drilling results. In this way, the entire program will be much more closely linked to other global geosciences initiatives.

III. FLUID CIRCULATION IN THE LITHOSPHERE

The movement of fluids in marine sedimentary sections, whether driven by gravity, mechanical stress, or heat is a poorly understood process. The transport of heat and material by these fluids affects the rates of geochemical cycling and is vital to understanding the oceanic and atmospheric abundances and variability of such materials as CO_2. In addition, fluid compositions are diagnostic of the chemical reactions occurring in these environments and illuminate the conditions at depths and temperatures beyond our ability to sample. In those regions that can be reached by the drill, the study of the changes in composition and mineralogy outlines the history of temperature, pressure and chemical reactivity which have brought marine sediments and the associated oceanic crust to their present condition. Some fluid-flow regimes lead to the deposition of metalliferous deposits which are analogous to land economic ore occurrences. ODP drilling presents a unique opportunity to sample and study these processes as they occur.

The role of fluids in the lithosphere is a new frontier of current marine research. Temperature-driven hydrothermal flow is ubiquitous in the global framework of ocean plate accretion at midocean ridges and back-arc spreading centers. Tectonically driven hydrologic flow determines the style of sediment accretion and mechanism of lithification at convergent margins. Ultimately, subducted fluids, escaping dewatering in accretionary prisms, may control the distribution of deep-focus earthquakes. Gravity-driven subsurface flow is increasingly recognized as a major process in chemical redistribution and alteration within the sedimentary regime of passive margins. Ocean drilling is the major scientific effort by which advances in our understanding of these fluid regimes has been initiated and will continue to be made at an ever greater rate.

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The interaction of fluids with sediment and oceanic basalt is a first-order process effecting the global cycle of elements and in recognizing sinks and sources in the mass transfer between the earth's reservoirs. Therefore, fine-tuning our knowledge of geochemical budgets and identifying reaction fluids, source depths and pathways of dewatering are the overall objectives in our quest for a better understanding of the role of fluids in the lithosphere as envisioned by ocean drilling.

IV. CAUSE AND EFFECT OF OCEANIC AND CLIMATIC VARIABILITY

Understanding the causes and consequences of global climatic and environmental change is one of the most important challenges facing us today. Virtually all aspects of the history of life on earth are controlled by the surface environment; an understanding of the complex interactions in the earth climate system is essential if we are to learn to deal with the consequences of future change. Paleoceanographic records give us the opportunity to reconstruct the temperature, chemical composition and circulation of the atmosphere; the changing wind- and water-borne flux of material from the continents; and the level of productivity of different regions of the ocean. We can also reconstruct the positions of the continents, the gateways from one ocean basin to another, the topographic barriers to deep circulation and the degree of flooding of the adjacent land

We have gained the ability to obtain superb records of the last few million years of the history of the earth's surface from which we can learn about the interactions among earth orbital geometry, atmospheric circulation and carbon dioxide level, ocean chemistry and circulation, the cryosphere and the biosphere.

masses. We can derive a history of fluxes in and out of the system resulting from processes at the ridge crests and subduction zones as well as from volcanic activity. Thus we have access to both the historical record of past climate over a range of time scales, and to the processes acting to control and change the climate system.

As a result of advances in conceptual and mathematical modeling (the latter benefiting from the computer revolution) we are uniquely well-placed to apply focused deep-sea drilling to the solution of key questions regarding how these basic controls on the global environment actually operate. We have gained the ability to obtain superb records of the last few million years of the history of the earth's surface from which we can learn about the interactions among earth orbital geometry, atmospheric circulation and carbon dioxide level, ocean chemistry and circulation, the cryosphere and the biosphere. We plan to extend this ability to obtain equally good sequences covering longer intervals during which sea level, continental position and changing chemical fluxes become critical controls on the global environment.

More than any other aspect of ODP, paleoceanographic research has evolved to the point where global systems models can be tested. The major objectives of the next phase of the drilling program will be the applications of new, high-resolution, recovery techniques, coupled with high-resolution downhole measurements, to the systematic collection of the critical temporal and spatial data necessary to test existing models and inevitably, to develop new ones.

To provide new fundamental contributions for improving our understanding of each of these four themes, a number of specific objectives will be addressed by ocean drilling. Specific drilling targets and an approximate number of drilling legs necessary to address these objectives are given in Table 2. These objectives represent unique contributions which can only be made by ocean drilling. **While they alone will not provide all the information necessary for understanding the earth's circulation system, without ocean drilling we will not be able to understand fully these basic earth processes.**

Table 2: Targets for Future Drilling

Theme	Drilling Targets		Number of Legs
Structure and Composition of the Lower Oceanic Crust and Upper Mantle [Objective 1]	Deepening of 504B; Deep holes on old crust: (i) fast spreading crust, (ii) slow spreading crust, (iii) thin crust; one hole to Moho.		12
Intraplate Volcanism [Objective 3]	Selected case studies, e.g., hotspots, near-axis seamounts, backarc spreading centers.		4
Magmatic and Hydrothermal Processes Associated with Crustal Accretion [Objectives 2, 10]	(i) Sedimented ridge crests (East Pacific), (ii) unsedimented ridge crests (East Pacific), (iii) Mid-Atlantic ridge crest, (iv) establish a single hole > 500 meters deep and at least two shallow holes at each location.		14
Dynamics of Oceanic Crust and Upper Mantle [Objective 5]	Global stress map (sites of opportunity). Specific experiments: e.g, NW Nazca Plate, S. Shetlands, Juan de Fuca, Philippines. Series of 100 to 200 meter instrumented holes.		3
Plate Kinematics [Objective 6]	One to two hotspot traces on each major plate. M-series dating.		4
Processes at Divergent Margins [Objectives 7, 11]	Young conjugate margins: e.g., Red Sea, Greenland-Norway, Gulf of Valencia-Lyon, Flemish Cap-Goban Spur.		10
Processes at Convergent Plate Margins [Objectives 4, 8, 11]	Clastic-dominated accretionary wedges: e.g., Nankai, Cascadia, S. Barbados, erosional: e.g., Peru, Japan. Gechemical Reference: deep crustal sites on downgoing plates in well-studied zones.		10
Intraplate Deformation [Objective 9]	Case studies in regions of mid-plate deformation.		2
Short Period Climate Changes [Objective 12]	Horizontal transect across oceanographic and atmospheric fronts; depth transect in major ocean basinss. Arctic and high latitude sections.		8
Longer Period Changes [Objective 13]	Deep stratigraphic sites on old oceanic crust, Arctic Basin, oceanic plateaus.		8
History of Sea Level [Objective 14]	Atoll and guyots drilling and passive margin transects.		6
The Carbon Cycle and Paleoproductivity [Objective 15]	High -productivity regions.		4
Evolutionary Biology [Objective 16]	Selected sites not sampled as part of other paleoceanographic studies.		2
		TOTAL	95

OBJECTIVES FOR STUDIES OF THE STRUCTURE AND COMPOSITION OF THE CRUST AND UPPER MANTLE

1. Exploring the Structure and Composition of the Lower Oceanic Crust and Upper Mantle

Drilling deep crustal sections would produce a quantum leap in our understanding of oceanic crustal processes.

We still have no direct knowledge of the structure, composition and physical properties of over two-thirds of the oceanic crustal section. Deep crustal drilling is essential for determining the bulk composition and *in situ* physical properties of the oceanic crust, interpreting the geological significance of seismically defined crustal layering, and understanding the alteration history and aging of the oceanic crust. Deep crustal drilling can provide definitive answers to major outstanding questions such as: How do ophiolites compare with "normal" oceanic crust? What are the compositions of primary mantle-derived melts and how are they modified by magma chamber processes? What is the origin of marine magnetic anomalies? Drilling deep crustal sections would produce a quantum leap in our understanding of oceanic crustal processes, and has been ranked a top priority by COSOD I, by Working Group 2 at COSOD II and by the JOIDES Lithosphere Panel White Paper.

Achieving this objective will probably require a hybrid drilling strategy involving two different approaches. Holes can be drilled in areas (e.g., proximal to fracture zones) where the plutonic foundations of the crust are exposed or the total crustal section is anomalously thin. It may be feasible to drill some of these targets successfully with existing rotary drilling systems. The ultimate objective, however, is to drill a complete crustal section through Layer 2 into the lower crust at sites considered "typical" of normal oceanic crust, although in the shorter term much could be learned from intermediate-depth holes (1-3 kilometer) that penetrate into seismic Layer 3. At a minimum, holes should be drilled on crust at fast and slow spreading ridges because a comparison of the crustal structure for these two end members would resolve many outstanding questions concerning the significance of spreading rate on the crustal formation process. This type of drilling is not now technically feasible, and will require significant advances in crustal drilling systems to improve penetration rates, increase core recovery and cope with drilling in high-temperature conditions. Achieving these long-term drilling goals will require close coordination between scientific planning and engineering development, and substantial commitments of drilling time.

2. *Magmatic Processes Associated with Crustal Accretion*

Sixty percent of the earth's surface is created at oceanic spreading centers as magma generated in the mantle is cooled to form oceanic crust. The crustal accretion process involves the complex interaction between magmatic, tectonic and hydrothermal processes, all of which are still poorly understood. Drilling can make four unique contributions to studies of magmatic processes at midocean ridges:

(1) drilling can sample deeper crustal levels not generally accessible at the seafloor and offers the best hope of recovering the relatively fresh rocks essential for detailed geochemical studies;

(2) drilling can provide a vertical stratigraphy of lavas, unavailable from dredging, which can be used to investigate temporal variations in magmatic activity at a single location on a time scale shorter than that required to construct Layer 2 (10^4-10^5 years);

(3) drilling can test our interpretation of geophysical horizons and provide unique *in situ* information on the physical properties of oceanic crust (e.g., velocity, density, porosity, permeability); and

(4) drill holes can be used for downhole experiments and long-term geophysical monitoring.

Ridge-crest drilling was the highest crustal drilling objective identified at COSOD I, and was highly ranked by Working Groups 2, 3 and 4 at COSOD II, as well as by the JOIDES Lithosphere Panel.

In devising a drilling strategy for ridge crests, the magmatic objectives outlined above and the hydrothermal objectives discussed under Objective 10 below are closely intertwined. The "natural laboratory" approach outlined in the COSOD I report is favored for both objectives. Along the fast spreading East Pacific Rise the highest priority is a single deep (> 1 kilometer) hole that penetrates as close as possible to the top of the axial magma chamber. Other targets include a transect of shallower holes (~500 meters) out onto older crust to investigate temporal variations in magmatic history and the alteration history of the crust, and a suite of holes along a ridge segment to study along-strike variations in magmatic activity. Drilling should also be carried out on sedimented and slow-spreading ridges, although somewhat different drilling strategies would probably be employed. The major technical limitation of this program, now that bare-rock spud-in is achievable, is hole stability and core recovery in young, highly fractured basaltic rocks. Other potential difficulties are the high temperatures and corrosive hydrothermal fluids that will be encountered when drilling in this environment. As in the case of deep crustal drilling, a significant commitment to developing improved crustal drilling technology will be required along with close coordination between scientific planning and engineering development.

3. *Intraplate Volcanism*

One of the highest priorities of future drilling is a characterization of the magmatic evolution of young hotspot volcanoes.

Intraplate volcanism is the second most common type of volcanic activity occurring in the ocean basins. It takes many forms including small, near-axis seamounts, linear volcanic chains, aseismic ridges, oceanic plateaus and massive off-axis flood basalts or intrusive complexes. Studies of the products of mid-plate volcanism can provide important constraints on the composition and chemical evolution of the upper mantle.

The range of products of mid-plate volcanism require different drilling strategies and technical capabilities. One of the highest priorities is a characterization of the magmatic evolution of young hotspot volcanoes. A single, relatively deep hole (>500 meters) near the summit of a target like Loihi could provide valuable, stratigraphically controlled samples of the juvenile, alkalic stage of Hawaiian volcanism and its transition to the main tholeiitic shield-building stage. Studies of seamounts formed near midocean ridges, the most abundant volcanoes on earth, will complement investigations of nearby spreading centers and should be part of a larger program of geological and geophysical studies of crustal accretion. Drilling is the only method that can unambiguously determine the age and composition of oceanic plateaus, and of sampling the mid-Cretaceous flood basalts and intrusive complexes found in the central and western Pacific.

Drilling is the only method that can unambiguously determine the age and composition of oceanic plateaus.

4. Magmatism and Geochemical Fluxes at Convergent Margins

At convergent margins oceanic lithosphere is recycled into the mantle, although some portion of the subducting plate is transferred to the overlying arc through accretion, underplating and arc volcanism. The geochemical fluxes between crust and mantle at convergent margins are critical to an understanding of the global solid earth geochemical cycle. There are two ways in which drilling can directly contribute to an understanding of these fluxes:

(1) quantifying the composition of sediments and crust on the down-going plate, and

(2) determining the nature and history of magmatic activity on the over-riding plate. Neither of these first-order quantities are well-known, and drilling is the only way to obtain these data.

In general, this type of drilling can be carried out with existing technology. Drilling should be concentrated along transects extending from the down-going plate across the forearc, arc and backarc at a few well-studied arc systems. The holes on the down-going plate should penetrate through the sediments into the crust far enough to sample the zone of greatest hydrothermal alteration. Holes in the forearc are needed to determine if the forearc is floored by normal oceanic crust or earlier products of arc magmatism. In the arc, clastic-apron drilling should be combined with baseline studies of volcanic and plutonic arc rocks. Finally, a suite of shallow basement holes should be drilled across an arc-backarc transition to study the magmatic evolution of backarc basin spreading centers.

OBJECTIVES FOR STUDIES OF THE DYNAMICS, KINEMATICS AND DEFORMATION OF THE LITHOSPHERE

5. Dynamics of Oceanic Crust and Upper Mantle

Stress measurements in holes drilled by ODP are required to address the unresolved global problems of why plates move and how they interact at plate boundaries.

Even though the observational basis for plate motions is well-established, the relative importance of the diverse forces—ridge-push, trench-pull, and plate-drag, for example—that act on the plates and actually make them move is unresolved.

More over, the stresses that act upon the oceanic lithosphere and continental lithosphere at and near plate boundaries are poorly understood. Determining the near- and far-field stresses required to drive slip along oceanic and continental-margin transform faults, for example, can yield important insights into the mechanical properties of the crust and the seismogenic potential of major faults like the San Andreas.

In order to establish the dynamics of plate motion (or circulation) on a global scale, it is essential to determine at least the orientations of principal stresses over as much of the earth as possible. At present, the global map of stress measurements is sparse; there are scattered direct downhole stress measurements on the continents, but very few from the oceans. Stress measurements in holes drilled by ODP are required to address the unresolved global problems of why plates move and how they interact at plate boundaries. Measurements could be made both in holes of opportunity that are drilled primarily to address other problems, and during especially designed local experiments consisting of several holes sited on plate boundaries, small plates, or near continental margins. An ocean drilling campaign would significantly complement such land-based studies of stress as those being conducted by the U.S. continental drilling program in conjunction with the Cajon Pass drill hole on the San Andreas Fault.

To address dynamics in the upper mantle the Ocean Drilling Program can make two unique contributions to these studies:

(1) expansion of the Global Seismic Network to include ocean bottom seismic stations located in drill holes to improve substantially the spatial resolution of mantle tomographic studies, and

(2) systematic mapping of older, sedimented crust, seamounts, oceanic plateaus and hotspot volcanoes to improve constraints on the global geochemical variability of the mantle.

ODP can link with the development of permanent land-based stations to provide information on global earth structure, lithosphere evolution, earthquake source studies, and tsunami warning and monitoring.

In the first of these programs, ODP can link with the development of permanent land-based stations to provide information on global earth structure, lithosphere evolution, earthquake source studies, and tsunami warning and monitoring.

6. Plate Kinematics

A full understanding of long-term global change requires a knowledge of past plate configurations. The evolution of the earth's hydrosphere, atmosphere and biosphere is inseparably linked to the past distribution of land and sea and hence to the former positions and movements of oceanic and continental plates. Although global displacement histories are fairly well determined for the past few tens of millions of years, they are poorly known prior to about 65 million years ago. It is essential to resolve pre-Cenozoic plate kinematics and plate configurations if we are to place paleoceanographic and paleoclimatologic models into a reasonable global context.

Ocean basins contain the majority of the information needed to reconstruct the former positions and the relative and absolute displacements of plates. Fracture zones and magnetic anomalies provide the only direct measurements of long-term relative plate displacements, and paleomagnetic data and hotspot tracks relate these displacements to various global reference frames.

Resolution of pre-Tertiary plate kinematics is dependent on dating hotspot tracks and Mesozoic crust. Drilling remains the only available technique for widespread sampling of ocean floor for dating and paleomagnetic measurements.

7. *Deformation Processes at Divergent Margins*

The information provided by drilling would be of great interest to continental geologists who are actively studying and modeling intraplate extension and rifting within continental crust.

Divergent margins formed by rifting continental crust are among the most prominent topographic features on the planet. Until recently, rifting was viewed as a symmetric tectonic process during which crust is stretched and eventually pulled apart. New geological and geophysical observations emphasize the importance of asymmetric structures in the crust, and correspondingly new models postulate that rifting is accommodated by crustal-scale simple shear. Each model carries important and different implications for the rheology of crustal rocks, the evolution of sedimentary basins, and the thermal history of progressively thinned crust (critical features of any ocean basin which determine such characteristics as the presence or absence of petroleum resources). The volumes and kinds of volcanic rocks produced during the early stages of rifting may provide an important clue to thermal history and hence the style of rifting. Some margins seem to have little or no volcanic rocks overlying extended continental crust, but on others, volcanic rocks cover broad areas and appear to be thicker than adjacent oceanic crust.

Because the symmetric "pure-shear" and asymmetric "simple-shear" models predict different patterns of subsidence, sedimentation, and volcanism, an obvious way to test them is to sample the sediment and volcanic rocks that have accumulated during the earliest stages of rifting. The vast majority of the relevant sedimentary and volcanic sections lie in deep water and under a thick overburden of syn- and post-rift sediments, so deep drilling on passive margins offers the only practical means of sampling. An additional dividend from geochemical studies of volcanic rocks is to test whether hotspots were instrumental in localizing rifting. Finally, the information provided by drilling would be of great interest to continental geologists who are actively studying and modeling intraplate extension and rifting within continental crust.

8. *Deformation Processes at Convergent Plate Margins*

Because active convergent margins are submerged, ocean drilling is essential if we are to address problems pertaining to material balance and mechanical state.

Convergent margins are first-order tectonic and topographic features where the oceanic crust created at divergent margins is consumed. Convergent margins are outstanding natural laboratories for studying material transfer and mass balance. In fact, a comprehensive synthesis of the global mass circulation system requires knowing: how much sediment is added to accretionary prisms and how much is subducted into the mantle; the contribution of subducted sediment and underlying oceanic lithosphere to magmatism at the convergent margins; and the sources and circulation of fluids derived from oceanic crust, overlying sediments and the tectonically dewatering prism itself. From a different perspective, some convergent margins are the locus of earth's largest earthquakes, yet others have been devoid of historical seismicity. Data on the mechanical properties and state of stress within accretionary prisms and along the decollement separating prisms from descending plates are directly relevant to the problem of why major earthquakes occur.

Because active convergent margins are submerged, ocean drilling is essential if we are to address problems pertaining to material balance and mechanical state. Information provided by drilling will complement on-land geological and geochemical studies of active and ancient magmatic arcs, ancient accretionary prisms, and active and ancient thin-skinned fold-and-thrust belts, which form in continental settings but are mechanical analogues to prisms. Three types of drilling-based studies are required. First, diverse mechanical models for the evolution of accretionary prisms or wedges can be evaluated if spatial and temporal variations in state of stress can be determined. We require *in situ* measurements not only of stress but also of such physical properties as fluid pressures, permeability and temperature. Inferences about mass balance (offscraping versus subduction) and strength (seismic versus aseismic behavior) will follow from these measurements. Secondly, in addition to measuring the presence of pore fluids, we need to study their chemistry and temperature in order to establish their source regions and fluid migration pathways (see Objective 11). Third, extensive sampling and analysis of sediments and crust descending beneath active volcanic arcs is necessary to refine quantitative models of geochemical fluxes and try to determine to what extent such materials contribute to the source for these volcanic sequences.

9. *Intraplate Deformation*

Because most interior regions of lithospheric plates are within ocean basin, ODP provides the primary means of studying processes of intraplate deformation on a world-wide basis.

The interiors of lithospheric plates, away from the complexities of divergent and convergent boundaries, are ideal localities for studying the behavior of the lithosphere under deviatoric stress. Here, the response of the lithosphere to various modes of loading can be studied. By comparing the displacements, subsidence/uplift history or other expression of the deformation within lithospheric plates to model prediction it is possible to learn a lot about the rheology of the crust and upper mantle. This information is of first-order importance if we are to predict better the behavior of the earth's crust to tectonic processes.

Because most interior regions of lithospheric plates are within ocean basin, ODP provides the primary means of studying processes of intraplate deformation on a world-wide basis. Ocean drilling provides the geometry and timing of deformation within plate interiors. Stress determinations will again play an important role in improving our understanding of both the deformation itself as well as the driving forces leading to the deformation.

OBJECTIVES FOR STUDIES OF FLUID CIRCULATION IN THE LITHOSPHERE

10. *Hydrothermal Processes Associated with Crustal Accretion*

Hydrothermal alteration of the oceanic crust is acknowledged to be a major process controlling the chemical composition of the oceans. The interaction of fluids and crust lead to chemical fluxes similar in magnitude to the weathering of the continents. Hydrothermal circulation also plays a major role in the cooling of the lithosphere. To understand this basic control of ocean chemistry more fully, we must improve our understanding of the physical and chemical processes associated with both high- and low-temperature alteration: the hydrologic regime, the generation of fluid chemistry, the depth of chemical exchange, the relative importance of low- and high-temperature exchange, and typical time scales. Other factors affect the impact of these processes: fast versus slow spreading ridges, magma-starved versus magma-rich systems, sedimented versus bare-rock systems and the nature of overlying sediments. An evaluation of these processes is vital not only for the understanding of chemical and thermal budgets but also of the processes of ore formation and also, in the case of sedimented ridges, of petroleum generation.

Drilling on transects will also permit the evaluation of the depth of fluid-rock interaction and the overall chemical exchanges from crustal generation to subduction.

Drilling is essential to extend the study of active hydrothermal systems to three dimensions. It allows the development of natural laboratories using innovative instrumentation to study flow and chemical composition through time (this aspect of drilling is critical for the success of such global programs studying ocean ridge processes as the RIDGE program). Drilling on transects will also permit the evaluation of the depth of fluid-rock interaction and the overall chemical exchanges from crustal generation to subduction.

11. Fluid Processes at Plate Margins

Continental margins are sites of large-scale fluid transport of dissolved matter, particularly volatile elements, back to the ocean, into the upper mantle by subduction, and via upward flow through the forearc. These poorly understood material-transport processes exert a first-order control on the geochemical and thermal balance of the earth's reservoirs. Studies of these regions, combined with studies of hydrothermal systems, are essential if we are to understand the processes that control the chemistry of these reservoirs.

Fluids in accretionary prisms originate by dewatering of pore fluids due to compaction and foreshortening and by deep-seated material dehydration reactions at high temperatures and pressures. In passive margins, continental meteoric waters are driven gravitationally over long distances across the margins and appear to be trapped in certain tectonic settings. The sources, sinks, transport paths and composition of migrating fluids and their global impact on geochemical cycles can be addressed only by drilling in a number of areas with a range of geologic settings, styles of deformation, and hydrogeological regimes.

Drilling is essential to obtain fluids and gases at *in situ* conditions, and to measure the physical properties which regulate fluid flow. Understanding spatial and temporal variations in flow rates, requires that point-measurements as obtained from drilling sites along margin transects be supplemented by long-term *in situ* measurements. Ultimately, achieving the objectives of thermal and compositional balances among the earth's reservoirs requires deep drilling into the zone of metamorphism.

OBJECTIVES FOR THE STUDIES OF THE CAUSE AND EFFECT OF OCEANIC AND CLIMATIC VARIABILITY

12. *Short Period Climate Change*

To reconstruct past atmospheric and oceanic circulation, ODP must continue to drill horizontal and depth transects of APC holes in sensitive regions where climatic and oceanic fronts and water-mass boundaries can be sampled and reconstructed.

Understanding the causes and consequences of global climatic and environmental change is one of the most important challenges facing us today. An understanding of the complex interactions in the earth's climatic system is essential if we are to predict future global change. The only way to sample a continuous and detailed record of the temperature, composition and circulation of the atmosphere, the changing wind- and water-borne flux of materials from the continents, the biological productivity of the ocean and the evolutionary biological response to these changes is by drilling in the ocean. Environmental changes on relatively short time scales (one thousand to one million years), especially those related to the changes in insolation caused by changes in the earth's orbit, can best be studied in young Neogene sediments where the rate of recovery using the advanced piston corer (APC) approaches 100%.

To reconstruct past atmospheric and oceanic circulation, ODP must continue to drill horizontal and depth transects of APC holes in sensitive regions where climatic and oceanic fronts and water-mass boundaries can be sampled and reconstructed. In addition, detailed studies of the record of the advance and retreat of glacial and pack ice in high latitudes will be required. The paleoenvironmental data collected as a result of ODP studies provide the only means available to test global climatic and circulation models as well as allow the examination of the response of the global ocean-atmosphere-cryosphere-biosphere system to a range of varying boundary conditions. ODP results thus provide critical input to International Geosphere-Biosphere Programs (IGBP) such as the World Ocean Circulation Experiment (WOCE) and the Global Ocean Flux Study (GOFS), which will greatly enhance the results of these important global programs.

13. Longer Period Changes

The earth's oceanic and atmospheric circulation are affected by processes operating on very long time scales up to hundreds of millions of years, processes governed by tectonic events of vast magnitude and very slow rate. These processes and the oceanic and climatic response to them control the stability of the earth's environment and the slowly operating trends which have governed the adaptation and evolution of life on earth. The record of these changes is also preserved in deeper sections of marine sediments, which are more difficult to penetrate with the drill and much harder to recover completely. For example, the Paleogene and Cretaceous, dominated by warm oceans, represent a vast period of time with circulation and sedimentation patterns entirely different from today's, which can only be sampled by drilling deeply into marine sediments.

In order to understand the earth system's response to long-period changes, ODP must continue to probe the older parts of the marine sedimentary record in sites where important records are preserved and to extend its reach to such sensitive regions as the Arctic Ocean.

In order to understand the earth system's response to long-period changes, ODP must continue to probe the older parts of the marine sedimentary record in sites where important records are preserved and to extend its reach to such sensitive regions as the Arctic Ocean. Improvements in drilling and coring technology that will improve recovery in older sections to the level currently possible with the APC in younger sediments will be required. The ability to drill transects in the older section is limited by the reduced area of old oceanic crust and by the motion of the oceanic plates during the past. This leads to a strategy of site selection based on plate reconstructions and careful, detailed site surveys to outline optimum drilling targets. By providing insights into the response of the earth-ocean system to significantly different climatic and circulation conditions, the results of ODP studies of long-period variations will be important tests of models of planetary climate and ocean circulation carried out as part of IGBP programs and will complement studies of sediments on the continents by the Global Sedimentary Geology Program and the International Geologic Correlation Program.

14. *History of Sea Level*

ODP drilling in thinner offshore sedimentary sequences, in a range of geologic settings where penetration to older layers is possible, can lead to an accurate reconstruction of sea level.

Fluctuations in sea level cause dramatic and pervasive changes in marginal marine environments and the global stratigraphic record. These fluctuations occur on a variety of time and magnitude scales right down to the rapid changes happening today. As our stratigraphic, geophysical and geochemical tools improve, the "eustatic sea level curve" has been recognized to be the result of a complicated interaction among sediment supply, tectonic history, sediment and water loading, and eustatic adjustment. The relationship between sea level and climate is particularly striking, reflecting, in part, the volume of ice stored in continental glaciers, but also associated with changes in ocean chemistry and circulation patterns. Fundamental questions remain with regard to the synchroneity of these events and the causal linkages among them. The sea level record currently stands upon a base of seismic reflection data that has been used to identify sediment packages resulting from changes in relative sea level. The separation of local relative sea level changes from the critically important eustatic sea level signal depends on the ability to correlate these sediment packages worldwide. Such temporal correlations can only be established by drilling.

The sediment accumulations on heavily sedimented continental margins (an obvious target for sea level studies) are too thick for the currently existing drilling techniques used by ODP. Nevertheless, ODP drilling in thinner offshore sedimentary sequences, in a range of geologic settings where penetration to older layers is possible, can lead to an accurate reconstruction of sea level. In addition, drilling on carbonate platforms, guyots and atolls will provide an independent record of sea level history in regions with vastly different geologic histories. Essential to these studies is the reconstruction of precise and accurate chronologies as well as advances in geophysical surveys, well logging and core recovery. Through a global distribution of sites and the application of multiple approaches, a detailed history of sea level as well as insights into its causes and effects will be derived.

15. *The Carbon Cycle and Paleoproductivity*

Studies of late Pleistocene climate records, carbon dioxide concentrations measured in ice cores, models of the Cretaceous climate and current concerns about the "greenhouse" effect all demonstrate that a more complete understanding of climatic change requires an improved understanding of the geochemical cycle of carbon. On geologically short time scales, the cycling of carbon and, ultimately, the concentration of CO_2 in the atmosphere are controlled by ocean circulation and biological productivity. On longer time scales, processes involving the burial of carbon in marine sediments, transfers of carbon between reduced and oxidized reservoirs by interaction with the sulfur and oxygen reservoirs, and regeneration by metamorphism are governed by tectonic processes. The only way to study processes occurring at depth within the sedimentary pile and to probe the sites of active carbon diagenesis in the deep sea is by drilling.

The only way to study processes occurring at depth within the sedimentary pile and to probe the sites of active carbon diagenesis in the deep sea is by drilling.

Although the record of carbon burial in sedimented continental margins is only partly accessible to ODP style drilling technology today, much can be done to study the processes governing the burial of carbon in marine environments.

Technological developments that will permit deeper drilling and the collection of samples from environments where safety considerations now prevent ODP drilling will make the study of carbon cycling even easier.

Technological developments that will permit deeper drilling and the collection of samples from environments where safety considerations now prevent ODP drilling will make the study of carbon cycling even easier. Drilling will concentrate on sites known to contain records of the processes and amounts of carbon storage, in particular transects across the continental margins, well-surveyed, closely spaced arrays of holes in high productivity zones. The results of these studies will provide important inputs to the climate models of the World Climate Research Program and other studies of global change in the earth's environment.

16. Evolutionary Biology

The processes of speciation and evolution of organisms are an important subject for study by modern biologists. ODP has collected a unique record of the succession of species of the important planktonic protozoans which, at least in the Neogene, is well preserved and complete. In addition, these samples are precisely placed in a highly accurate oxygen isotope and magnetic anomaly stratigraphy. The opportunity to study the evolution of these organisms using ODP material has not been heavily exploited by students of evolutionary biology despite its potential importance to their studies concurrent with its continuing use by paleoceanographers. ODP samples are available through the well-developed ODP core repository system and are described in the "Initial Reports" volumes.

ODP will continue to maintain this important resource and make it available to the biological community. Future drilling, especially for the purpose of understanding global climate change will continue to provide resources for these investigations.

SITE SPECIFIC DRILLING

The thematically driven, global system approach to drilling outlined above, has de-emphasized "regional" drilling in favor of the selection of sites within a framework of critical, global, scientific questions. There is, however, one ocean, the Arctic, where so little is known that a "regional" approach is warranted. The absence of Arctic data leaves a critical gap in the global lithosphere and climatic circulation cells described earlier. We cannot complete global tectonic reconstructions without knowledge of the age and nature of the crust beneath the Arctic Ocean, nor can our paleoclimatic reconstructions ever be complete without knowledge of the development of cold-water masses and permanent sea-ice. Both bottom-water and sea-ice development play key roles in global climate evolution through heat transfer and albedo and thus their history must be determined if we are to understand the evolution of the earth's environment.

The absence of Arctic data leaves a critical gap in the global lithosphere and climatic circulation cells described earlier.

TECHNICAL REQUIREMENTS OF SCIENTIFIC OBJECTIVES

Introduction

Two essential elements are necessary for the successful implementation of the objectives defined by the Ocean Drilling Program. First, we must plan for and develop the necessary technical elements of the program (including drilling technology as well as downhole experiments). Second, we must acquire and review necessary field studies in preparation for defining and planning a drilling experiment. The former is an integral part of the planning and execution of the Ocean Drilling Program while the latter depends on the general community of scientists involved in geologic studies of the ocean and on financial support from outside of the Ocean Drilling Program.

TECHNICAL AND LOGISTICAL REQUIREMENTS

The technical requirements of this plan can be divided into five categories:

(1) drilling and sampling (including logging) in young brecciated, sometimes hot, igneous rocks;

(2) drilling very deep sites in both igneous rocks and unconsolidated, sometimes sandy, sedimentary sections;

(3) improvements of downhole measurements, especially in high-temperature and corrosive environments, and including downhole seismometers, and *in situ* sampling of physical properties, pore waters, and dissolved gases;

(4) overall improved sample recovery, including complete and undisturbed recovery in soft and semi-soft sedimentary sequences and absolute orientation of all samples; and

(5) options for use of alternative drilling platforms to the *JOIDES Resolution* to address drilling in very shallow water or in areas of extensive sea-ice coverage.

Technical Developments

Perhaps more than any others, Objectives 1 through 5 and 10 will require major new technological developments in drilling systems, logging equipment and borehole instrumentation. In terms of drilling systems, three major problems must be overcome:

(1) penetration and sampling of young, highly fractured, extrusive basalts comprising the uppermost part of oceanic Layer 2;

(2) low penetration rates, short bit life, hole instability and incomplete flushing of cuttings in deeper crustal holes; and

(3) low recovery rates.

In order to solve these major engineering problems, a major commitment of effort and funds to engineering developments will be required.

While it is impossible to predict with any confidence the pace at which this engineering development effort can proceed, the following schedule for engineering developments is required to achieve the variety of drilling programs outlined under Objectives 1 through 5 in Table 2 (page 69):

By 1992: Routine drilling, with a minimum of 75% recovery, to depths of 1000 meters below the basement-sediment interface

By 1996: Drilling to 2000-3000 meters into hard rock, well within oceanic Layer 3

By 2000: The capability of drilling through the entire crustal section to Moho

Improvements in logging equipment and borehole instrumentation will also be required for a successful long-term lithospheric program included in Objectives 1 through 5. Both ridge-crest drilling and deep crustal boreholes are likely to encounter high temperatures up to and possibly exceeding 400°C. These high temperatures will necessitate special temperature-resistant logging tools and borehole instruments. A collection of slim-line logging tools may also be needed if the experimental mining coring systems, which appears to have the highest potential for improving drilling and recovery, can only be optimally designed to drill a hole with a maximum diameter of about 10 centemeters (4 inches).

A second major need is for improved borehole sampling techniques. A reliable side-wall coring technique could significantly improve the representativeness of the material recovered from crustal holes and reduce the need for very high recovery rates when drilling. New methods of borehole fluid sampling are critical for many hydrothermal and pore-water geochemistry studies. Techniques need to be developed for sealing boreholes after drilling and logging operations are completed, with some method of access for later work.

Finally, improving the utilization of drill holes for a variety of possible hole-to-hole experiments, seafloor experiments and long-term measurements and sampling will be a major part of other programs studying the earth. Of particular importance is developing methods for remote data storage and retrieval from borehole-emplaced, long-term instrumentation.

The successful completion of Objective 5 requires the development of long-term borehole seismometers. The seismometers should be able to both remain in the seafloor for extended periods of time and transmit data to shore-based facilities either through a direct connection or other means. This equipment could be emplaced using the drill ship or using wireline reentry capabilities being developed outside of ODP.

Special technical requirements of Objectives 7, 8, 11, 13 and 14 involve drilling 2- to 3-kilometer deep holes in unconsolidated sediments. Two problems may be encountered during drilling of these programs. First, hole instability in deep sedimentary sections is a problem. Second, there is a concern for safety while drilling in sedimentary sequences of passive and active margins;

the *Resolution* does not have blow-out protection if significant hydrocarbon concentrations are encountered. In many cases sites can be selected in which safety is not a problem, though this may not always be the case.

In addition, in order to unravel the chemical changes that result from tectonic processes associated with Objectives 7, 8 and 11, further development in downhole measurements and experiments is required. Specifically, this involves the ability to measure *in situ* properties of stress, mechanical properties of the sequence being drilled and the ability to sample of pore fluids and dissolved gases.

The high resolution paleoclimate and paleoceanographic studies to be conducted as part of Objectives 12, 13 and 15 require the recovery of undisturbed, continuous sediment sequences. Of primary concern is the recovery of older sequences in which alternating layers of soft and hard (especially cherts) sediments will be encountered. In addition, improved absolute orientation of samples is critical for associated paleomagnetic studies of the recovered sequences.

Objectives 16 and 17 present a different technical problem from the others. Much of the drilling needed to address the fundamental scientific questions identified within these objectives requires drilling in environments not accessible to the *JOIDES Resolution.* Shallow water drilling in lagoons of atolls might best be addressed using smaller jack-up rigs while drilling in regions where ice cover prohibits the use of the *Resolution,* requires special drilling platforms. In both cases, it is essential that the drilling and coring capabilities of the "alternate" platforms are at least equivalent to those of the *Resolution.*

Use of Alternate Drilling Platforms

Several objectives outlined in this document may require drilling procedures not available from the *Resolution* and thus require the use of other drilling platforms. In general, the use of alternate platforms to address the scientific objectives fall into two general categories:

(1) platforms which could be used on a contract basis to address very specific scientific targets, and

(2) platforms, such as a light drilling vessel, which could be incorporated into the continuous planning process and operated by ODP in addition to the *Resolution*.

Only the former category is required by this Long Range Plan.

Several objectives outlined in this document require drilling techniques not available from the Resolution *and thus require the use of other drilling platforms.*

The *Implementation Plan* discussed in this document identifies the use of alternate platforms for specific scientific tasks. Two uses are identified:

(1) the use of jack-up shallow water drilling platforms for addressing certain of the objectives related to the *History of Sea Level;*

(2) drilling platforms designed to drill in regions of pack-ice to address objectives of high-latitude programs.

The option of using alternate riser-drilling platforms to drill in regions of thick sediment sections where both safety and deep drilling objectives are beyond the present capabilities of the *Resolution* is not considered in this document. It is difficult to estimate costs so far into the future but it is believed that the use of such a platform may be prohibitively expensive. As discussed in the next section, the development of a slimline riser deployable from the *Resolution* represents the most cost-effective approach to address the scientific objectives of ODP.

The use of a second drilling platform, such as the light drilling vessel discussed in the COSOD II document, that would be incorporated into the Ocean Drilling Program on a more continuous basis is also not a requirement of the implementation plan presented in this document. A second platform would, however, greatly add to the scientific return from ocean drilling. For example, one of the major objectives for future drilling and scientific investigation of the ocean is the establishment of long-term observatories and monitoring systems within drill holes. A second platform (envisioned to be smaller and less costly than the *Resolution*) with deep water reentry and drilling capability would be a cost-effective method for servicing and installing instrumentation packages in drill holes previously drilled by the *Resolution*. Such a platform could be used for shallow-sediment drilling, specifically with piston coring technology, and shallow basement drilling. However, the regions of the ocean where this approach would be of great benefit may be limited. The very high stability of the *Resolution*, and the resulting high quality piston cores collected, are essential for the success of many objectives to be addressed by ocean drilling (especially Objectives 12, 13 and 16).

PRE-DRILLING DATA BASES NEEDED

Pre-drilling regional studies are essential to optimize both planning and the interpretation of drilling programs, this was recognized and outlined by both COSOD I and COSOD II. These pre-drilling regional studies are essential for planning well-designed drilling experiments:

Objectives 1, 2, 3, 4 and 10

The site survey requirements and selection criteria for deep crustal drilling and ridge crest drilling have been discussed in the reports of COSOD II and of the JOIDES working group on East Pacific Rise Drilling. For both kinds of drilling, sites should only be selected after exhaustive site surveys. Regional bathymetric, side-scan, magnetic and gravity surveys will be required to define unambiguously the tectonic setting of candidate sites. The crustal structure near drill sites should be determined using multichannel seismic reflection techniques (CDP and expanding spread profiles), OBS seismic tomography studies and medium-scale electromagnetic sounding experiments. Near ridge crests this work should be accompanied by detailed mapping and sampling to characterize the petrologic and geochemical diversity of the area, and water-column geochemistry studies to define the distribution of hydrothermal vents and constrain the advective heat output from the ridge.

Objective 1:
Exploring the Structure and Composition of the Lower Crust and Upper Mantle

Objective 2:
Magmatic Processes Associated with Crustal Accretion

Objective 3:
Intraplate Volcanism

Objective 4:
Magmatism and Geochemical Fluxes at Convergent Margins

Objective 10:
Hydrothermal Processes Associated with Crustal Accretion

A major challenge for ridge-crest drilling is the use of heatflow and other geophysical techniques which can be used to delineate fluid circulation. However, measurement of heat flow in unsedimented ridges is technically not feasible using present techniques.

This site-survey work should begin as soon as possible to develop the necessary databases for at least six candidate sites for deep crustal drilling and four sites for ridge-crest observatories so that site selection can proceed in a timely fashion. In addition, pilot experiments should be carried out at selected boreholes (e.g., near Hawaii), to begin to address the technical issues related to the establishment of seafloor seismic observatories and global stress mapping.

Objectives 5 and 9

Sites for the study of plate dynamics and intraplate deformation require extensive regional geophysical surveys to determine the regional context of the planned drill sites.

Objective 5:
Dynamics of Oceanic Crust and Upper Mantle

Objective 9:
Intraplate Deformation

Objective 6

Objective 6:
Plate Kinematics

Pre-drilling data sets for drilling sites for oceanic crust and seamounts require the normal spectrum of marine geophysical techniques. Most ocean crust sites to be drilled to address kinematics of ocean plates will likely be sedimented, and apart from bathymetric and seismic data, the single most important parameter to be mapped is the magnetic-anomaly field. Through a systematic magnetic survey grid (e.g., < 10 kilometer spacing) the grain and structure of the crust can be established. This is essential to ensure that a basement age sample comes from normal, lineated crust (undisturbed by transforms, propagators, etc.) from which the direction and polarity of spreading can be determined. In terms of seamounts and hotspot lineations, detailed bathymetric (e.g , SEABEAM) and swath mapping (e.g., SeaMARC, GLORIA) are also essential to locate flows, slumps, incised canyons and other features that should be either avoided or targeted in a drilling strategy. Preliminary dredging should be carried out both to provide supplementary information for drilling results and to optimize planned sites. Sites should be located within a context such that it will be clear whether samples are likely to be the last eruptive phase, early flows or typical edifice geology.

Objectives 7 and 11

Objective 7:
Deformation Processes at Divergent Margins

Objective 11:
Fluid Processes at Plate Margins

The primary objective of rifted margin studies is to recognize and characterize the transition between oceanic and continental lithosphere and to understand the geologic processes that control the evolution of this transition. To plan drilling in these settings adequately, pre-drilling geophysical data must be able to discriminate pre-rift structures and syn-rift versus post-rift sedimentary successions within rifted basins. Acquisition methodologies should provide data allowing direct comparison between conjugate margins in terms of age and volcanic and tectonic history. Imaging of the deep crust and upper mantle is required because interpretation of:

(a) detachment faults;

(b) the role of pure versus simple shear extension mechanisms; and

(c) the importance of magmatism during extension, depend heavily upon establishing the nature of the lower crust and the manner in which it deformed.

Objectives 8 and 11

Objective 8:
Deformation Processes at Convergent Plate Margins

Objective 11:
Fluid Processes at Plate Margins

To address the scientific objectives of drilling at convergent margins requires a clear understanding of the geometry of the structures to be drilled. Detailed seismic surveys are required to image:

(a) the top of the undeformed lower plate and subducted sediments;

(b) the internal geometry of the wedges, including folds, thrusts, normal faults, complexes, and mud diapirs; and

(c) the lateral changes in the structures including thrust faults and ramps. Accurate depth-corrected images must be available. This requires improved estimates of the velocity structure of these regions.

Objective 12, 13, 14, 15 and 16

Objective 12:
Short Period Climate Change

Objective 13:
Longer Period Climate Change

Objective 14:
History of Sea Level

Objective 15:
The Carbon Cycle and Paleoproductivity

Objective 16:
Evolutionary Biology

As the models we test and the information that we gather from ODP boreholes grow more sophisticated, we need to re-evaluate our concept of pre- (and perhaps even post-) drilling site surveys. Site surveys must no longer be viewed as a formality to be completed in order to meet a safety requirement, but rather, we must look at them as key components in the overall drilling program; the site surveys allow us to put the drilling results in a regional perspective and can optimize the results through the careful selection of drilling targets. For most paleoceanographic and paleoclimatic objectives, the survey requirements are fairly straight-forward. Detailed high-resolution (typically watergun) seismic data are necessary to establish the position of the drill sites within regional sedimentation patterns. Surveys should seek the highest seismic resolution achievable without compromising full penetration of the sedimentary section. Digital acquisition allows for post-survey processing and quantitative analysis of the high-resolution seismic record.

Recent studies have demonstrated that it may be possible to extract paleoceanographic information directly from the seismic record and thus pre- (or even post-) drilling site surveys can add tremendously to the paleoceanographic results of a drilling program.

Whereas seismic data will be essential for establishing the overall regional sedimentation patterns, pre-site surveys should also include extensive box- and piston-coring programs. These cores will provide first hand knowledge of the sediment distribution (at least for the near surface) and provide an unambiguous look at those sediments near the mudline (not necessarily recovered from the drill ship). This is particularly critical to our high-frequency objectives (Objective 12) and can provide an important record of geologically more recent oceanographic variations and the resulting sedimentation patterns. The ultimate link to studies of modern-day oceanographic variability and fluxes can be provided with concomitant physical oceanographic and sediment-trap studies. Such studies should be strongly encouraged in concert with our high frequency drilling objectives. Thus, to the paleoceanographer, direct sediment sampling is as much a part of pre-drilling studies as seismic reflection.

The most stringent site survey requirements of the studies of ancient climates are related to the history of sea level objectives. The passive margin approach outlined for sea level studies requires an industry quality multichannel seismic data base in the region to be drilled. The long lead times and large expense associated with these types of surveys mandates that these surveys be planned as early as possible.

Site Specific Drilling

The Ocean Drilling Program and its predecessor have recovered samples from all ocean basins except the Arctic. Two major difficulties exist which prohibit the program from sampling this important region of the earth, the technical difficulty of drilling in the environment of the Arctic and the lack of high resolution regional geologic data necessary to adequately plan drilling programs. This lack of regional marine geologic data also reflects the logistical problems of working at high latitudes.

IMPLEMENTATION AND FOCUSING OCEAN DRILLING

Introduction

A summary of scientific objectives and estimates of drilling efforts to achieve these objectives are listed in Table 2 (page 69). Table 2 lists 95 legs, which would constitute over 16 years of drilling. While this would exceed the proposed time during this phase of ocean drilling by over two years, this is not an unreasonable estimate of what can be achieved during the interval of time discussed in this document. Within these 95 legs we have identified objectives which could be addressed within the same drilling targets. Specifically we envision a number of "superlegs" that refer to legs that encompass an approach requiring high-resolution seismic surveys, multi-purpose drilling sites, long-term instrumentation and post-drilling experiments and instrument deployments. These legs will address many questions about tectonic, geochemical and sedimentological processes in many important regions of the ocean.

In addition, the proposed set of objectives will rely heavily on the ability to develop important new drilling and borehole instrument technology. It is possible that some of the technologies will not come to fruition. Even so, there still are significant amounts of first-order programs that can be achieved with less ambitious technical planning.

Implementation

The success of ocean drilling will require a careful integration of scientific planning and engineering developments. This integration is presented in terms of an implementation plan that consists of three phases (Table 3). The first phase of this plan is scheduled to be completed during the last part of the present phase of the Ocean Drilling Program. Within each phase, scientific objectives are presented that can be achieved given the anticipated level of technical developments. Each successive phase adds scientific objectives requiring incremental increases in technical capabilities.

TABLE 3: Implementation Plan

THEME	PHASE I 1989 - 1993	PHASE II 1993 - 1997
Structure and Composition of the Oceanic Crust and Upper Mantle [Objective 1].	Deepen Site 504B or other crustal holes [2 legs].	Drill 3 holes in ocean crust; one on thin crust [4 legs]. Extend one crustal hole to Moho depth (5 km) [6 legs].
Mantle Dynamics, Structure and Geochemistry [Objective 5].		Development & testing of downhole seismic instrumentation [1 leg]. Deployment of 6 down-hole seismic stations inholes 100-200 m deep [2 legs]. Stress measurements in specific tectonic settings - e.g., Nazca Plate [1 leg].
Intraplate Volcanism [Objective 3].	Drilling into young hotspot volcanoes [2 legs].	Drilling oceanic plateaus, backarc spreading centers [2 legs].
Magmatic and Hydrothermal Processes Associated with Crustal Accretion [Objectives 2, 10].	Initial drilling on sedimented and unsedimented ridges - EPR/JDF [4 legs].	Complete EPR drilling. Start slow-spreading centers at MAR [4 legs].
Plate Kinematics [Objectives 6 and 3].	Refine Mesozoic magnetic anomaly dating in Pacific. Refine Pacific hotspot reference frame [2 legs].	Drilling hotspot chains [2 legs].
Processes at Divergent Margins [Objective 7, 11 and 14].	High-resolution geophysical studies of conjugate margins.	Drilling of rifted conjugate margins; volcanic/non-volcanic margins [4 legs].

PHASE III 1997 - 2002	ENGINEERING DEVELOPMENTS
	Improve depth capability and recovery in igneous rocks to 2 km.
	Develop drilling technology to drill 3 km into igneous crust.
	Capability to drill regularly to Moho (~5 km)
	Develop and test seismic instrumentation
Deployment of 6 additional down-hole seismometers in 100-200 m deep holes [2 legs].	Refinement of downhole instrumentation and data recovery.
Stress measurements in specific settings - e.g., S. Shetlands, Antarctica [2 legs].	Further development of stress-measurement techniques, including improved packer experiments.
	Improved capability for drilling and logging in fractured, hot, and brecciated volcanic rocks.
	Develop drilling and logging technology for high-temperature drilling in highly corrosive environments.
Complete MAR drilling [2 legs].	
Establish ridge-crest volcanic observatories [4 legs].	Develop capability for long-term, real-time observatories.
	Development of technology for fully oriented samples. Improved capability of drilling fractured and brecciated volcanic rocks.
	Development of drilling capabilities to deep levels in sedimentary environments (2.5 km).
Deep drilling to early detachments and into initial rifting sequences	Deep drilling in clastic and organic-rich sequences where complete circulation and safety control will be necessary.

TABLE 3: Implemenation Plan (continued)

THEME	PHASE I 1989 - 1993	PHASE II 1993 - 1997
Processes at Convergent Plate Margins [Objectives 4, 8, and 11].	Complete one case study of deformation and fluid flow in accretionary wedge; e.g., Nankai/Cascadia/Barbados [3 legs]. Diapirism in forearc [1 leg]. Study ridge crest-trench collision (including ophiolite obduction) [2 legs]. Determination of chemical composition of down-going slab near a single convergent zone [1 leg].	Deformation and fluid studies in pelagic and heavily sedimented accretionary prism. Start to drill to deep levels in upper parts of sediment wedge [3 legs]. Geochemical studies of down-going slab and overlying sediments [2 legs].
Intraplate Deformation [Objective 9].		Lithospheric compression and/or extension studies [2 legs].
Neogene Paleoceanography [Objectives 12, 15, and 16].	Neogene transects [6 legs].	Neogene transects [3 legs].
Longer Period Climate Changes [Objectives 13, 15 and 16].	Pre-Neogene transects [3 legs].	Pre-Neogene transects [3 legs].
Mid-Ocean Records of Global Sea Level [Objective 14].	Atoll and guyots drilling in Pacific. Contintental margins [2 legs].	Shallow water atoll drilling [4 months].
Arctic and Other Site Specific Drilling	Site survey data acquisition in support of ocean drilling in ice-covered Arctic [not directly part of ODP].	Use of alternate platform to drill in ice-covered area [6 months].

PHASE III 1997 - 2002	ENGINEERING DEVELOPMENTS
	Develop fluid sampling and techniques for measuring *in situ* environmental and physical properties.
	Development of drilling capabilities to deep levels in sedimentary environments (2500?? meters).
Fluid and tectonic deformation studies at deepest levels in accretionary prisms; establish long-term observatories of deformation and fluid processes [4 legs].	Deep drilling in clastic sequences where complete circulation and safety control will be necessary. Possible use of alternate platform.
High productivity transects [3 legs].	Improve XCB recovery to APC standards, improved core orientation.
	Improve XCB recovery to APC standards, improved core orientation.
Deep stratigraphic tests [6 legs].	Capability for deep, stable holes with high recovery.
	Improved drilling and recovery in chert/chalk sequences and in shallow water carbonates.
	Jack-up alternate drilling platform.
Six months alternate platform.	Alternate platform for drilling in ice-covered ocean.

Focusing Ocean Drilling

Given the extensive list of scientific objectives discussed in previous sections we must be able to focus our efforts during each phase of the proposed program and especially be able to prioritize the necessary engineering developments.

The sixteen major objectives discussed in this long range plan represent a distillation of over four years of panel discussions and the conclusions of two major international scientific conferences. The ranking of such diverse objectives, which aim to understand the formation and evolution of the earth's crust versus objectives whose goal is to understand the earth climate system, is not a straightforward exercise. However, to achieve the ultimate scientific goals outlined by ODP, it is essential that we focus the planning in such a way as to maximize the scientific return given the limited resources of both engineering developments and scientific operations.

For each phase of this long range plan we have selected on the order of five objectives on which to concentrate during that phase. This does not to exclude other objectives but is intended to emphasize the relationship between important scientific problems and the technology that is needed to complete these objectives. Also, in the event that technological requirements of some of the objectives outlined in this plan cannot be achieved, either due to technological feasibility or budgetary constraints, there are still many first-order scientific problems that can then become part of the main focus of ocean drilling.

The implementation defined for each of the three phases outlined in this plan reflects available technology within each phase and some assumptions about technological developments. As noted above, we cannot predict the pace at which technological developments can be made, but it is essential that we commit enough resources, both in terms of engineering and operations, to a specific requirement to assure its proper completion. It is also difficult to predict technical developments which will be made outside of the Ocean Drilling Program and can be adapted to scientific drilling. Thus, the implementation plan made for each phase of drilling reflect the technology in hand as well as the assumptions being made about the development of new technology.

Finally, the technology priorities are divided into two groups, one reflecting technological developments directly within the ODP and the other of developments outside the program.

PHASE I IMPLEMENTATION

Scientific

Given the present level of technology and the present status of planning, the following objectives will be part of the main focus of ODP:

- high-resolution Neogene paleoceanographic transects especially within the Pacific Basin;
- sea level studies with drilling on guyots and atolls;
- 1- to 1.5-kilometer deep holes in accretionary wedges;
- plate kinematic studies of the Pacific Plate;
- initial, 0.5- to 1-kilometer deep holes at fast spreading, unsedimented ridge crests and intermediate spreading, sedimented ridge crests; and
- start of coordination of Arctic drilling efforts.

Technology

The technological developments to be concentrated on within ODP during this phase of operations include:

- application of the high-speed, top-drive, diamond mining coring system for drilling in igneous rocks and other consolidated materials;

- development of strategy for addressing deep drilling in both basement and sedimentary rocks; and
- development of downhole tools and drilling techniques for study of high-temperature environments.

Developments outside of ODP which will greatly contribute to programs in later phases include:

- development of borehole seismometers;
- development of drilling and sampling techniques in unconsolidated coarse-grained sediments;
- development of drilling and sampling techniques in shallow water carbonate environments; and
- development of techniques or systems to drill in the ice-covered Arctic.

PHASE II IMPLEMENTATION

Scientific

Assuming the planned technological developments in Phase I are achieved, the following objectives will be part of the main focus of ODP:

- intermediate-depth drilling in divergent and convergent margins with emphasis on tectonic, geochemical and paleoceanographic (sea level studies) processes;
- intermediate-depth ridge crest drilling;
- intermediate-depth studies of older crustal section;
- pre-Neogene low-resolution climate change studies;
- deployment of initial array of borehole seismometers; and
- start of drilling efforts in the Arctic Ocean.

Technology

The technological developments to be concentrated on within ODP during this phase of operations include:

- evaluation of the diamond coring system for use in both deep sediment drilling as well as for deep crustal drilling;
- solution to the recovery of alternating soft-hard sediment sequences; and
- development of fully-oriented core samples in all environments.

Developments outside of ODP which will greatly contribute to programs in later phases include:

- Development and initial deployment of long-term observatories for ocean ridge and tectonic environments.

PHASE III IMPLEMENTATION

Scientific

Given the present level of technology and the present status of planning the following objectives will be part of the main focus of ODP:

- deep crustal drilling to Moho;
- deep drilling in passive and active margins;
- deployment of long-term observatories;
- deep stratigraphic test sites; and
- complete Arctic drilling program.

Technology

The technological developments to be concentrated on within ODP during this phase of operations include:

- complete development techniques for drilling deep sites with adequate well control.

Developments outside of ODP which will greatly contribute to programs in later phases include:

- enhanced long-term observatories.

PROGRAM REQUIREMENTS

The annual funding levels presented in Table 4 are the best available estimates for maintaining a scientific ocean drilling program that is on the leading edge of ocean research and technology. The budget is separated into two main categories: standard operations and special requirements. Standard operating funds enable drilling and logging to continue year-round, *ODP Proceedings* to be published, modest engineering development to continue, and allows the ODP Site Survey Data Bank, JOIDES Office, and administrative offices to maintain operations. To meet many of ODP's scientific goals over the next ten years, there are also special program requirements. Some of these include:

- development of drilling and logging technology for high-temperature drilling in highly corrosive environments;
- further development of the diamond coring system as well as slimline logging tools in order to improve ODP's capability to core and log in fractured, hot, and brecciated rocks;
- purchase or rental of slimline risers and blow-out preventers so that ODP can drill into initial rifting sequences where organic-rich sequences may be found, and drill deeply into accretionary complexes for fluid and tectonic deformation studies where complete circulation and safety control will be necessary;
- rental of ice-support vessels so that the drill ship can operate safely in high latitudes;
- rental of a jack-up rig so that ODP can drill shallow-water atolls; and
- further development of packers, fluid samplers, and other tools so that the *in situ* properties of the rocks and fluids in the boreholes may be properly measured.

Other special requirements include replacing drill pipe, drydock expenses, replacing shipboard laboratory equipment,

Table 4: Long Range Plan Budget

Standard Operations	**1989**	**1990**	**1991**	**1992**	**1993**	**1994**
Science Operator						
Headquarters	1,664,500	1,773,847	1,888,038	1,971,595	2,059,769	2,152,824
Science Services	3,152,677	3,449,049	3,637,101	3,835,870	4,045,981	4,268,098
Drilling & Engineering	3,121,660	3,164,132	3,297,628	3,437,443	3,583,906	3,737,363
Technology & Logistics	3,035,832	3,485,463	3,650,608	3,824,343	4,007,142	4,199,510
Science Operations	956,831	1,002,083	1,053,566	1,107,878	1,165,183	1,225,650
Subtotal	**11,931,500**	**12,874,574**	**13,526,941**	**14,177,129**	**14,861,981**	**15,583,445**
Ship Operations	18,572,500	19,019,008	19,589,578	20,177,266	20,782,584	21,406,061
Subtotal	**30,504,000**	**31,893,582**	**33,116,519**	**34,354,395**	**35,644,565**	**36,989,506**
Wireline Logging						
Operations	1,280,912	1,357,664	1,414,749	1,474,528	1,537,140	1,601,700
Schlumberger Subcontract	1,677,088	1,756,555	1,861,948	1,973,665	2,092,085	2,217,610
Other Subcontracts	65,000	25,000	25,000	25,000	25,750	26,523
Subtotal	**3,023,000**	**3,139,219**	**3,301,697**	**3,473,193**	**3,654,976**	**3,845,833**
Program Management						
Subtotal	**1,600,000**	**1,671,999**	**1,755,599**	**1,843,379**	**1,935,548**	**2,032,325**
Total Standard Operations	**35,127,000**	**36,704,800**	**38,173,815**	**39,670,967**	**41,235,088**	**42,867,664**
Special Requirements *						
Science Operations						
Science Services	0	0	203,500	203,500	271,000	271,000
Drilling & Engineering	405,000	979,600	1,940,000	1,940,000	2,902,500	2,402,500
Technology & Logistics	0	0	195,000	195,000	195,000	195,000
Science Operations	17,000	170,000	335,000	335,000	335,000	235,000
Ship Operations	588,000	0	0	1,000,000	0	2,000,000
Wireline Logging						
Special Tools	0	82,600	382,600	282,600	350,000	350,000
Program Management						
Special Program Needs	13,000	63,000				
Total Special Requirements	**1,023,000**	**1,295,200**	**3,056,100**	**3,956,100**	**4,053,500**	**5,453,500**
TOTAL PROGRAM (in U.S. Dollars)	**36,150,000**	**38,000,000**	**41,229,915**	**43,627,067**	**45,288,588**	**48,321,164**

1995	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**
2,251,042	2,354,719	2,464,171	2,579,730	2,701,748	2,830,600	2,966,680	3,110,407
4,502,922	4,751,198	5,013,713	5,291,302	5,584,850	5,895,294	6,223,624	6,570,891
3,898,180	4,066,743	4,243,461	4,428,762	4,623,103	4,826,963	5,040,848	5,265,295
4,404,978	4,615,109	4,839,498	5,075,775	5,324,606	5,586,695	5,862,788	6,153,674
1,289,462	1,356,812	1,427,901	1,502,946	1,582,176	1,665,830	1,754,166	1,847,453
16,346,584	**17,144,581**	**17,988,744**	**18,878,515**	**19,816,483**	**20,805,382**	**21,848,106**	**22,947,720**
22,048,243	22,709,690	23,390,981	24,092,710	24,815,492	25,559,956	26,326,755	27,116,558
38,394,827	**39,854,271**	**41,379,725**	**42,971,225**	**44,631,975**	**46,365,338**	**48,174,861**	**50,064,278**
1,668,972	1,739,069	1,812,109	1,888,218	1,967,523	2,050,159	2,136,266	2,225,989
2,350,667	2,491,707	2,641,209	2,799,682	2,967,663	3,145,722	3,334,466	3,534,534
27,318	28,138	28,982	29,851	30,747	31,669	32,619	33,598
4,046,957	**4,258,913**	**4,482,301**	**4,717,751**	**4,965,933**	**5,227,551**	**5,503,351**	**5,794,121**
2,133,941	**2,240,639**	**2,352,670**	**2,470,304**	**2,593,819**	**2,723,510**	**2,859,686**	**3,002,670**
44,575,725	**46,353,823**	**48,214,696**	**50,159,280**	**52,191,727**	**54,316,399**	**56,537,898**	**58,861,069**
271,000	271,000	271,000	231,000	231,000	231,000	231,000	231,000
2,902,500	2,402,500	1,337,500	987,500	1,337,500	987,500	175,000	175,000
195,000	195,000	195,000	195,000	195,000	195,000	195,000	195,000
235,000	235,000	235,000	235,000	235,000	135,000	135,000	135,000
2,500,000	1,000,000	0	0	1,000,000	600,000	0	0
250,000	200,000	250,000	250,000	250,000	250,000	250,000	250,000
6,353,500	**4,303,500**	**2,288,500**	**1,898,500**	**3,248,500**	**2,398,500**	**986,000**	**986,000**
50,929,225	**50,657,323**	**50,503,196**	**52,057,780**	**55,440,227**	**56,714,899**	**57,523,898**	**59,847,069**

increasing the number of staff scientists and marine technicians, computer and curatorial improvements, and increasing publications staff to speed up production of *ODP Proceedings* volumes. The feasibility of using a light drilling vessel in tandem with the *JOIDES Resolution* is also being explored. In addition, it is expected that member nations will continue to contribute to the overall ODP effort by funding supplemental programs including geophysical surveys of potential drill sites and the drilling-related research projects of individual scientists.

Standard budgets were calculated by using FY90 as the base year for projections to the year 2002. An inflationary rate of 6% per year was used for payroll while 3% was used for most other "standard" items. Exceptions to this rule are the Schlumberger logging subcontract where historically the increase has been greater than 3% and publications where costs for paper, printing, and typesetting are anticipated to be about 6% per year. Current economic trends indicate that the ship's dayrates will continue to rise, though it is difficult to forecast by exactly how much; an increase of only 3% per year was used here.

The annual special requirements budget for engineering and operational expenses was calculated by dividing the three-phase budget presented in Table 5 into expected yearly expenditures. The three-phase budget is the best estimate currently available for the items listed. Some of these items, such as a 6-kilometer sea-going diamond coring system, have not yet been engineered, let alone constructed, so that the cost estimates may be off significantly.

TABLE 5: Cost Estimates for Engineering Developments and Special Operations

	Engineering and Operational Requirements	Scientific Objective Addressed	Phase I 1989-1992 *(x $1,000)*	Phase II 1993-1996 *(x $1,000)*	Phase III 1997-2002 *(x $1,000)*
1.	4km Diamond Coring System	1, 2, 3, 4, 7, 8, 9, 13	1,390	——	——
2.	6km Diamond Coring System	1, 2, 3, 4, 7, 8, 9	——	1,000	200
3.	Slimline riser and blow-out preventer	1, 2, 3, 7, 8, 9, 10, 11	300	5,000	1,500
4.	Improved sediment-coring systems	7, 8, 9, 10, 11, 12, 13	250	200	150
5.	Borehole seismometers and operations of seismic systems	2, 4, 5	600	600	600
6.	High-temperature systems	3, 4, 11	1,000	1,510	750
7.	Improved packer and fluid samplers	4, 5, 8, 11	800	500	300
8.	Oriented core samples	1, 2, 5, 6	250	250	——
9.	*In-situ* pressure sampler	7, 8	250	250	150
10.	Slimline logging and borehole experiments	1, 2, 3, 4, 7, 8, 9, 10, 11, 13	650	2,000	——
	TOTAL		5,490	11,310	3,650
11.	Alternative vessels	1, 7, 8, 13, 15			
	Jack-ups		——	2,000	2,500
	Arctic D/V		——	——	——

Table 5 Explanatory Notes:

Item	Comments
1,2.	The adaptation of small-diameter, high-speed diamond coring from a mining technique to a full fledged deep sea coring system is envisioned as evolving through several stages. The terms "4 kilometer DCS" and "6 kilometer DCS" do not signify a simple extension of depth capability, but rather represents points of the learning curve for a *totally new technology*.
3.	A slimline riser system appears to be the only feasible and affordable way we can conduct riser drilling in water depths greater than about 2,500-3,000 meters. The longest existing conventional riser is about 7,500 feet (2,200 meters) and it seems unlikely that the oil industry will build a larger one in the near term. The cost to ODP of leasing a second drilling vessel equipped with an up to 10,000 foot riser to drill a special hole would be prohibitive. However, there is no technological reason that the *JOIDES Resolution* cannot be modified to handle a "slim riser" at more affordable costs by the end of Phase II. In fact, the development of the DCS can be considered the forerunner of a slimline riser system in that two strings of pipe, i.e., a drill rod inside the standard ODP drill pipe, are being handled successfully in the prototype DCS. Although this is not in any sense a riser system with circulation capabilities and blow out control, it conceivably could be developed in that direction. The $300K in Phase I is intended only to develop concepts and designs that go beyond the pipe-within-a-pipe of the DCS. The $5,000K in Phase II would buy the riser system materials and fabrication. Testing of the system would be completed during Phase II so that it would be in operation for the Phase III of this plan. The $1,500K in Phase II represents an increase in expenses due to the greater operating costs of riser drilling.

4. This item encompasses a variety of tasks aimed at minimizing core disturbance and increasing core recovery. They include the ongoing efforts to improve the extended core barrel (XCB) and advanced piston coring (APC) hardware, and the design and testing of new bits and efforts to extend the life of coring components so as to reduce operating costs.

5. The development of borehole instruments is not now part of normal ODP operations. The estimated costs shown for each phase represents estimates associated with deployment and operations. The exact mechanism for developing such borehole instruments as seismometers is not considered in this document.

6. Many aspects of drilling into regions of high-temperature in the ocean environment are an undeveloped technology. However, based on experience from on-land drilling of hydrothermal systems it is clear that certain critical elements of the ODP drilling and coring systems now in use must be redesigned and fabricated with different materials. The Phase I costs would include a period of intensive study and experimentation which by Phase II would provide the tested tools for addressing the scientific objectives of ODP. It is assumed that cost during Phase II will be principally for operations.

   Operations in high-temperature regimes also require significant modifications of the present ODP downhole measurements operations because of the high temperatures and highly corrosive environment expected. The logging approach used must be consistent with the type of drilling utilized: either a 10-12" hole or, more likely, a small diameter diamond-coring hole. The two approaches require much different strategies for downhole measurements, with different financial implications.

   With a 10-12 inch conventional hole (or a 5 inch diamond-coring hole, see note 10), nearly all of our present downhole tools could be used in most hot holes. With a carefully

Table 5 Explanatory Notes (continued):

Item	Comments
	monitored program of cooling the hole by circulation, the tools would never exceed their 150°C operating limits and the adverse effects of corrosive pore fluids would be minimized. Approximately $20,000 per year in 1990-1992 would be required for modeling studies of the effect of different circulation strategies on borehole temperatures, culminating (after field experiments) in software to guide real-time decision-making so that adequate cooling is maintained with minimum expenditure of ship time. Some holes will have active advection of high-temperature fluids into the borehole, overwhelming the ability of circulation to cool the hole. Such aquifers must be spotted with a hot-hole temperature tool ($60,000) at the beginning of logging, studied and sampled with the wireline packer, and then probably cemented in and redrilled before other logging.
7.	Packers and fluid samplers are examples of specialized tools which have been mostly developed outside of ODP by "third" parties. However, the objectives for drilling in high-temperature regimes will require significant improvements to existing tools. Since circulation will not solve the hot-hole problem for every tool and every hole, drill string packers and particularly the wireline packer will require the development of high-temperature packer elements. In addition the entire wireline packer will need to be replaced with one capable of sampling high-temperature, corrosive fluids. These developments are estimated to cost about $300,000 and are planned for Phase I. Other costs during Phase I and costs shown for Phases II and III reflect added operational expenses associated with the deployment and use of these tools.
8.	At present the only core samples which are routinely oriented are collected by the APC system. Orientation of cores cut with rotating bits is a much more difficult task. The

lack of effort to develop this technology reflects the limited budget for technological developments within the present ODP program. The relatively small costs shown here envision the testing of a number of concepts during Phase I with ultimate deployment of a successful method during Phase II.

10. At the present time it is difficult to estimate the cost of converting the more highly sophisticated logging tools now used by ODP to a small diameter diamond coring system. The cost will depend on which size hole will ultimately be drilled with the DCS envisioned under items 1 and 2. The size of hole also effects the estimates for cost of the DCS. For this cost estimate we assume that the DCS will drill a 4 inch diameter hole. This size hole can be drilled by a DCS system using the existing drill string on the *JOIDES Resolution.* A larger diameter DCS system requires a larger drill string and thus would require significant costs to modify the ship and purchase new drill string and associated hardware. Since the DCS is still under development and there are a number of uncertainties about the system, we therefore make this assumption. However, we will continue to examine the cost trade offs of slimlining downhole measurement tools versus up-sizing the DCS.

    With a 4 inch DCS hole, none of the many downhole tools deployed in previous ODP operations can be used. We will need either to lease or to purchase and modify slimhole tools. One possible option is that ODP will lease tools already designed and used at temperatures of up to 400°C and in highly corrosive environments. Leasing charges are currently $60,000 per leg for a suite consisting of sonic, density, gamma ray, neutron, resistivity, caliper, and temperature tools. Alternatively, we could purchase these kinds of slimhole tools (for about $450,000) and repackage them in dewared pressure cases to increase their capabilities from 65°C and 1,500 psi to 300-400°C and 10,000 psi (for about $200,000). The costs for purchasing are listed as part of Phase I.

Table 5 Explanatory Notes (continued):

Item	Comments
	To move from this relatively primitive downhole logging capability closer to the capability already employed by ODP at such basement sites as Site 504, we would need to design and build high-temperature slimhole versions of the following:
	Temperature tool ($60,000); waveform sonic (because existing slimhole sonic tools will not provide reliable velocities in highly fractured rock, $150,000); wireline packer ($100,000 for high-temperature packer elements, $200,000 for measurement and sampling of hot corrosive fluids, $150,000 for a slimhole design); televiewer ($100,000 for high-temperature modification of the WBK televiewer); DCS packer ($200,000); and magnetometer ($75,000). Modification of the geochemical tools (except maybe K, U, Th), formation microscanner, and susceptometer would face design limitations that make slimhole conversion completely unfeasible or prohibitively expensive (>$1,000,000). These costs are included in Phase II.
	Unfortunately, at present a 4 inch diamond coring hole would result in the loss of the ability to log holes with all the advanced tools introduced during ODP.
11.	For drilling deeply into lagoonal areas of atolls, the use of a jack-up rig, specially leased for this purpose seems to be the most economic approach. Estimates shown here assume that this mode of atoll drilling will be programmed after 1992, and that in Phases II and III, single drilling campaigns of 60 days each will be conducted.
	Arctic drilling represents the only regionally oriented scientific priority presented in this document. However, the importance of this region in terms of the evolution of earth's global climate alone makes drilling in this region a very high priority, but at this time it is not possible to estimate the cost associated with operations within the permanent ice of the Arctic.

As can be seen in Table 4, the additional cost above the normal operations of ODP of this implementation plan is on the order of $24M over the 14 years represented by the three phases of this document. While this represents an average of only $1.71M per year it is clear that a significant increase in development monies is required during Phase II.

EPILOGUE

Drilling in the deep sea has and continues to bring to light new understanding of the earth and its interconnected circulation cells—the atmosphere, hydrosphere, cryosphere, lithosphere and asthenosphere. More importantly, it provides new understanding on how these cells vary and ultimately control the environment in which the earth's biosphere depends.

Because of the complex nature of the earth and the wide variety of scientific disciplines represented by the geoscience community, the Ocean Drilling Program aims to address a wide variety of scientific objectives identified by the JOIDES advisory structure. This variety is well illustrated by the sixteen objectives outlined in this document. It is in this variety of themes that the strength of ODP lies. As the largest international program studying the ocean basins today, it also brings together a very large community of scientists. This variety also makes ODP an extremely cost-effective scientific enterprise. Scientists dream of living in a world where costs are not a problem but unfortunately we do not live in such a world. Thus, funds are not available to conduct all the engineering efforts desired by the community nor to conduct all the drilling operations proposed. However, by being able to plan and conduct a wide variety of drilling operations, addressing high-priority scientific objectives in a number of areas, we will be able to mesh the technological developments that require resources of time and money with an active scientific program.

As outlined in this document, Ocean Drilling will continue to address first-order scientific problems about the earth. It is clear, however that to address the objectives outlined here it is essential that the modest increase in engineering and operational costs be available to assure the success of Ocean Drilling into the 21st Century.