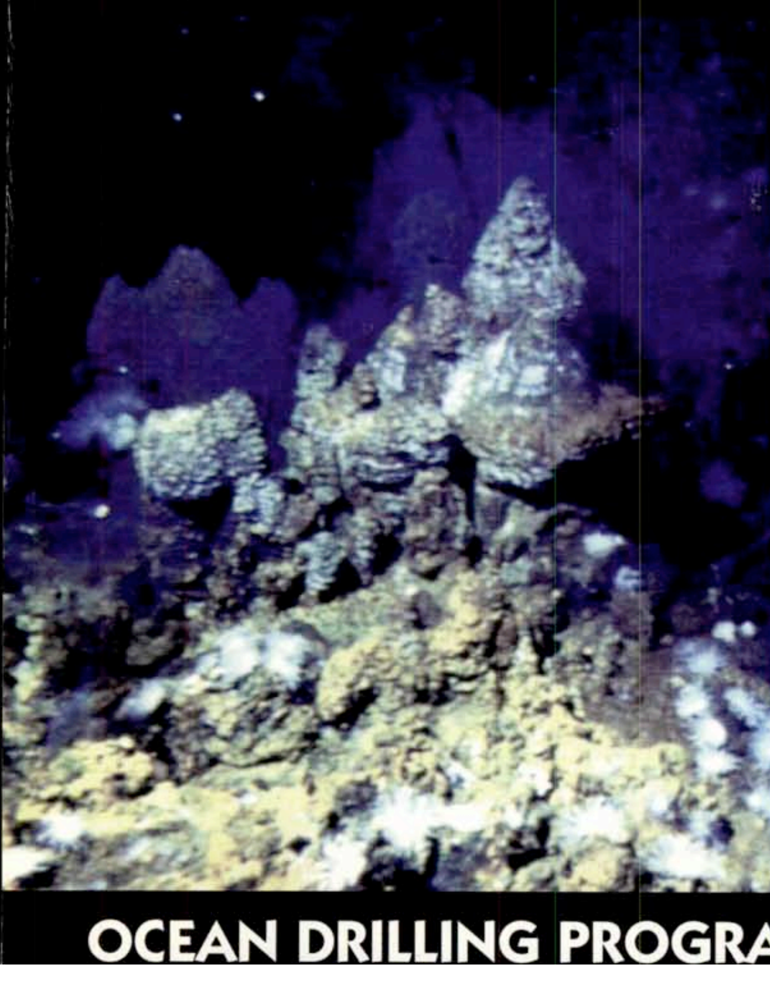
UNDERSTANDING OUR DYNAMIC EARTH THROUGH OCEAN DRILLING



OCEAN DRILLING PROGRAM LONG RANGE PLAN

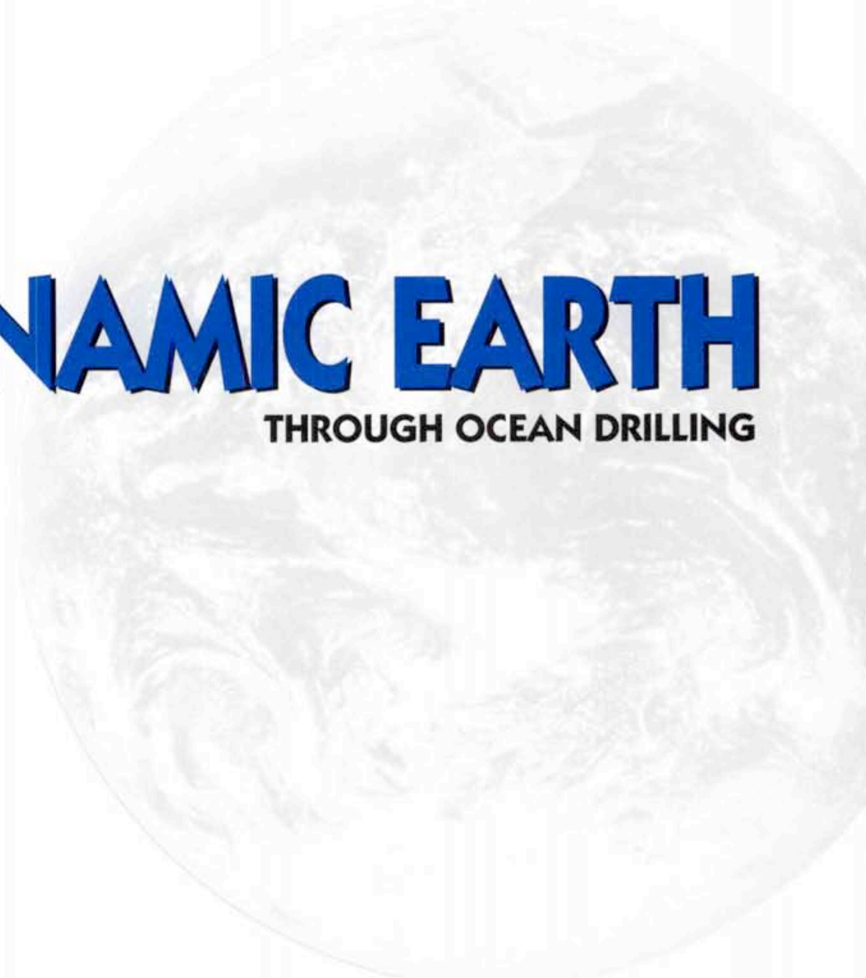
FRONT COVER:

Top left: Submarine eruption of basaltic pillow lavas off Hawaii. This flow of lava is the dominant form of heat transfer from the mantle to the crust. The lava also constitutes much of the geologic material drilled by ODP at mid-ocean ridges and in large igneous provinces. Photo courtesy of the National Geophysical Data Center (NGDC).

Top right: Geologic information on past changes in Earth's climate suggests that melting of large icebergs associated with glacial retreat perturbs ocean circulation patterns and results in large climate shifts over time periods as short as decades.

Bottom left: White smoker (1-2 m high) in the "Kremlin" area of the Trans Atlantic Geotraverse, Mid-Atlantic Ridge. Drilling into active, volcanic-hosted sulfide mounds allows ODP scientists to increase their understanding of hydrothermal activity associated with young oceanic crust. Photo courtesy of Susan Humphris (Woods Hole Oceanographic Institution).

Bottom right: Global sea level has never been constant — in fact, it is increasing slightly today. All civilization has occurred within a short period of high sea level. Yet, only 18,000 years ago sea level was about 120 meters lower than the present. The ODP seeks to improve our understanding of past sea-level changes and the forces that produced them, such as climate, plate tectonics, ice and snow, and ocean circulation.



UNDERSTANDING

OUR DYNAMIC EARTH

THROUGH OCEAN DRILLING

OCEAN DRILLING PROGRAM

LONG RANGE PLAN

INTO THE 21ST CENTURY

March 1996

In April 1994, the Long Range Planning subgroup of the JOIDES Planning Committee began developing this plan. The subgroup received input from JOIDES advisory panels, JOIDES member countries' ODP committees, and other international community science programs. Development of this plan continued throughout the tenure of two JOIDES offices (University of Washington and University of Wales, Cardiff) and was completed and refined by JOI following the advice of the JOIDES Executive Committee and ODP Council.

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Special thanks are extended to the ODP Science Operator at Texas A&M University, the ODP Wireline Services at Borehole Research Group of Lamont-Doherty Earth Observatory of Columbia University, and to the numerous scientists who contributed their time, energy, and ideas to this plan.

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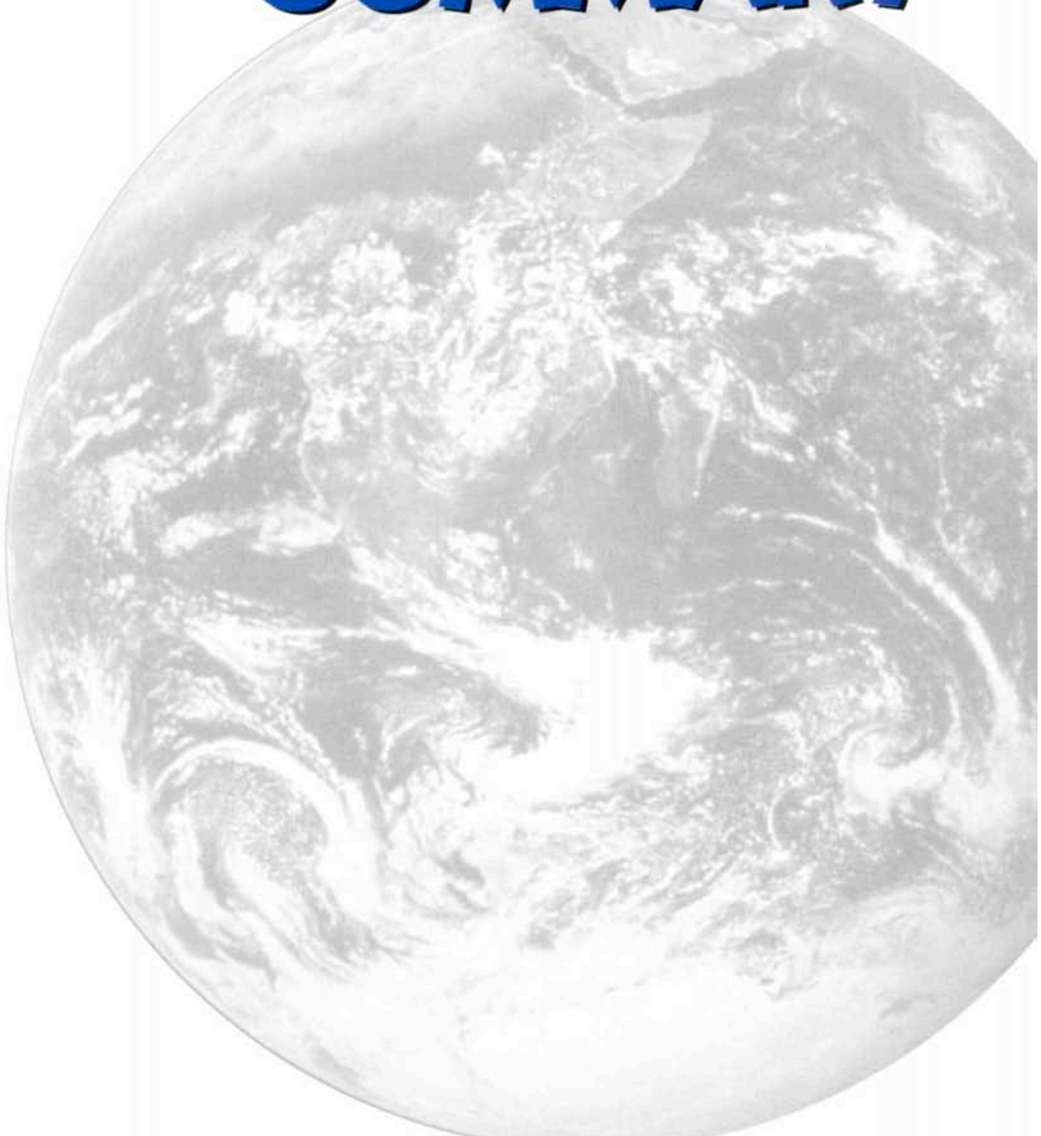


VISION FOR A NEW ERA OF EXPLORATION

Recent advances in technology and scientific understanding position the international Ocean Drilling Program (ODP) on the threshold of a new era. Capabilities now exist to:

- read the ocean's record of past environmental change with greater accuracy, and in unprecedented detail — to better comprehend the critical processes and mechanisms of the climate system, enabling us to provide the context for recognizing human-induced changes, and unraveling these from natural variability;
- emplace geophysical and geochemical observatories in the unique environment of seafloor boreholes — to provide a clearer view of Earth structure and a means to monitor, over the long-term and in real time, Earth processes and hazards;
- penetrate previously inaccessible regions beneath the seafloor — to explore the materials and mechanisms that form continents, rifts, oceanic crust, and economic resources (precious metals, ore, energy).

Building on its record of achievement, the ODP will proceed in new directions into the next century. This Long Range Plan identifies two major research themes:

- Dynamics of Earth's environment, and
- Dynamics of Earth's interior.

These encompass a vast range of fundamental scientific questions to be explored by ocean drilling. Within these themes, the ODP will emphasize three frontier initiatives which capitalize on new drilling and logging technologies and on advances in our scientific techniques and conceptual frameworks:

- Understanding natural climate variability and the causes of rapid climate change,
- *In situ* monitoring of geological processes,
- Exploring the deep structure of continental margins and oceanic crust.

The ODP will also begin a pilot program to explore the newly discovered living biosphere beneath the seafloor — to advance our understanding of the evolution of life and to search for novel life forms with biotechnological potential.

These initiatives directly address many aspects of our changing planet that concern society, such as natural resources, global environmental change, risks from earthquakes, volcanoes, and sea-level rise, and the capacity of Earth to sustain life. The pursuit of these initiatives complements and extends other scientific challenges that the ODP will address, and gives the Program the flexibility to pursue new challenges as they emerge. Understanding our dynamic Earth requires international cooperation. For this reason, and in order to make the best use of available resources, the ODP will continue to strengthen collaborative efforts with other national and international earth science programs.

STRATEGY

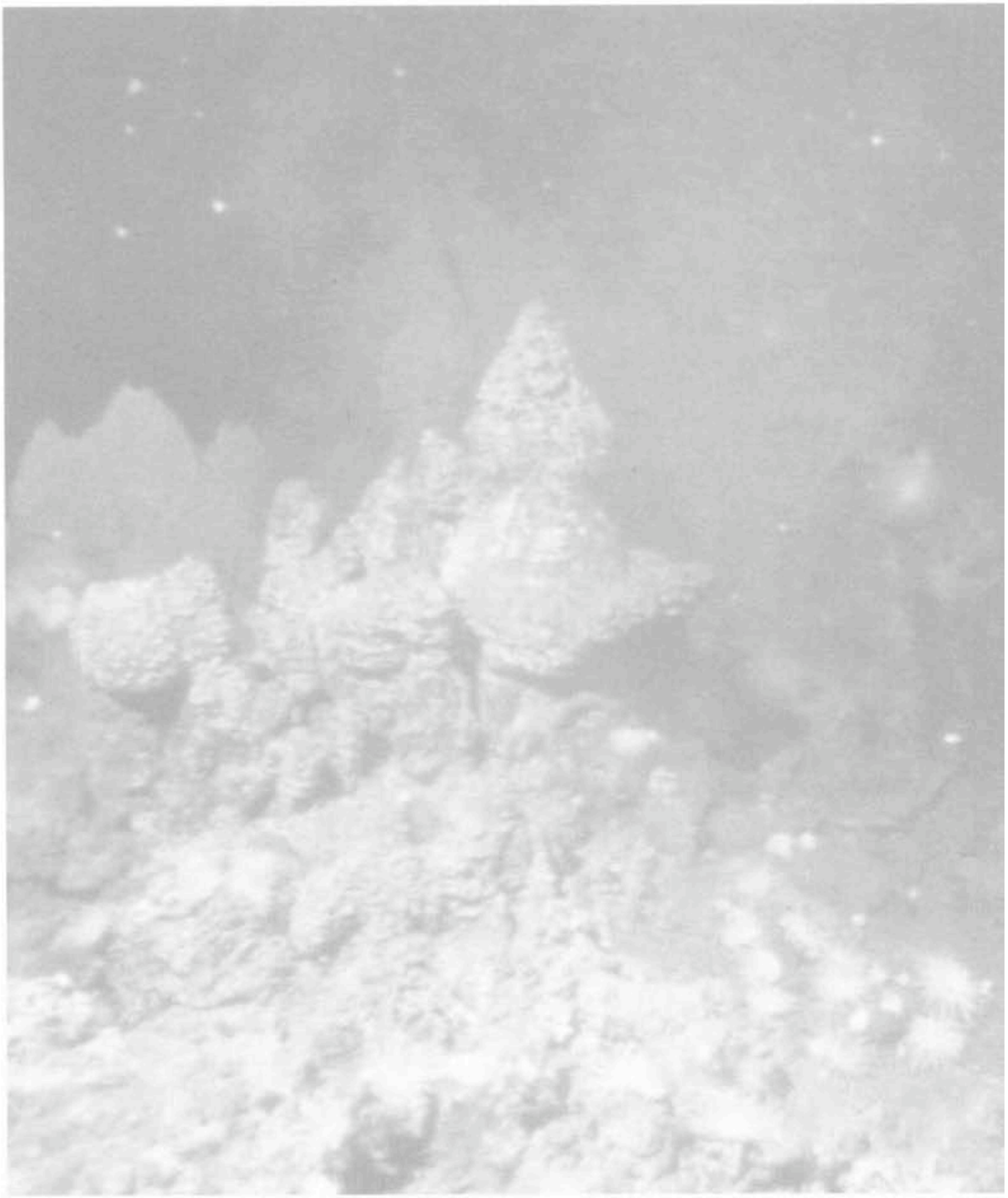
We present a three-phase strategy to implement the science proposed in this Long Range Plan. This strategy launches the ODP in new directions and extends the conceptual framework presented in the 1990 Long Range Plan.

Completion of Phase II (1998) will set the stage for Phases III (1999-2003) and IV (beyond 2004). Beginning in 1996, proposals for drilling will address, and be evaluated within, the context of this new plan. To ensure long-term coordination of science and engineering plans, we will modify the structure of Joint Oceanographic Institutions for Deep Earth Sampling (JOIDES), the scientific planning body of the ODP. In addition, ODP management will institute "project-based management" to increase operational efficiency. Phase II will see greater emphasis on the rapid publication of results in the general scientific literature, ensuring an audience that is wider and more appreciative of drilling achievements. A major reorganization and upgrade to the ODP computer database will also be completed, making information easier to use. Through the end of this phase and into Phase III, the ODP will be more closely linked with other international earth science programs, and cooperative initiatives will expand drilling platform capabilities. JOIDES is already coordinating with programs such as International Ocean Network (ION), International Ridge Inter-Disciplinary Global Experiments (InterRIDGE), and Nansen Arctic Drilling (NAD), whose objectives intersect those outlined in this Long Range Plan. These links to other programs will produce well-designed experiments to monitor earthquake hazards, to explore deep crustal structure and fluid fluxes, and to understand processes that drive climatic change, particularly over short time scales.

Phase III drilling will directly address the scientific themes and initiatives of this Plan. These initiatives will require multi-leg or multi-year programs. Improved drilling capabilities will allow the ODP to tackle problems in Phase IV that focus on the exceptional heat transfer that forms hydrothermal fields at ocean ridges and enormous outpourings of lava in large igneous provinces. Environmental objectives will include expanding the global array of detailed records of climate change, investigating global carbon cycling, and establishing the history of sea-level change and ice sheet growth, distribution, and decay.

Two drill ships will be required to meet the scientific goals of Phase IV. A *JOIDES Resolution*-type vessel will provide standard coring operations, but a riser ship is essential to meet some of the unique scientific objectives, such as drilling deeply into previously inaccessible oceanic crust. Riser drilling will also provide the well control necessary to permit drilling in key areas, such as continental margins, whose scientific and economic potential have never been explored by scientific drilling because of safety considerations. The principal proposal for adding riser capabilities has been put forward by the Japanese Science and Technology Agency (STA/JAMSTEC) and is known as "Ocean Drilling in the 21st Century."

INTRODUCTION



ASSETS

THE ODP ORGANIZATION

The ODP is an international partnership established to explore aspects of Earth's history, structure, and processes that can best, and often only, be addressed by ocean drilling. Joint Oceanographic Institutions for Deep Earth Sampling (JOIDES) is a partnership of ten U.S. oceanographic institutions and six non-U.S. partners, representing 18 countries, that establishes the ODP's scientific objectives through an advisory structure of panels and committees. An Executive Committee (EXCOM) presides over JOIDES and advises the ODP prime contractor, Joint Oceanographic Institutions (JOI), on policy issues.

JOIDES invites proposals for drilling and related work from individuals, groups, and established programs. Proposals are reviewed and ranked for excellence and thematic relevance by the JOIDES advisory panels. Next, they are checked for feasibility and safety. Only the best proposals are finally considered for drilling. The Planning Committee (PCOM) packages the top proposals into logistically feasible drilling legs and recommends them to the EXCOM for implementation.

The JOIDES advisory structure is currently guided by the 1990 ODP Long Range Plan, a distillation of a four-year planning process and the conclusions of two major international Conferences on Scientific Ocean Drilling, COSOD I and II.

Program funding and membership is provided by agencies in the 18 ODP member countries through Memoranda of Understanding with the U.S. National Science Foundation (NSF). After consulting the ODP Council, which represents all the JOIDES member countries and funding agencies, the NSF acts on the Council's behalf by disbursing co-mingled funds through a contract to JOI to manage the ODP.

In turn, JOI subcontracts major ODP operations to a Science Operator (currently Texas A&M University – TAMU) and Wireline Services Operator (currently Lamont-Doherty Earth Observatory of Columbia University – LDEO). The Science Operator organizes shipboard drilling, coring, and logging, archives the cores, maintains databases, and publishes ODP results, interpretations, and syntheses. The Wireline Services Operator manages the acquisition, processing, and distribution of logging data.

JOIDES RESOLUTION

The ODP's unique drillship, *JOIDES Resolution*, is specially equipped to withstand hostile oceanic conditions while exploring the seafloor below. The *JOIDES Resolution* also contains the world's most advanced research equipment in operation at sea with dedicated facilities for studying sedimentol-

ODP PARTNERS

AUSTRALIA/CANADA CONSORTIUM

EUROPEAN SCIENCE FOUNDATION CONSORTIUM FOR OCEAN DRILLING
(Belgium, Denmark, Finland, Iceland, Italy, The Netherlands, Norway, Spain, Sweden, Switzerland, Turkey)

FRANCE

JAPAN

GERMANY

UNITED KINGDOM

UNITED STATES OF AMERICA

ogy, micropaleontology, petrology, geochemistry, geophysics, paleomagnetics, and physical properties.

CORE REPOSITORIES AND MICROPALEONTOLOGICAL REFERENCE CENTERS

Shore-based sample repositories and data reference centers provide materials for research long after operations at sea are complete. Four core repositories contain all Deep Sea Drilling Project (DSDP) and ODP material and serve the scientific community by providing scientists with samples for further study. To date, scientists have taken over 600,000 samples from more than 100 km of ODP core that have been recovered.

Located at eight sites on four continents, micropaleontological reference centers provide scientists from around the world with an opportunity to examine, describe, and photograph microfossils of various geological ages and provenance.

ODP DATABASES

A vast amount of data has been generated for databases associated with scientific ocean drilling. All DSDP and most ODP data are contained in the computerized ODP database and are also available from the National Geophysical Data Center on CD-ROM. Geological and geophysical data can be selected by providing specified search criteria. These data, as well as photos of ODP/DSDP cores and seismic lines, are available to scientists in a variety of formats.

Another data source, the ODP Wireline Log Database, consists of Schlumberger logs (conventional geophysical, geochemical, and Formation MicroScanner™ images), logs from specialty tools (borehole televiewer, multichannel sonic, and temperature), and DSDP original, unprocessed logging data. These data are available to scientists in raw and/or processed format. The entire database will soon be accessible through the World Wide Web (WWW).

A redesigned ODP database management system (the Janus Project), slated for completion by 1997, ensures comprehensive input of data and easy WWW retrieval by users from around the world. The new system will use the relational database approach to improve the quality, productivity, and visibility of ODP science.

Another rich source of ODP-related data is the Site Survey Data Bank, located at LDEO, which holds drilling-related, site survey data. Through the WWW, scientists will be able to browse the list of Data Bank holdings, determine what site-survey data they require for drilling proposal preparation, and submit a detailed request for data. Some industry data are restricted for specific periods of time.

CORE REPOSITORY LOCATIONS

La Jolla, CA	College Station, TX
Palisades, NY	Bremen, Germany

MICROPALEONTOLOGICAL REFERENCE CENTERS

Palisades, NY	Lower Hutt, New Zealand
Washington, DC	Moscow, Russia
College Station, TX	Tokyo, Japan
La Jolla, CA	Basel, Switzerland

SCIENTIFIC PUBLICATIONS

ODP publications form a collection of scientific information that has become a fundamental source of data and concepts for the marine geosciences and other disciplines. This information consists of articles in scientific and trade journals; *ODP Proceedings Volumes*, both the "Initial Reports" and "Scientific Results;" and data collections on CD-ROM and other media.

ACHIEVEMENTS

The achievements of the Ocean Drilling Program represent an era of international cooperation and scientific discovery without precedent or parallel in the earth sciences. Synopses of major program achievements are presented in the Scientific Themes section of this document and are listed below.

GLOBAL OCEAN CONVEYOR BELT (page 21)

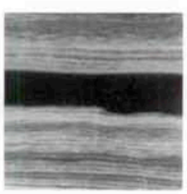
Data from several ODP legs allow paleoceanographers to reconstruct the ocean's deep water chemistry and circulation (and their links to climate change) through the entire Neogene and into the Paleogene.

NORTHERN HEMISPHERE GLACIATION (page 22)

Drilling in the North Atlantic Arctic gateway region has pointed to a relationship between climate evolution and water mass exchange from the Arctic to the other major ocean basins, and has uncovered, in unprecedented detail, the history of major ice sheets that have waxed and waned over the past few million years.

CENOZOIC SEA-LEVEL CHANGE (page 23)

The ODP has drilled along continental margins and into coral atolls to improve our understanding of the magnitude, age, and mechanisms of Cenozoic sea-level change. These data aid scientists in evaluating the effects of sea level on sedimentation, climate, and ice-ocean interactions, thus allowing better predictions of future sea-level change and their potential impacts on society.



ULTRA-HIGH-RESOLUTION RECORDS (page 24)

Studies of ODP cores from the Santa Barbara Basin found that past changes in the oxygen content of bottom waters can be matched, in extraordinary detail, to short-lived climatic excursions in the Greenland ice sheet, suggesting large-scale climate communications over vast distances.

ASTRONOMICALLY TUNED GEOLOGIC TIME SCALE (page 25)

Scientists using ODP cores have developed a geologic time scale based on past variations in Earth's orbital geometry that stretches millions of years into the past and is far more precise than that achievable by radiometric dating alone.

YOUTHFUL GREAT BARRIER REEF (page 27)

Australia's Great Barrier Reef has been shown by the ODP to be much younger than previously thought. It has survived exposure during sea-level low-stands and has recovered and regrown during high-stands, with these cycles having an impact on atmospheric CO_2 levels.

OCEANIC LITHOSPHERE (page 33)

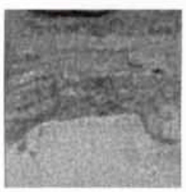
The ODP has provided core samples and downhole geophysical data from the youngest oceanic crust to the oldest. These data are essential for understanding global geochemical cycles and for evaluating Earth's resources.

HYDROTHERMAL MINERALIZATION (page 35)

The ODP has drilled into active hydrothermal systems where volcanic- and sediment-hosted sulfide mineral deposits are forming. Penetration into massive sulfides and/or the underlying stockwork provides insight into the development of these types of deposits, and may aid in land-based mineral exploration.

NORTH BARBADOS RIDGE (page 36)

ODP scientists are using several innovative techniques to understand fluid and rock properties in zones where plates collide. Deformation of large volumes of rock and the role of fluids in faulting have been measured and monitored by downhole observatory, logging, and seismic techniques.



NORTH ATLANTIC RIFTED MARGINS (page 38)

Drilling along both volcanic and non-volcanic margins in the North Atlantic has revealed the effects of a variety of fundamental processes responsible for continental rifting and early subsidence.

FLUID FLOW IN THE LITHOSPHERE (page 40)

Only recently, through ODP drilling, have scientists been able to document fluid pathways, sources, rates, and effects in the oceanic lithosphere. The ODP has collected fluid flow data in seafloor environments such as oceanic crust, accretionary prisms, and sedimented spreading centers.

BEYOND RESEARCH

Participation in the ODP and the JOIDES planning process brings more than the immediate tangible products of basic scientific research. The proposal-driven, international structure in which the Ocean Drilling Program is conducted promotes interdisciplinary approaches, positive competition and high-quality science. It also stimulates cross-national education and development of science infrastructure, helping to maintain the planet beneath the oceans as a shared scientific frontier.

SCIENTIFIC TRAINING

The ODP plays a major role in training future earth scientists, primarily through the shipboard participation of graduate students (about 20 percent of the scientific parties). The *JOIDES Resolution,* in effect, serves as an international university where young scientists participate in drilling legs as an on-the-job training exercise. Cruises teach important skills such as project conceptualization and planning, hypothesis testing, scientific drilling methods and strategies, geophysical data acquisition, core sampling, core data analysis, data synthesis, scientific writing, and team work. Through their involvement with the ODP, scientists are also offered the opportunity to establish and maintain an international scientific network of peers and potential collaborators that can enrich their careers.

EDUCATION

The ODP databases, core repositories and micropaleontological reference centers are available to all scientists. These extensive collections provide the foundation for a wide variety of undergraduate and graduate educational activities in universities around the world. Core physical property data, paleontological samples, and wireline logs constitute a vast educational resource used to teach laboratory methods, provide study materials for undergraduate project work, and contribute to postgraduate research and thesis topics.

REGIONAL DATABASE DEVELOPMENT

In its pursuit of thematic scientific objectives, ODP drilling has helped individual countries increase their understanding of their regional offshore geology. This local picture often helps a nation evaluate the resource potential of its exclusive economic zone, as well as legal continental shelf, which in some areas can extend beyond 200 nautical miles offshore. Deep-water scientific drilling data, of the type collected and published by the ODP, are generally unobtainable by other means.

RESOURCE POTENTIAL

ODP drilling has, on a number of occasions, altered the perceptions of petroleum and mineral exploration companies regarding resource potential. Results of ODP drilling often provide new conceptual information and data on the distribution of petroleum source rocks or reservoir potential that influence commercial resource exploitation. Prospects identified by the ODP in one geographic area have been shown to be readily applicable in other areas of the same region, or even worldwide. Several new sedimentary basins with previously unknown petroleum potential have been found offshore Australia and within island chains in the southwest Pacific. The structure of various metallic ore bodies in the process of formation on, and beneath, the seafloor at a spreading ridge have been identified. These may serve to improve our understanding of, and exploration for, similar ores in ancient rocks on land.

COLLABORATION

The ODP plays an important role in breaking down cultural and geographic barriers to international scientific cooperation. Scientists from relatively small universities and agencies can participate in the ODP by submitting drilling proposals, serving on board the drillship and on JOIDES panels, requesting samples, and querying databases. By working together, scientists from all the participating universities and agencies have established collaborative scientific relationships and have co-ownership of joint scientific research findings.

INNOVATIONS

The ODP often drills into environments of enormous pressure, elevated temperature, and chemical toxicity. Scientific advances in these environments have been made possible by parallel advances in ODP drilling technology. Several recent developments, highlighted below, have made the ODP a leader in exploring planetary dynamics.

SEDIMENT ANALYSIS AND AGE MODELS

Marine sediment and rock samples faithfully record pages of Earth history. The ODP is in the vanguard in developing laboratory tools and scientific concepts that enable us to "read" this history with increasingly higher resolution and greater understanding. One major innovation is the suite of instruments arrayed along the ship's multisensor track (MST). As soon as a core arrives in the shipboard laboratory, these instruments provide automated, centimeter-scale measurements of a host of physical and magnetic properties. Some variations in these properties are the result of changes of oceanographic processes (biological productivity, deep water chemistry, etc.) in response to regional and global climate conditions. The MST can thus provide extremely detailed (tens to thousands of years, depending on the sedimentation rate) records of climate change. Progress in MST innovation has been paralleled by advances of the astronomical tuning concept, namely correlating time series of detailed sedimentary variations to orbitally induced changes in solar radiation reaching Earth. Development of highly precise age models now enables scientists to accurately calculate sediment and chemical fluxes and constrain biological variations which shape our knowledge of how the ocean and climate system changes. These major innovations will continue to evolve during the next phase of the ODP. The MST variations can also be related to the record of physical properties determined by borehole logs, allowing the unambiguous establishment of the true stratigraphic position of important climate events. These data serve two purposes: first, they accurately reveal Earth history; and second, they provide reliable links between the geologic records of boreholes that may be kilometers apart.

TOOL ENHANCEMENT

On many occasions the ODP by itself, or in cooperation with external ventures, has redesigned drilling and downhole logging tools (some of which have been adopted by the commercial sector), coring systems, high-temperature logging tools, a wireline heave compensation system, and seafloor drilling guide bases. The ODP routinely uses reentry systems that it developed to enable the drillship to return, sometimes repeatedly, to the same hole in the seafloor to conduct sequential drilling and monitoring activities.

SEAFLOOR OBSERVATORIES

A collaborative effort between scientists and ODP engineers has developed a system that seals selected boreholes ("CORKs") and monitors downhole temperature, pressure, and fluid composition for periods up to three years. These specialized systems yield valuable information about how rock properties change over time.

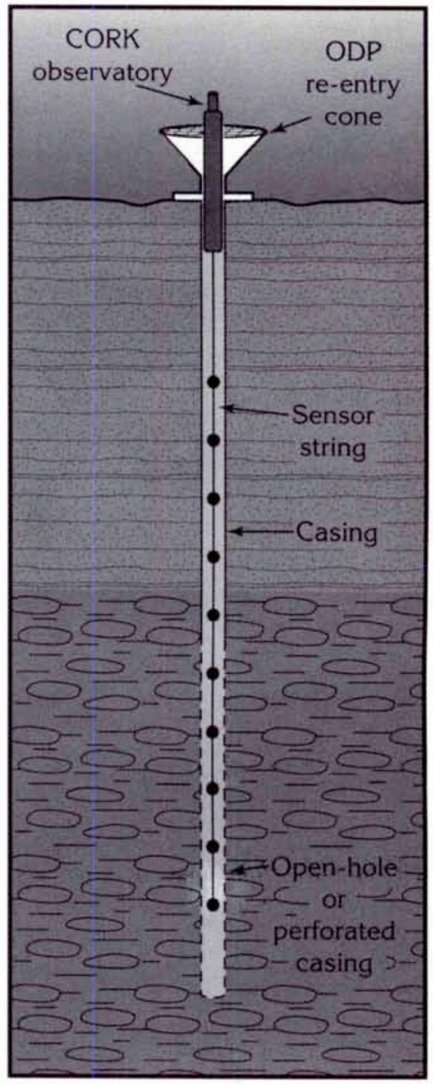
Recognizing that the overwhelming majority of Earth's seismic events occur beneath the ocean, and cannot be detected and precisely located with land-based tools, seismometers designed in cooperation with ODP engineers have been placed in boreholes to monitor earthquakes and the overall state of stress in oceanic crust.

MEASURING *IN SITU* CONDITIONS

Downhole logging tools developed by the oil industry have been deployed in ODP holes to allow scientists to remotely measure physical properties of sediments, rocks, and pore-filling fluids at *in situ* conditions. Use of the Formation MicroScanner™, which has been redesigned for ODP use, can yield a resolution of about 1 cm, a phenomenal level of precision that assists in the reconstruction of detailed histories of climatic, oceanographic, and depositional cycles that may surpass a 50-year resolution. The ODP led the first deep sea use of the logging-while-drilling technology developed by the oil industry. This technique provides conventional logging data during the actual drilling process, and returns superior data less likely to be degraded by the collapse of the borehole sides. Furthermore, this technique yields *in situ* information from environments either too shallow or too difficult to investigate with standard logging tools.

SOFTWARE DEVELOPMENT

Specialized software applications and database management tools have been developed by ODP to catalog, retrieve, and manipulate the enormously large volume of information currently provided by drilling and monitoring an ODP borehole. Packages developed for the integration of downhole logging and laboratory MST data have been critical in registering thin and discontinuous markers in the geologic record.



Schematic cross section of an ODP CORK installation.

JOINT VENTURES

Many of the drill bits, coring techniques, downhole tools, shipboard laboratories and software applications now in use have been developed by ODP in conjunction with industrial applications. These fruitful relationships represent unique joint ventures of truly global proportions between scientific need and industrial savvy. Among the partner industries (and their particular specialization) who contribute towards scientific ocean drilling are SEDCO/Forex (drilling operations), Schlumberger (downhole tools), Christensen Drillers (bit technology), and Adara (oil field engineers).

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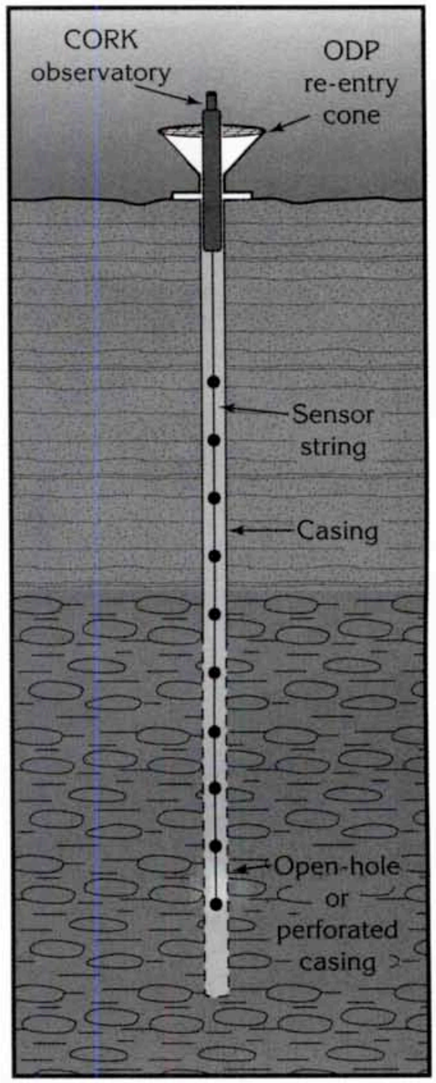

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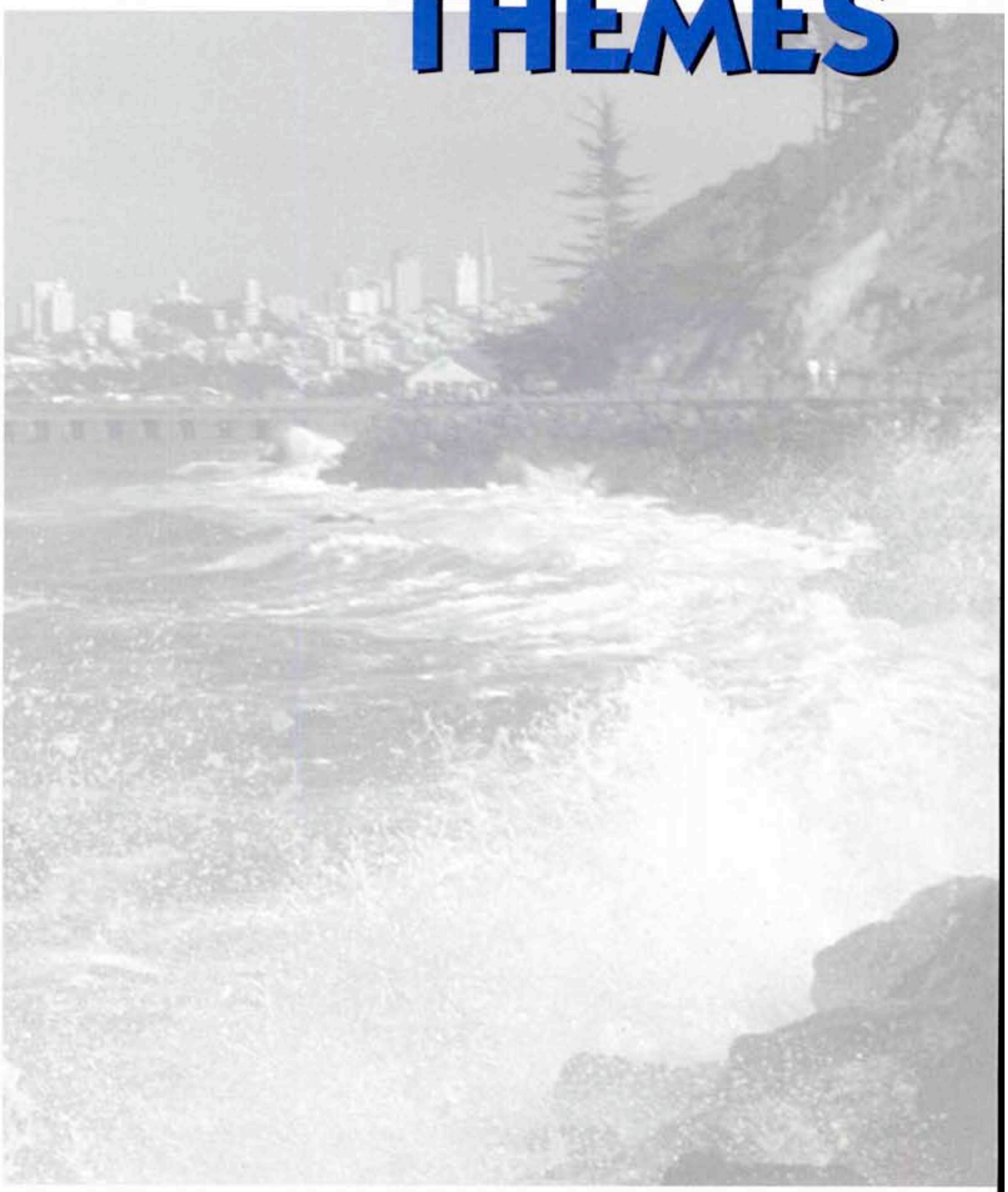
SCIENTIFIC THEMES



SCIENTIFIC THEMES

DYNAMICS OF EARTH'S ENVIRONMENT

- **Understanding Earth's changing climate**
- **Causes and effects of sea-level change**
- **Sediments, fluids, and bacteria as agents of change**

DYNAMICS OF EARTH'S INTERIOR

- **Exploring the transfer of heat and materials to and from Earth's interior**
- **Investigating deformation of the lithosphere and earthquake processes**

The Ocean Drilling Program's developing approach to scientific ocean drilling parallels the evolving recognition that Earth is a large, complex, interactive, and dynamic system. While any division of the "Earth system" is inherently arbitrary, we have divided the discussion of future drilling objectives into two major themes: Dynamics of Earth's Environment and Dynamics of Earth's Interior. Within these broad themes, several more specific "core" themes are identified, themes where ocean drilling is either the best or the only means of solving outstanding problems of a fundamental scientific nature. These "core" themes include: Climate Change; Sea-Level Change; Sediments, Fluids and Bacteria as Agents of Change; Transfer of Heat and Materials to and from Earth's Interior; and Deformation of Earth. The themes are closely linked to studies of natural resource potential, the global environment, and natural hazards. From a consideration of these scientific themes, and the technology that will be available to the ODP over the next decade, three program initiatives are also proposed and are discussed in detail in the next section. Two of these initiatives will involve major collaborations with other global programs over the next phase of drilling while the third requires a major step in drilling technology that will not become available until post-2003, but must be planned for within the next phase. The ODP will emphasize these initiatives in its call for future drilling proposals.

Embedded within this section are summaries of several important ODP achievements. These represent only a handful of the exciting scientific problems that the ODP has tackled in the last decade. Because most of these achievements are recent, there is still much more to be learned by the detailed analyses the leg participants, and others, will be conducting in the coming years.

Understanding Earth's changing climate

ODP paleoclimatic objectives now focus on questions concerning the recent discovery that climate is directly forced on the millennial time scale and responds to internal processes on century and decadal time scales. For example, deep-sea sediment cores and Greenland ice cores clearly document large natural changes in climate that have occurred on the millennial, century, and even decadal scale, that is, within human lifetimes. New results have documented the existence of climate cycles that culminated with the launching of massive armadas of icebergs from the Laurentide ice sheet into the North Atlantic at regular intervals during the past 70,000 years. As they melted during their traverse from the northwest Atlantic towards Europe, these bergs released large amounts of fresh water and glacial sediment into the ocean. The injection of this water disturbed the density structure of the surface ocean, thereby affecting the production of deep water, and thus the global conveyor-belt of ocean circulation, a key factor controlling climate.

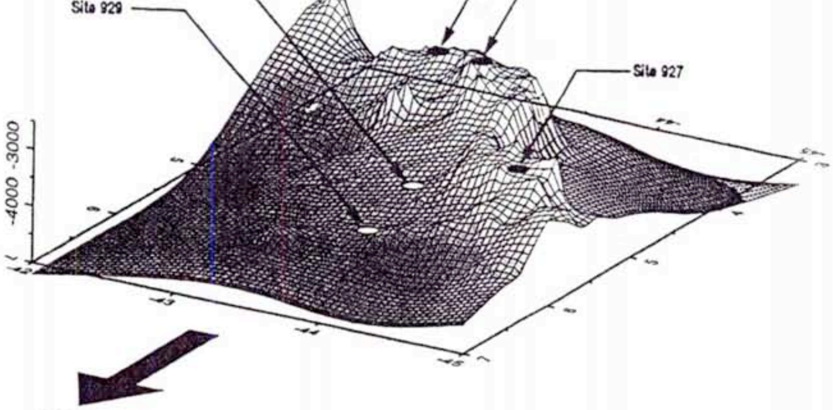
A second example of climate change being explored by ODP is that associated with the mass extinctions at the Cretaceous/Tertiary boundary (~65 million years ago). The leading hypothesis for the extinctions is a meteorite impact, which undoubtedly had catastrophic consequences for global climate. By drilling near the presumed impact site, scientists on ODP Leg 165 will learn more about the ocean-atmospheric interactions and changes in global climatic boundary conditions that occurred at that time. Exploring the causes and effects of rapid and dramatic climate change are essential to understanding our climate system and particularly its response to global warming from greenhouse gases.

The approach to coring for paleoclimatic reconstructions is straightforward. In some instances key areas are targeted to address questions pertaining to specific events, such as drilling in the Caribbean to learn more about the meteorite impact in Mexico. In other cases, such as exploring the geographic distributions and relationships of oceanographic and climatic phenomena (e.g., biological productivity or wind patterns), spatial transects of cores are collected across critical oceanographic boundaries (e.g., surface current boundaries). Investigation of depth-related phenomena, such as carbonate dissolution and water mass structure, requires the drilling of cores along depth transects. The location of these transects must be carefully chosen with the knowledge that the plate upon which the sediment is accumulating is moving laterally and subsiding.

Traditionally, there has been a trade-off in the approach to global climate reconstruction from deep-sea cores. Short, detailed records (10^2 to 10^3 year resolution) have been recovered by conventional piston cores for many years. These records often have the fidelity to present a precise picture of oceanographic and climatic change, but their limited length precludes the construction of records that are long enough for rigorous statistical analysis. Furthermore, short cores cannot penetrate the deeper sedimentary sections containing evidence of large climate transitions in earlier times. Longer, lower resolution records have been recovered by the ODP but these rarely had the accumulation rates necessary to address the detailed mechanisms of short-term climate response. As a result, the ODP has made significant contributions primarily to our understanding of the longer-term factors involved in climate evolution, such as Milankovitch cycles, mountain building and oceanic gateway evolution. However, recent ODP-led developments in core recovery and analysis have revolutionized the speed and resolution at which we can extract paleoclimatic data from the sediments. The stage is set for a new era of drilling that will target areas where sediments have accumulated rapidly in order to provide the long, yet extremely high-resolution (century-scale, and in certain environments, annual to decadal-scale) records needed to piece together a detailed picture of the causes and effects of environmental change.

ACHIEVEMENT: Global ocean conveyor belt

The Ceara Rise was targeted by the ODP as the ideal location in the western equatorial Atlantic for a suite of drill sites designed to explore a variety of paleoceanographic and paleoclimatic objectives. The water depths of the drill sites were selected to span the hydrographic boundary separating two principal water masses that flow in opposite directions. Changes in the chemistry and volume of the southward flowing North Atlantic Deep Water (NADW) and northward flowing Antarctic Bottom water will be painstakingly reconstructed from the recovered sediment cores that span the last 55 m.y. Understanding the history of deep water circulation in this region is important because it affects (1) global circulation patterns since NADW is the origin of the "global ocean conveyor belt;" (2) the ocean heat budget, which is a major influence on climate; and (3) the uptake and release of carbon dioxide from the oceans to the atmosphere, influencing global carbon cycling and atmospheric temperature. The Ceara Rise location was also chosen to complement the global array of depth transects that has been acquired during the past decade of ODP drilling (Leg 108, eastern equatorial Atlantic; Leg 113, Maud Rise; Leg 115, Madingly Rise; Leg 117 Owen Ridge; Leg 130, Ontong Java Plateau; Leg 145, Detroit Seamount). Comparison of Leg 154 data to similar depth transects in other oceans will allow paleoceanographers to constrain reconstructions of deep water chemistry and circulation (and their links to climate change) through the entire Neogene and into the Paleogene.

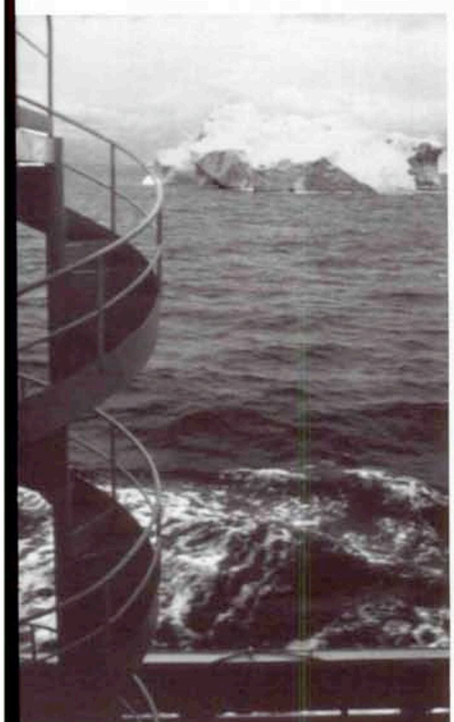


Perspective view of Ceara Rise from the northwest to southeast, which points out the steep slopes on the southwest margin and gentle dips on the northeast flank. The prominent platform tops of the rise are usually shallower than 3200 m. Several of these platforms were selected for shallow coring (Sites 925-927). The deeper coring sites of the bathymetric transect fall on the gently sloping northeast flank (Sites 928-929).

New drilling results will be used to address the role of greenhouse gases in climate change, and specifically to determine how natural variations in atmospheric CO_2 and methane are linked to changes in oceanographic conditions. By drilling transects and key specific locations we will evaluate warm climates of the past, and explore whether episodes of moderate to extreme global warmth were the result of changes in atmospheric composition or poleward heat transport by ocean currents. Within this context, the effect of mountain-building on climate will also be examined.

Finally, new developments in stratigraphic resolution, digital imaging, databases, and biochemical techniques will advance our understanding of the spatial patterns and timing of biological extinctions and natural changes in biodiversity. Paleontological and paleoenvironmental studies at drill sites, located in a variety of depositional settings and spanning a range of geologic time, will address questions of how the biosphere responds to climatic change (and vice versa) and how ecosystems respond to mass extinctions.

ACHIEVEMENT: Northern hemisphere glaciation



Until recently, scientists had only a fragmentary understanding of the onset and history of glaciation in the northern hemisphere and the evolution of the equator-to-pole thermal gradient. This gradient is an essential component of Earth's climate regime because it exerts great control over ocean and atmospheric circulation. A recent phase of drilling in the North Atlantic Arctic Gateway region aimed to study the relationship between climate evolution and water mass exchange across the marine connections from the Arctic to the other major ocean basins, and the history of major ice sheets (North America, Greenland, Eurasia) that have waxed and waned over the past few million years. We now know that glaciers existed in the Norwegian-Greenland Sea region as far back as 12 Ma, older than previously thought. These early glaciers were followed by a phase of intense cooling at 6-7 Ma which coincided with an expansion of glaciation in Antarctica and a lowering of global sea level. This lowering was great enough to isolate the Mediterranean from the Atlantic Ocean, resulting in desiccation and accumulation of massive evaporite deposits. Another major phase of global cooling began at about 3 Ma. This led to the initiation of the glacial-interglacial climate regime at 2.7 Ma, and an intensification at 0.8 Ma.

Drilling results suggest that Greenland is a climatically sensitive region and that full-fledged ice sheets developed much earlier here than in Arctic Eurasia. These ice sheets eroded and sculpted landscapes, changed continental margins, and altered the physical boundaries of the climate system. North Atlantic ocean circulation (the "conveyor belt") plays a key role in the evolution of the equator-to-pole thermal gradient because it brings warm water to the north to melt ice sheets but it also brings moisture to feed ice-sheet growth during cooling phases. Together with the Greenland ice cores, ODP/DSDP cores are being extensively used to demonstrate that oceanic heat transport is highly unstable in the North Atlantic and that rapid and repeated shifts from warm to cold climates have occurred during the last glacial cycle on time scales as short as decades. This new picture of a jittery climate system is an important target for climate modeling and raises many key questions concerning predictions of future climate change.

Causes and effects of sea-level change

The obvious importance of understanding sea-level fluctuations is that they have a tremendous economic and environmental impact on coastal zones, lowland areas and oceanic islands. The relevance of sea-level shifts to petroleum resources may be less obvious, but drilling demonstrates that such shifts control the locus of sedimentation on continental margins which, in turn, determines where hydrocarbons can be trapped and whether petroleum source rocks are preserved or destroyed.

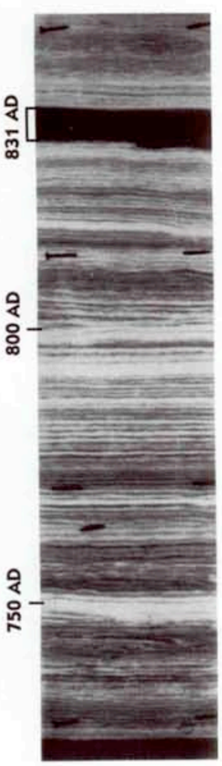
Sea level has never been constant throughout Earth history, and it is rising slightly today. Tide gauges show an average sea-level rise of 2.4 cm since 1930. The oxygen isotopic composition of marine microfossils indicates significant waxing and waning of continental ice sheets over the past 30 million years, which caused sea-level oscillations of 10 to more than 100 meters over periods ranging from 20,000 to 100,000 years. On longer time scales of tens of millions of years, changes in spreading rates of mid-ocean ridges account for sea-level changes of up to 200 meters. Though debated, the first and most rapid of these three scales of change (i.e., the rise since 1930) is attributed to a climatically forced reduction in the volume of the polar ice caps, thermal expansion of sea water, or both. The second scale is more widely accepted as the result of orbitally induced climate changes that give rise to the growth and decay of ice caps. Many argue that the third scale has its origin deep in the mantle, where the vigor of asthenospheric convection controls the rate of seafloor spreading.

ACHIEVEMENT: Cenozoic sea-level change

ODP drills into continental margins and coral reef atolls to improve our understanding of the magnitude, age, and mechanisms of Cenozoic sea-level change. One of the greatest successes to date has come from the New Jersey continental margin. Seismic and drilling results both onshore (Leg 150X) and offshore (Leg 150) New Jersey have identified Holocene to Oligocene unconformities separating the sedimentary record into distinct sequences. Models based on these empirical studies are developing the means to determine the complex relationships between margin deposition and sea-level fluctuations. Oxygen isotopic records from other ODP datasets provide a proxy for glacioeustatic changes during this Icehouse world. Correlations thus far indicate that many of the unconformities along the New Jersey margin formed during times of falling sea level, corresponding to periods of glacial ice growth. The long-term goal of this research is to drill a variety of passive margin transects which will enable scientists to stack the results from various sequences, in different settings, in order to remove local tectonic and depositional effects. The final product will be used to independently corroborate well-known "coastal onlap" curves and to evaluate sequence stratigraphic architecture. By determining the timing and amplitude of past global sea-level changes, the effects of sea level on sedimentation, climate, and ice-ocean interactions can be evaluated and the effects of future sea-level changes predicted using model simulations.

The geologic record is the only means available to test hypotheses of sea-level change and to explore the complex relationships among planetary climate, orbital dynamics and thermal convection of Earth's interior. Land-based outcrop studies are restricted to those time intervals and locations for which there are relatively undisturbed, high-resolution sedimentary deposits exposed. The more continuous and globally distributed marine record has clear advantages and the ODP plans to exploit this opportunity. Three general areas are being targeted: (1) siliciclastic sediments deposited near sea level along passive continental margins; (2) carbonate reefs, platforms and lagoons deposited near sea level along passive margins or oceanic islands; and (3) pelagic carbonate oozes where the oxygen isotopes provide an index of global ice volume. In addition, long (3 to 5 km), continuous coring from areas such as the New Jersey Margin would provide critical documentation of the long-term

ACHIEVEMENT: Ultra-high-resolution records



This core from the Santa Barbara Basin shows sediment layers, in rare detail, that accumulated between the years 720 and 850 AD.

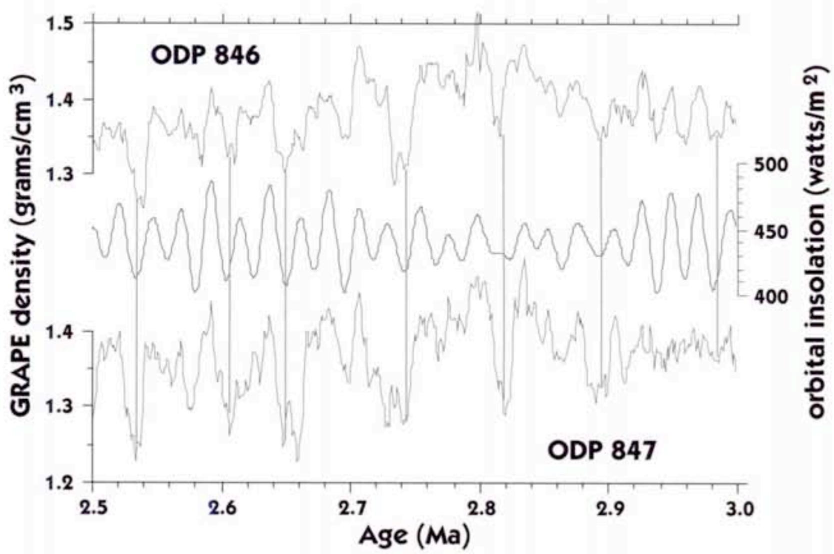
The ODP has drilled into sedimentary deposits that contain long and extremely detailed records of climate change. The advantage that the ODP has over other coring operations is that it can recover sedimentary sections much longer than the traditional ~30 to 50 m limit of conventional piston cores. This enables ODP scientists to piece together a detailed and long history. Such a history is much more amenable to time series analysis that provides insight into the amplitude, phasing, and ultimately, the causes of climate change. For example, the ODP drilled in the Santa Barbara Basin, an unusual marine setting in that it contains a mixture of marine and terrestrial sediments that accumulated at remarkably high rates with minimal sediment disturbance. The sedimentary record recovered from Site 893 extends back in time to approximately 160,000 years, which is 150,000 years longer than previous piston core results from the basin, but equal in age to the ice core records. The sedimentary section consists of subannual pairs of laminae produced by the shifting seasonal dominance between river input of land sediments and marine input from surface biological productivity. The laminae were preserved in the Santa Barbara Basin, unlike in other basins within the California Borderland Province, because the bottom waters in this basin are nearly anoxic, which prevents the habitation of bottom-dwelling creatures. When present, these animals disturb the fine annual layering by burrowing through the sediment. Recent studies at Site 893 found that changes in past oxygen levels can be matched, in extraordinary detail, to short-lived climatic excursions in the Greenland ice sheet, suggesting large scale climate teleconnections. This sedimentary record, which accumulated at rates greater than 120 cm/k.y., will give earth scientists the rare opportunity to study climate oscillations at high frequencies over a long period of geologic time, an unusual combination. Scientific objectives include the analysis of subdecadal-scale events, such as the El Niño Southern Oscillation, and the integration of marine results with tree-ring and other regional continental records of climate change. Initial results show that the ocean switches rapidly between different states, and not just locally. The contrast between these states is amplified in the Santa Barbara Basin record. Drilling in the Cariaco Basin and a return to the California margin will provide other ultra-high-resolution records of climate change.

record of sea-level change back to the Cretaceous when it is thought that continental ice volume did not play a major role in sea level.

Future ODP drilling will address key questions of timing, rates and magnitude of sea-level change. In addition, the ODP is well-situated to explore how changes in sea level are related to large-scale mass wasting events on continental margins and oceanic platforms in an effort to determine whether understanding this relationship will allow us to predict these geohazards.

ACHIEVEMENT: Astronomically tuned geologic time scale

A recent accomplishment of scientists using ODP cores has been the development of an astronomically tuned geologic time scale that stretches millions of years into the past and is far more precise than that achievable by radiometric dating alone. Using this tuning approach, a late Neogene time scale extending back to 6 Ma was developed by the scientific party of Leg 138 (eastern equatorial Pacific) by matching GRAPE density variations to the orbital insolation record. This scale is fully orbitally tuned and provides a reliable, absolute time scale for the seafloor anomaly scale, for the oxygen isotope record, for the seismic stratigraphy of the Pacific Ocean, and, of course, for all those aspects of climatic and oceanographic variability that transfer the astronomical record of varying insolation into quasi-cyclic sedimentological variability. With this time scale, ODP scientists can explore and compare the rates at which environmentally important events take place, and can determine the flux rates of critical components within the global geochemical system. Most of these components, such as carbon and biologically important nutrients, require hundreds to many thousands of years to cycle through the earth-ocean-atmosphere system. We can now begin to determine how fluxes of these components vary with time and relate these changes to perturbations in atmospheric and oceanic circulation, differences in the rates at which these materials are supplied (by wind, rivers, ground water, hydrothermal vents, etc.) and changes in the mechanism and locations of their storage in sediments. Recent efforts in time scale development by participants on Leg 154 (Ceara Rise, Atlantic) will further refine the Leg 138 results and will push the calibrated time scale back to 14 Ma, perhaps to the latest Oligocene.



Sediments, fluids, and bacteria as agents of change

Marine sediments are the products of complex interactions among organic and inorganic material from the continents, deposition from the marine biosphere, and circulation of fluids through deposited material. The ODP explores the processes that form these sediments by focusing on three areas: (1) the carbon cycle, which is the major link among biota, climate, ocean chemistry and sediments, and as such is a direct indicator of global environmental conditions that support and influence life, (2) the formation and distribution of gas hydrates, and (3) patterns of fluid flow and the geochemical evolution of fluids in sediments and rocks, including reactions with organic compounds and living bacteria.

THE CARBON CYCLE

Vast accumulations of calcium carbonate on the seafloor play a key role in mediating long-term changes in atmospheric CO_2 which, in turn, influences global climate. In addition, when organic carbon is buried in sufficient quantity and preserved in the proper geologic setting, it can become a source material for the formation of petroleum. Despite these critically important aspects of the carbon cycle, the pathways and rates of exchange of carbon in the global system are far from understood. The ODP has played an important role in establishing the temporal and spatial history of calcium carbonate and organic carbon distribution. Future drilling will take advantage of new, high-resolution stratigraphic and geochemical techniques, combined with a growing global array of strategically located latitudinal and depth transects, to address questions about the rates and controls of carbonate dissolution. The program will also focus on the factors controlling the rates of removal of organic matter and the roles of anoxia, productivity and sedimentation rate in preserving organic matter.

The principal strategy for new drilling aimed at understanding the carbon cycle is to explore modern environments that locally produce strong perturbations to the cycle. Examples include high-productivity areas, restricted anoxic basins, continental margins with high sedimentation rates, and sedimentary sequences strongly influenced by Pleistocene fluctuations in climate, ice volume and sea level. Many of these environments have been inaccessible in the past because of the lack of a riser drilling platform that has well control capabilities.

THE FORMATION OF GAS HYDRATES

An enormous amount of methane (CH_4) is stored in the form of frozen gas hydrates beneath the seafloor at relatively shallow depths. Gas hydrates are estimated to represent a significant fraction of the total mass of hydrocarbons at or near Earth's surface, making this a large and poorly understood reservoir in the global carbon system. It is also potentially one of the most volatile carbon reservoirs. Gas hydrates can be remotely detected using seismic techniques from surface ships. Thus, their distribution can be easily mapped, though their full extent has yet to be established. Very little is known about the dynamics of how gas hydrates are formed and destroyed in the marine environment.

Preliminary drilling of gas hydrates has been undertaken by the ODP. Leg 164 constituted a full leg of gas-hydrate drilling off the eastern seaboard of the United States. This leg found a significantly larger reservoir of methane than was anticipated from predrilling estimates. To explore the variety of gas hydrates and the mechanism of their formation, continued drilling in a variety of settings on the outer continental margins is a high priority of the ODP. This future drilling will seek to put constraints on the volume of gas trapped in hydrated sediments, its composition and lateral variability. Analyses of recovered hydrates will seek to determine their source and, coupled with regional geophysical studies, their migration paths (if they are not produced locally). The role of gas hydrates in stimulating fluid flow on the margins will also be evaluated, as will the relationship between hydrate formation and changes in atmospheric concentrations of methane, another greenhouse gas, during glacial-interglacial cycles.

ACHIEVEMENT: Youthful Great Barrier Reef

For nearly 200 years scientists have studied the varied biota and remarkable rock-forming character of "coral" reefs, in part because of their unique sedimentological, structural, and geochemical features. The living reef forms merely a veneer over the massive skeletal platform which is built almost entirely by a complex assemblage of carbonate secreting plants and animals. The high diversity of reefs and their growth within specific environmental conditions provide sensitive indices of environmental change. Such change may be dominated by climate (warming or cooling, varying salinity, "bleaching" events, El Niños, etc.) or it may be related to larger-scale variations in sea level, reflecting orbital cycles or tectonic activity. ODP drilling into carbonate platforms has given us new insights into the environmental factors controlling reef initiation, growth, and demise. In particular, significant progress in our understanding of reef evolution came from the ODP efforts on the northeast Australian margin. One of the most exciting results was the recognition that the Great Barrier Reef is much younger than previously thought. It was determined to be no older than one million years and is possibly younger than 500,000 years. The initiation of the Great Barrier Reef temporally coincides with a major change in climate response to orbital forcing. The advent is correlated with a regional shift in oxygen isotope data indicating a 5°C rise in surface-water temperature. The current working hypothesis is that this temperature rise was caused by an intensification of the equatorial Trade Winds which drive warm tropic waters into the Western Pacific. This would not only have had consequences for reef growth, but would also have been linked to changes far-field, such as increased upwelling in the eastern Pacific, changes in ocean chemistry related to rapid removal (basin to shelf fractionation) of calcium carbonate into the Great Barrier Reef, and a synchronous release of CO_2 to the atmosphere. The role of rapid reef growth in controlling or influencing oceanic and atmospheric levels of CO_2 remains an important and unresolved issue. Because reef ecosystems can influence atmospheric chemistry, as can tropical rain forests, their continental counterparts, study of reefs is of paramount importance in our quest to understand the fundamental factors influencing Earth's environment.

Aerial view of Australia's Great Barrier Reef.

FLUIDS IN SEDIMENTS AND ROCKS

One of the ODP's major accomplishments in its first years was to demonstrate that fluids move through rocks not just at highly fractured mid-ocean ridges, but also at continental margins. These fluids move in response to the compaction of sediments and can become concentrated along porous horizons and fracture networks in the rocks. The fluids react with silicate and carbonate minerals in the sediments and with organic matter. The ODP's discovery of living bacteria in sediments deep below the seafloor has emphasized their potential biochemical role in these reactions. The ODP has successfully investigated fluid flow at both spreading ridges and in deforming sedimentary formations near deep ocean trenches. Regardless of the setting, fluids change composition as they flow, in response to chemical exchanges with the host sediments and reactions with organic material or bacteria. In some cases, the fluid flow leads to deposition of important types of metalliferous concentrations. Elsewhere, transformation of organic matter may reach the stage where it too can behave as a fluid in the form of petroleum, and migrate to porous reservoirs.

Taking advantage of innovations in sampling techniques and borehole monitoring, future ODP drilling will investigate the causes, rates and fluxes of fluids within various tectonic settings, as well as questions of biochemical transformations, cementation and ore formation.

EARTH'S DEEP BIOSPHERE

Bacteria play an important, yet unheralded role in the deep ocean biosphere. The ODP's recent discovery of a living, deep subsurface, possibly primordial biosphere — whose existence amounted to speculation only a few years ago — has raised notions about evolution to the level of testable hypotheses. Drilling has revealed bacteria living in sediments as far as 500 m below the seafloor, much deeper than previously thought possible. Bacteria have also been discovered within the inhospitable environment of volcanic rock voids formed at mid-ocean ridges. These discoveries require a substantial revision of conventional thinking on the ecology of the deep biosphere.

It is a mystery how bacteria survive the high temperatures and pressures within deeply buried sediments. Bacteria tolerant of both elevated temperatures (120° C and possibly higher) and high salinities have been observed in hydrothermal vent areas. In deep ocean sediments, bacteria survive in dormant stages until nutrient levels and environmental conditions are adequate for extremely low rates of metabolism or growth. The ability of bacteria to enter and exit from a dormant state may account for their successful habitation in the deep ocean. Whatever their origin, bacteria in the deep biosphere are uniquely adapted to survive in exceedingly harsh environments. This knowledge, in conjunction with other recent research into the role that bacteria play in global biogeochemistry, is beginning to influence ideas about nutrient cycling, dolomite formation, biomineralization, biomagnetization, biological adaptation, and, perhaps more fundamentally, the size of the biosphere beneath the seafloor, which appears to have been greatly underestimated.

Bacteria isolated from hydrothermal environments have already made a major impact on biotechnology, and the deep biosphere represents an even more diverse source of bacteria for bioremediation, waste treatment, microbial enhanced oil recovery, and biominerals. Some bacterial populations appear to have survived on buried organic matter for millions of years and thus must have some remarkable enzymes and metabolic rates. Other bacteria have adjusted to changing conditions during deep burial that provide a rare opportunity to study adaptation and evolution. This deep ecosystem may also contain new types of bacteria. The ODP provides the only access to this environment, and ODP's interdisciplinary cruises provide the ideal approach for studying the deep biosphere.

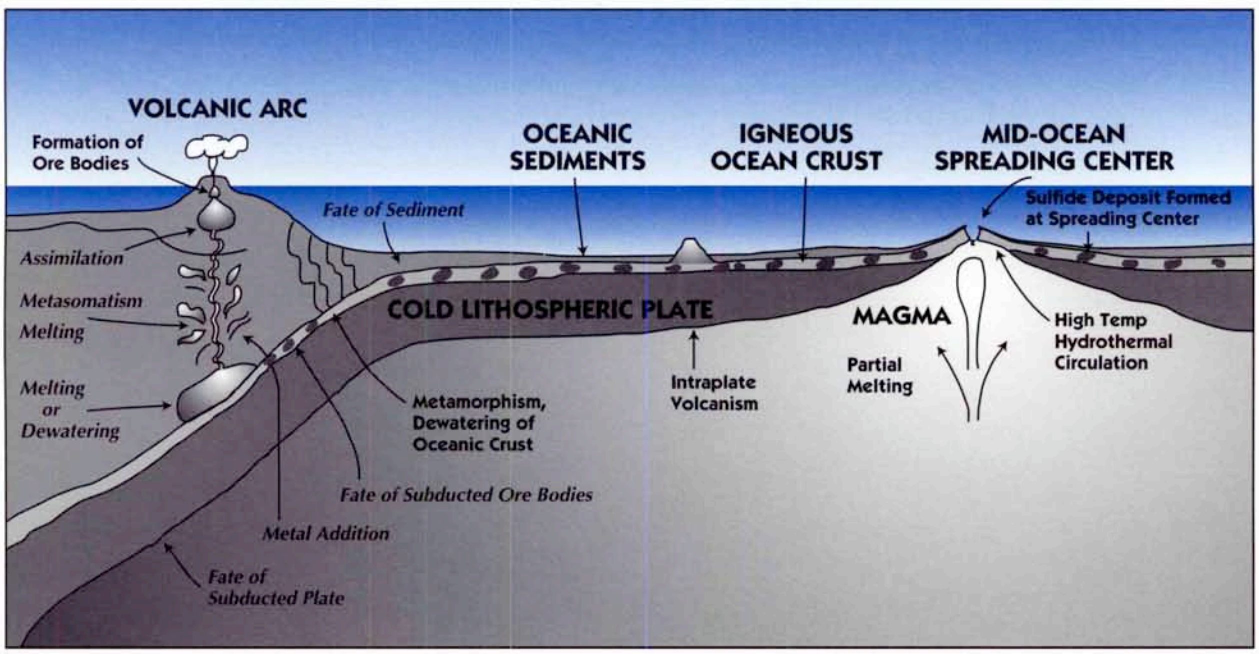
The seafloor provides many suitable settings for sampling the deep biosphere and for establishing experiments to understand microbiological activity. The oceanic environment may be preferable to terrestrial sites for measuring subsurface microbiological processes or fluid flow in support of biological communities because it is often stable, and is uncomplicated from a structural and tectonic perspective. In addition, the deep ocean is relatively uncontaminated by human activity, in contrast to potential study sites on land.

PILOT PROJECT: *To meet the emerging challenges in the study of the deep biosphere, the ODP will embark on an effort to explore the nature and extent of the sub-seafloor biosphere. When opportunities to recover bacteria arise, the ODP will target specific and planned drill sites. This enterprise will be coordinated with other programs such as InterRIDGE and the Subsurface Science Program of the U.S. Department of Energy, which has developed land-based drilling and sampling expertise.*

DYNAMICS OF EARTH'S INTERIOR

The ODP is an essential element of a multidisciplinary effort to explain the properties and processes within the dynamic interior of Earth. The spatial and temporal record of the global cycling of mass and energy can only be fully determined with access to a drillship that can directly sample old oceanic crust buried by thick sediments, that can reach the inaccessible deep layers within the crust and at continental margins, and that can recover the long, continuous sections of sediment or rock that are essential to reconstruct the history of past volcanic and tectonic activity. Drill holes also provide opportunities for measuring critical physical properties of the crust *in situ* and for making long-term observations that can provide unique insight into mantle dynamics, lithospheric deformation processes and fluid flow.

THE PLATE TECTONIC CYCLE



The plate tectonic cycle showing some of the geological fluxes and the processes that control them.

Exploring the transfer of heat and material to and from Earth's interior

Interactions between Earth's mantle and crust occur in diverse settings and through a variety of processes, and are intimately connected to mantle convection and plate tectonics. Within this broad theme, the ODP will contribute to understanding processes involved in several important scientific lines of inquiry: (1) mantle dynamics, (2) oceanic crust, (3) hydrothermal processes and sulfide mineralization, and (4) mass balance and temporal variability at subduction zones.

MANTLE DYNAMICS

Over the last decade our understanding of Earth's deep mantle has evolved rapidly because of numerical simulations, images derived from global seismic tomography, and experimental studies of materials at simulated mantle conditions. Together they suggest mantle dynamics that are considerably more mobile and complex than those outlined in the classic layered model.

From a physical and chemical perspective, the core-mantle boundary is now regarded as one of Earth's most dynamic interfaces. The mantle has been shown to be heterogeneous over a variety of scales. Numerical simulations predict extensive plume-like upwelling of a fundamentally unstable (chaotic) nature. When these rising plumes encounter the lithosphere, they cause massive outpourings of volcanics manifested as flood basalts on continents, and massive plateaus on the seafloor. These marine large igneous provinces (LIPs) represent some of the largest volcanic events in Earth history and are believed to indicate major episodic transfers of heat and mass from the mantle to the lithosphere. There is growing evidence that the timing and location of these volcanic events are closely linked to the lithospheric dynamics of continental breakup and subduction. Volatiles released by this volcanic activity, such as CO_2, have likely influenced climate.

While the deep reaches of Earth's interior are obviously inaccessible to the drill, the ODP can address a number of important questions related to mantle geodynamics. By establishing seafloor borehole observatories in remote areas of the ocean basins, scientists will be able to continuously record broadband seismic data. This will enable the acquisition of mantle tomographic images of much higher resolution than currently possible. These images will be used to determine the relationship between mantle dynamics and lithospheric processes. By drilling deeply into oceanic plateaus and volcanic margins, the chronology and geochemistry of LIP emplacement can be determined, which will enable scientists to investigate how mantle circulation has changed over time and how it is related to lithospheric dynamics. Variations in the temperature and composition of the mantle over the past 200 m.y. will be assessed by drilling shallow holes into sedimented lithosphere, and mapping geochemical patterns in the crust.

OCEANIC CRUST

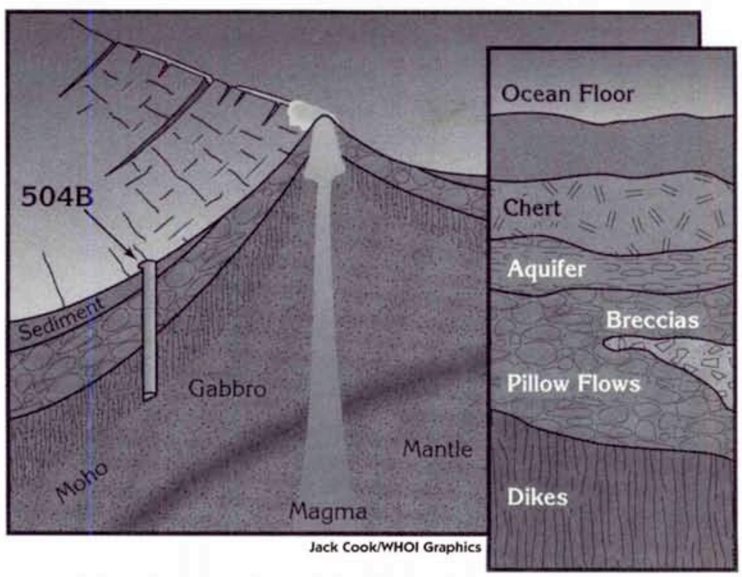
The formation of new oceanic crust along mid-ocean ridges plays a large role in controlling the flux of heat, mass, and volatiles from Earth's interior. Understanding mid-ocean ridge processes requires a characterization of the composition and physical properties of oceanic crust, and their relationship to variables such as magma supply and spreading rate. To date, the DSDP and the ODP have successfully drilled through only the upper 30 percent of the oceanic crust. This drilling, together with dredging and submersible sampling of seafloor outcrops, has established both the igneous stratigraphy of the upper crust and its *in situ* physical properties (e.g., porosity, permeability, magnetization, alteration history). However, our direct knowledge of the composition and physical properties of the lower two-thirds of the oceanic crust is extremely limited because only partial sections of the lower crust and upper mantle have been sampled in isolated tectonic exposures on rift valley walls or in oceanic fracture zones.

ACHIEVEMENT: Oceanic lithosphere

Knowing the structure and composition of the oceanic crust is essential for understanding global geochemical cycles and for evaluating Earth's resources. The 500 m of gabbro recovered at Hole 735B on the Southwest Indian Ridge is the first stratigraphic section of *in situ* lower crustal material recovered from the oceanic basement. This unique section consists of small intrusions with no evidence of the well-developed crystal layering and systematic variation in gabbro composition typical of large, layered igneous intrusions on land. The complex stratigraphy documented in this hole indicates multiple phases of magmatism, alteration and ongoing deformation in the zone of lithospheric necking and crustal accretion beneath a slow-spreading ridge. Detailed chemical mapping of the gabbros indicates that evolved melts are sometimes mobilized in response to crustal deformation and that melt flow may be either diffused through intergranular networks or focused along centimeter-scale channels. In contrast, gabbros recovered at Hess Deep, on the East Pacific Rise, display no evidence of high-temperature deformation such as that seen in Hole 735B, but display spectacular magmatic foliation similar to that documented in some ophiolites.

At Site 895 in Hess Deep, several holes were drilled into mantle peridotite providing new information on the percolation of magmatic fluids in the mantle beneath a fast-spreading center. These residual mantle rocks were deformed at high temperature, then subsequently intruded by melt forming dikes that reacted with the surrounding peridotite. Holes drilled just a few hundred meters apart produced various proportions of residual and magmatic rocks, suggesting that the magmas feeding the crust are channeled along narrow pathways. This is consistent with recent detailed field mapping of the mantle section in Oman, which has shown the importance of diking in transporting melt to the base of the crust.

These offset-drilling results complement the relatively deep drilling now accomplished at Hole 504B on the Costa Rica Rift. Hole 504B is now over 2 km deep and has penetrated most of the sheeted dike complex and may extend into the top of Layer 3. Complementary logging studies in Sites 418A and 395A in the Atlantic, and at Sites 801C and 765C on Jurassic crust in the Pacific and Indian Oceans, have provided comparative sections of the physical properties of variously aged, altered crust.



Hole 504B near the Costa Rica rift. This hole was drilled in 3,475 meters of water to a depth of 2,111 meters below the seafloor during several visits of the drillships* Glomar Challenger *(DSDP) and* JOIDES Resolution *(ODP).

ODP drilling will make several unique contributions to our knowledge of the fundamental structure of oceanic crust, and the processes that create it. These contributions will form an integral part of the broad multi-institutional InterRIDGE effort to understand mid-ocean ridge processes. By drilling arrays of shallow holes on tectonic exposures of lower crustal and upper mantle rocks, the composition, deformation, and alteration history of the lower crust and upper mantle will be determined. The Diamond Coring System under development by ODP can be used to drill into zero-age crust along mid-ocean ridges to examine the compositional evolution of the extrusive products that form the oceanic crust and to sample the deeper levels of an active magmatic system. By obtaining a continuous vertical section through the entire crust at fast and slow spreading ridges, drilling can also contrast the apparently different crustal structures formed at different spreading rates.

HYDROTHERMAL PROCESSES AND SULFIDE MINERALIZATION

Seawater circulates through cracks, fissures and faults into hot, young volcanic crust that forms at mid-ocean ridges — resulting in chemical exchanges that influence the composition of the world's ocean, form metalliferous sulfide deposits, and provide energy for a unique and possibly ancient chemosynthetically based biological community. The chemical fluxes and biological impacts associated with these hydrothermal systems are still poorly known, especially in regions off of the ridge axes, where oceanic lithosphere cools and ages.

Although hydrothermal fluids and their associated sulfide deposits can be directly sampled at the seafloor, they are but the final product of a chemical reaction zone that may extend 5 to 6 kilometers below the seafloor. Drilling is the only way of directly investigating the geochemical and mineralization processes that occur in the root zones of these hydrothermal systems. Drilling also enables scientists to make *in situ* measurements of the physical properties of the crust that control fluid flow deep within these hydrologic systems.

We are just beginning to study the longevity of these hydrothermal systems, the factors that control the along-axis distribution of venting areas, the chemical and temporal variations of vent fluids and precipitating sulfides, and how these variations influence vent organisms. The pioneering development of CORKs to investigate the temporal variability of these systems is underway. CORKs allow scientists to monitor the *in situ* thermal and hydrological properties and fluid chemistry in boreholes long after the holes have been drilled.

Although less dramatic than vent circulation, lower-temperature hydrothermal circulation through older oceanic crust is important because it is responsible for a large fraction of the total heat and chemical flux. Drilling offers the only way of directly sampling these off-axis hydrothermal systems because this older volcanic crust is generally buried by sediment.

MASS BALANCE AND TEMPORAL VARIABILITY AT SUBDUCTION ZONES

Convergent margins are an equally important component of the solid Earth geochemical cycle. Subducted oceanic lithosphere may be carried into Earth's deep interior, where it ultimately mixes convectively with other mantle materials. Eventually, this material may be recycled to Earth's surface at a large igneous province, an oceanic volcano or a spreading ridge. Alteration and dewatering reactions in the down going slab have a profound influence on the structural and magmatic evolution of convergent margins.

Vertical sections recovered by drilling are essential for quantifying geochemical fluxes, for examining temporal records of magmatic activity (recorded in volcanic ash layers), and for deciphering the history of tectonic deformation (uplift, faulting, subsidence) in both forearcs and backarcs. Past DSDP and ODP drilling in convergent margins has established the broad characteristics of the

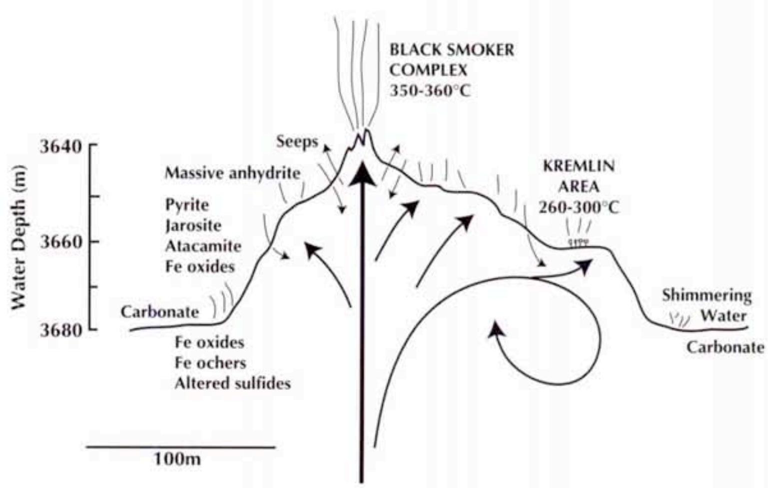
ACHIEVEMENT: Hydrothermal mineralization

SEDIMENT-HOSTED SULFIDE DEPOSITS

Some of the most exciting ODP results of the last five years have come from work in hydrothermal systems at sedimented ridges. Drilling in Middle Valley, the sediment-covered portion of the northern Juan de Fuca Ridge, succeeded in penetrating an active hydrothermal system and safely coring and logging in rock temperatures approaching 300°C. The composition of the active hydrothermal field was demonstrably linked to convective circulation of seawater and is controlled by sub-seafloor metamorphism of the overlying sedimentary and basaltic rocks. A major accomplishment was the penetration into 95 m of massive sulfide formed in a slightly older hydrothermal system. The chemical composition of this deposit indicates that it formed from hydrothermal fluids that interacted primarily with basaltic rock at significantly higher temperatures than the active hydrothermal system drilled 5 km to the northwest.

VOLCANIC-HOSTED SULFIDE DEPOSITS

Further progress in understanding hydrothermal activity associated with young oceanic crust was made by drilling into a large, active volcanic-hosted sulfide mound (200 m wide by 40 m high) situated in the median valley of the Mid-Atlantic Ridge on crust about 100,000 years old within a hydrothermal field discovered only 10 years ago during a reconnaissance survey called Trans-Atlantic Geotraverse (TAG). The TAG mound is composed of iron, copper and zinc sulfide minerals that have precipitated onto the seafloor during the past 40,000 years. Recovery of a stratigraphic section through the mound and into the underlying stockwork documented that accumulation of sulfides occurs both by direct precipitation on the seafloor and by hydrothermal replacement beneath the surface of the mound, and that the mound has gone through several distinct episodes of active growth. The TAG mound is particularly intriguing because it serves as a modern analog to massive sulfide ore deposits, such as those found on the island of Cyprus.



Schematic cross section of the active TAG mound from northwest to southeast. Arrows show the fluid flow directions inferred from the mineralogy and chemistry of the deposits and the smoker fluids.

deformational and magmatic processes that are active in forearc, arc and backarc regions. In the next two phases of ODP operations, the emphasis will be on quantifying mass balances at subduction zones and determining the temporal variation in arc, forearc and backarc volcanic and tectonic activity. This will require drilling deep reference holes that are seaward of trenches in order to constrain the chemical composition of the entire sedimentary and crustal section that is being subducted. It will also require transects of shallower holes across the forearc, arc, and backarc to constrain the history of volcanism and the tectonic links among these settings. This drilling plan would be part of a broader, Margins-related program of structural, geophysical and petrologic studies of arc processes.

ACHIEVEMENT: North Barbados Ridge

"When plates collide" was the theme of Leg 156 (June/July 1994) which drilled and logged the wedge-shaped sedimentary body (accretionary prism) and the underlying plate-boundary fault (décollement zone) just north of Barbados. To understand the structure and tectonics of this convergent plate boundary, scientists are combining information from several sources including: (1) *in situ* measurements of permeability and fluid pressures; (2) two years of regularly collected fluid temperature, pressure, and chemistry; (3) structural fabrics observed in rock sequences; and (4) wireline logs through the prism and the décollement. To successfully combine these data sets, three technological innovations were necessary. First was the development of a borehole seal (CORK) by ODP engineers. The seal is a seafloor-mounted observatory from which strings of temperature and pressure sensors probes and a fluid sampler hang down inside the borehole. These strings were developed by French, Canadian and U.S. teams. The two-year CORK experiments are in progress and the data will constitute the first "time series" of fluid flow ever collected at an ODP site. The second innovation is a technique called logging-while-drilling. The first ever complete set of logs, including resistivity, natural gamma-ray, density, and neutron porosity were collected from an unstable accretionary-prism environment. Logging-while-drilling measurements recorded prominent density inversions, including several meter-thick intervals within the fault zones indicating fluidized sediment, a type of natural hydrofracture. The major success of this technique bodes well for improved acquisition of logging data on future legs, especially in precarious drilling conditions. The third innovation was a seismic reflection survey off Barbados, which produced a three-dimensional spatial framework and predicted that the plate-boundary fault was generated by an undercompacted, high-fluid pressure section. This leg produced the first formation pulse and flow tests in a hydrologically isolated active plate-boundary fault. Two sites reached lithostatic pressure (essentially "floating" the rocks) over intervals several tens-of-meters thick. This leg has also shown how polarity and amplitude variations of seismic images relate to variations in fluid pressure, permeability, and other sediment physical properties. Information from this leg will assist in the use of seismic data to as a predictor of fluid properties in fault zones, which has applications for understanding earthquake hazards and for studies of ground water and hydrocarbon migration.

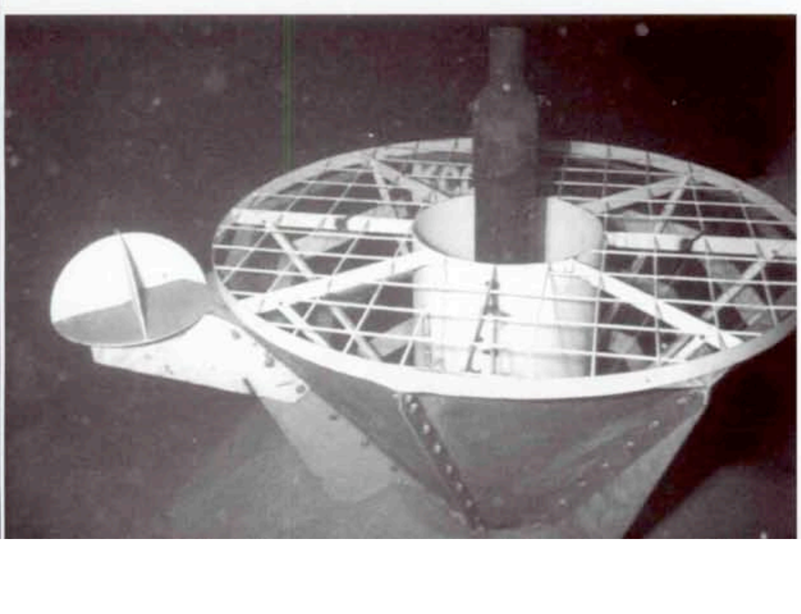


Photo of an ODP CORK (borehole seal), which enables scientists to record temperature and pressure at* in situ *conditions within the borehole for several years.

Investigating deformation of the lithosphere and earthquake processes

Large-scale deformation of the lithosphere primarily occurs in response to lithospheric plate motion and hence is focused largely at plate boundaries. The driving forces of plate motions are "slab-pull" (the descent of a cold, dense slab into the mantle) and "ridge-push" (the forces associated with a cooling, increasingly dense lithosphere sliding down the sides of thermally elevated ridges). These large-scale forces vary slowly, but near the plate boundaries, interplate motions are often episodic as stresses are stored and released, giving rise to earthquakes and associated faulting. In some regions, weak and hot boundaries are known to deform in a more continuous manner through ductile processes associated with aseismic creep. The nature of the deformation is fundamentally controlled by the strength of the lithosphere in relation to the size of the tectonic driving forces. The lithosphere's strength is determined by physical and chemical conditions occurring during deformation and the inherent properties of deforming rock types.

Fundamental to understanding lithospheric deformation is knowledge of the *in situ* stress and strain fields at all types of plate boundaries and in plate interiors. Equally important is an assessment of how measurements of stress and strain compare to the predicted strength of the rocks and their observed deformation. ODP boreholes provide a unique means to measure the distribution and amount of stress and strain within oceanic plates at various plate boundaries and across vast regions. Hence boreholes provide valuable information about the forces that drive tectonic plates and how these forces are accommodated in different parts of the lithosphere. Ocean drilling will investigate deformational processes and earthquake mechanisms that occur at extensional, translational, and convergent plate boundaries.

EXTENSIONAL BOUNDARIES

Lithospheric extension leads to the development of "passive" (divergent) continental margins. Their structure and stratigraphy provide information about the deformation of continental lithosphere, the embryonic stages of ocean basin formation, the vertical movement (uplift and subsidence), and changes in relative sea level. Although the basic architecture and kinematic evolution of divergent margins is reasonably well known, fundamental questions have arisen as to the critical processes and mechanisms that give rise to the margins structures. Many of these have been identified by the multi-institutional Margins research initiative, which seeks to focus studies on an understanding of the basic processes that operate on all plate margins. Key among the processes at extensional margins, is the role of low-angle normal faults in continental breakup. Drilling can provide a unique perspective on this basic geodynamic problem by sampling structure imaged in seismic studies of ancient margins that have the geometric attributes of low angle detachments. Perhaps more importantly, drilling can provide boreholes that can be used as natural laboratories for monitoring changes in stresses, thermal conditions, fluid pressures and other parameters that are likely to control activity on these structures. By drilling deep sections in margins, research can be performed to learn more about the controls on rifting and volcanism along the axes of continental breakup and about the nature of the transition between continents and ocean.

ACHIEVEMENT: North Atlantic rifted margins

VOLCANIC MARGINS

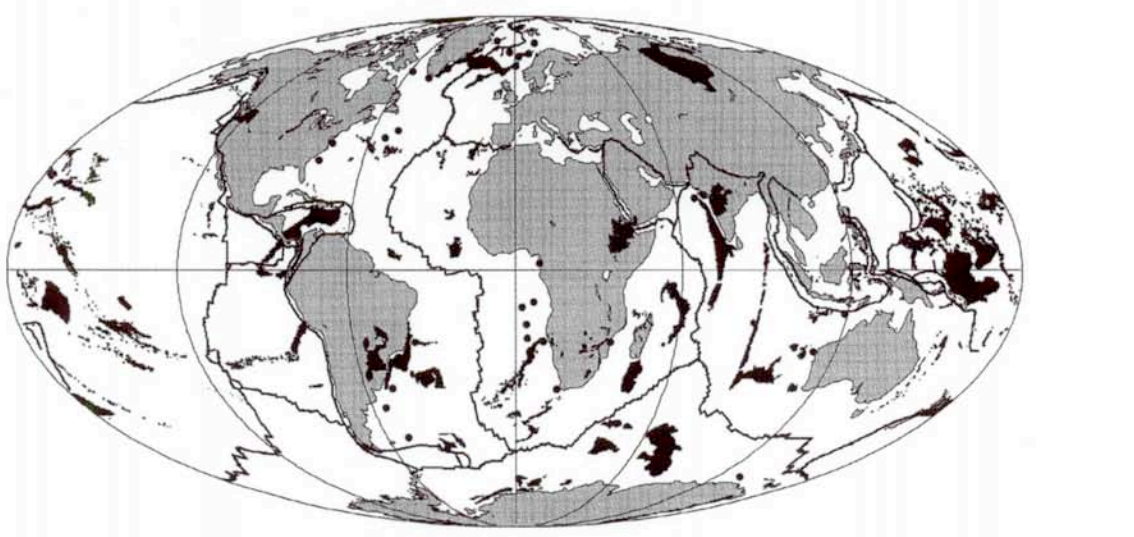
Marine volcanic margins and their terrestrial counterparts, continental flood basalts, constitute the planet's large igneous provinces. The Northeast Atlantic volcanic margins and continental flood basalts are estimated to comprise as much as 2 x 10^6 km^3 of basaltic extrusives. The only parts of this massive accumulation which have been thoroughly studied are the five percent exposed onshore. Thus, offshore studies offer high potential for expanding our understanding of the breakup of continents and the attendant fundamental processes of extension.

ODP drilling on the Vøring Plateau, in the North Atlantic, established that the seaward-dipping reflector sequences identified on multichannel seismic records consist of volcanic accumulations rapidly emplaced near the time of continental separation. Dacites and andesites were sampled beneath the seaward-dipping wedge, suggesting that it may have been emplaced within fragments of continental crust. Drilling results from the southeast Greenland margin complement those from the Vøring Plateau, and strongly suggest that the main part of the anomalous igneous crust along volcanic-rifted margins is created by Icelandic type oceanic crustal accretion. Recovery of high-magnesium picritic lavas shows that a high temperature asthenosphere plays an important role in continental breakup and the formation of volcanic rifted margins, and hence, mantle plumes are somehow important in this development.

NON-VOLCANIC MARGINS

Scientific results from the volcanic-rifted margin dovetail with those from the Galician and Iberia margins, where peridotites and other mantle rocks appear to have been lifted above sea level by extension and faulting in the absence of voluminous volcanism. The ODP's non-volcanic rifted margin program is designed assess the degree of symmetry in the structures and the evolution of the geophysically well-characterized Newfoundland Basin-Iberia Abyssal Plain conjugate margin.

A transect of holes drilled across the Galicia margin established the timing of the extension and separation that occurred between Iberia and the Grand Banks of Canada. Further drilling identified zones of serpentinized ridges parallel to the Iberia margin which are about 50 km wide and continue for several 100s km along strike. These zones of serpentinized mantle rocks are believed to represent either subcontinental lithosphere exposed by large-scale, low-angle faulting (tectonic unroofing), or slow-spreading crust (also involving tectonic extension). In either case, volcanic activity is minimal and melt production in the mantle is minor.



Large igneous provinces (LIPs), including volcanic passive margins (black dots), and oceanic plateaus, submarine ridges, seamount chains, ocean basin flood basalts, and continental flood basalts (all solid black), now account for 5-10% of the heat and magma expelled from Earth's mantle. During parts of the Cretaceous Period, LIPs may represent 50% of the flux. LIP emplacement may or may not be associated with active plate boundaries (solid lines). Because the vast majority of LIPs lie underwater, ODP provides a vital tool for understanding how mantle fluxes vary temporally among LIPs, spreading centers, and subduction zones. In turn, this information sheds light on how the dynamics of the mantle varies through space and time, increases our knowledge of how catastrophic volcanism affects the global environment.

TRANSLATIONAL BOUNDARIES

At transform margins where major oceanic fault zones intersect continental margins, key questions include the thermal history and the mechanisms of uplift and subsidence; the structure and deformation history of large oceanic transforms, and the tectonic and sedimentary history of rifted basins in transform settings. Deep penetration is required to answer these questions.

CONVERGENT BOUNDARIES

Some fundamental answers are needed before a clear understanding of deformation at compressional margins can be established. For instance, the mechanisms responsible for the initiation of subduction have not been resolved. It is commonly believed that the process starts along fracture zones or along passive margins, and several candidate areas have been identified. Collisional processes at compressional margins have formed many of the world's greatest mountain belts. Deep drilling in sedimentary sections at key locations can reveal details of the initiation and rates of collisional processes.

At convergent plate boundaries, part of the descending plate is scraped off, creating a wedge of deformed rocks in an accretionary prism that forms between the trench and the volcanic arc. Drilling in such active margin settings can provide essential data on the subsidence history and the magnitude and rate of removal of accreted material. These data would address key questions, such as the distribution of deformation throughout an accretionary prism, the controls on what material is accreted and what is subducted, and the role of fluids and fluid flow in deformation of the prism.

Fluids are the main coupling agent between tectonic, sedimentological and chemical processes, at convergent margins and elsewhere. At convergent plate boundaries, we need to understand the fluid-linked diagenetic and tectonic processes in the rapidly deforming geochemical factory of the accretionary wedge. Drilling here provides insights on phenomena such as hydrocarbon migration and structurally linked diagenetic processes operating only at greater depths in normal sedimentary basins. The plate boundary fault or décollement zone is a conduit that can be tapped at shallow depths to monitor the pulse of deeply seated deformational processes, including earthquakes. Finally, the excellent seismic imaging of the décollement (for example, see the figure on page 41) and other active faults provides the opportunity to use such images as proxies for physical properties in fault zones. Because the décollement zone faults are accessible by drilling we can calibrate these properties and associated processes (fluid pressure, permeability, hydrofracture) and potentially apply these insights to seismogenic faults.

Subducted material includes seamounts, submarine ridges, island arc systems, and sediments. During collision, large slices of oceanic crust may be emplaced on continental margins. How these topographic irregularities interact with the forearc and how collision affects the distribution of deformation is poorly understood. Drilling of actively subducting features can establish vertical movements, lithospheric strength and overall deformational style, and, ultimately, the nature and timing of earthquake activity.

ACHIEVEMENT: Fluid flow in the lithosphere

OCEANIC CRUST

Large-scale fluid flow through the oceanic crust was first recognized along mid-ocean ridge hydrothermal systems. Much of what we know about fluid pathways and crustal alteration in this environment has come from interpretations of multichannel seismic records and from land-based studies of ophiolites. An important accomplishment of ODP drilling has been to complete downhole logging programs in three of the deepest crustal holes drilled during the DSDP (Holes 395A, 418A, and 504B). The extensive suite of state-of-the-art borehole experiments carried out in these holes has provided unique data on the physical properties of oceanic crust. An unforeseen result at Hole 504B was that hydrothermal circulation was not possible in the lower crust because the low permeability of the pillow lavas and sheeted dikes of Layer 2 were sealed, despite being only 5.9 m.y. old. The single highly permeable section of the crust in this hole is the upper 100-200 meters of pillow basalts. The latest results from Hole 504B indicate that the bottom of the hole, at 2111 meters below seafloor, is approaching the fossil high-temperature "reaction zone" just above a crustal magma chamber. These results are extremely important for modeling rock-water interactions in ridge-crest hydrothermal systems at mid-ocean ridges and understanding the alteration history of the oceanic crust.

ACCRETIONARY PRISMS

Fluids return to the ocean from marine sediments at active continental margins by tectonic compaction and diagenesis of subducted and accreted material. Although it has long been recognized that high fluid pressures facilitate thrust faulting and are therefore important to accretionary prism development, it is only recently, through drilling, that scientists have been able to document fluid pathways, sources, rates, and effects. Pore water chemistry, temperature anomalies, and structural observations from ODP drilling along active margins indicate that fluids are moving principally through zones controlled by fracture permeability associated with faults, and secondarily along stratigraphic levels controlled by intergranular permeability. Anomalies in pore water chemistry of drill cores have demonstrated that fluids can migrate laterally and vertically over tens of kilometers from their source, primarily along faults. Fluid flow rates measured at numerous local fluid venting sites, for example, at the Barbados, Nankai, and Cascadia accretionary complexes, are two to six orders of magnitude larger than estimated based on steady-state flow models. This discrepancy in fluid volume suggests either that confined aquifer fluid flow is transient, expulsion is localized, and/or that a major external fluid source exists.

SEDIMENTED SPREADING CENTERS

The ODP has pioneered the study of hydrogeological processes at sediment-covered spreading centers, which provide an unparalleled opportunity for quantitative studies of the fundamental physical and chemical processes associated with submarine hydrothermal systems and metallogenesis. A regionally continuous, relatively impermeable sediment cover over zero-age crust limits the recharge and discharge of hydrothermal fluids, and conductively insulates the underlying igneous basement. Where discharge of fluids does occur, large hydrothermal sulfide deposits can form. The sediments may also preserve a relatively continuous stratigraphic record of magmatic, tectonic, and thermal events, providing clues to the spatial and temporal variability of these processes.

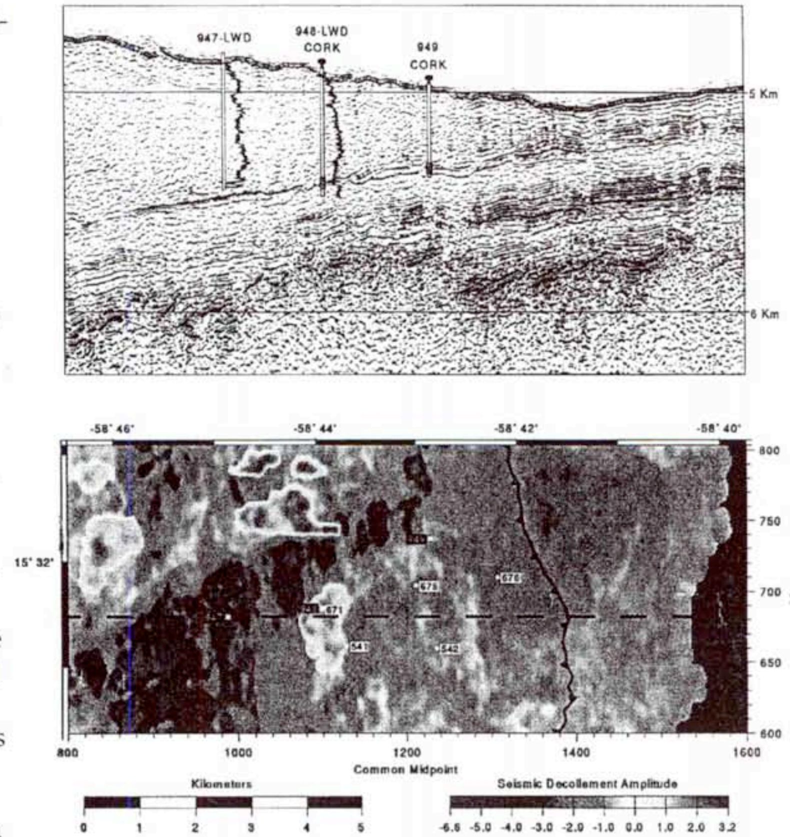
A surprising result from drilling in the Middle Valley of the Juan de Fuca Ridge is the high absolute permeability of zones within the sediment and basement sections. The sediment permeability is inferred to be highly anisotropic; while vertical flow is probably impeded by clay-rich layers, significant horizontal flow appears to be permitted by continuous coarse-grained layers. Scientists also found high basement (upper crust) permeability and high rates of downhole flow induced by circulating cold seawater during the drilling operations. In one hole, the rate of flow of ocean bottom water into the new drill hole measured by a flowmeter was so great (>10,000 liters per minute) that the ship's pumps (at 3,000 liters per minute) could not keep up with it.

White smoker (1-2 m high) in the "Kremlin" area of the Trans Atlantic Geotraverse, Mid-Atlantic Ridge.

EARTHQUAKE MECHANISMS

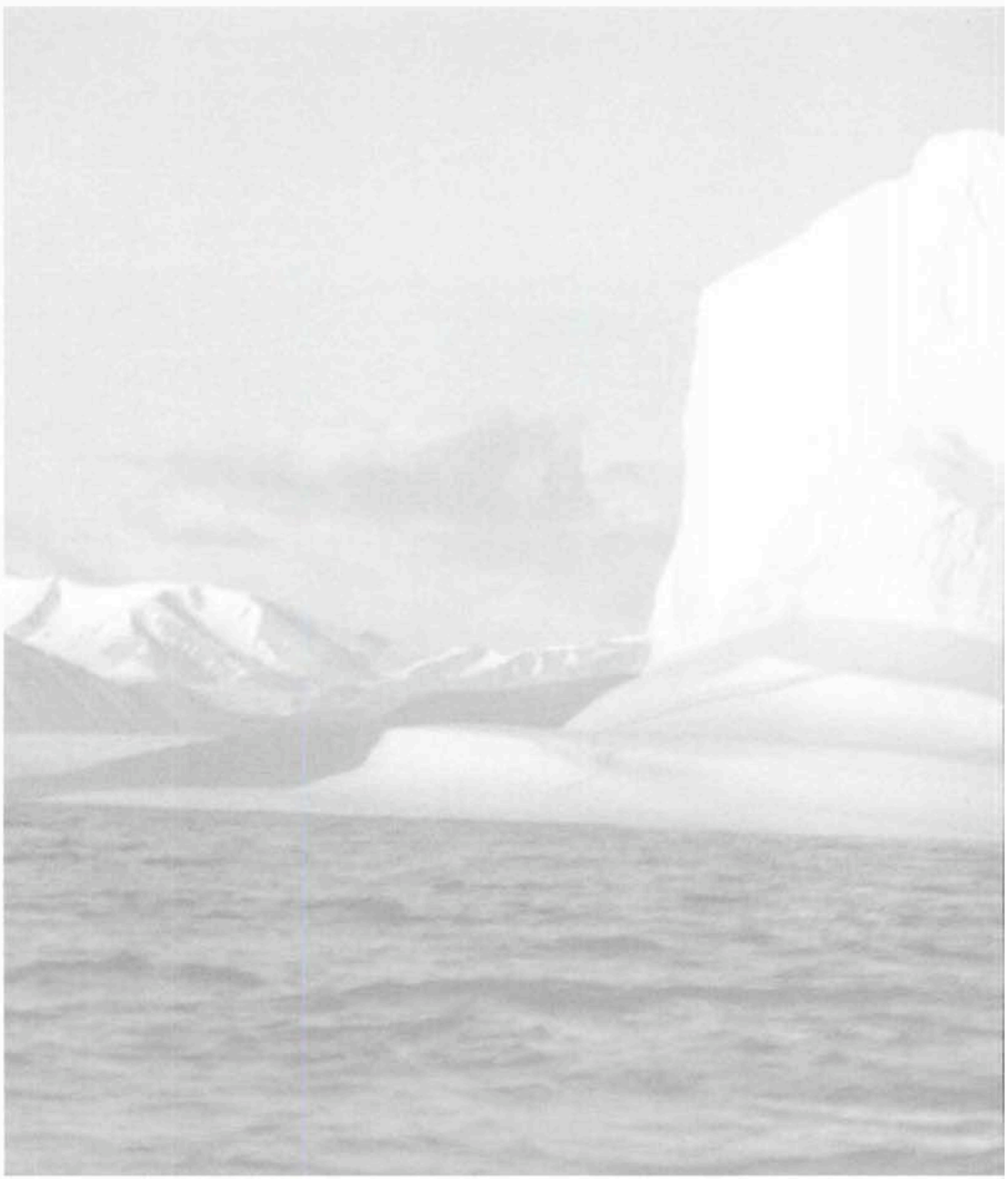
Ocean drilling can contribute to understanding many aspects of earthquake processes including how plate interaction and the release of stress relate to the geometry and kinematics of subduction; how crustal deformation leads to large earthquakes at these plate boundaries; how large earthquakes at plate boundaries rupture, and whether strain between underthrust and overthrust plates occurs primarily along the décollement. Mounting evidence suggests that many large earthquakes in subduction zones cannot be simply explained by interplate slippage. The accumulation of stress and strain at plate boundaries before an earthquake may be observable immediately above the earthquake fault so that measurements of stress and strain accumulation can be established by instrumented seafloor borehole observatories. Earthquake processes are largely controlled by the fluid pressure in the sediments and the flow of fluids through the margin. Successful results from the first installation of monitoring instruments into the décollement zone of the accretionary prism off Barbados in 1994 have fostered a major new goal for ODP in future phases — to understand the deformation processes in subduction zones through borehole instrumentation and monitoring in collaboration with other international initiatives, such as the International Ocean Network (ION) initiative.

CARIBBEAN AND NORTH AMERICAN PLATES BOUNDARY



Cross section and map of the boundary between the Caribbean and North American plates. The cross section shows a slice through a 3D seismic data volume. Logs acquired while drilling show density variation with depth. The map shows spatial variations in peak amplitude associated with the décollement zone reflections. Positive amplitude values represent normal velocity-density increase with depth, and negative amplitudes indicate a reversal in velocity-density relationships with depth. Drilling shows that areas of positive polarity are overpressured. However, regions of high negative polarity represent zones of extensive physical dilation and hydrofracturing due to extreme overpressures at or above those exerted by the overburden.

INITIATIVES



INITIATIVES

The previous section of this Long Range Plan identifies two major research themes that encompass the vast range of fundamental scientific questions we plan to explore by ocean drilling. Within these themes, the Dynamics of Earth's Environment and the Dynamics of Earth's Interior, the ODP will emphasize three major initiatives which capitalize on new frontiers in drilling/logging technology and in scientific approaches and on broader collaboration within the scientific community.

INITIATIVE I: UNDERSTANDING NATURAL CLIMATE VARIABILITY AND THE CAUSES OF RAPID CLIMATE CHANGE

- To use the sedimentary record of past climate change and sea-level fluctuations (over appropriate time scales and intervals) to understand and estimate the sensitivity and response of climate processes as a foundation for model-based projections of future environmental conditions.

INITIATIVE II: *IN SITU* MONITORING OF GEOLOGICAL PROCESSES

- To locate geophysical and geochemical observatories in the uniquely quiet environment of seafloor boreholes — to provide both a clearer view of Earth structure and a means to monitor, in real time, Earth processes and hazards, such as earthquakes.

INITIATIVE III: EXPLORING THE DEEP STRUCTURE OF CONTINENTAL MARGINS AND OCEANIC CRUST

- To penetrate hitherto inaccessible regions beneath the seafloor — to explore the underlying processes that form continents, rifts, oceanic crust, and economic sources, and to test models of active processes occurring at convergent margins.

These initiatives aim to provide data which will significantly enhance our understanding of many elements of Earth's environment that concern society, including natural resources, climate change, and earthquake and volcanic hazards. The pursuit of these initiatives complements and extends other scientific challenges that the ODP will address and will not impede the ODP's flexibility to pursue new and perhaps even more promising challenges as they emerge.

Initiative I: Understanding natural climate variability & the causes of rapid climate change

Theory predicts that climate change clusters within four distinct time scales: annual, suborbital (10 to 10^3 yr), orbital (10^4 to 10^5 yr), and tectonic (> 10^5 yr). The ODP continues to advance our understanding of the longer time scales and is now poised to lead the intellectual assault on the shorter ones, those more relevant to society.

Scientists have recently documented dramatic changes in climate variability on the decadal-to-millennial scale, such as Dansgaard-Oeschger oscillations and Heinrich events that occurred about every 2.5 kyr and 7-10 kyr, respectively, during the last ice age. These changes have been observed and quantified in records from the ODP and other marine sediment cores, continental sequences, corals and ice cores by applying newly developed high-resolution analytical techniques. The magnitudes and rates of change in this scale were a surprising discovery, as there is yet no well known forcing external to Earth's climate system that could drive these changes directly (as orbitally-forced insolation variations drive the lower frequency changes). This discovery challenges our understanding of climate change and motivates research in this direction. The driving force behind these climate cycles is uncertain, but potential culprits include global ocean circulation, which thoroughly mixes the ocean in about 2,000 years, and variations in solar radiation. The goal of the ODP's first initiative is to take advantage of new analytical techniques and unique drilling capabilities, and to cooperate with other international science initiatives — all in an effort to understand the causes and consequences of natural climate variability over shorter time scales.

Scientific drilling to learn about the nature and timing of these rapid fluctuations is extremely pertinent to our ability to understand the climatic impact of global warming most likely caused by human activities. This warming is one of the most pressing environmental issues we face as we enter the 21st Century. Climate change studies will also provide critical input to the evolving array of General Circulation Models and will serve as a means of testing model sensitivity. If warming causes partial melting or surging of Antarctic or Greenland ice sheets, then the input of fresh water to the polar seas could modify oceanic circulation on a global scale by suppressing surface ocean formation of deep waters that sink and fill the ocean basins. Some scientists have speculated that small perturbations in Earth's climate could be amplified into a rapid "jump" to another climate mode, with potentially large impacts on rainfall and other patterns that would have a serious impact on agriculture and other human activities. Likewise, large-scale melting of polar ice caps would cause a rise in sea level, adversely affecting coastal cities and low-lying countries by flooding populated areas and by reducing shoreline stability.

Future ODP opportunities will enable us to move beyond the realm of speculation about these climatic scenarios by applying new technologies and a global perspective to understanding the processes of rapid climate change from the record preserved in marine sediments. ODP scientists have led the recent development of new tools and approaches for analyzing deep-sea sediments in unprecedented detail. This approach revolves around using rapid, near continuous and nondestructive techniques to measure the physical, spectral, and magnetic properties of the cores. It relates these properties to various components of the paleoclimate system (for example, in many environments the bulk density of the sediment — measured by gamma ray attenuation — is directly related to carbonate content). When these techniques are combined with newly developed stratigraphic "spectral tuning" approaches, scientists can extract extremely detailed histories of different components of the climate system, (for example, carbon chemistry from carbonates, and wind and sedimentation patterns from magnetic properties and color reflectance data). Improved resolution from downhole logs provides similar data from boreholes, which is especially important in places where the sediments are difficult to recover.

As an example, North Atlantic cores reveal sand layers from melting icebergs that were launched from continental ice sheet surges that occurred over decades or centuries during the last ice age. Today, such surges of the Antarctic ice sheet might reasonably be anticipated if global warming trends continue. It is of utmost importance to assess the climatic impact of these surges and their consequences, such as the maximum rate of sea-level rise during intervals of rapid warming. This will be done by collecting and analyzing a wide range of paleoclimatic proxies at critical time periods. We want to know what the ice, wind, and ocean circulation patterns looked like in order to establish a picture of the state of the ocean-atmosphere system. While some of these questions can be addressed through conventional piston cores (which are typically tens of meters long), only ODP drilling will allow us to study materials accumulating rapidly enough (resulting in sequences that are hundreds of meters thick) to reveal the fine details of climate and sea-level changes during periods with different climatic background conditions.

While this North Atlantic example is an important part of establishing the nature of rapid climate change, the key to extracting a global climatic response (and thus addressing the fundamental question of climate mechanisms) lies in establishing a global array of high-resolution climate records. With such an array, we can answer questions about the state of the North Atlantic and other specific regions during a rapid climate event, and we can also extract broad-based information about the simultaneous behavior of the ocean currents and circulation systems, marine geochemistry and chemical mass balances, biodiversity, and wind patterns. In essence, we put together a global snapshot of the state of the ocean-climate system at a given time.

Gathering such a global database is beyond the capabilities of any one nation and requires the international collaboration demonstrated by the ODP and by other evolving international geoscience programs. Recognizing this need, the ODP has begun to actively solicit and pursue cooperative projects with other national and international research programs.

These other programs, operating their own specialized platforms and working in partnership with the ODP, will provide exciting new opportunities for climate studies in regions not readily accessible to the *JOIDES Resolution*. For example, the Nansen Arctic Drilling (NAD) program is targeting the Arctic regions presently covered by sea ice. ANTOSTRAT is working on the climate history of Antarctica recorded in sediments accumulating near great ice streams that channel icebergs into the Southern Ocean. The international IMAGES (International MArine Global changE Study) and the U.S. MESH (Marine Earth System History) programs are obtaining conventional piston cores in the global oceans, expanding geographic coverage for studies of the last few ice ages.

The high Arctic represents a critical, though previously inaccessible, piece of the climate puzzle. The extent of sea and land ice in this area is thought to be a powerful source of climatic feedback for it reflects sunlight and insulates the cold polar atmosphere from oceanic heat. As yet, the Arctic is poorly explored. The NAD Program will provide specialized platforms for studying this ice-covered region, operated on or accompanied by powerful icebreakers. NAD will interact closely with the ODP, seeking advice for proposal evaluation by the JOIDES advisory structure, storing cores in ODP repositories and data in ODP databases, and sharing information on drilling technology and data analysis. We anticipate cooperative NAD/ODP science programs, with ODP drilling platforms obtaining samples in open waters while NAD simultaneously works within ice-covered areas.

The combination of these programs, each with their own specialized platforms and unique capabilities, sets the stage for major advances in understanding the mechanisms responsible for rapid climate oscillations by providing a global array of multiparameter paleoclimatic records from a range of environments.

Initiative II: *In situ* monitoring of geological processes

To date, ODP technologies have been used to sample sediments and rocks and to make borehole measurements with wireline logging — all to provide essential information on the physical, chronological, climatic and tectonic history of the site. The ODP has supported the idea that providing boreholes for conducting long-term experiments is an important Program objective. Efforts in this direction began in 1989, with the drilling and casing of Hole 843B, near Hawaii (OSN-1 hole), in support of pilot experiments for the Ocean Seismic Network (OSN) program. In a concurrent undertaking, ODP engineers began a long-term, collaborative effort with a group of scientists to establish borehole observatories to collect time-series measurements of parameters such as temperature and pressure. The first of these CORK (borehole seal) observatories was established in 1991 in Middle Valley of the Juan de Fuca Ridge, and several others have since been emplaced in the ODP boreholes.

This effective, post-drilling use of boreholes represents an expansion of the ODP's focus from mainly acquiring samples and downhole geophysical data while the drillship is present, to making long-term observations or conducting active experiments in concert with other earth science programs. Borehole observatories allow us to record continuous changes (e.g., pore pressure fluctuations in tectonically active regions) and/or discontinuous phenomena (e.g., natural seismicity), while some sub-seafloor characteristics such as permeability can be ascertained by active experimentation.

FLUID FLOW IN THE LITHOSPHERE

It is widely accepted that fluid circulation through porous oceanic crust and sediment has a strong influence on Earth's chemical and thermal balances. Despite this, fluid flow remains poorly understood in detail, largely because it is an active process that requires *in situ* study—which is not possible with conventional oceanographic techniques. Standard hydrogeologic tests must be conducted *in situ* because they involve perturbation of the natural pore water system and observation of that system's recovery.

The availability of ODP boreholes is essential for assessing the physical and chemical nature of the widespread fluid circulation because the boreholes provide "windows" into fluid flow systems. Such "windows" allow scientists to sample circulating fluids, measure the properties that control the circulation (permeability, porosity, and pressure gradients), and monitor the active processes over the long-term.

Full understanding of subsurface fluid regimes requires numerical modeling. At present, the boundary conditions to constrain such models in fluid-active submarine environments are so poorly known that solutions are not unique. Borehole observatories are necessary to monitor pressure over time periods from hours to decades, and to provide sites for active hydrogeologic tests to define *in situ* permeability and the volume of fluid stored in the reservoir. These data, combined with complementary structural and geophysical results, are necessary to formulate realistic three-dimensional models of subsurface fluid flow.

GEOCHEMICAL FLUXES

The mass balance of the major chemical constituents of seawater is not well understood. While there is some reasonable control on river input, the rates and composition of the exchange among the ocean, marine sediments, and oceanic crust is still a matter of great debate. Most of the oceanic exchange takes the form of hydrothermal output from mid-ocean ridges, sediment dewatering at active margins, circulation of fluids through carbonate platforms, and hydrologic fluxes from terrestrial aquifers.

The best place to sample fluids from geologic formations is in an ODP borehole after drilling has ceased. Contamination of formation fluids with seawater is a problem if samples are taken during or immediately after drilling. ODP drilling is required for this type of observatory experiment because it is necessary to drill through the sediment column and into the oceanic crust. To date, our knowledge of the composition of fluids within the oceanic crust has mostly been inferred from data on the pore fluids of the overlying sediments.

IN SITU PHYSICAL PROPERTIES OF OCEANIC CRUST AND SEDIMENTS

In situ properties of the oceanic crust and the sediment column can be adequately characterized only through measurements in seafloor boreholes. Seismic, gravity, magnetic, and heat flow data collected by ships are simple expressions of complex subsurface processes and structures. Borehole data from the ODP are required to better interpret them. In addition, post-drilling experiments allow for the collection of data not available from shipboard measurements due to time constraints, hole equilibrium criteria, or physical constraints (e.g., ship heave).

Borehole observatories are required to understand the relationship between pore pressure and seismicity. Long-term monitoring of pore pressures along fault zones in accretionary prisms will help discover the extent to which pore pressures influence the timing and location of earthquakes and landslides (or are influenced by those events).

Borehole observatories will enable long-term monitoring of the effects of phase changes on physical and mechanical properties below the seafloor. In hydrothermal systems or in areas of cold seeps, precipitation of minerals in pore spaces should produce measurable differences in formation velocity, permeability, and electrical resistivity over time spans realistic for borehole observatories. This may also be true of the reestablishment of methane hydrate layers disturbed by drilling.

MANTLE DYNAMICS AND GLOBAL SEISMIC MONITORING

To resolve mantle features with sufficient accuracy for meaningful comparisons with numerical models, it is essential to close the large gaps that exist in the global network of geophysical stations by establishing seafloor observatories that can record continuously broadband seismic, geomagnetic and geodetic data. Poorly distributed island stations cannot fill the gaps. In particular, these holes prevent mapping of much of the core-mantle boundary and the lowermost mantle — the region where hot spots probably originate and where old, subducted slabs may end up. The gaps also introduce bias into spectral studies of mantle convection; presently mantle convection models and spectral estimates of heterogeneity are incoherent, probably because of sampling biases.

In a very different application, the improved coverage of global seismic stations afforded by ocean floor observatories can decrease the threshold at which scientists can detect earthquakes in many areas. This would enhance their ability to discriminate among earthquakes, chemical explosions used in mining, and nuclear explosions — an essential component of nuclear test ban verification programs.

The establishment of seafloor observatories also will greatly contribute to the solution of a long-standing scientific question in global and regional studies: the extraction of an azimuthal anisotropy signal. Anisotropy is related to dynamic processes, especially convection, so such measurements are key to understanding the dynamic behavior of Earth's interior. But anisotropy is often substantially weaker than the isotropic heterogeneity caused by thermal or compositional variations. To resolve the anisotropy, each element of Earth's surface must be sampled by seismic rays traveling in different directions. Such measurements become more possible with increased global seismic monitoring.

SPREADING CENTERS, LARGE IGNEOUS PROVINCES, AND INTRAMANTLE FLOW

Several regional scientific problems associated with mantle dynamics may be solved by determining lateral heterogeneity, anisotropy, and seismic activity from oceanic observatories. The fundamental advantage of seafloor stations for these studies is that the seismic wave propagation is unadulterated by movement through a continental margin or from the oceanic lithosphere to an island station. One example of an important regional problem is the nature of velocity anomalies beneath spreading centers, which can be used to determine if these regions are dominated by passive or active upwelling. Another is the nature of mantle roots beneath oceanic plateaus and other LIPs, and the related goal of resolving hotspot plumes in the mid-mantle, including their form and diameter. LIPs represent some of the largest volcanic events in Earth history and indicate major episodic transfers of heat and mass from deep within the mantle. Some may have influenced the pattern of continental breakup and the transfer of volatiles, such as CO_2, that may have exerted an influence on climate. Their formation in the Pacific, accompanied by heating of the surrounding lithosphere, displaced large volumes of seawater, potentially causing sea-level fluctuations.

Initiative III: Exploring the deep structure of continental margins and oceanic crust

Historically, most scientific ocean drilling has depended on holes penetrating only a few hundred meters into sediments or igneous rock. Only a small percentage of holes exceed 1 km in total penetration. Only one hole extends more than 2 km below the seafloor. This hole, 504B, was drilled into 5.9 m.y.-old oceanic crust in the Panama Basin. Many fundamental scientific questions related to the structure and composition of oceanic crust can only be addressed by drilling a small number of deep (greater than 2 km) holes in a few carefully selected locations. These questions focus on the early rifting history of continents, fluid flow and deformation at convergent margins, and the magnitude of the geochemical fluxes between the mantle, crust and oceans. The marine science community's long-standing goal of deep drilling has been frustrated largely because the *JOIDES Resolution* cannot met the considerable technical challenge of drilling deep, uncased holes in water depths of up to 3 to 4 km. In addition, the ship cannot drill in areas with potential hydrocarbon reservoirs for it lacks the equipment necessary to prevent an accidental oil spill. This has severely limited drilling on continental shelves to investigate the history of sea-level variation and to test models of tectonic subsidence and sedimentation history of these margins.

Deep drilling in the ocean basins and in areas with possible hydrocarbons represent a major new scientific opportunity for the ODP. However, it will require technology not presently available to the marine science community — a deep-water, riser drilling system. Such drilling will be expensive and technologically challenging. Nevertheless, the scientific benefits would be enormous, and would allow the ODP to initiate previously unfeasible studies of great importance. The development of deep-water riser drilling will intrigue industry and will lead to industry-academic collaboration which may broaden the ODP funding base. Examples of the types of challenges that can be addressed with deep drilling include: (1) the deep structure of rifted continental margins, (2) deformation at convergent margins, and (3) the deep structure of oceanic crust. The important deep-drilling objectives related to the causes and effects of sea-level change and crustal mass balance are addressed in the Scientific Themes section of this plan.

DEEP STRUCTURE OF RIFTED CONTINENTAL MARGINS

Passive (Atlantic-type) continental margins are vast storehouses of information on the crustal deformation processes that break up continents, the magmatism that accompanies this rifting, and paleoenvironmental change. The sedimentary basins along these margins also contain economically important hydrocarbon reservoirs. The past two decades have seen major advances in our understanding of rifting processes and in the development of testable models for the relative influences of brittle and ductile deformation and magmatism on margin evolution. However, important questions remain regarding the role of low-angle normal faults in continental breakup, the processes that control variations in volcanism and rifting observed between margins, and the nature of the ocean-continent transition. Intermediate depth drilling (2-4 km) of rifted passive margins to explore the role of low-angle normal faulting in continental breakup will remain a global objective.

Direct sampling of the deepest portions of these extensional margins by drilling, as well as by imaging via borehole logging and geophysical studies, will reveal structural details from which major extension processes can be inferred. Deep drilling will help constrain the distribution of extrusive and intrusive volcanic rocks and their relationship to extensional structures, as well as the uplift and subsidence history of the margin. Of particular importance will be sampling pre-rift basement rocks, rift-related volcanics, and the oldest sediments deposited on the margin, which record the syn-rift and immediate post-rift evolution of the margin.

Along most margins, these volcanic rocks are buried by several kilometers of sediment and are unreachable with present drilling technology. A deep-water riser drilling system would allow scientists to sample, for the first time, the essentially unknown deeper levels of these margins. Possible drilling targets include the East Greenland margin, where hot spot models of rift-related volcanism can be tested, the Iberian margin where the S-reflector could be drilled as an example of a possible simple shear detachment fault zone, and the New Jersey margin, where the long record of post-rift subsidence could be documented. Such drilling would be an important component of the broader Margins initiative. Continental drilling (through ICCD, the International Consortium of Continental Drilling, for example) and ocean drilling could be effectively linked by drilling transects that extend across the entire margin onto unrifted continental crust.

DEFORMATION AT CONVERGENT MARGINS

At convergent plate boundaries, part of the descending plate is scraped off, creating a wedge of deformed rocks, known as an accretionary prism. ODP drilling has made great advances in understanding and quantifying both tectonic and hydrogeological processes in these accretionary settings (e.g., Nankai, Barbados, Cascadia). Holes a few hundred meters deep drilled through the toe of accretionary complexes and into the subducting sediments have permitted an initial characterization of the décollement zone and the critical role that fluid flow plays in these deformational processes. However, deeper holes are needed to test alternate models of décollement formation, fluid flow, and chemical fluxes in the accretionary wedge. These holes must penetrate through the entire accretionary wedge and into the subducting plate at different distances between the toe of the wedge and the major forearc thrust. This will require holes with total penetration of greater than 2 to 4 km. These holes will also provide natural laboratories in which *in situ* measurements, logging, and downhole geophysical experiments can characterize the physical (porosity, permeability, temperature) and mechanical (strength, cohesion, internal friction, compressibility) properties of the accretional wedge sediments and relate them to the deformation history of the accretionary prism.

DEEP STRUCTURE OF OCEANIC CRUST

Oceanic crust covers 60 percent of Earth's surface. Its composition and evolution are central to any understanding of geochemical cycling among Earth's mantle, crust and hydrosphere. For example, chemical fluxes from hydrothermal circulation in oceanic crust are important in controlling the abundance of several elements in seawater. A knowledge of the composition of the oceanic crust is also essential to understanding both volcanism at convergent margins, as well as the composition of the mantle. However, to date, we have only directly sampled the uppermost 30 percent of the oceanic crust by drilling. A major and still unrealized goal of ocean drilling is to sample a total 6- to 7-km section of oceanic crust.

Sections through the entire oceanic crust would provide definitive answers to at least five long-standing problems, including: (1) the validity of the ophiolite model for the structure and igneous stratigraphy of the lower oceanic crust; (2) how the igneous stratigraphy and *in situ* physical properties of oceanic crust relate to the seismically defined crustal layers; (3) the nature and relative importance of the magmatic and tectonic processes in forming the lower oceanic crust; (4) the depth and nature of the hydrothermal interactions in the crust, and the resultant chemical fluxes between crust and sea water, and (5) the bulk composition of subducted oceanic crust and its suitability as a source for arc volcanics.

The offset drilling strategy presently being pursued by the ODP utilizes shallow holes drilled in natural tectonic exposures in settings like oceanic fracture zones to retrieve samples of deep crustal or upper mantle rocks. While this approach has achieved important successes, it is not a substitute for having the technical capability to drill deep holes routinely through an entire crustal section. These tectonic exposures are by their very nature often in anomalous tectonic settings, and are comparatively rare along intermediate and fast spreading ridges. This can make it challenging to relate drilling results to crustal accretion processes and to geophysical structures in more normal settings. These tectonic exposures are also usually located in young crust and thus provide little information on the long post-emplacement alteration history of oceanic crust. Finally, by sampling only partial crustal sections in different locations it is impossible to directly relate the history of volcanism recorded in the extrusive section to the magmatic evolution of the underlying plutonics and upper mantle.

TECHNOLOGY DEVELOPMENT

TECHNOLOGY DEVELOPMENT

Most major advances in marine geosciences are predicated upon technological innovations and the ODP's vision for the next 15 years is no exception. The technology deemed essential to accomplish ODP's scientific goals is outlined below.

Drilling technology

RISER DRILLING

Future drilling with a riser system was an integral part of the 1990 Long Range Plan. Despite the updating and refocusing of the ODP's objectives outlined here, this long-term requirement remains unfulfilled. The riser system circulates drilling mud from the ship to the borehole, which provides hole cleaning and stability, as well as the return of drill-cuttings to the ship's rig-floor. The ODP's ambitions to drill deeply both in thick sediment sequences and in oceanic crust can only be achieved with riser drilling.

Drilling with a riser, however, provides a direct path for oil or gas from the geologic formation to the ship, should hydrocarbons be encountered accidentally. To mitigate the potential danger and minimize pollution risks associated with drilling in hydrocarbon-bearing formations, and to avoid the inherent liability issues associated with the unintentional release of hydrocarbons into the environment, the drillship must be equipped with the capability to safely seal off (kill) a borehole. A common addition to a riser system is a conventional blowout preventer (BOP). The use of an industry-standard BOP at the seafloor will enable the drillship to "kill" a borehole and this capability will be essential for deep penetration in continental margins and ocean basins where hydrocarbons are likely to be encountered.

A drillship equipped with a riser system and BOP has never been available for scientific ocean drilling; consequently, many important scientific objectives have not yet been addressed. Deep-water drilling objectives require that the drillship have a riser system with a BOP capable of drilling in water depths greater than 4 km with penetration of up to 6 km beneath the seafloor. The Japanese Science and Technology Agency (STA) and the Japan Marine Science and Technology Center (JAMSTEC) have proposed a plan for ocean drilling in the 21st Century (OD-21) with a drillship whose riser drilling capability would be water depths of 2.5 km initially and 4 km eventually. It is anticipated that this vessel would become available for drilling after 2003.

Also under consideration by JOIDES panel experts is the feasibility of a slimline riser system that addresses the problem of the weight placed on a vessel drilling in water depths greater than 3 km. The use of a slimline riser would potentially permit the drilling of deep, well-cleaned and stable holes in areas, such as in oceanic crust, where a BOP would not be needed. However, in some applications, a slimline riser system may require a new generation of appropriate slimline downhole tools and equipment.

Earth's crust varies significantly over both large and small spatial scales. Drilling holes in close proximity and in multiple directions would reveal such variability. A riser system could provide new opportunities to study this variation by permitting directional drilling. Application of such oil-field techniques to ocean drilling would, for example, enable studies of the processes controlling the distribution and flow of fluids in deep fault zones and the distribution of subsurface mineral deposits.

OTHER PLATFORMS

The scientific objectives outlined in this plan will require occasional access to drilling platforms other than ODP's "core" vessel, currently the *JOIDES Resolution*, and the proposed Japanese riser ship. Shallow-water rigs have recently been used by ODP researchers drilling on continental margins. These scientists have expanded their research programs by establishing separately funded projects in coastal regions (e.g., offshore New Jersey, the Bahamas Platform and Northeast Australia). Similar access to shallow water regions is required by some of the future science goals, in particular, those investigating the core theme "Causes and Effects of Sea-level Change". Similarly, objectives related to "Understanding Earth's Changing Climate" would clearly benefit from associated drilling in ice-prone polar regions, which will require extended work at high latitudes and the occasional use of specialized platforms. The ODP can accomplish these aims in collaboration with polar programs, such as the NAD and Antarctic Stratigraphy (ANTOSTRAT).

Coring technology

Development of coring technology has been a constant theme within the ODP and many tools are modified and improved to meet scientific demand.

ADVANCED PISTON CORER (APC)

The APC has been a major success in scientific ocean drilling because it provides undisturbed samples in unconsolidated sediments by hydraulically coring ahead of the drill-bit. Based on this success, and on the need for high core recovery and abundant core material, a number of researchers interested in paleoceanographic objectives have recently called for longer, larger-diameter versions of the APC.

VIBRO-PERCUSSIVE CORING

The ODP has been experimenting with coring techniques that vibrate or hammer core barrels into substrates ranging from unconsolidated sandy sediments to hard sedimentary rocks. Near-term coring objectives on continental margins require that increased effort be given to achieving successful core recovery in sands and glacial sediments.

PRESSURIZED CORING

Development is required for routine recovery of gas-bearing (e.g., gas hydrates) sediments in undisturbed condition and methods must be developed to facilitate accurate sub-sampling of such sediments under pressure. This is a fundamental need for biogeochemical cycling studies.

DIAMOND CORING/ MOTOR DRIVEN CORE BARREL

Recently, motor-driven core barrels adapted from the mining industry have been used to successfully drill young crustal areas. Together with diamond coring, they constitute a potential advance that may prove fruitful once current problems with control of heave compensation are surmounted. Successful deployment of a diamond coring system in the post-1998 period may provide a new focus for objectives to drill young ocean crust, as well as chert and chalk sequences that are important for environmental change objectives.

Downhole and shipboard technology

LOGGING-WHILE-DRILLING (LWD)

Recent results have proven that logging difficulties in the shallower parts of boreholes and in unstable holes can be overcome by using LWD technology. New developments in this method will likely include sonic-while-drilling and real-time data transmission. The latter will enable ship- and shore-based investigators to make rapid drilling decisions while the drill-bit is still at the bottom of the hole.

NEW DOWNHOLE TOOLS

New tools for collecting *in situ* data from boreholes are continuously being developed by industry. These tools includes one that images geological structures in complex environments and another that samples *in situ* fluids. Transfer of these technologies to the ODP can be made by using a larger-diameter riser/drilling system, increasing overlap with industry, and encouraging new joint ventures in engineering.

SITE SURVEY NEEDS

The proposal-driven nature of the ODP puts the onus of regional and site-specific surveys on the proponents. Many of the objectives outlined in this plan will require surveys of significantly greater detail and sophistication than have been needed in the past. Three-dimensional seismic surveys will be necessary to tackle objectives focusing on sea-level history, and on accretionary margins and deeper passive margins. High-resolution morphological surveys will also be needed before drilling into young oceanic crust. Finally, shallow water drilling objectives will require special hazard surveys.

HEAVE COMPENSATION: IMPROVED DATA PRECISION AND RESOLUTION

Several scientific objectives under the "Dynamics of Earth's Environment" theme call for improved downhole logs, particularly from the upper parts of drill holes. Scientists seek stratigraphic resolution on logs that is comparable with MST data from cores. Some of the disparity in log-core resolution is due to the difficulties of working in unstable sedimentary sequences and to uncertain depth-in-hole measurement, but in other cases, new high-resolution logging tools are needed. To improve the precision and vertical resolution of ODP data, the wireline-depth and core-depth systems will require a more advanced approach to depth measurement and heave compensation. Implementation of such an approach will significantly improve the data that are used to study climate change and other environmental topics. When using LWD and/or a riser system, depth and heave compensation for both logging and core data can be the same. Industry uses such combined wireline/riser heave compensator systems to improve depth measurements. The ODP will benefit by taking this approach to drill string heave compensation and depth measurement.

IMPROVED SHIPBOARD LABORATORIES

Improvements to existing shipboard laboratory equipment for scanning, imaging and analyzing core materials are expected to continue, and in a scenario where more than one platform is operating, parallel installation of key equipment should occur. These labs are the root of the scientific accomplishments of the ODP and their support and growth is essential.

SHIP-TO-SHORE DATA TRANSMISSION

Current satellite technology makes it possible to distribute data efficiently, in nearly real-time, between ship and shore-based labs. This capability will enable: (1) off-site conferencing for rapid on-site decision-making, to enhance safety and drilling effectiveness, (2) greater scientific evaluation and quality control of data, and (3) increase educational opportunities in marine geology by linking classrooms to the ship. The post-1998 period will see increases in the number of cores and data. In addition, a riser drillship will spend long periods, possibly 6-12 months, on a single site. Sending data to a shore-based scientific party to monitor data quality, process data, and interpret results will be essential to successfully meet these objectives.

SHIPBOARD/SHORE-BASED DATABASES

The ODP has undertaken a major upgrade of its database system. The goal of this upgrade, called the Janus Project, is to ensure comprehensive input of data into the database and easy retrieval by users in order to improve the quality, productivity and visibility of ODP science. After completion, the next database effort will focus on the migration of older ODP and DSDP data into the new system. With the increased volumes of sample recovery envisaged in this ambitious Long Range Plan, the security and ease-of-use of these databases will be an essential component of the program well into the next century.

SEAFLOOR OBSERVATORIES

Instrumentation of seafloor observatories has been driven by drilling proponents. The ODP has taken responsibility for providing boreholes that are suitable for long-term experimentation. In some cases, as with the CORK experiments, the ODP has also installed the instruments. Scientists retrieve the data from these instruments by returning to the borehole site on conventional research vessels. In other cases, such as with seismometers, scientists emplace the instrument(s) at some time period after the hole has been drilled and cased. Installation by methods such as "fly-in" reentry, are also accomplished from a conventional research vessel. We envision a rapid increase in the need for this kind of experimentation, which will include collaboration with new initiatives such as Borehole Ocean Laboratories and Experiments (BOREHOLE) and International Ocean Network (ION). We foresee a major increase in the use of seafloor observatories to study dynamic processes that occur during earthquake and volcanic events.

IMPLEMENTATION STRATEGY

IMPLEMENTATION STRATEGY

The science plan focuses on a few high-priority projects and a small number of emerging scientific opportunities. Individual scientists and global geoscience programs are encouraged to develop drilling proposals within this framework. In most cases, multi-leg, multi-year drilling programs will be dedicated to a single problem, or to a single hole in some cases. This plan also calls for the use of alternative drilling platforms. The ODP is aggressively seeking to implement new ocean drilling technology for the purpose of expanding scientific opportunities. In some cases, such as riser drilling, the technology will require several years of development and implementation. However, once riser drilling is accessible, it will finally enable scientists to explore critical regions that were previously unreachable. This will permit ODP scientists to address fundamental scientific questions. Thus, for scientific, logistical, and technological reasons, implementation of the proposed science plan will be in phases.

The elements of the Implementation Strategy can be addressed under six headings:

- **SCIENCE DELIVERY** outlines the upcoming major scientific phases of the Program in the context of identified operational, technological, and fiscal constraints.
- **PROGRAM MANAGEMENT AND OPERATIONS** addresses organizational issues and the changes required to meet the needs of the science program to 2003 and beyond.
- **SCIENCE ADVICE AND COORDINATION** addresses the JOIDES Advisory Structure and its support facility, the JOIDES office.
- **PARTNERSHIPS** addresses the environment external to the ODP, such as cooperation with other scientific programs, industry (in pursuit of technology development), and engaging the scientific institutions of countries not currently ODP participants.
- **DRILLING PLATFORM OPTIONS** addresses the major issues concerning the data collection capabilities of the Program.
- **FUNDING** addresses the issues of Program financial requirements and potentially new sources of Program funds.

To develop detailed plans for Phase III and IV, EXCOM has identified specific roles for the current management, operational, and scientific coordination functions of the ODP, as well as the JOIDES structure and Japanese agencies involved in planning OD-21. These plans are intimately linked with this Long Range Plan and will be used to demonstrate full accountability of the entire Program.

SCIENCE DELIVERY

The current phase of the ODP (Phase II) extends through 1998. In Phase III (1999 to 2003), the *JOIDES Resolution* will continue to be the program's primary drilling platform. Phase IV (beginning on October 1, 2003) is envisioned as a two-ship program, involving a globally deployed "*JOIDES Resolution*-type" vessel and a riser-equipped ship for deep drilling. Throughout Phases III and IV, the ODP will address scientific problems outlined under Dynamics of Earth's Environment and Dynamics of Earth's Interior, emphasizing the three major new initiatives previously outlined.

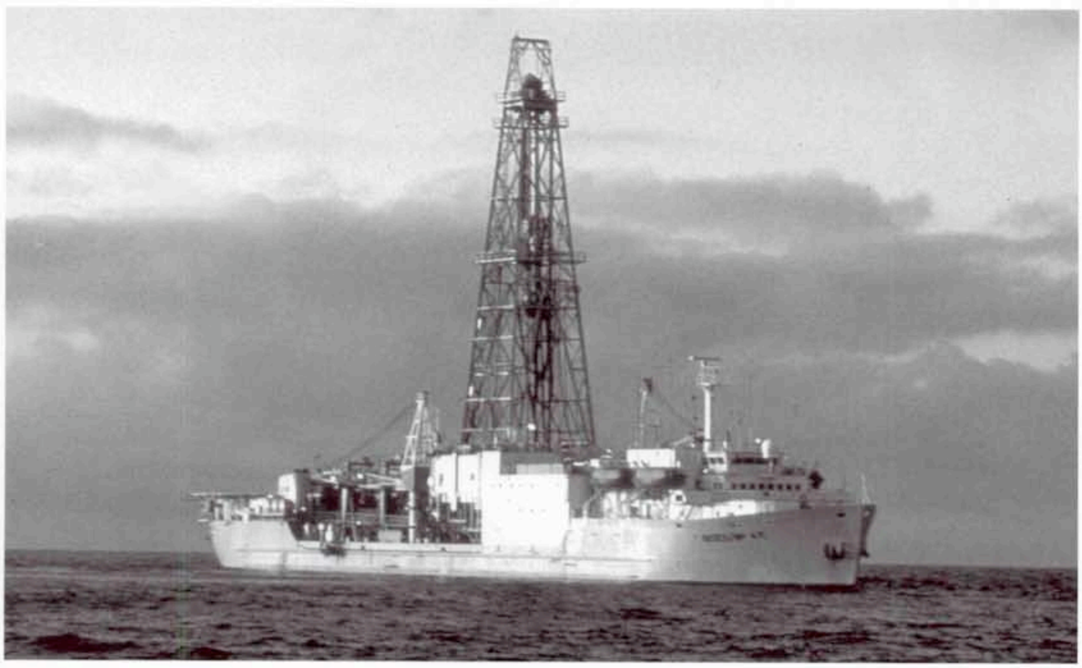
PHASE II (PRESENT TO 1998)

Drilling proposals active in the JOIDES review system, or those submitted in January 1995, have now been used to produce an operations schedule for 1997. Based on highly ranked global objectives, the JOIDES Planning Committee set a four-year strategic plan from 1996, which states that the *JOIDES Resolution* will "move from Middle America into the North Atlantic, thence the South Atlantic and Indian Ocean to the Western Pacific."

By 1998 we will have made significant progress in tackling a number of scientific problems that require multiple legs of drilling over the course of several years. Many of these problems address objectives of both the old and new Long Range Plans, and will set the stage for Phase III of the Program as planned herein. For example, legs are planned for Phase II that:

- will complete two passive margin transects (carbonate and clastic) to

THE *JOIDES RESOLUTION*



address questions of timing and magnitude of sea-level change,
- will recover extremely high-resolution records of climate that will anchor a global array of such sections and will be used to address the long-term character and variability of climate in unprecedented detail,
- are aimed at recovering high-resolution stratigraphic sections near the Antarctic margin that will be used to construct a detailed history of southern hemisphere glaciation, and which will enable comparison to high-resolution records from the northern hemisphere (e.g., Leg 162),
- investigate the global carbon budget beginning with gas hydrate formation and continuing with organic carbon sequestration in coastal upwelling zones,
- broaden investigation of the temporal and spatial variability of the lower oceanic crust and upper mantle by targeting tectonic exposures of these sections,
- study lithosphere extension mechanics by drilling into an actively rifting margin and installing an observatory to measure processes such as strain along listric faults,
- complete one convergent margin transect specifically designed to test models of lithosphere mass balance in subduction zones,
- complete the second phase of drilling in a sedimented ridge hydrothermal system, and instrument holes for "time-series" observations and experiments,
- investigate structural, mechanical, and geochemical processes at convergent margins using newly developed techniques such as logging-while-drilling, and
- conduct experiment to test models for the origin, growth, and evolution of large igneous provinces (LIPs).

In addition, by the end of Phase II, the feasibility of the diamond coring system will have been determined and appropriate testing completed. Another borehole seismic observatory site may be drilled in cooperation with ION. The new database management system will have been fully implemented and accessible via the World Wide Web. It is also critical that the ODP strengthen and formalize its relationship with other earth science programs during the remaining years of Phase II to ensure that common scientific and, in some cases, technological goals will be attained in the most efficient and cost-effective manner.

PHASE III (1999 TO 2003)

The start of this phase represents the first fully operational year addressing scientific problems identified in this Long Range Plan. **From the beginning of the 1997 planning year, priority will be given either to proposals that directly address issues raised in this Long Range Plan, many of which require multi-leg, multi-year programs, or to outstanding science not envisaged at the time this plan was written.** Plans for this phase include:

- expanding the global array of extremely high-resolution records of climate change,
- establishing a hemisphere-by-hemisphere detailed history of ice sheet growth, distribution and decay,
- accurately measuring biogeochemical cycling and fluxes within the Earth system,
- describing and documenting climatic extremes (cold and warm periods) which (1) test the sensitivity of existing climate models, and (2) provide parameters for new model runs used to predict future climate change,

- continuing the investigation of global carbon cycling and ocean circulation patterns by drilling additional latitudinal and depth transects, and taking advantage of new stratigraphic and geochemical techniques,
- investigating the microbial processes deep in the sedimentary column and links to sediment diagenesis,
- completing mass balance experiments at a convergent margin by sampling the deeper portions of a forearc to constrain fluid and mass partitioning,
- continuing the offset-section characterization of the lower crust, focusing on sampling long sections through the transition zones between principal components of oceanic crust,
- examining the characteristics of reaction zones beneath large hydrothermal deposits, and,
- evaluating the dynamics of mantle reservoirs by defining geochemical domains and augmenting seismic observatory installation in drill holes.

During Phase III, preliminary drilling to intermediate depths (2-4 km) will be carried out in a few locations to assess the technical feasibility of drilling deeper in the future. This will be done using a system such as the diamond coring system, or other method(s) for drilling in resistant rock formations. Phase III will also see the first use of additional drilling platform capabilities, as required.

PHASE IV (2004 AND BEYOND)

The ODP plans for two modes of operations during Phase IV. One utilizes a drilling vessel equipped with a riser and well control capabilities to drill deep holes into oceanic crust, and at passive and convergent margins. This will tackle primary objectives such as the deep structure of the oceanic crust, the early history of continental rifting, the origin of sea-level change in an ice-free world, faulting and deformation at convergent margins, mass fluxes at subduction zones, and the long-term record of carbon and nutrient burial. Each deep hole may require the drillship to spend long periods (six months or more) on station. Subsequent returns to deepen and conduct experiments in the same holes are likely. Riser capabilities will also be required to estimate and better understand the sensitivity and response of climate processes by drilling in more dynamic and high-risk environments such as high-accumulation rate continental margins and shallow waters.

The second operational mode will involve a vessel with *JOIDES Resolution*-type capabilities. The ODP envisions enhanced coring/recovery capabilities to obtain continuous, complete, and high-quality Neogene, Paleogene, and Cretaceous sediments so that orbital- and suborbital-scale variations in biotic, chemical, and sediment components can be quantified under different boundary conditions. Additional work will be undertaken on the Neogene stratigraphic record to establish global synchroneity of sea level.

Installation of seafloor observatory sites in support of deep Earth structure studies will remain a priority. It is also envisaged that some scientific problems falling under the Dynamics of Earth's Interior theme will also be addressed by such a multipurpose drilling vessel.

PROGRAM MANAGEMENT AND OPERATIONS

PROGRAM MANAGEMENT

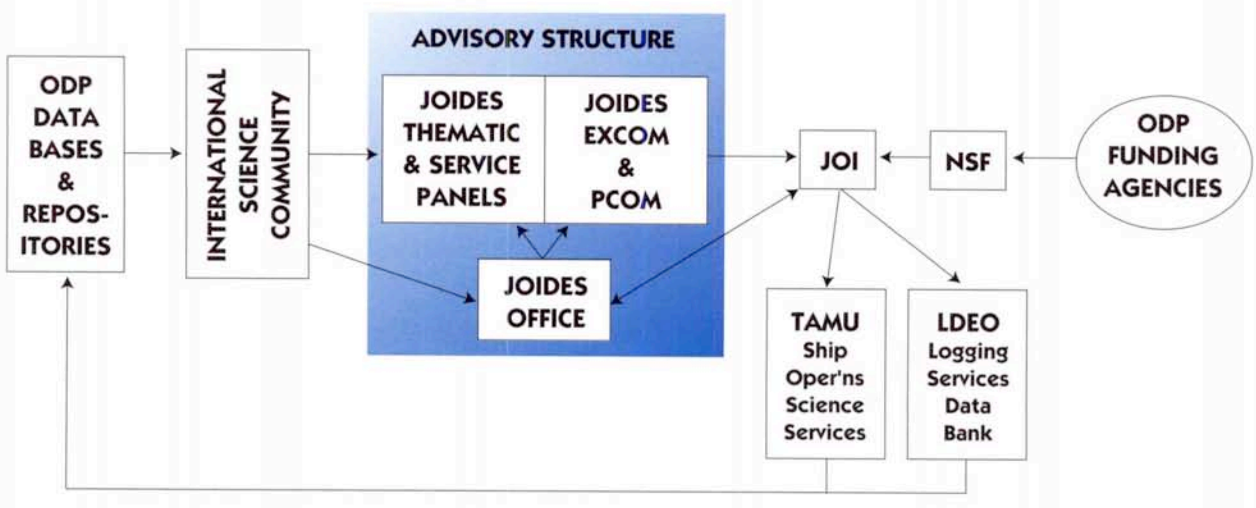
The Executive Committee of the ODP has judged that the overall management of the Program is best handled through a single prime contract between the U.S. National Science Foundation (acting on behalf of all the ODP funding entities) and an appropriate scientific program management organization. It has been determined that the appropriate scientific program management organization will be Joint Oceanographic Institutions, Inc., at least through 2003.

JOI, Inc. will continue as a "not for profit" organization incorporated in the U.S. All JOIDES members support JOI to continue acting on their behalf as the prime contractor for the ODP through at least Phase III.

The identity and role of the Program contracting entity or entities for Phase IV has not yet been decided. EXCOM has asked STA/JAMSTEC, MONBUSHO, and JOI to develop options for international management and operations beyond 2003 for supporting a program that includes a Japanese riser ship and a *JOIDES Resolution*-type vessel. Funding bodies who commit to support scientific ocean drilling during Phase IV, and possibly beyond, will need to make a decision by 2001.

The role of the prime contractor will be to continue to manage the ongoing Program planning and reporting processes, the operational subcontracts, and program "change." In the context of this last responsibility JOI began a process of "management improvement" across the ODP in 1995, including the introduction of "project-based" management principles. Project management is scheduled to be fully in place by the beginning of Phase III.

MANAGEMENT, OPERATIONAL, AND SCIENCE ADVISORY STRUCTURE



PROGRAM OPERATIONS

All program operations are subcontracted by JOI. These include such major components as ship charter and science operations, logistics, engineering operations and development, database and core curation, publications, wireline logging, and site survey databank. Through Phase II, all of these components are subcontracted to Texas A&M University, except for the last two, which are subcontracted to Columbia University (Lamont-Doherty Earth Observatory). Options for Phase III operational subcontracts have been evaluated by JOI which has decided that wireline logging and site survey databank services will be re-tendered.

Through the end of Phase II and early in Phase III, particular emphasis will be placed on enhancing the following operational components:

- increased efficiency and cost-effectiveness of all elements of scientific operations, plus a continuing strong focus on the quality of service and on occupational health and safety issues;
- increased use of electronic forms of scientific publication, compatible with community acceptance;
- increased coordination with governments and research institutions to support and fund broad-based research and development efforts in engineering and wireline logging that are required to fulfill the goals of the Long Range Plan;
- effective scientific database operation and service delivery;
- effective public communication of the scientific results of ocean drilling and their significance to society;
- increased emphasis on the rapid publication of important scientific results in the general scientific literature.

The form and mechanisms for subcontracting Program operations beyond October 2003 will be decided in 2000, in the context of the mechanism for Program management selected for Phase IV.

SCIENCE ADVICE AND COORDINATION

Scientific advice, in support of the ODP, will come from the JOIDES Advisory Structure, at least through Phase III. The Executive Committee (EXCOM), Planning Committee (PCOM), Thematic and Service panels will act as advisory subcommittees to the JOI Board of Governors (Board of Directors). The JOIDES Advisory Structure will continue to represent U.S. and all full non-U.S. members of the ODP and will be wholly member supported, that is, without the use of co-mingled Program funds. EXCOM has directed PCOM to develop a detailed implementation strategy for the Long Range Plan, including necessary changes to the JOIDES Advisory Structure. EXCOM will begin reviewing proposed changes in June 1996.

Science Coordination will continue to be carried out through the JOIDES office, under a JOI subcontract, through at least Phase III. Woods Hole Oceanographic Institution will host the JOIDES office from October 1996 to October 1998. The office will then alternate between a non-U.S. institution and a U.S. institution every two years from the start of Phase III. As now, the JOIDES office will call for scientific ocean drilling proposals (in the context of this Long Range Plan), manage the proposal review and ranking process, and otherwise support the JOIDES Advisory Structure. It is expected that the specific mandates, or terms of reference, of thematic and/or service panels will be changed by EXCOM, on advice from PCOM, to more appropriately match Long Range Plan themes and strategies.

PARTNERSHIPS

COOPERATION BETWEEN THE ODP AND OTHER SCIENTIFIC PROGRAMS

The ODP has maintained close scientific links with a wide range of national and international scientific programs through the years, and these links are now set to strengthen and grow. JOIDES is currently considering a mechanism to establish formal ties with international groups involved in studying the seafloor using drilling platforms, or proposing to use ODP platforms, such as *JOIDES Resolution*. These ties might take shape in a variety of ways, such as: representation on JOIDES thematic panels; proposal review; site survey review; safety review; access to site survey background data and services; acceptance of data in the ODP Data Bank; acceptance of core materials into ODP repositories; and engineering and logging support and other operation support. The ODP will encourage other national and international science programs to seize the opportunity created by this type of strategic alliance, and seek additional funding to enhance the science through ocean drilling and other cooperative ventures.

COOPERATIVE TECHNOLOGY RESEARCH AND DEVELOPMENT

The ODP has traditionally sole-funded research and development to meet its special engineering and wireline logging requirements. This has led to a remarkable range of innovations, some of which have found commercial application.

However, the cost and risk of continuing to sole-fund the kind of engineering developments required by this Long Range Plan are well beyond current Program resources (i.e., through co-mingled funds). The ODP is, therefore, exploring the possibility of carrying out such research and development under cooperative or "joint venture" arrangements. A joint venture would involve sharing costs, risks and benefits with government agencies and/or industry in any JOIDES partner country.

Major engineering systems that could be developed under cooperative technology R&D arrangements are outlined in the section on Required Technical Developments. Examples of such systems include:

Major science initiatives, such as the International Ocean Network (ION), International Ridge Inter-Disciplinary Global Experiments (Inter-RIDGE), Margins, International MArine Global changE Study (IMAGES), and Marine Aspects of Earth System History (MESH) were consulted in the development of this Long Range Plan and provided input. The ODP encourages drilling plans and/or proposals from such program organizations, in addition to the traditional proposals put forward by individual scientists.

- a slimline riser for use in very deep water (> 4 km);
- a hard rock coring system, to improve core recovery in locations that are difficult to drill; and
- a long, large diameter piston corer—particularly one that can be readily transferred to a contract drilling platform.

All these systems have potential for commercial application and they should attract joint venture partners. Funding contributions from such partners can be effectively viewed as increases in the total funding level of the Program.

WIDENING INTERNATIONAL PARTICIPATION IN THE ODP

In 1995, the ODP embarked upon a campaign to expand the current membership of the Program. The principal benefits were seen to be:

- enhancing the international dimension of the Program;
- expanding the ODP's scientific and engineering expertise and access to regional databases;
- improving educational linkages and scientific cooperation.

It was recognized that new partners were most likely to be drawn from the newly industrialized nations of the Pacific Rim and South America. Such potential ODP participants were unlikely to be able to support a full membership contribution, nor were they likely to coalesce into "natural" consortia in the first instance. Therefore, the ODP will, in the future, accept "Associate Members," whose annual program contribution will be set in increments of one-sixth of a full member contribution. It is hoped within three years of joining as an "Associate Member" of the ODP, a full membership will be sustained, either through a consortium or as an individual country partnership. In the meantime, the rights of "Associates" will be in direct proportion to the level of their contribution.

It is anticipated that the number of "Associate Members" that will be recruited to the Program over the remainder of Phase II and through Phase III could total the equivalent of one additional full member. This will constitute a important increase in the Program's funding level.

DRILLING PLATFORM OPTIONS

The ODP plans to operate the *JOIDES Resolution* as its primary drillship through the year 2003. The *Resolution* will undergo a refit in 1998 that will extend its working life. Central to the scientific achievement of Phase IV, however, is access to at least two deep-sea drilling platforms – one with the capabilities of the present *JOIDES Resolution* and another with deep water well control (riser) capabilities. During all phases of the Long Range Plan, the ODP will also consider expanding operations by using alternate platforms.

RISER DRILLING

There are currently two main options for acquiring riser drilling capability:

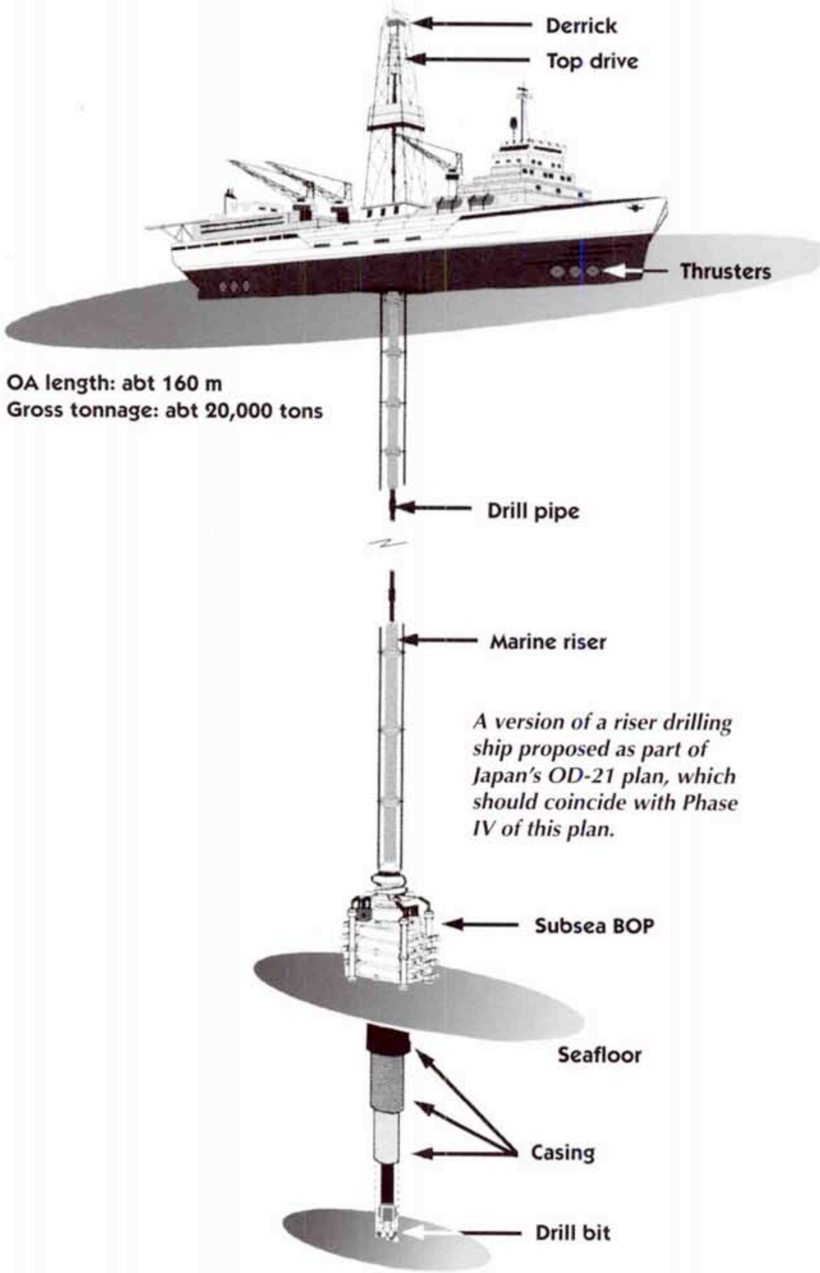
- The principal proposal under consideration has been put forward by the Japanese Science and Technology Agency (STA/JAMSTEC), which is currently seeking funds to build a large (160 m, 20,000 ton) research drilling vessel capable of full diameter (maximum 40 cm) riser operation in 2 km of water by 2003. This proposal is known as "Ocean Drilling in the 21st Century," or OD-21. A subsequent goal is a riser system that will operate in water depths as great as 4 km. An increase in operating costs (relative to the current *Resolution*) can be anticipated.
- An alternative option, should the OD-21 proposal not be successful, is to have the *JOIDES Resolution* undergo a major refit in 2003, which would include stretching the vessel amidship to make space for riser deployment. The capital cost of such a refit is not identified in this plan and an increase in operating costs can be anticipated. If OD-21 is successful, the *JOIDES Resolution*, or a similar vessel, will be refit to meet Phase IV goals that do not require a riser platform.

ALTERNATE PLATFORMS

The ODP is also considering alternate platforms to supplement drilling, such as:

- Rental of a commercial jack-up or other style of conventional or exploration drilling platform to tackle Long Range Plan scientific objectives that require shallow water drilling that is beyond the current capabilities of the *JOIDES Resolution*. It is essential that any commercial rig have the drilling and coring capabilities of the *JOIDES Resolution*.
- A recent Nansen Arctic Drilling Program (NAD) initiative identified at least one Russian ice-breaking drilling platform capable of operating in the Laptev Sea in water depths of less than 200 meters. Such a platform could service potential NAD/ODP cooperative program objectives around the Arctic continental margins as early as 1999.
- A similarly recent initiative by a group of European scientists, interested in relatively shallow penetration coring (up to about 300 meters) in intermediate water depths (generally up to about 2000 m) around the European continent, identified a number of commercial vessels that could be equipped for such operations using the ODP's Hydraulic Piston Corer (HPC). Subject to reasonable fitting-out costs, this would provide a platform that could service many site proposals aimed at objectives under the theme Dynamics of Earth's Environment.

DEEP OCEAN DRILLING VESSEL



A version of a riser drilling ship proposed as part of Japan's OD-21 plan, which should coincide with Phase IV of this plan.

FUNDING

PROGRAM FUNDING REQUIREMENTS

Forecasts of funding requirements for the ODP to carry out this Long Range Plan are based on the following assumptions:

- The base program cost for operations will be $44.9M.
- There will be normal increases in Program staff salaries, and operating and contract costs. A goal is to offset some of these increases by efficiency gained through progressive introduction of "project-based" management.
- The needs for special technology development are central to the success of this plan. A conservatively estimated increase of $1M per year, starting in FY 97, growing to $2M per year by FY 02, is suggested as a base level target.
- Funding for alternative drilling platforms has been allowed for, rising from $3M in FY 99 to $6M after FY 04.
- The additional cost of operating the Japanese riser drilling option is estimated to be $30M to $50M per year, although the cost will vary significantly depending on the mode and duration of riser operation. Should OD-21 not succeed, the additional cost of operating a slimline riser from a stretched *JOIDES Resolution* is estimated at $4M in FY 04, rising to $4.4M in FY 08.

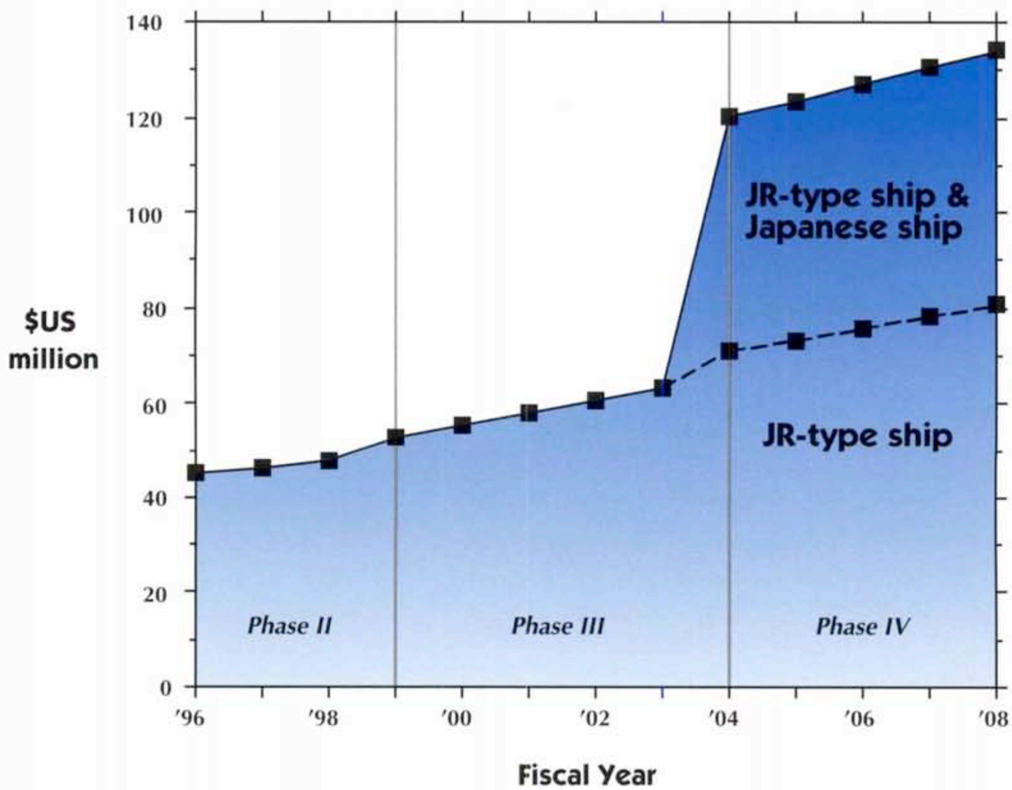
Operational funding requirements from FY 96 to FY 08 are illustrated in the chart.

PROGRAM FUNDING SOURCES

Additional funding will be required to operate more than one drillship and EXCOM has recognized the need for immediate and concerted actions to secure the necessary financial support. EXCOM has also endorsed a recommendation of the 1996 ODP Mid-Term Review that calls for an annual growth in the overall budget of 2 to 3% in real terms. Finally, a special "riser surcharge" will need to be levied, beginning in FY 04, to cover the additional costs of riser operations on either the proposed Japanese riser vessel or the stretched *Resolution*.

When OD-21 is realized, STA/JAMSTEC is prepared, in principle, to make a significant contribution to the operation of the riser drill ship. The number of associate members to the ODP are also expected to grow, thus increasing overall funding for ODP operations. Special funding (contributions) for additional drilling platforms will be sought outside the normal ODP funding streams in most cases.

ODP COST PROJECTIONS



The ODP cost projections for the 12 year period from 1996 through 2008. The projections assume an annual growth rate of 2 to 3%, plus inflation, through the remainder of Phases II and III. Some of this total growth is expected to come from new membership and special funding. The Phase IV option, which involves the operation of a Japanese "riser" drillship and a JOIDES Resolution*-type vessel, is predicated on a significant contribution from STA/JAMSTEC.*

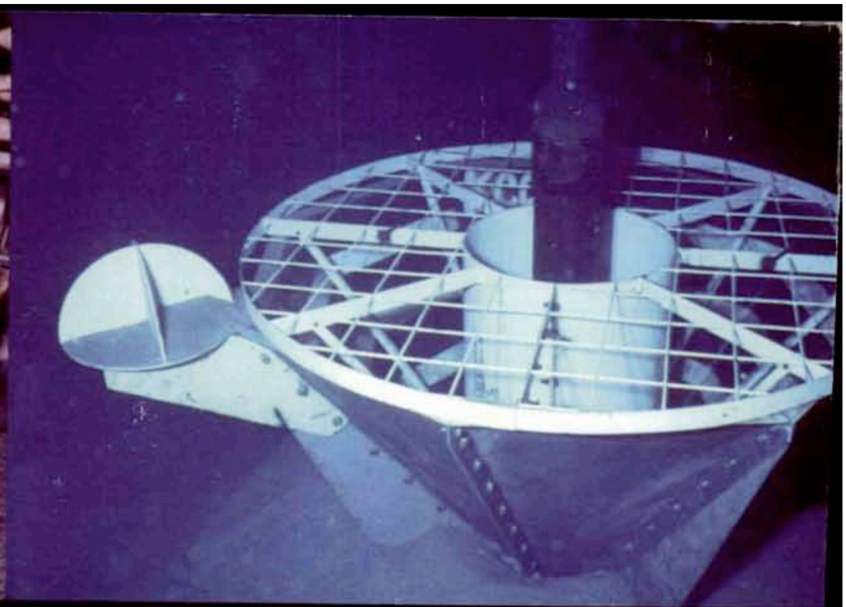
BACK COVER:

Top left: Schlumberger engineers and a wireline logging tool. The logging tool, an active probe or sonde, is lowered to the borehole where continuous measurements of the physical and chemical properties of the formation are made. Photo courtesy of ODP/TAMU.

Top right: Photo of an ODP CORK (borehole seal), which enables scientists to record temperature and pressure at *in situ* conditions within the borehole for several years. The photo was taken by Keir Becker (RSMAS) while on the submersible *Alvin*.

Bottom left: Reentry cone being lowered through the moon pool of *JOIDES Resolution*. The cone will drop down the drill string to the drill site on the seafloor and will allow future reentry of the borehole. Photo courtesy of Ellen Kappel (Joint Oceanographic Institutions).

Bottom right: An ODP marine technician marks a nine meter core, newly arrived on *JOIDES Resolution*, for sectioning into 1.5 meter lengths. The core will be moved into the shipboard laboratory complex for analysis and testing by the scientific party. Photo courtesy of ODP/TAMU.

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