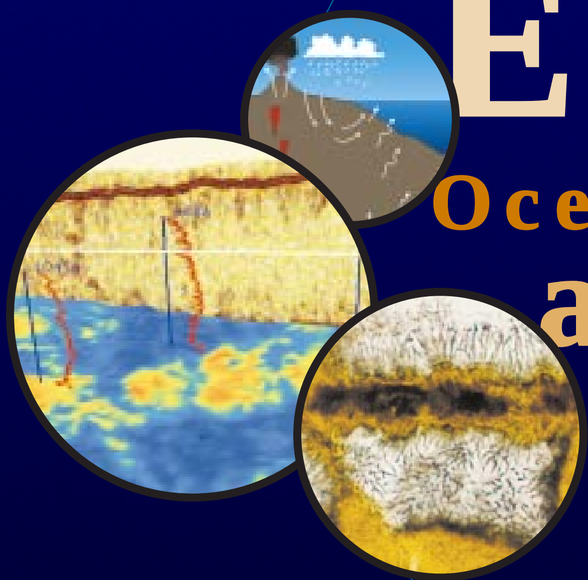
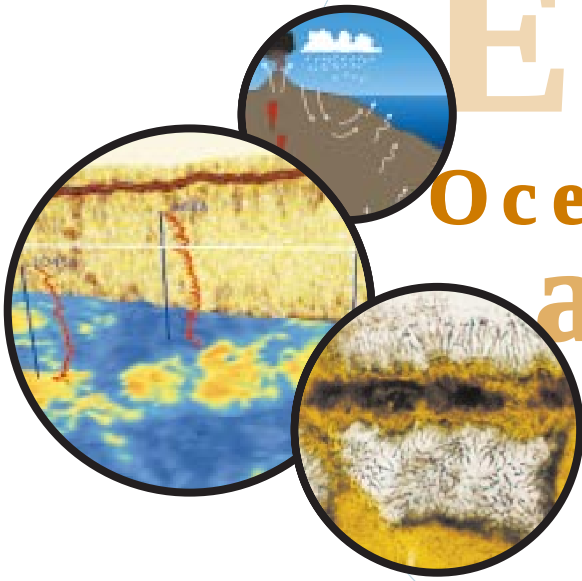


Earth, Oceans and Life

Scientific Investigation of the Earth System
Using Multiple Drilling Platforms and New Technologies

Integrated Ocean Drilling Program
Initial Science Plan, 2003-2013

Earth, Oceans and Life



Scientific Investigation of the Earth System
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Integrated Ocean Drilling Program
Initial Science Plan, 2003-2013

May 2001

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Contents

A Letter from IPSC

The most ambitious program of ocean drilling and exploration ever conceived is contained in this Initial Science Plan. An international community of earth scientists gathered on several occasions over the past three years, sharing scientific goals, challenging one another's imaginations and generating ideas which IPSC used to develop this plan for the first decade of the Integrated Ocean Drilling Program (IODP). Even as mankind prepares for extraterrestrial exploration beyond the Moon to Mars and the outer planets of our solar system, earth scientists will embark upon this exciting expedition to "inner space." Building upon 30 years of scientific achievements, this Initial Science Plan defines the goals of an international ocean drilling program, synthesizing the results of a comprehensive suite of conferences and workshops, including CONCORD* and COMPLEX.** It highlights new process-oriented directions for addressing the Earth system, and it proposes a fundamentally new multiple drilling platform approach to the science of ocean drilling.

Ocean drilling achievements have set the stage for understanding the complex linkages among the different parts of the Earth system. The Deep Sea Drilling Project (DSDP, 1968-1983) validated the theory of plate tectonics, began to develop a high-resolution chronology associated with study of ocean circulation changes, and carried out preliminary exploration of all of the major ocean basins except the high Arctic. The Ocean Drilling Program (ODP, 1985-2003), capitalizing on DSDP's momentum, probed deeper into the oceanic crust to study its architecture, analyzed convergent margin tectonics and associated fluid flow, and examined the genesis and evolution of oceanic plateaus and volcanic continental margins. ODP has also greatly extended our knowledge of long- and short-term climate change.

These ocean drilling achievements, and many others, have set the stage for understanding the complex linkages among different parts of the Earth system. This new, integrated Earth view is fundamental to IODP's vision, which is to better understand, among other things: (1) the nature of the earthquake-generating zone beneath convergent continental margins, (2) the nature of the complex microbial ecosystem that inhabits

*Conference on Cooperative Ocean Riser Drilling, Tokyo, July 22-24, 1997

**Conference on Multiple Platform Exploration of the Ocean, Vancouver, May 23-27, 1999

Earth's subseafloor and (3) gas hydrates, the tremendous frozen carbon reservoir that lies beneath continental margins. Other primary IODP goals and initiatives include a more complete understanding of past climate extremes and rapid climate change as potential indicators of the sensitivity of Earth's climate system to anthropogenic inputs; examination of the role of continental breakup in sedimentary basin formation as one key to future resource exploration; the formation and evolution of volcanic margins and plateaus as an example of Earth's non-steady-state behavior through time; and the "21st Century Mohole," the drilling and monitoring of a complete section of oceanic crust. These goals will be realized through the use of multiple drilling platforms and the most advanced sampling and observing technologies available, and by forging new collaborations with other international earth science initiatives and with industry.

As Earth grows smaller, mankind's relationship with it must improve. IODP will help to provide the information that can make that possible.

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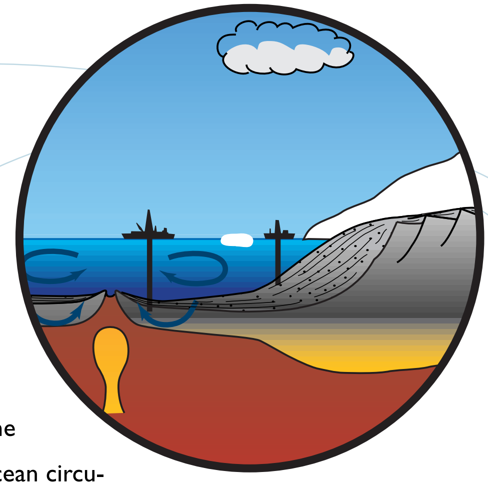
A Vision for Scientific Ocean Drilling

Executive Summary



Earth's surface veneer of seafloor sediment and extrusive volcanic rock represents the most recent snapshot of geologic time. Beneath that veneer, buried in sedimentary sections and the underlying crust, is a rich history of the waxing and waning of glaciers, the creation and aging of oceanic lithosphere, the evolution and extinction of microorganisms and the building and erosion of continents. More than thirty years of scientific ocean drilling have explored this history in increasing detail, revealing the complexity of the processes that control crustal formation, earthquake generation, ocean circulation and chemistry, and global climate change. Drilling has also revealed that deep within marine sediments, rock pore spaces and rock fractures is an active environment where ocean water circulates, microbes thrive and natural resources accumulate.

The Integrated Ocean Drilling Program, planned to begin October 1, 2003, envisions an ambitious expansion of exploration beneath the oceans, made possible by increasing drilling capability, from the single-ship operation currently in use, to the multiple-drilling platform operation of the future. The centerpiece of IODP's deep-water efforts will be a brand new riser-equipped, dynamically positioned drillship, to be provided and operated by JAMSTEC (Japan Marine Science and Technology Center). This vessel will be partnered with a modern, non-riser, dynamically positioned drillship, a successor to the Ocean Drilling Program's *JOIDES Resolution*, to be supplied and operated by the US National Science Foundation. These drillships will be supplemented with additional drilling platforms as needed (e.g., drilling barges, jack-up rigs and seafloor drilling systems). European and circum-Pacific nations are establishing initiatives to provide some of these "mission-specific" drilling technologies. Enhanced downhole measurement devices and long-term seafloor observatories complete the suite of sophisticated, state-of-the art tools planned for the new program. This new technology and multiple-platform approach will allow scientists to conduct experiments and collect samples in environments and at depths never before attempted.

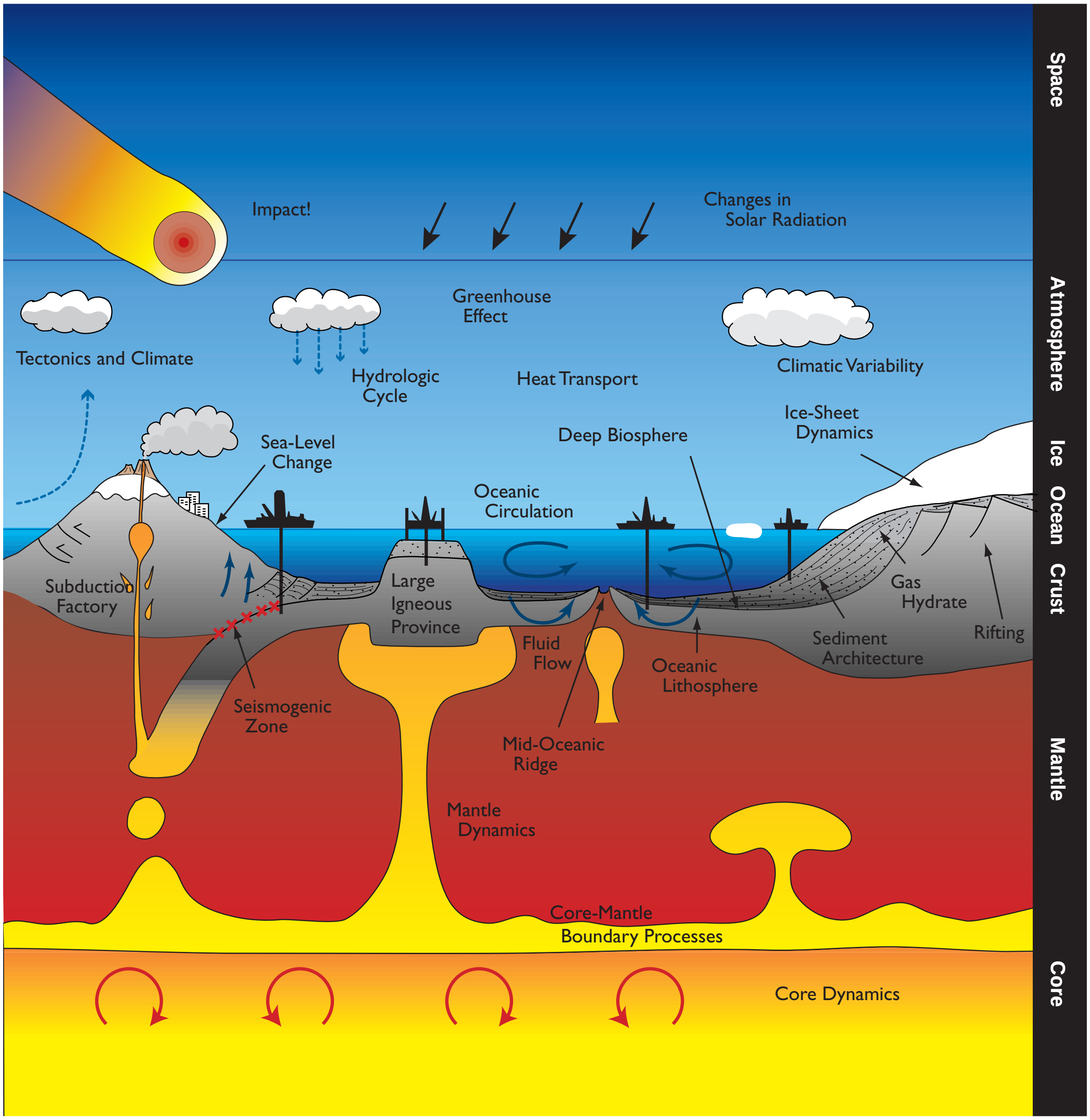


Figure 1. Earth system components, processes, and phenomena. Figure courtesy of Asahiko Taira, University of Tokyo.

The international community of ocean drilling scientists has devised a bold new strategy for investigating the Earth system that takes full advantage of these new drilling, sampling and observing capabilities. The IODP Initial Science Plan organizes scientific study by major Earth processes, encouraging specialists to broaden their proposals to include cooperative work with colleagues in related disciplines. Using the new multiple-platform approach to scientific ocean drilling and a new process-oriented approach to research, IODP will focus on three broad scientific themes:

- **The deep biosphere and the subseafloor ocean.** New evidence suggests that vast microbial populations may live within a broad range of temperatures and pressures, where sediment and rock appear to provide life-sustaining resources. Microbes that characterize these extreme environments are now broadly considered a potential source of new bio-materials and are the basis of ideas for new biotechnical applications, such as water treatment and microbially enhanced oil recovery. Little is known about the architecture and dynamics of the vast subseafloor plumbing system, where flowing water alters rock, influences the chemical composition of the ocean, lubricates seismically active faults, concentrates economic mineral deposits and may teem with life. IODP will probe this environment globally, providing the first comprehensive characterization of this ocean below the seafloor.

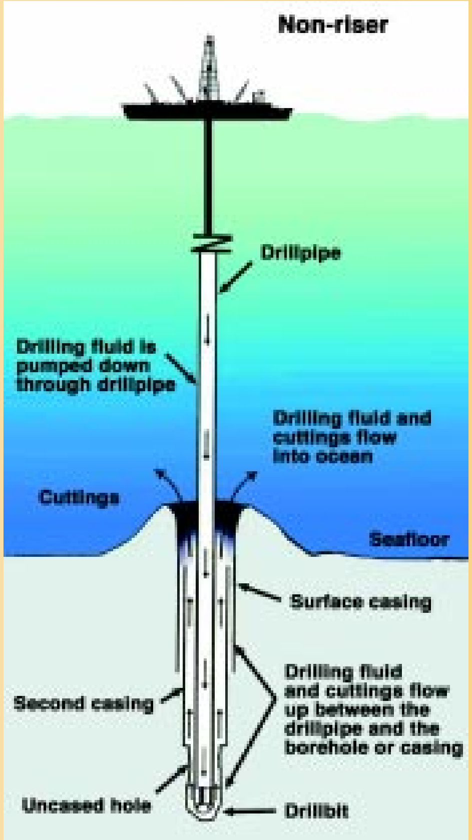
- **Environmental change, processes and effects.** Ocean sediments provide a unique record of Earth's climate fluctuations and permit detection of climate signals on four time scales: tectonic (longer than about 0.5 m.y.); orbital (20 kyr to 400 kyr); oceanic (hundreds to a few thousand years); and anthropogenic (seasonal to millennial). Studies of drill cores indicate that the pace of climate change has varied over time, from gradual to abrupt. What needs to be fully explored, however, is what initiates these changes, how they are propagated, what circumstances amplify or reduce the climatic effects of large and small events and what processes bring about change in Earth's environment. IODP will recover cores from as yet poorly sampled environments, such as the Arctic Ocean basin, atolls, reefs, carbonate platforms, continental shelves beneath very shallow waters and settings where sediments accumulate very rapidly (especially anoxic basins). Combined with drilling results from a global array of sites, these new sediment samples will allow a more sophisticated analysis of the causes, rates, sequencing and severity of change in Earth's climate system over all time scales. They also permit a more thorough investigation of the relationship among climate extremes, climate change and major pulses in biological evolution.

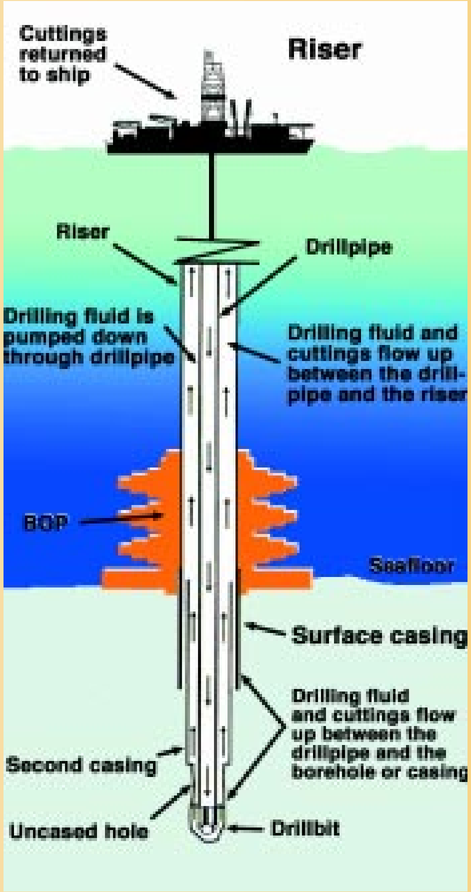
- **Solid earth cycles and geodynamics.** The vast amount of energy stored within the Earth is regularly brought to our attention by transient and often destructive events such as earthquakes, volcanic eruptions and tsunamis. These punctuating events are part of the solid Earth cycle, which involves the creation and aging of oceanic crust, its recycling at subduction zones and the formation and evolution of continents. The rates of mass and energy transfer from the mantle to the crust and back again are not constant through time. The causes of these variations and their influences on the global environment are poorly understood. Using new IODP technologies, some pioneered by DSDP and ODP, researchers will sample and monitor regions of the seafloor that currently have the greatest mass and energy transfers, as well as regions where these transfers were largest millions of years ago. IODP will also drill deeper into Earth's crust than ever before, providing new insight into—and perhaps answers

What is a Riser?

A riser is a metal tube (pipe) that extends up from the seafloor to a drilling platform, such as a drillship's rig floor. Its inner diameter is large enough to let pass the drillpipe, the drillbit, logging tools, additional casing strings and any other devices that scientists may want to place in the hole. The top end of the riser must be attached to the drillship and the ship must bear the weight of the device. The bottom end of the riser must be firmly attached to the top of the drillhole in the seafloor. This connection is made to a casing string, which lines the upper part of the hole and is cemented into the seafloor. After the casing is set, the riser is lowered to the casing and the two tubes are locked together by a riser connector. A "blow-out preventer" (BOP) is an automated shut-off device placed at the seafloor between the casing and the riser. It provides protection against unintentional release of high-pressure fluids and gases into the surrounding seawater.

The riser provides a way to return drilling fluid and cuttings, the ground up bits of rock, from the drillhole to the drillship. Removing cuttings from the hole is essential for drilling holes deep into the sediment and crust. The *JOIDES Resolution* currently uses seawater as its primary drilling fluid, which is pumped down through the drillpipe. This pumping cleans and cools the bit and lifts cuttings out of the hole, piling them in a cone around the hole. The seawater also tends to wash out of the sides of the hole as it rises to the seafloor. A riser returns the drilling fluid and the cuttings to the ship via the space between the riser and the drillpipe (annulus). Because most of the drilling fluid can be reused when drilling with a riser, it is possible to use drilling mud rather than seawater as the primary drilling fluid. Drilling mud, because of its greater density and viscosity, is much better than seawater as a drilling fluid when certain drilling problems arise, such as slow penetration, hole instability or a buildup of heavy cuttings.





Figures modified from Sawyer, D., JOI/USSAC Newsletter, November 1996.

to—long-standing questions about the processes related to oceanic crust formation and deformation, including the origin of marine magnetic anomalies and the role of fluids in earthquake generation. During its first phase, IODP will attempt to core, measure and monitor, for the first time ever, the deep seismogenic portion of a subducting plate boundary. This experiment will contribute significantly to our basic understanding of earthquake generation and to develop global policies on earthquake hazard mitigation.

These future scientific challenges, which include eight specific initial drilling initiatives, require IODP to deploy closely linked drilling platform types simultaneously. The drillship with riser capability will permit IODP to address deep objectives that require drilling for months to a year or more at a single location. Deep objectives include the "seismogenic zone" experiment, designed to determine the behavior of earthquake-generating faults in subduction zones; the deep crustal and intra-sedimentary biosphere; the three-dimensional structure of oceanic and Large Igneous Province (LIP) crust; and the processes of continental breakup and sedimentary basin formation (Figure 1). The drillship without riser capability will enable IODP to reach the ocean's greatest depths, while continuing to expand the global sampling coverage and disciplinary breadth characteristic of ODP and DSDP. Mission-specific platforms will permit unprecedented examination of the history of sea-level change in the critical region near the shoreline, the recovery of high-resolution climate records from atolls and reefs in shallow water areas and the exploration of climatically sensitive, ice-covered regions not yet sampled by drilling, such as the Arctic Ocean basin.

Of fundamental importance to successful drilling from these platforms will be the deployment of new or improved drilling, sampling and downhole petrophysical tools, which will allow scientists to recover drilled sections more completely, to obtain uncontaminated samples at ambient pressures, to isolate and record data on the physical properties of specific intervals within boreholes and to initiate drilling and recovery of exposed hard rocks. DSDP and ODP have laid a solid technological foundation in most of these areas. Some tools, such as the advanced piston corer (APC) developed for scientific ocean drilling by ODP, will require little engineering improvement. Significant improvement of tools, such as hard rock drilling systems, will require that IODP closely interact with scientific users, and call upon the advice and technical expertise of the drilling industries. As IODP drilling progresses into harsher environments, where the challenge of recovering biologically, chemically and physically intact samples continues to increase, improved tools will be critical for achieving the program's scientific goals.

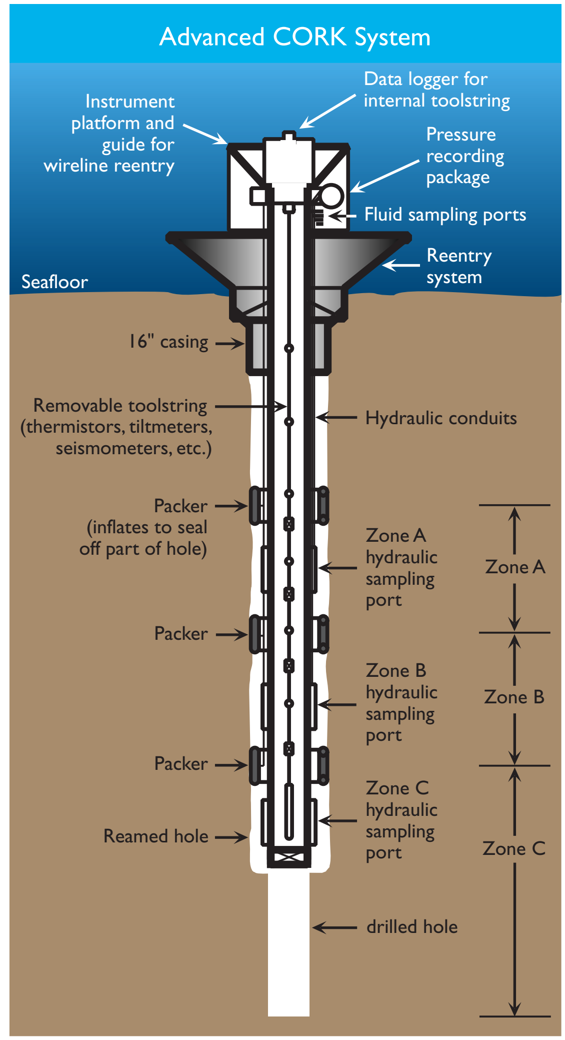


Figure 2. Fluid circulation in subseafloor formations profoundly affects a wide range of Earth processes, from hydrothermal circulation that controls heat and chemical balances and possibly subsurface microbiological communities in young oceanic crust, to dewatering in subduction settings intimately related to earthquake cycles and carbon cycling. A key IODP goal is to use boreholes to understand these hydrogeological systems by direct sampling and by borehole experiments. Effective use of boreholes as hydrogeological laboratories requires sealing them to allow recovery from drilling perturbations to *in situ* conditions. This need motivated development of the CORK (Circulation Obviation Retrofit Kit) hydrogeological observatory in ODP. A new generation of "Advanced CORKs" will incorporate the capability to separately seal multiple zones in a single hole, more closely corresponding to natural hydrogeological structures and opening new opportunities for subseafloor hydrogeological observatories. Figure courtesy of Earl Davis, Geological Survey of Canada, and Keir Becker, University of Miami. Modified from original.

Post-drilling observations and experiments in boreholes, pioneered by ODP, will grow in importance in IODP. Sustained time-series recordings by instruments sealed within boreholes will be required to investigate active processes such as pore-water flow, thermal and chemical advection and crustal deformation (Figure 2). Boreholes will also be used for perturbation experiments to investigate *in situ* physical properties of sediments and/or crust, and their associated microbial communities. A global network of geophysical observatories for imaging Earth's deep interior is also planned.

Another important element of our new vision for scientific drilling is the development of closer links between marine geoscientists and their continental drilling and industry colleagues. For example, many fundamental scientific questions to be addressed over the next decade "cross the shoreline." Attacking these problems will require an integrated approach combining continental studies (e.g., lake and continental crust drilling, field-based mapping, onshore-offshore geophysical transects) and drilling into the seafloor. Close interaction with international scientific programs, such as InterRidge, InterMargins, the International Ocean Network (ION), International Geosphere-Biosphere Program of Past Global Changes (PAGES), International Marine Past Global Change Study (IMAGES), Nansen Arctic Drilling (NAD) and the International Continental Drilling Program (ICDP) will continue to contribute greatly to the quality of IODP science. Ongoing industry-academic dialogue is also defining broad overlap in fundamental research problems that are of interest to both communities. As hydrocarbon exploration rapidly expands into deeper water and the international scientific community gains interest in using deep- water riser technology, opportunities for intellectual and technological collaboration should continue to grow.

To guide us in the opening phase of IODP, this Initial Science Plan also contains an implementation strategy, which is based on the scientific and technical needs of the new program, the areas of emphasis spelled out in this document and the logistical constraints of platform availability. It is not meant to usurp the scientific planning process that has been and will continue to be the key to the successful execution of scientific ocean drilling programs by the international community, but rather it outlines how IODP's scientific goals could be achieved as technology becomes available. As the goals become more clearly defined by specific drilling proposals, or as new discoveries and goals are established, this implementation plan can and will be modified.

Setting the Stage for the Future

In recent decades, scientific ocean drilling has revealed much about Earth's dynamic nature. Over millions of years, continents rift apart, ocean basins open and close and new mountain ranges form where continents collide (Figure 1). These large-scale plate tectonic interactions cause short-lived phenomena, such as large, destructive earthquakes at subduction zones (*e.g.*, Japan's Nankai Trough) and along continental transform faults (*e.g.*, the San Andreas fault in California), and explosive volcanism in island arcs (*e.g.*, Mt. Pinatubo in the Philippines). We are just beginning to recognize that these tectonic processes, and accompanying change in ocean circulation and climate, have profoundly affected both biological evolution and biogeochemical cycling.

On intermediate time scales, variations in Earth's orbital parameters have led to periodic variations in climate, the most dramatic of which is the alternating expansion and contraction in global ice volume since ~34 Ma. The more gradual, evolutionary or cyclic change has been punctuated by as yet unexplained abrupt shifts in climate, by very short-term oscillations in Earth's climate system and by catastrophic events such as the impact of large extraterrestrial bodies. Whether the observed current change in the Earth system is anthropogenic or natural, the geological record as deduced from ocean drilling shows that Earth history is more appropriately characterized by change than by stasis.

Scientific drilling also provides a powerful tool to study both the critical processes of short-term change and the long-term natural variability of the Earth system prior to human influence. A unique, global historical record of Earth's changing tectonics, climate, ocean circulation and biota is preserved in marine sedimentary deposits and underlying basement rocks. Detailed and complete records of this history are accessible only through ocean drilling because many of these critical processes (*e.g.*, subduction-related earthquakes, formation of massive sulfides and extensive sequestration of carbon in sediments) are active only in submarine environments. Only through understanding the history of the Earth system can we attempt to predict its future, a time that may involve far-reaching change on societal time scales.

Since the beginning of scientific ocean drilling in 1968, we have gradually expanded the scope of our investigation and pushed the limits of available technology. The ocean basins have proved to be both a rich archive and an ideal global laboratory in which to study physical, chemical and biological processes and their interrelationships. The international scientific drilling community, which has grown steadily over the past three decades, has successfully begun to investigate many of these processes, including those that control climate, the vast circulation of fluids within Earth's crust, the nature of life on and within Earth and the dynamics of lithospheric formation and recycling. These achievements have set the stage for a new era of drilling and discovery, in which a more complete understanding of fundamental Earth processes is within our grasp.

Major Achievements of Scientific Ocean Drilling

The Deep Biosphere & the Subseafloor Ocean

- **Extensive Microbial Populations Beneath the Deep Seafloor.** Sampling deep within the marine sedimentary section and in basaltic crust has revealed what appears to be a diverse and often very active microbial ecosystem. Recent sampling efforts have demonstrated that uncontaminated samples of these microbes can be recovered for laboratory study.

- **Frozen Methane Reservoir Beneath the Seafloor.** Extensive reservoirs of gas hydrates beneath the seafloor have been sampled by ocean drilling, providing valuable information regarding their possible impacts on the global carbon budget, submarine slope stability and their resource potential. Currently, only ODP technology is capable of retrieving and maintaining gas hydrates samples from the subseafloor marine environment at *in situ* pressures.

- **Fluid Pressure and Discharge along Main Thrust Fault Zones.** Drilling through the décollement and related thrust faults at convergent plate boundaries has confirmed three-dimensional seismic observations that fluids actively flow along the slip zone. These fluids have distinctive geochemical signatures and are likely involved in the mechanics of thrust faulting (Figure 3).

- **Hydrothermal Fluid Flux in the Upper Oceanic Crust.** Drilling of marine sedimentary and crustal sections is beginning to determine the sources, pathways, compositions and fluxes of fluids associated with mineralization within active submarine hydrothermal systems, and the influence of fluid circulation on ocean chemistry, crustal alteration and the crustal biosphere.

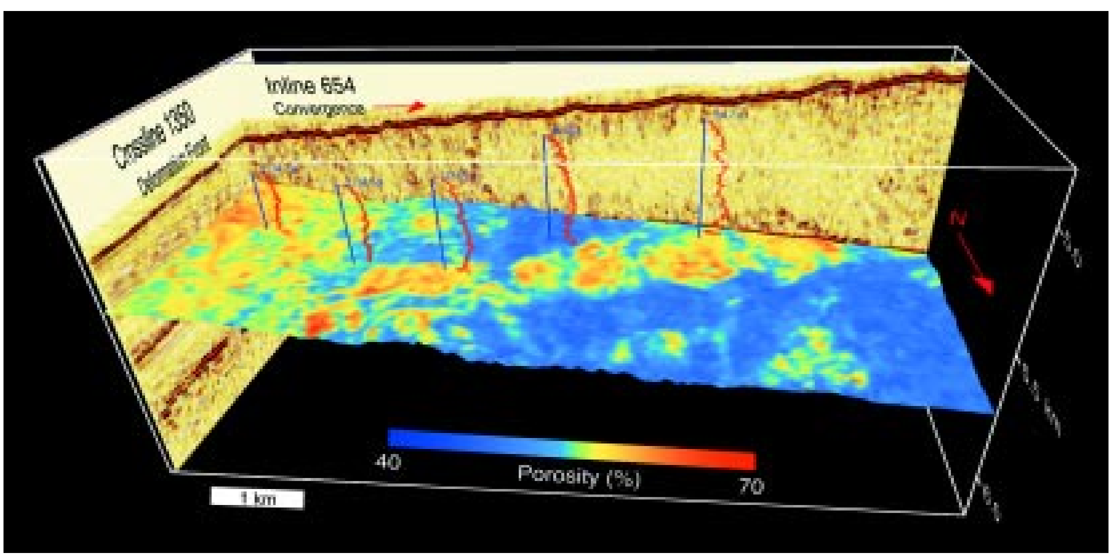


Figure 3. A perspective view of the Barbados Ridge three-dimensional seismic reflection data volume acquired in 1992. Crossline and inline profiles are shown on the east and south faces of the volume. The décollement surface at the base of the accretionary wedge is also shown, with colors representing porosity estimated from the seismic reflection data and calibrated with ODP Legs 156 and 171A logging-while-drilling logs. Vertical black lines are boreholes and red lines are corresponding density logs. High porosities, and presumably high fluid pressures, extend from the deformation front along a semi-continuous, NE trending zone interpreted to be a major fluid conduit. Figure reprinted from Bangs, N. L., T. H. Shipley, J. C. Moore, and G. F. Moore, *Jour. of Geophys. Res.*, 104, 20,399-20,414, 1999, Plate 4, p. 20,412.)

Figure 4. Beginning with the early days of DSDP, the recovery of core sample material has been a critical aspect of scientific ocean drilling. The recovery of a geologic section that is as complete as possible sets scientific ocean drilling apart from drilling conducted by the hydrocarbon exploration industry, and has resulted in the continued improvement of sampling and measurement technologies. In the early days of scientific ocean drilling, core assessment was almost exclusively based on visual inspection and discrete samples. As more advanced technologies have become available, we have progressed through hand-held devices for optical scanning and measurement of core sample properties (left) toward more sophisticated, continuous digital scans of the cores. In IODP this trend will continue, with more complete and detailed quantitative descriptions of the physical and chemical properties of cored materials. Photo courtesy of the Ocean Drilling Program.

Environmental Change, Processes and Effects

- **Development of the Field of Paleoceanography.** The near-global network of continuous stratigraphic sections obtained by ocean drilling is the foundation of the field of paleoceanography. Paleoceanographers study changes in the life, chemistry and surface, intermediate and deep circulation of the oceans through time. Paleoceanography provides the reference frame for nearly all other investigations of global environmental change (Figure 4).

- **Orbital Variability during the Cenozoic.** By linking the record of climatic variation preserved in deep-sea sediments to calculated variations in Earth's orbital parameters, scientists have demonstrated the role of orbital variability in driving climate change.

- **Development of High-Resolution Chronology.** Complete recovery of fossiliferous marine sedimentary sections has greatly facilitated linking Earth's geomagnetic polarity reversal history to evolutionary biotic changes and to the isotopic composition of the global ocean. Also of great significance is the orbitally tuned determination of time within marine sections, which has resulted in a greatly refined calibration of the Geomagnetic Polarity Time Scale back to 30 Ma. This newly calibrated, globally applicable time scale is crucial for determining rates of processes operating in every aspect of the terrestrial and marine geosciences.

- **Ocean Circulation Changes on Decadal to Millennial Time Scales.** The record preserved in marine sediments and recovered by ocean drilling has clearly demonstrated that deep- and surface-ocean circulation is variable on decadal to millennial time scales, confirming results from ice cores. This body of marine-based data has provided the evidence linking ocean-atmosphere-cryosphere interactions in and around the high-latitude North Atlantic to instabilities in thermohaline circulation, which propagates abrupt climate change to the farthest reaches of the globe.

- **Ocean Biogeochemical Cycles.** The concept of Earth System Science has evolved with detailed analyses of the relatively complete deep-sea sedimentary sections recovered by ocean drilling. These studies have revealed major changes in biogeochemical cycling through time, especially in the complex carbon cycle, resulting from evolutionary changes in the biota, tectonic changes, changes in climate, variations in seafloor hydrothermal activity and major alterations in ocean circulation.
- **Global Oceanic Anoxic Events.** Deep-sea sediments exhibit specific times when the surface water productivity of large areas of the ocean was unusually high. At these times, the global ocean developed zones of depleted oxygen content, and vast amounts of organic carbon were incorporated and preserved in marine sediments as black shales. Scientific ocean drilling has provided insights into oceanic anoxic events, which are a key to understanding short- and long-term perturbations in global climate and carbon cycling, as well as the timing of significant petroleum source-rock deposition (Figure 5).
- **Vast Sand Deposits in Deep Water.** Drilling has confirmed that the construction of deep-water fan systems, such as that off the Amazon River, are controlled largely by changes in sea level. The hydrocarbon industry is intensively exploring deep-water sand "plays" contained in the these fan systems for their proven economic potential.

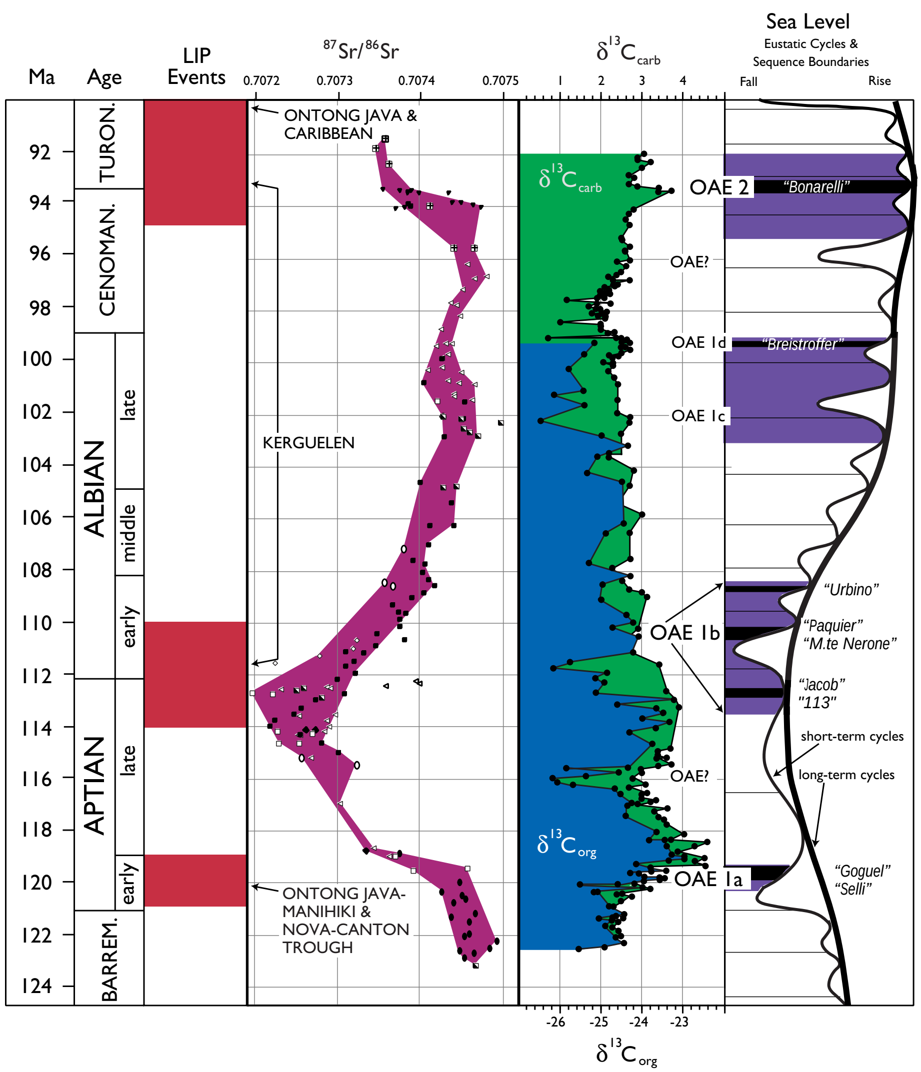


Figure 5. The mid-Cretaceous record of major black shales and Oceanic Anoxic Events (OAEs) in the context of the carbon isotopic record, changing global sea level and seawater chemistry, and emplacement history of Large Igneous Provinces (LIPs). Data are from both land-based sections and DSDP/ODP deep-sea cores. Organic matter production and preservation during the mid-Cretaceous appears to be closely related to submarine volcanism and hydrothermal activity, which may have stimulated productivity through the input of nutrients, particularly trace elements such as iron. Increased hydrothermal output during LIP emplacement may thus be linked to the three major OAEs. As a result of ocean drilling, the chrono-stratigraphic and biostratigraphic control on deep-sea sections has greatly improved, enabling better temporal resolution of geological processes. Figure compiled by Mark Leckie, University of Massachusetts, Amherst.

- **Timing of Ice-Sheet Development in Antarctica and the Arctic.** Drilling has revealed that Earth's entry into its current Ice Age extended over 50 m.y. and involved a complex history of uni-polar, then bi-polar, ice-sheet buildup. Ice streams reached the Antarctic seas as early as 40 Ma, but major ice-sheet formation on Antarctica apparently did not occur until some 25 m.y. later. Northern hemisphere ice sheets did not begin to develop until sometime after 15 Ma, and major northern hemisphere continental glaciations did not start until after 4 Ma. This extended period of climate change appears to have occurred in relatively rapid steps, each associated with major tectonic changes that affected both atmospheric and oceanic circulation.

- **Impact Events and Biological Evolution.** Drilling has established the global effects of a major bolide collision with Earth at approximately 65 Ma, including the extinction of as much as 90 percent of all planktonic organisms, and the subsequent repopulation of plankton in the global oceans from a few surviving species (Figure 6).

- **Sea-Level Change and Global Ice Volume.** Marine sediments recovered from shallow water areas have shown that important global sea-level change have occurred synchronously through at least the past 25 m.y., and that these changes can be matched to oxygen isotope records of climate produced from the deep sea. The new understanding of global eustacy has become a primary interpretative tool in unraveling the history of continental margin growth and in the search for hydrocarbons in margin settings.

- **Uplift of the Himalayas and the Tibetan Plateau.** Drilling in both the Indian and Pacific Oceans has helped to establish the timing of the Tibetan Plateau uplift, and to determine change in coastal upwelling, carbon sequestration, and regional and global climate associated with this tectonic event. Drilling results have shown that the onset and development of both the Indian and Asian monsoons are the result of climate change associated with this uplift.

- **Desiccation of the Mediterranean Ocean Basin.** Drilling demonstrated that the deep Mediterranean basins were sites of salt deposition as recently as ~5 Ma when flow into the basin was restricted and the level of the waters within the basin fell hundreds of meters through evaporation.

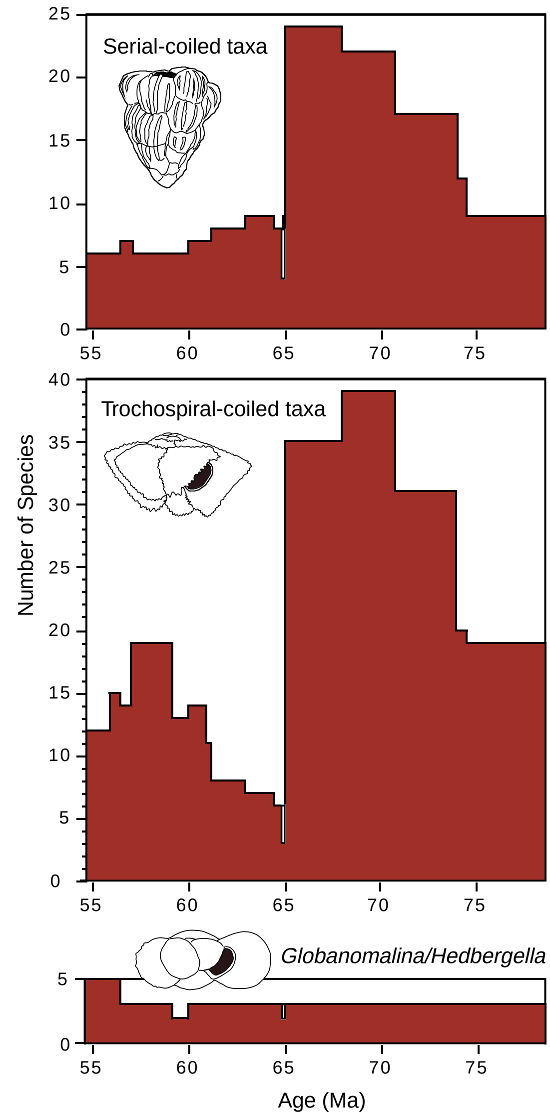


Figure 6. Species diversity across the Cretaceous-Tertiary boundary for three large groups of planktic foraminifera. Diversity increases rapidly during the ~5-10 m.y. before the boundary then plummets at the extinction. There is a modest rebound of diversity in the first 5 m.y. of the Paleocene. Species diversity reaches late Cretaceous values about 10-15 m.y. after the impact and mass extinction. Figure courtesy of Richard Norris, Woods Hole Oceanographic Institution.

- **Environmental Controls on Growth and Demise of Carbonate Platforms.** Drilling has illuminated the development and abrupt demise of large carbonate platforms along with their response to changing climate, sea level, oceanic circulation and gradual movement of the lithospheric plates.

Solid Earth Cycles & Geodynamics

- **Validation of Plate Tectonic Theory.** Dating of igneous basement rocks and overlying sediments recovered by scientific ocean drilling has demonstrated that the age of the oceanic crust increases systematically away from ridge crests, validating a fundamental prediction of plate tectonic theory.

- **Non-volcanic Passive Margin Evolution and Alpine Geology.** Drilling results and seismic data from the Iberian passive rifted margin have facilitated the development of new rifting and extensional deformation models of the continental crust where there is little attendant volcanism. These models imply nearly amagmatic thinning of the crust, with attendant widespread exposure of mantle rocks, a very different process than occurs on magma-rich margins. Rifted margin structure and stratigraphy strikingly similar to those found on the western Iberian margin have been identified in the Alps.

- **Large Igneous Provinces Associated with Continental Breakup: Volcanic Margins.** Drilling has established that seaward-dipping reflections identified on multichannel seismic reflection data from many passive continental margins consist of vast subaerial outpourings of lavas rapidly emplaced during the time of final continental separation and the initial formation of ocean basins. In some instances, enhanced melt production can be related to mantle plume heads thousands of kilometers wide, but other instances appear unrelated to known plumes (Figure 7).

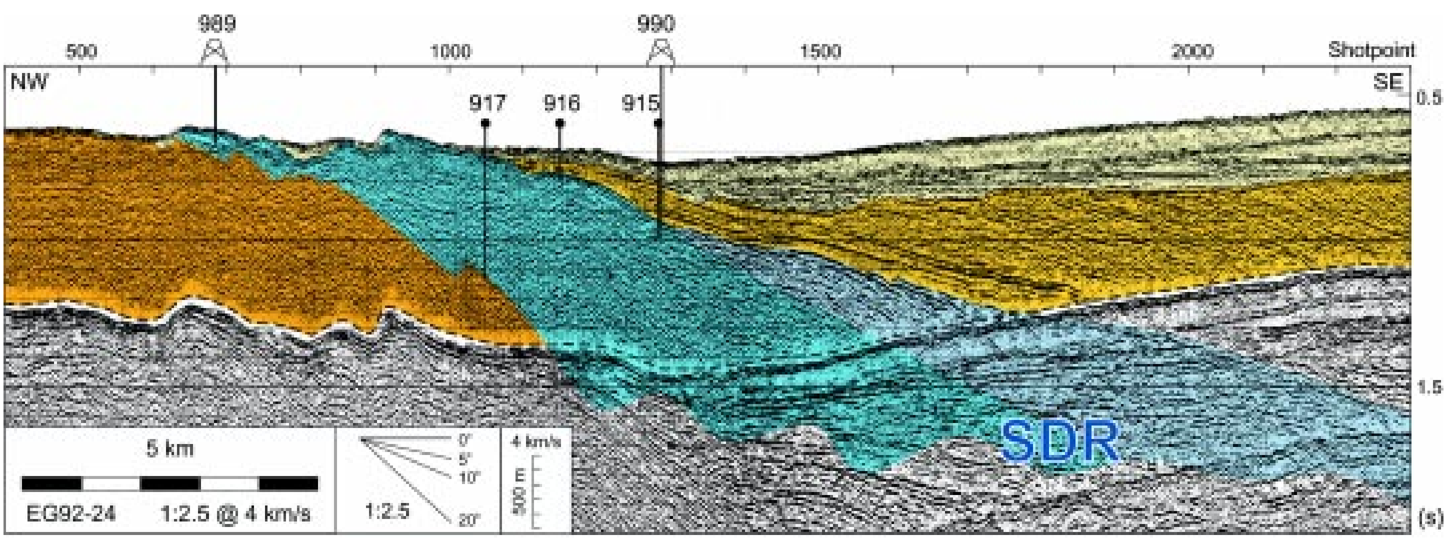


Figure 7. High-resolution seismic image of the inner part of the seaward-dipping reflections (blue) on the SE Greenland Margin. Subaerially emplaced basalts were recovered in five holes drilled during ODP Legs 152 and 163. The entire volcanic sequence was penetrated by Hole 917, bottoming in pre-breakup age sediments (orange). The average P-wave velocity of the basalt pile is 4 km/s, giving a 2.5 times vertical exaggeration of the profile. Figure courtesy of Sverre Planke, Volcanic Basin Petroleum Research, and is based on Planke, S., and E. Alvestad, 1999, Seismic volcanostratigraphy of the extrusive breakup complexes in the northeast Atlantic: Implications from ODP/DSDP drilling, *ODP Sci. Res.*, 163, 3-16.

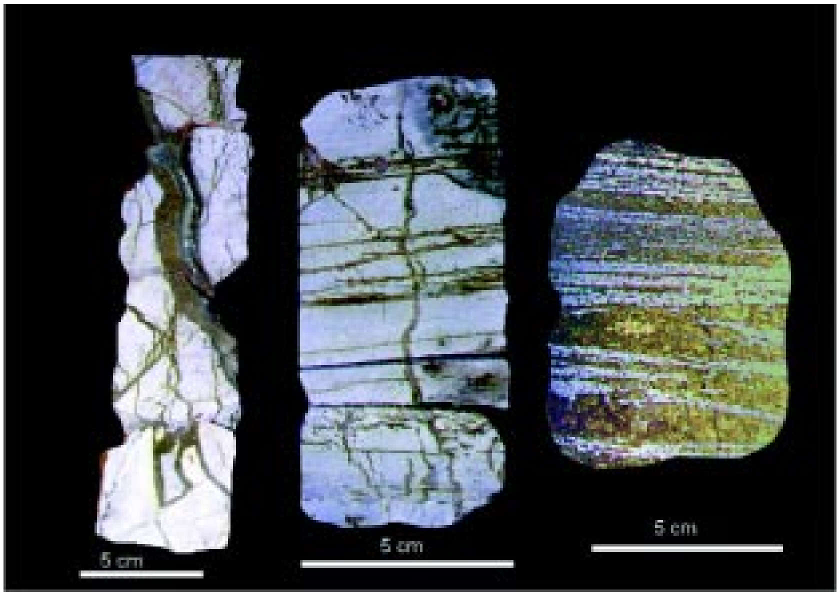


Figure 8. ODP cores recovered in a sedimented ridge crest in the Northeast Pacific Ocean are examples of feeder zone and deep copper zone mineralization below the Bent Hill massive sulfide deposit. Left: predominantly vertical crack-seal veins filled with pyrrhotite and Cu-Fe sulfide in altered turbiditic mudstone (856H 24R-1 50-70 cm, 134 mbsf). This style of mineralization is characteristic of the upper feeder zone underlying the center of the hydrothermal upflow zone. Center: less intense feeder zone mineralization underlying the south flank of the Bent Hill massive sulfide deposit. Mineralization consists of simple vertical and horizontal veins filled with pyrrhotite, sphalerite and Cu-Fe sulfide in graded fine sand to silt turbidites. Mineralization also occurs as subhorizontal replacement and disseminations along bedding planes (1035F 12R-2 43-55 cm, 112 mbsf). Right: Deep copper zone mineralization in cross-laminated turbiditic sandstone. Replacement of rock by Cu-Fe sulfide mimics original cross lamination; the matrix is extensively recrystallized to silver-gray colored chlorite and quartz (856H 31R-1, 99-107 cm, 202 mbsf). (Photo courtesy of Robert Zierenberg, University of California, Davis.)

- **Large Igneous Provinces: Origin of Oceanic Plateaus.** Drilling of two oceanic plateaus, which reach diameters of 2000 km and crustal thicknesses of 35 km, has established that their uppermost crust consists of basaltic lava flows with individual thicknesses of up to a few tens of meters. Major portions of these two plateaus were emplaced in geologically short time spans of a few million years or less, and may be the product of rising mantle plume "heads." Accretion of such plateaus to continental margins constitutes a form of continental growth by a mechanism not predicted by standard plate tectonic theory.

- **The Oceanic Crust.** To date, knowledge of the oceanic crust and shallow mantle has been largely restricted to geophysical observations, seafloor dredge samples and ophiolite studies. Limited ODP drilling into the oceanic mantle and principal crustal layers partly confirms models derived from these earlier studies, but also reveals major discrepancies that will change the estimates of the flux of heat and mass between mantle, crust and oceans over the last 250 million years. ODP drilling results have also challenged the assumption, critical to estimating the composition and volume of the oceanic crust, that seismic structure and igneous stratigraphy can be directly correlated.

- **Massive Sulfide Deposits.** Drilling into two actively forming volcanic- and sediment-hosted metal sulfide deposits sites has established that seafloor sulfide deposits are direct analogs with on-land massive sulfide deposits, in terms of ore-forming process, and with respect to size and grade of mineralizations. New insights gained by ocean drilling may aid in land-based mineral exploration (Figure 8).

- **Convergent Margin Tectonics and Subduction Recycling.** Strikingly different styles of convergent margin tectonics have been imaged by seismic data and constrained by scientific drilling, ranging from dominantly accretion to the overriding plate, to subduction of most trench sediment, to erosion at the base of the overriding plate. Drilling of down-going slabs and comparison with arc magmatism have provided the beginning of a quantitative understanding of subduction recycling.

- **Hot Spot Tracks on the Oceanic Crust.** Dating of sediment and basaltic rock recovered by drilling has documented a systematic age progression along several seafloor volcanic chains or ridges, verifying the hypothesis that these features were formed by relatively stable hot spots beneath the moving lithosphere. These drilling samples also provide the main observational evidence that hot spots are generated by deep mantle plumes. In addition, this work has helped establish the absolute movement of lithospheric plates with respect to the lower mantle. Paleomagnetic data from drilled seamounts demonstrate the motion of Atlantic versus Pacific hot spots with respect to each other.

- **Hydrated Mantle in Many Tectonic Environments.** Unexpected mantle-derived serpentinites at shallow crustal levels have been documented by drilling in a variety of tectonic settings from rifted continental margins to fore-arcs to spreading ridges. These results indicate that upper mantle alteration is much more pervasive than previously believed (Figure 9).

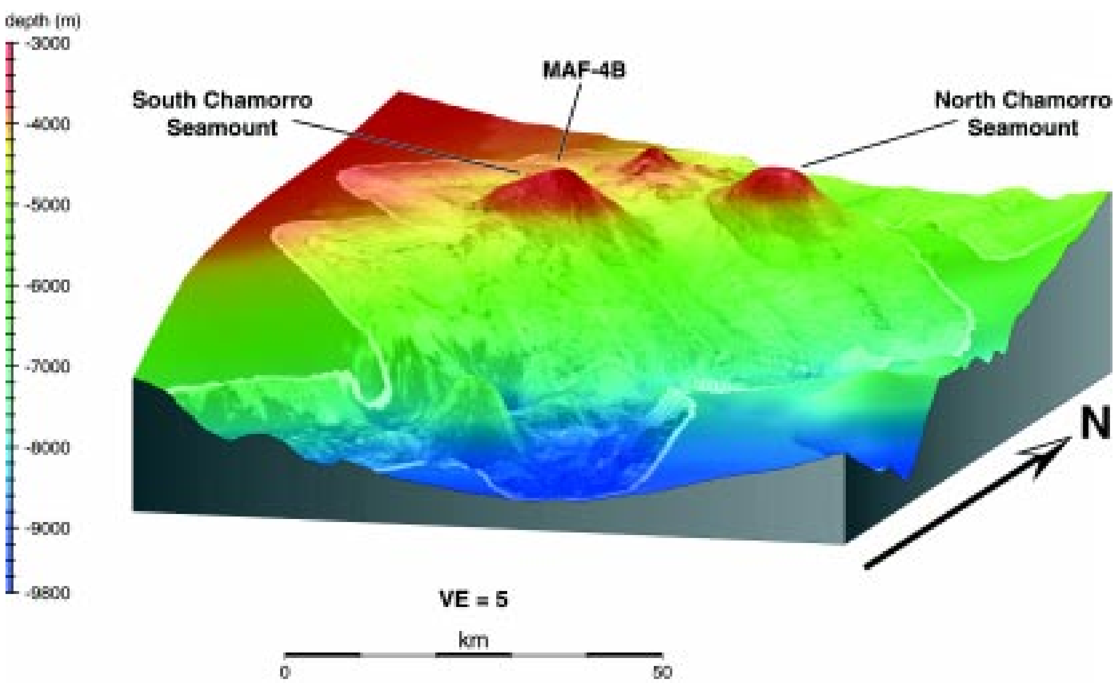
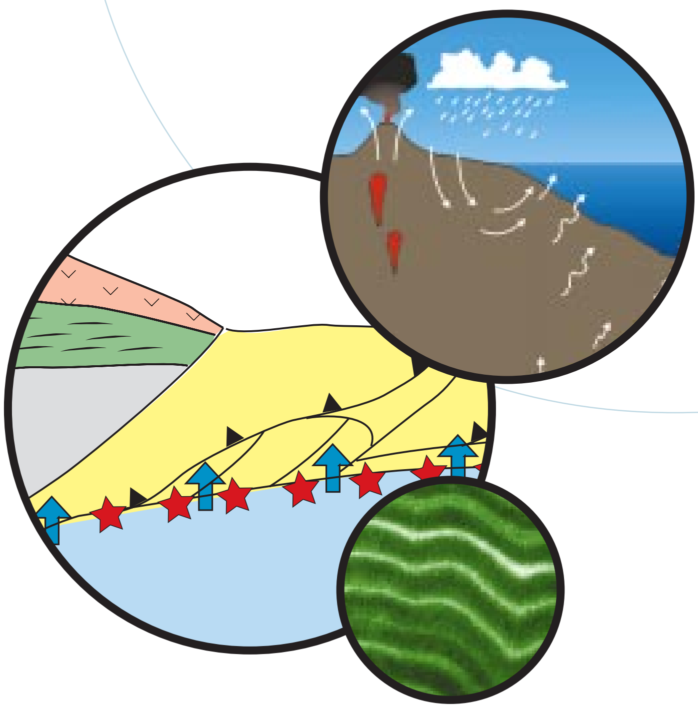


Figure 9. This side-scan sonar image, draped on bathymetry, shows several southern Mariana seamounts that are approximately 20 km in diameter and 2 km high. Most seamounts are basaltic volcanoes, however, ODP drilling along western Pacific forearcs has shown that edifices similar to ones shown in this image are mud volcanoes composed of fine-grained serpentine muds, fragments of serpentinized mantle derived from the overriding plate, and metamorphosed basalts from the subducted slab — materials derived from depths of up to 29 km. Pore fluids in cores from the active conduits have slab-derived geochemical signatures and support communities of organisms. The seamount in the foreground is currently active, and will be drilled by ODP in 2001; MAF-4B is one proposed drillsite. Figure courtesy of Patricia Fryer and Nathan Becker, University of Hawaii.

Science Plan

Discussion of IODP's scientific objectives is organized into three major themes: The Deep Biosphere and the Subseafloor Ocean; Environmental Change, Processes and Effects; and Solid Earth Cycles and Geodynamics. Within each of these broad themes, two or three specific core themes are identified that are closely linked to key topics such as biotechnology, climate change, earthquake hazards, natural resource potential, sea-level change and volcanic eruptions. Eight major new program initiatives are proposed for IODP, which incorporate novel scientific approaches and require major advances in drilling platforms and technologies. Each initiative will involve critical collaborations between IODP and other global research programs, and will require the scientific ocean drilling community to expand to include new areas of specialization such as microbiology. As our understanding of the complex Earth system develops, IODP's research goals will evolve and proceed along both well-established and unexpected pathways. We anticipate new and exciting research avenues to emerge over the next decade.



The Deep Biosphere and the Subseafloor Ocean

A massive and dynamic plumbing system cycles the entire volume of the ocean through the seafloor every one million years. Seawater circulates through faults, fractures and other permeable conduits in the crust and mantle and redistributes heat by advection. In doing so, the seawater alters the host rock, influences the chemical composition of the oceans and forms massive mineral deposits. Water carried by the crust into subduction zones affects the strength of the host rock and lubricates seismically active faults. Water carried to greater depths serves as a fluxing agent in the production of mobile hydrous minerals and magma for arc volcanoes. Fluids seeping through sediments in various continental margin settings transport hydrocarbons and concentrate them at natural migration barriers.

Over a surprisingly broad range of subsurface depths, temperatures and pressures, this subseafloor ocean hosts an extensive microbial population comprising the deep biosphere. As much as two-thirds of Earth's microbial population may be deeply buried in oceanic sediment and crust. Recognition that this pervasive subseafloor ocean may teem with microbial life poses new, fundamental questions about the evolution and distribution of life and the operation of the carbon cycle. How this huge biomass survives in an environment of apparently meager resources poses basic questions for biochemistry, microbial physiology and microbial ecology. Sampling and characterizing new extreme microbial life forms is also broadly recognized as a potential source of new materials and ideas for biotechnological applications, such as water treatment and microbially enhanced oil recovery. ODP provided the first sediment samples demonstrating that viable microbes can live at depths greater than 750 m below the seafloor. This exciting discovery has set the stage for exploration of an entirely new ecosystem using drilling technology. Further sampling of the deep, subseafloor for microbes will clearly yield unexpected and exciting results. For these reasons, IODP selects this topic as one of its major research initiatives.

Although the presence of gas hydrates in marine sediments has been known for a long time, the volume of frozen methane locked up in them has only recently been fully appreciated. Even the most conservative estimates suggest that gas hydrates contain more energy than all other hydrocarbon sources combined. Although their commercial potential may thus far be limited, they comprise a major pool of carbon that is closely linked to the ocean-atmosphere carbon cycle. Methane, bound in the clathrate structure, is recognized as an important greenhouse gas. Changes in bottom-water temperatures and/or pressures could potentially destabilize subseafloor hydrate deposits on a global scale, releasing massive volumes of methane to the atmosphere with an ensuing major impact on climate. Additionally, large hydrate deposits that might be destabilized in tectonically active regions may affect climate more abruptly than other tectonic processes. ODP's pressure core sampler (PCS) has provided some of the purest samples of gas hydrates ever recovered from the seafloor, allowing detailed laboratory examination of this large natural resource. The PCS enables scientists to take and maintain hydrate samples at the *in situ* pressure conditions in which they form until they are returned to the drillship laboratory for analysis of gas quantity and composition. Intriguing initial results from scientific ocean drilling, combined with the potential importance of gas hydrates as a hydrocarbon resource, as a factor in rapid global climate change and as a cause of major offshore slope instability, has led IODP to propose the study of gas hydrates as a major initiative.

Scientific ocean drilling has opened up numerous new and exciting avenues of exploration and experimentation of the vast subseafloor ocean. Such exploration has also been instrumental in gathering the first long-term measurements of subseafloor fluid flow using innovative tools built collaboratively by ODP and the international scientific research community. ODP also drilled, for the first time, through the décollement at a subduction zone, confirming that fluids flow along the earthquake-generating slip zone. Because of scientific ocean drilling, we now know that fluids play a fundamental role in diverse geological settings, including seafloor spreading centers, the young flanks of mid-ocean ridges, and carbonate platforms, as well as along rifted, transform and subduction plate boundaries. Yet, we still have little understanding, and few measurements, of the pathways and residence times of water below the seafloor. Further progress in the study of fluid flow in all of these environments (Figure 10) will require careful experimental design, highly coordinated, multidisciplinary efforts, and long-term time-series observations in addition to new, *in situ* sampling tools and observatories.

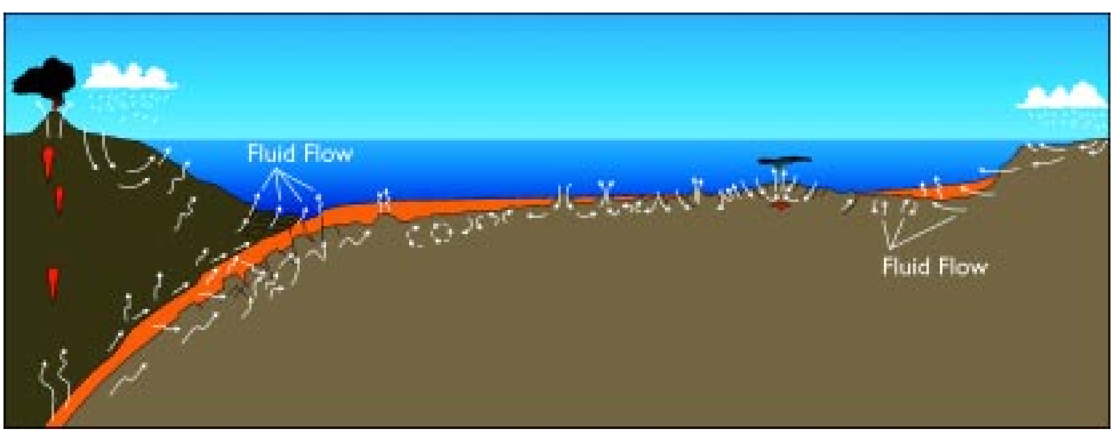


Figure 10. Fluids move through subseafloor formations in a wide variety of settings. Flow is driven by compositionally or thermally generated density contrasts, tectonic compaction, and topographic head, and is responsible for large heat and elemental fluxes, both within the crust and between the crust and the oceans. Water carried to great depths in subduction zones stimulates the production of arc volcanics. High interstitial fluid pressure weakens rock and thus influences deformation and seismic rupture. Figure courtesy of Earl Davis, Geological Survey of Canada.

The Subseafloor Ocean in Various Geological Settings

The uppermost, extrusive volcanic layer is the most permeable portion of the igneous oceanic crust. Dikes, sills and intrusive rock found at greater depths are less permeable, but are faulted and fractured. Energy balances and observations of fluid flow both indicate that copious heat is transferred by fluids moving through pores, joints and fractures at ridge crests and on ridge flanks (Figure 11). The process is attenuated as rocks cool and as sediments accumulate, restricting flow between igneous crust and the ocean. The depth, extent and consequences (physical, chemical and biological) of fluid flow in the crust and upper mantle are not, however, well known, nor are the fluxes of heat and mass between the lithosphere and oceans. Much work is needed to quantify the exchange of energy and matter between the crust and oceans and to extend this determination through space and time. Concurrently, we need to determine the alteration state of the crust when it returns to the mantle at subduction zones, and the nature, distribution and concentration of life within the oceanic crust.

- **Mid-ocean ridges:** Fluids flow vigorously through Earth's crust at mid-ocean ridges where they are driven through, and react with, highly permeable rock. Temperatures of fluids exiting this system are commonly 300-350°C, and sometimes exceed 400°C. Fluid density contrasts that generate this buoyancy-driven flow can be nearly 2:1. Driving forces and chemical activities can be enhanced by phase separation, either at sub- or super-critical conditions. Consequences of such active hydrothermal circulation include rapid exchange of elements and heat between the crust and oceans, accumulation of extensive mineral deposits at the seafloor, nourishment of unique animal communities at seafloor vents, and possibly sustenance of large microbial populations in the subseafloor.

  Virtually everything learned about deep water-rock interaction to date has been inferred from remote sensing (e.g., reflection and earthquake seismology), from hydrothermal fluids and minerals sampled in the upper crust and at the seafloor, and through laboratory experiments and modeling. Deeper "reaction zones" involving magmatic and hot rock bodies are unquestionably also involved, although little is known about the range of thermal, hydrological and chemical conditions where heat is tapped and minerals are dissolved. Drilling in this environment has long been a challenge because of the highly fractured nature of young igneous crust, but there have been some successes. Along the Mid-Atlantic Ridge, ODP drilled into an actively forming massive sulfide deposit. From the cores retrieved at this site, scientists have been able to determine the fluid chemistry and thermal conditions required to build such a mineral deposit.

  Long-term monitoring in sealed boreholes at sedimented spreading centers drilled by ODP have provided the best opportunity to date for extended studies of fluid-flow processes at ridge crests. Although sedimented ridge settings are uncommon, drilling conditions are considerably better there than atop unsedimented ridges. In addition, in sedimented-ridge settings, high temperatures can be reached at relatively shallow depths, and microbiological studies within the sediment cover can be carried out in a stable thermal environment. Initial results from ODP's long-term studies at sedimented spreading centers suggest that fluids may move through the upper igneous crust at average rates of tens of meters per year, and may carry heat and solutes laterally over distances of many tens of kilometers.

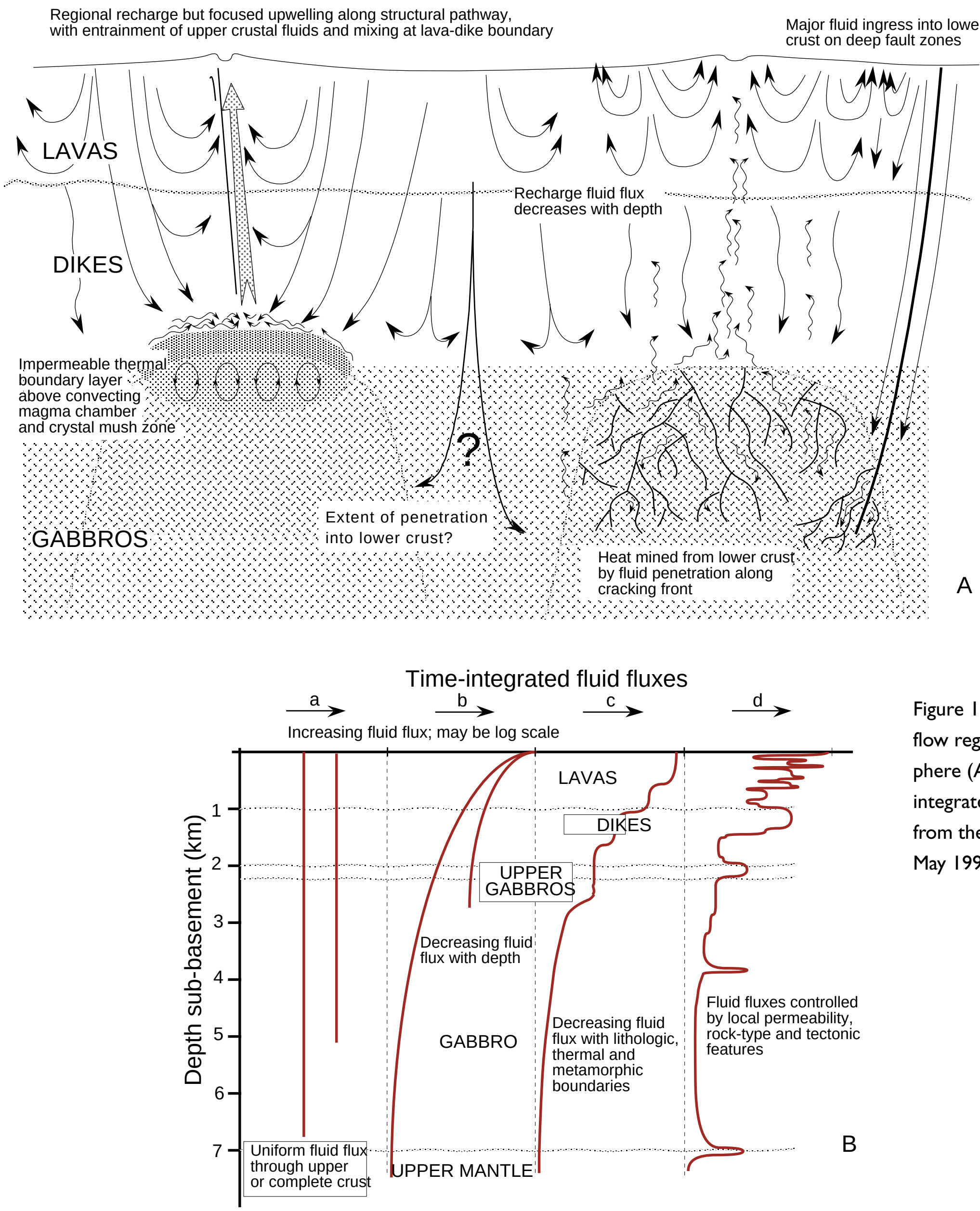


Figure 11. Sketches of possible fluid flow regimes within the oceanic lithosphere (A), resulting in different time-integrated fluid fluxes (B). Reprinted from the COMPLEX report, JOI Inc., May 1999.

Drilling into, sampling and monitoring highly fractured, young igneous crust remain a challenge, but they are necessary to: (1) characterize the three-dimensional hydrological structure of spreading centers (e.g., determine the nature and relative importance of flow, both recharge and discharge, in the planes parallel and perpendicular to spreading), (2) observe conditions and assess the importance of phase separation in a deep, high-temperature "reaction zone," that is, in actively fracturing, hot rock units, or in sections overlying axial magma chambers, and (3) determine the level of biological activity as a function of depth. Use of nested casing strings and drilling mud to stabilize holes should enable consistent, successful drilling. The new Hard Rock Reentry System, now being tested by ODP, will help establish landing bases so that drillpipe can be advanced into the bare rock. Once holes are established, experiments using new Advanced Circulation Obviation Retrofit Kits (ACORKs) for long-term monitoring and sampling of fluids will document processes that vary temporally (Figures 2 and 12). Drilling and observatory results, combined with samples and measurements taken by scientific initiatives in collaboration with IODP, are critical to creating a better understanding of fluid pathways, heat flow and mineral reactions within the subseafloor ocean.

- **Ridge flanks, large igneous provinces and old ocean basins:** Global seafloor heat-flow compilations suggest that fluid-circulation rates in the crust wane with increasing crustal age, extent of alteration and thickness of sediment cover. However, direct observations of the circulation rates are limited primarily to very young seafloor, and these have confirmed that fluxes are large. Faults in the older crust and overlying sediments may provide conduits for focused fluid flow, but drilling has intersected few such faults, and hence their influence on crustal hydrogeology is not well-documented. In the future, better seismic imaging, coupled with thermal and geochemical studies at the seafloor, will provide improved contextual information for targeting such focused fluid-flow systems, sampling them, and conducting active experiments and monitoring.

Observations at outer-trench flexural zones suggest that permeability can be "rejuvenated," although whether this is common and to what depth it extends are unknown. The view that blanketing sediments pervasively restrict fluid circulation may also be oversimplified. Permeable pathways through sediments can be established during or after deposition and these could allow geochemically significant fluxes in otherwise well-sedimented areas. Permeability of the blanketing sediments may also depend

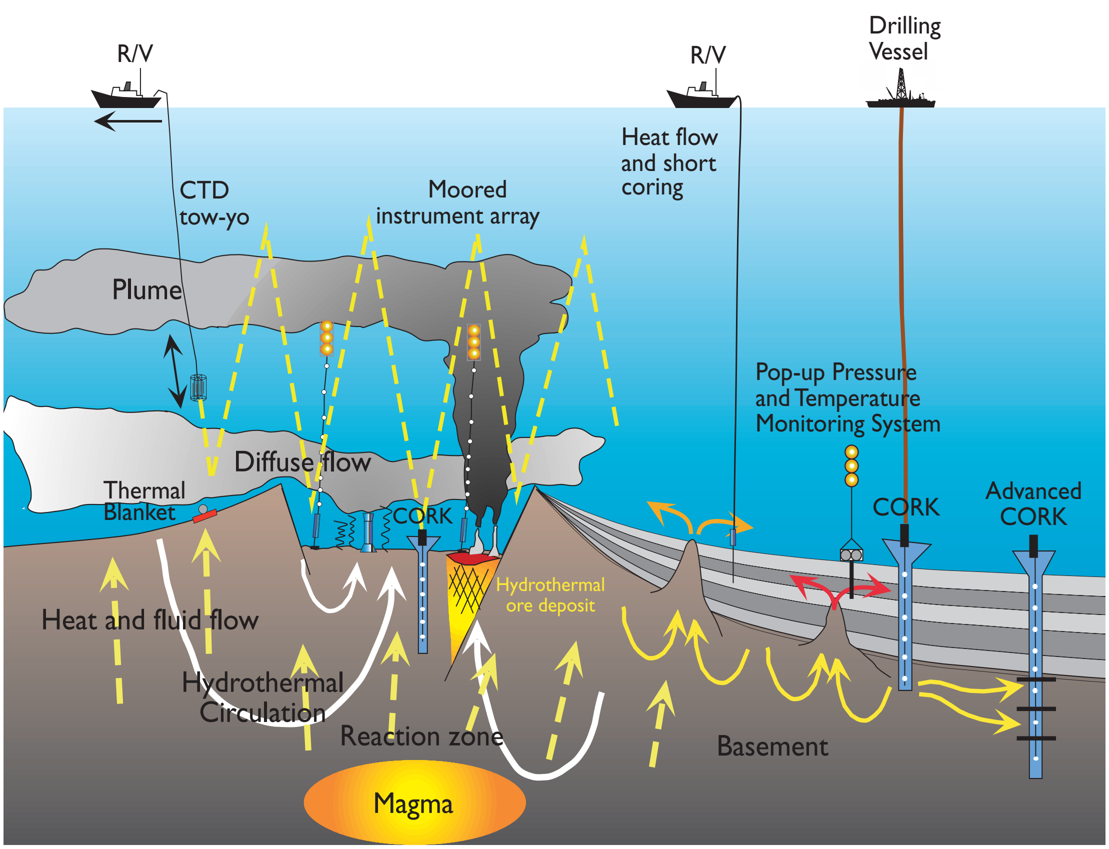


Figure 12. Diagram showing how a wide array of borehole, seafloor and sea-surface experiments could be integrated within one or more crustal settings at or near a mid-ocean ridge. Some of the best quantitative information about ocean crustal circulation has been provided by post-drilling observations made using the "CORK" capability developed to seal, draw fluids from, and instrument cased holes for long-term monitoring. Multidisciplinary experiments will help to leverage the maximum possible scientific return from ocean crustal drilling. Reprinted from the COMPLEX report, JOI Inc., May 1999.

on sediment type and degree of compaction. The lateral extent to which flowing fluids can generate geochemically significant fluxes is unknown, although recent drilling in partially sedimented regions has set a lower limit of fewer than a hundred kilometers.

We know little about fluid-flow regimes that are found in the vast majority of the oceanic crust, nor do we appreciate how this flow might alter the chemical composition of crust locally or regionally. In addition, because the major Large Igneous Provinces (LIPs) forming today are significantly smaller than those formed during the Cretaceous, we do not know how hydrothermal activity associated with very large, ancient hotspots and LIPs may have affected ocean chemistry. The strategy for extending our sketchy knowledge involves work on two major fronts. First, fluid-flow measurements and sampling in older, ridge-flank, LIP and ocean-basin settings will be carried out to assess change in permeability, internal fluid flux and ocean-crust chemical exchange and to determine hydrological properties at old, tectonically stable and fully sedimented areas. Characteristic sites will be defined and targeted. Second, deep drilling and observations of the physical and chemical character of the sections will be undertaken at a few sites that are considered optimal for other objectives, such as for the study of the three-dimensional volcanic and tectonic structure of the crust.

- **Subduction zones:** Scientific ocean drilling at convergent margins has yielded a basic understanding of their hydrogeology. Fluids are continuously supplied by the slow compaction of sediments imported into the subduction system and by dehydration of the subducting slab. Generally low permeabilities in accretionary prisms lead to disequilibrium between production and drainage and hence to overpressured conditions, whereas the highly fractured nature of most non-accretionary prisms at these margins provides egress for fault-channeled fluids derived from the slab. Variations in permeability, and in rates of deformation, loading and fluid production, are believed to produce large variations in pore pressure and rates of flow along the décollement and within accretionary prisms. Locally, pressures can approach lithostatic levels, and fluid flow can be highly compartmentalized or focused. Similar compartmentalization of flow may occur in non-accretionary convergent margins. In both cases, these fluids may contribute to defining the limits of the earthquake-generating Seismogenic Zone.

  Despite our understanding of certain fundamental aspects of these two basic types of convergent margins, important problems remain unsolved. Among them are: (1) the role of water in controlling deformational style in both types of convergent margins (*e.g.*, ductile vs. brittle; distributed vs. fault-concentrated), (2) the influence of chemical fluxes on alteration of the overriding sediments and basement, (3) how alteration and metamorphism in the overriding plate combine with deformation to influence the fluid transmission properties of the overriding plate, (4) the differences both in composition of fluids emanating from pressure-controlled dehydration reactions within the subducting plate at various depths and in magnitude of fluxes produced, (5) the partitioning of fluid fluxes between the shallow outer forearc regions (prism or hard rock) and depths where fluids contribute to forearc mantle metamorphism or melt production, (6) the role of fluids in seismic rupture, and how earthquakes influence fluid flow through the generation or release of pore-fluid pressures within the rupture zone, and (7) the relative importance of transient vs. steady-state hydrological processes.

Episodic events, possibly associated with major earthquake rupture and accompanying ground motion, may dominate fluid flux at convergent margins. All of the results to date, however, are based on non-riser, relatively shallow drilling and the use of the first-generation borehole seals (CORKs). In combination with non-riser drilling, access to the new ACORKs and to deep, riser drilling will enable us to address fully the very important, outstanding questions of fluid flow within subduction zones. Addressing these questions fully will also require long time-series observations and improved capabilities for sampling sediments and fluids with recovery at *in situ* conditions.

- **Passive rifted margins and carbonate platforms:** The hydrological regime of passive rifted margins is largely unknown. Fluxes may be very large, with consequently strong influences on diagenesis, on shaping the morphology of margins by way of mechanical and chemical erosion, on the migration and accumulation of hydrocarbons including gas hydrates, and on geochemical exchange between the crust and the oceans. Conditions differ from those in the more-explored, better-characterized settings of active tectonic margins, and scientific ocean drilling operations on passive rifted margins and around carbonate platforms remain exploratory.

At many passive rifted margins, hydrological regimes may be influenced strongly by meteoric systems on land, with flow driven by a topographically induced hydraulic head. The systems may be very extensive, reaching across continental shelves to continental slopes and continental rises. High-resolution seismic data can often better image the structural and depositional framework in passive margin settings than in the more structurally complex subduction margins. Thus, a better definition of structural and depositional controls on flow pathways can be achieved. Using such detailed, high-resolution seismic surveys, clear models of fluid flow and structural and stratigraphic trapping can also be developed. Testing such models will require IODP to drill in the full range of water- and subseafloor depths over which the flow systems operate. This can only be done with the diverse suite of drilling technologies and platforms available in IODP, including non-riser, riser and mission-specific platforms, as well as co-operative partnerships to undertake onshore drilling. Fluid compositions, sediment/rock alteration histories, lateral pressure gradients, and permeabilities must all be observed. Microbes may play an important role in many parts of the systems, and accumulations of hydrocarbons and gas hydrates may be the products. A better understanding of the controls on fluid flow operating at passive rifted margins will also be important in deciphering fluid migration pathways and rates in the more complex transform and subduction margins.

The Deep Biosphere

Two of the fundamental and unanswered questions facing Earth and life scientists today are, what is the extent of Earth's deep biosphere and what is the character of the extreme life forms populating it? During the last decade, ODP began to explore and sample this largely undocumented biosphere (Figure 13). Initial results indicate that microbial ecosystems thrive in both oceanic igneous crust and in deep (more than 750 m) subseafloor sediments, regions previously thought to be barren.

Before the discovery of the deep, subseafloor biosphere, bacteria isolated from hydrothermal environments had already made a big impact on biotechnology by providing enzymatic catalysts for the polymerase chain reaction, which has revolutionized molecular biology. In the deep-sea environment, some of these hydrothermal bacteria have been found to be active at temperatures well above 100°C, and are likely to live several kilometers beneath the subseafloor surface, despite a temperature increase of 30°C/km. This brings bacteria into the "oil window" and resurrects a long-standing question as to the degree to which microbes are involved in the formation of mobile hydrocarbons. It has been known for some time that large bacterial populations emerge with production fluids from some oil reservoirs, but their presence in other, less carbon-rich, sediments in the deep subseafloor environment has been more surprising. Given the diversity of habitats, the deep biosphere will likely provide even more new species of bacteria than have been discovered thus far in seafloor hydrothermal environments. As a result, recovery of new bacteria by drilling could have a profound impact on biotechnology.

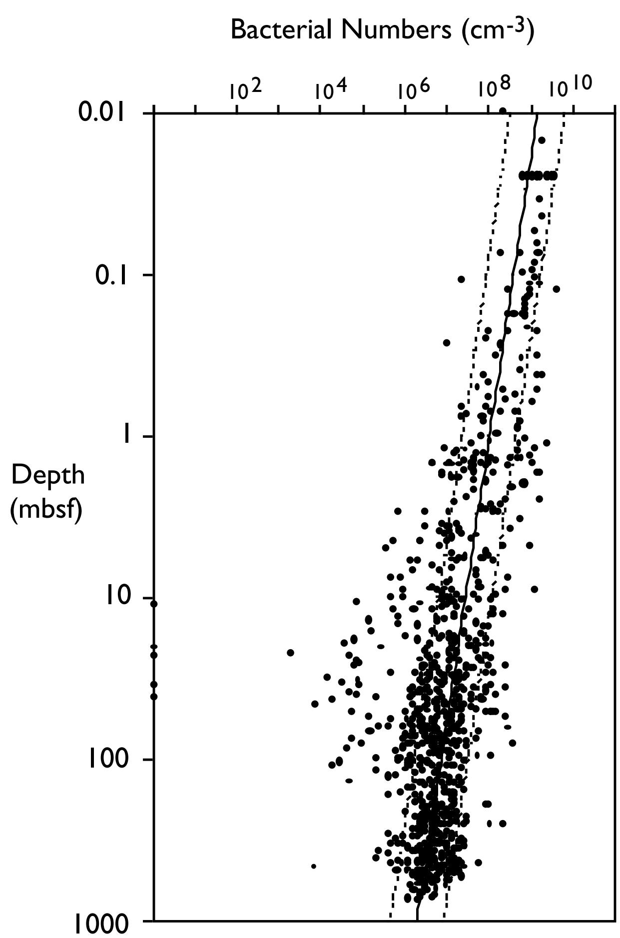


Figure 13. Bacterial abundances as a function of sub-bottom sediment depth as seen in ODP boreholes down to ~ 750 mbsf. Figure reprinted with permission from Parkes, R.J., B.A. Cragg and P. Wellsbury, Recent studies on bacterial populations and processes in subseafloor sediments: A review, Hydrogeol. Jour., 8, Figure 2b, p.15, copyright Springer-Verlag, 2000.

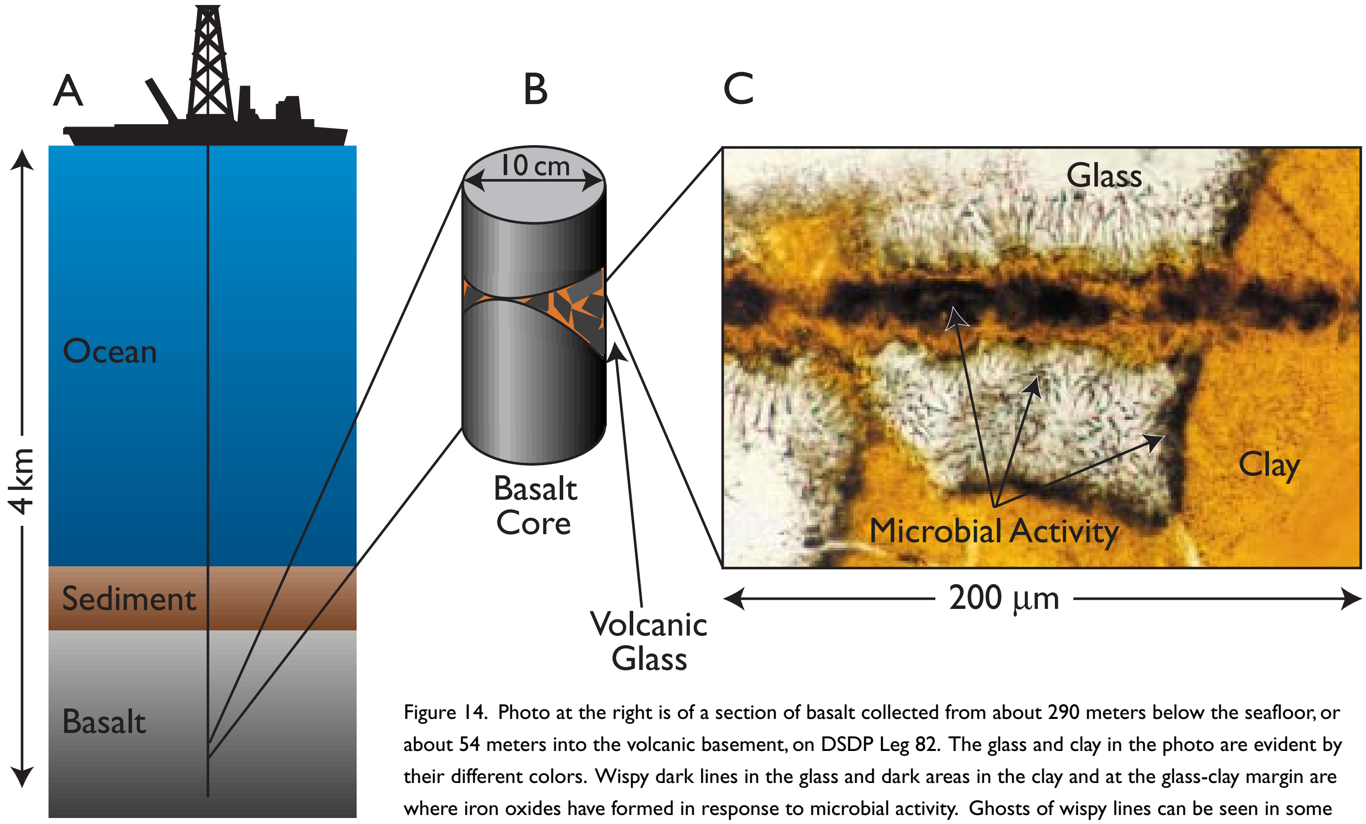


Figure 14. Photo at the right is of a section of basalt collected from about 290 meters below the seafloor, or about 54 meters into the volcanic basement, on DSDP Leg 82. The glass and clay in the photo are evident by their different colors. Wispy dark lines in the glass and dark areas in the clay and at the glass-clay margin are where iron oxides have formed in response to microbial activity. Ghosts of wispy lines can be seen in some areas of clay near the glass. ODP samples have established that this type of alteration exists throughout the ocean basins and at all depths and ages of rock. Figure courtesy of Martin Fisk, Oregon State University.

Deep sampling by ODP showed that subseafloor microbial communities are active in elemental cycling. At the sediment-hard rock interface, bacteria interact strongly with minerals in the rocks, thus catalyzing weathering reactions that have been traditionally viewed as abiotic (Figure 14). Within the sediment column that blankets the hard crustal rocks, sulfate-reducing bacteria are among the most numerous. In some settings, acetate is the main substrate for these organisms, but the sources of the acetate (thermogenic or biogenic) are poorly known. Methane and other gases are additional important energy sources for bacteria, fueling communities from the seafloor to great depth. Complex microbial groups exist downward into gas hydrate deposits and the deeper, free-gas zones. The relationships among various bacteria, their depth ranges, and their interactions with surrounding sediment and pore water are topics of current discussion and research.

The synthesis and maintenance of this huge biomass from the seemingly meager resources that exist at great sedimentary depths is remarkable; how bacterial populations have survived on buried organic material for millions of years is unknown. Distinct metabolic processes and enzymatic catalysts may be involved, and these will be of interest not only for pure science, but also for biotechnological applications. The only way to explore this new biologic world is through scientific ocean drilling and the advanced coring technology first developed and tested in ODP. This technology and others aimed at an accurate assessment of the microbial environments of the subseafloor will be further developed in IODP.

Initiative: Deep Biosphere

The deep, subseafloor biosphere has environmental boundary conditions that support and limit its existence. An important first step for IODP is to define the bounding temperatures, pH and redox potential of this ecosystem. Samples will also be taken globally, and in different tectonic settings, to study how sediment and rock lithology and porosity, organic carbon content, and rates of sediment accumulation and depth of burial may influence this ecosystem. Integrating this global assessment with tectonically oriented drilling programs will make it possible to examine the influences of tectonic settings on the structure, size and turnover rates of subseafloor communities. Global mapping of the depth and geographic extent of these populations is an important part of this effort, and will enable us to refine current estimates of the integrated global biomass in the deep bacterial biosphere.

Another top priority for IODP is to evaluate the biogeochemical impacts of the subseafloor microbiota. Carbon and redox budgets for the deep bacterial community are completely unknown. If, as appears possible, this community intercepts reduced substances ascending with fluids from the sediment-hard rock interface, modulation of its activities could have substantial effects on climate and atmospheric composition. The effects of the subseafloor microbial community on sedimentary geological and geochemical records are apparent, in retrospect, from previous studies of mineral authigenesis and diagenesis in deep-sea cores, but the importance of the microbial factors cannot be evaluated in any detail from such evidence. Future deep sampling will aim to provide more robust constraints on the hypothesis that the deep bacterial biosphere is being nourished to a significant extent by hydrogen or organic compounds produced abiotically at the sediment-hard rock interface, rather than depending entirely on organic material from the overlying water column and sediments.

IODP will provide uncontaminated samples necessary for the high-priority studies of deep-biosphere trophic strategies and means of survival, and the molecular, cellular and ecological mechanisms used by subseafloor communities. Processes by which cells maintain viability when rates of energy production must be very near the minimum required to repair damaged enzymes and genetic materials are not known and are of major interest. Community structures, that is, numbers of species present and their relative abundances, are essentially unknown. In most bacterial communities, metabolites are transferred among species of organisms very intricately. The same is likely to be true within the deep bacterial biosphere. No information is currently available about systematic differences between microbial populations in carbonate versus siliceous versus siliciclastic sediments, nor is it understood how these populations can successfully adapt to wide variations in the availability of energy sources, for example, between seafloor hydrothermal vents and abyssal plains. Finally, it is possible that the immobility of these organisms, coupled with their isolation within sedimentary matrices, has provided conditions favorable for the preservation of Miocene and older genotypes, which will offer unique opportunities to trace evolutionary patterns and processes.

The role of the deep biosphere in biogeochemical cycles must also be determined, and will require studies of microbial populations, pore-water chemistry and organic-chemical compositions over substantial subseafloor depths in different environmental and tectonic settings. It is likely that this would require the development of *in situ* microbial laboratories, perhaps in association with the deployment of the newly developed ACORK system or with the development of new side-wall probes. Drilling in diffuse-flow zones at spreading centers will provide information on deep communities growing over a wide range of temperatures at readily accessible depths in the sediment column and underlying igneous crust. Drilling in subduction zones will provide evidence about possible bacterial involvement in the remobilization of materials from descending plates and about responses of communities to fluids migrating from greater depths. Examination of microbial populations around seafloor mud mounds and other sites of hydrocarbon-related diagenetic activity will provide information about the role of bacteria in the degradation of fossil fuels. Drilling, logging and sampling through methane gas/gas hydrate boundaries will enable studies on the long-term stability of such biogenic deposits and about global budgets for this important greenhouse gas. Studies at organic-rich/organic-poor interfaces within the sediment column (*i.e.*, where turbidity currents have covered organic-rich strata, or where marine sediments have buried terrigenous coals, lignites or sapropels) may provide new information about mechanisms of organic carbon remineralization, a major process within the carbon cycle.

Finally, the deep subseafloor environment represents a unique habitat in which organic and inorganic chemical reactions and geological processes are interlinked. Reliable estimates of the full extent and global scale of biogeochemical cycling require knowledge of processes relating the geochemistry of carbon with those of sulfur and iron and other metals. Indeed, chemical, biological and physical processes are highly interlinked, and must be understood in a full, mutual context. This knowledge is paramount to any attempt to interpret geochemical and geological records. It is also indispensable for applied geotechnological developments that rely on accurate predictions about how the Earth system will respond to changes affecting the delivery of biochemically reactive materials to the seafloor. The only way to get samples to address these research topics is by scientific ocean drilling. Some of these studies, especially those aimed at determining rates of change and community or chemical evolution, will undoubtedly require carefully designed experiments. In our studies of the deep biosphere, we are still very much in an exploratory mode. Microbiologists will become a standard component of IODP's shipboard scientific parties, and their findings will lead to a clearer definition of exciting new opportunities. It is likely that our very first efforts will be aimed at defining the physical and chemical limits of subseafloor microbial communities (see Deep Biosphere Initiative).

Gas Hydrates

Clathrates of gas, commonly called gas hydrates, are crystalline solids composed of gas and water that are stable at high pressure, low temperature, and high gas concentration, conditions that are met in the upper few hundred meters of sediment on many continental slopes and deep ocean basins. Gas hydrate crystals, resembling ice in appearance, have been retrieved from the seafloor at several locations (Figure 15). In most of these cases, the dominant gas in the solid phase is methane, produced through the bacterial decomposition of organic matter in deep-sea sediments. Some gas hydrates, however, have been recovered with high concentrations of CO_2, hydrogen sulfide, or thermally generated methane, ethane and heavier hydrocarbons. Because of contamination problems with most recovery methods, other gases, such as noble gases, and other chemical constituents in the crystal lattice, have not been examined rigorously. The complete range of compositions of natural marine gas hydrates is unknown.

Individual gas hydrate deposits are complex and dynamic systems in which gas molecules can be transferred among solid hydrates, gas bubbles and dissolved phases as conditions change. New gas is generated at shallow depth by bacteria and at much greater depth by heat. As this dissolved gas migrates upward, it forms gas bubbles where the pore waters are saturated, and eventually may form gas hydrate where the temperatures and pressures are appropriate. The deposition of sediment over time buries the solid phase, slowly

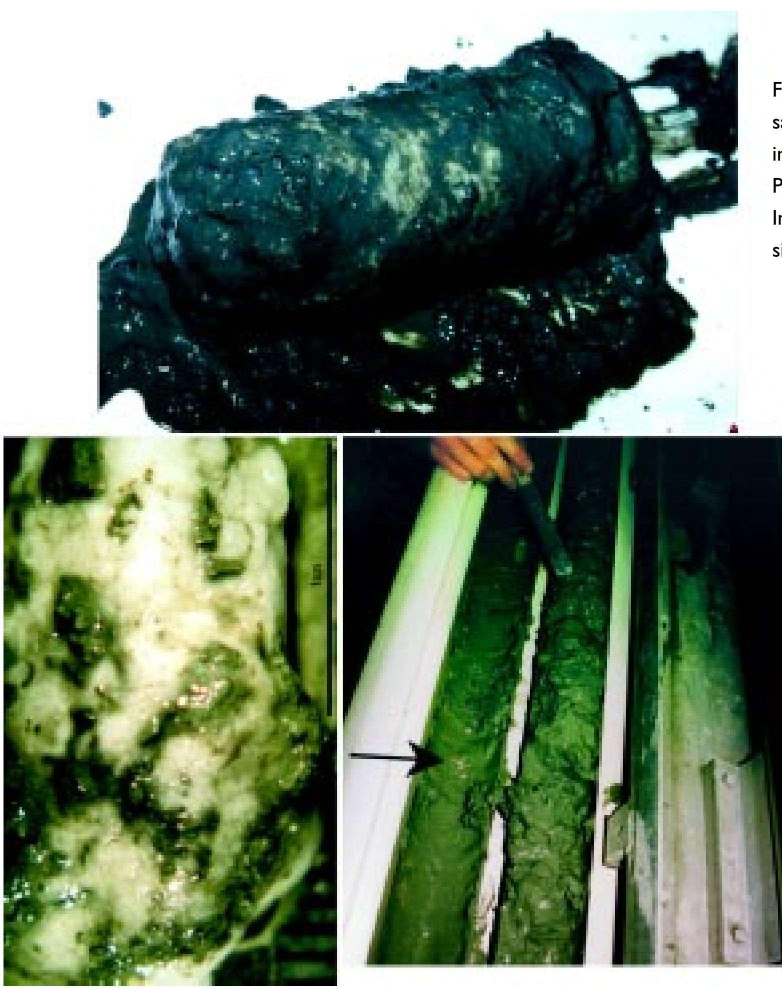


Figure 15. Photographs of gas hydrate samples recovered during ODP Leg 164 in 1995. Photos courtesy of Charles Paull, Monterey Bay Aquarium Research Institute, and Ryo Matsumoto, University of Tokyo.

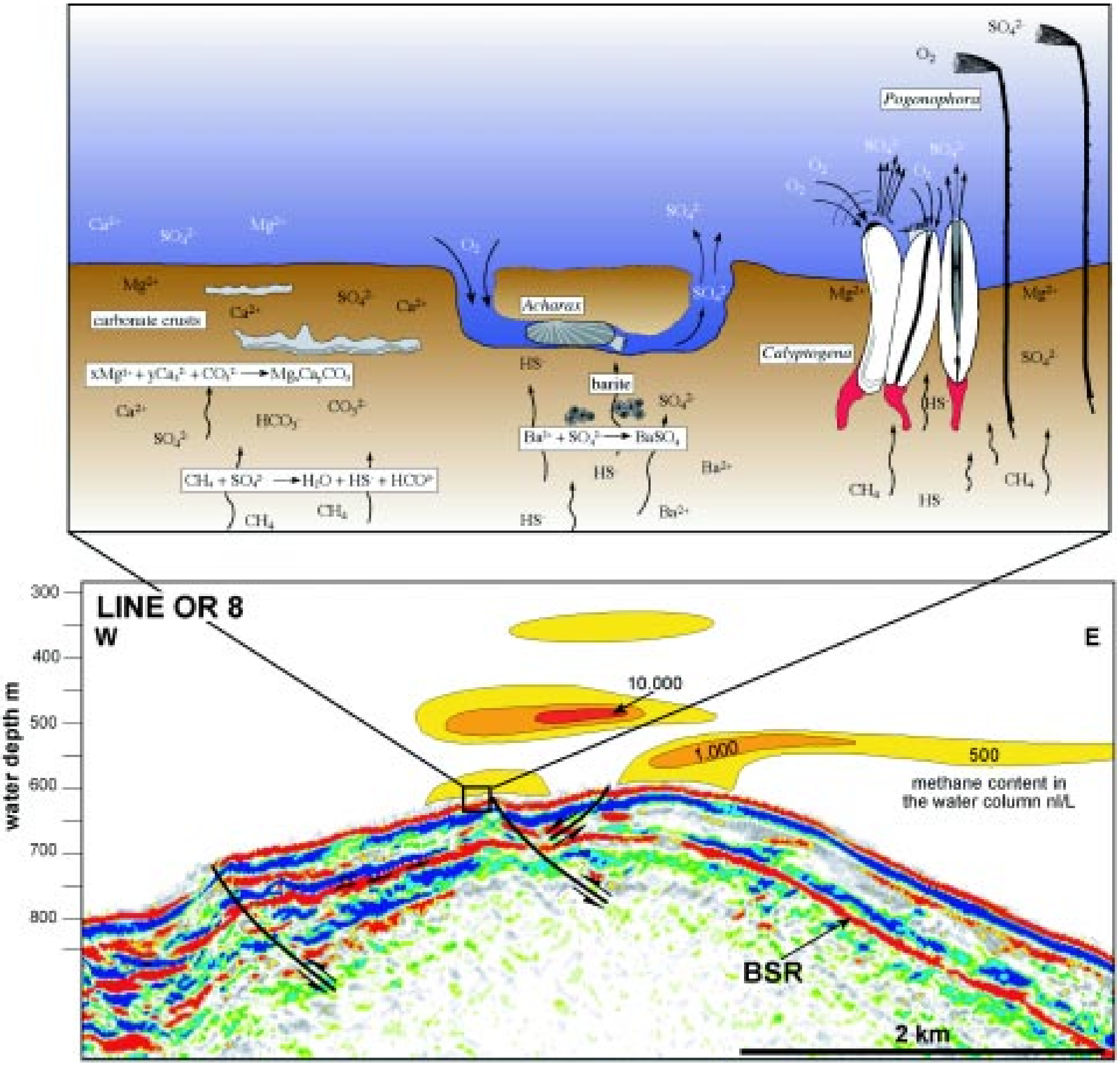


Figure 16. Gas plumes, bottom-simulating reflectors (BSRs) and vent fauna at the Hydrate Ridge of the Cascadia accretionary complex. The BSR is thought to mark the transition from gas hydrate to free methane gas in the sediment column. Fluid and gas are vented into the water column to form plumes, where the methane concentration (in nL/L) exceeds 1000-times the saturation value of methane in the atmosphere. The gas emanations generate specific ecosystems with chemoautotrophic biota and authigenic mineral precipitates (close up: *Calyptogena* sp.; *Acharax* sp.; Pogonophora; carbonate and barite precipitates). Figure from Suess, E. et al., Gas hydrate destabilization: Enhanced dewatering, benthic material turnover and large methane plumes at the Cascadia convergent margin, Earth, Planet. Sci. Lett., 170, 5, 1999, Figure 2e, p. 5. Reprinted with permission.

bringing gas hydrate to higher temperatures with increasing depth. At some pressure and temperature, gas hydrate is no longer stable and re-dissociates to gas-saturated water and free gas bubbles. While much of the gas released at depth is retrapped after migrating to cooler zones, some escapes to shallow depths, to the seafloor or to the water column where it is oxidized by bacteria (Figure 16). The rates and magnitudes of these carbon fluxes and their variations over time have not been quantified.

The global distribution of gas hydrates has been inferred from geophysical observations. By far the most widely discussed indicators are bottom simulating reflectors (BSRs), which are observed on seismic profiles across many continental margins and in the deep ocean basins. These BSRs represent contrasts in acoustic impedance that track the depth of the seafloor. Because the depths of many BSRs coincide stratigraphically with the pressure and temperature conditions of methane hydrate stability, they are interpreted as representing the phase boundary between overlying gas hydrate and underlying free gas bubbles. This hypothesis has been confirmed by ODP on the Chile margin, Cascadia margin and Blake Ridge by drilling through the BSR. Hydrate and free gas were present in the recovered drill core, and the BSR's existence independently confirmed by sonic logging of the drill hole. For each of these locations, however, pressures and temperatures at the BSR do not precisely coincide with expected conditions at the gas hydrate/free gas interface. Moreover, gas hydrate has been recovered at several locations without a BSR.

Estimates of 7 to 15 x 10^{12} metric tons of carbon are common for the total mass of marine gas hydrates, making them an immense global carbon reservoir which may contain 15 to 20 times more carbon than the entire terrestrial biosphere. These estimates have been calculated by using gas concentrations measured in small regions and extrapolating the results to the entire ocean margin; substantial quantities of free gas have not been accounted for in these global estimates.

Because the stability of gas hydrates depends on pressure and temperature, the dynamic cycling of gas in ocean hydrate deposits can be perturbed from steady-state by tectonism, sea-level change or by changes in the overlying bottom-water temperature. In particular, a rise in the temperature of the intermediate-depth waters along continental slopes could destabilize hydrates and increase the outward flux of gas to the seafloor and water column. For example, near the time of the Paleocene-Eocene boundary, 55 Ma, the climate was characterized by high atmospheric CO_2 and globally increasing warmth. An extraordinary injection of isotopically light carbon into the ocean and atmosphere, detected by analysis of ODP cores, may have been caused by a massive release of methane from gas hydrate deposits, resulting in a sudden 2-3°C warming of global temperatures. This is but one of the very warm climatic events addressed by the Extreme Climates Initiative.

The distribution of inferred gas hydrates on the continental slope apparently correlates with regions having prominent slumps and slides. Free gas buildup at the base of the gas hydrate stability zone, perhaps because of a drop in sea level or an increase in bottom water temperature, may cause excess pore pressure at depth and, consequently, failure in the overlying sediment column. Such destabilization may pose a hazard on the continental slope for purposes of hydrocarbon exploration or production. At the same time, marine gas hydrates may comprise an enormous natural resource potential, although the gas is not concentrated exclusively in layers but found mostly dispersed in the pore space of the sediments and are distributed over thousands of square kilometers in considerable water depths. To date, relationships among gas hydrates, slope stability and oceanographic change have never been rigorously tested. Furthermore, the economic potential of gas hydrates, as well as the technical feasibility of their extraction, is unknown.

Gas hydrates have been known in marine sediments since the early days of DSDP, but for a long time they were avoided as a potential drilling safety problem. As a result of recent increased interest in gas hydrates, and a better understanding of how to safely drill into such environments, ODP is now developing tools and experimental strategies to study them. With continued advances in coring technologies, it will be possible to retrieve gas hydrates at *in situ* hydrostatic pressures and to examine the processes associated with the formation, stability and disassociation of these deposits. While it is now apparent that the hydrate system is an important component of the global carbon cycle, much remains to be learned about the mechanisms of the inputs and outputs from the hydrate system and about the size of the hydrate reservoir of carbon. We have only begun to quantify the role of hydrates in the marine environment. Because of their large contribution to the global carbon reservoir, gas hydrates represent one of the most significant problems in Earth and environmental sciences. Therefore, early IODP efforts will concentrate on defining the range of environments under which gas hydrates occur and some of their key attributes (see Gas Hydrate Initiative).

Initiative: Gas Hydrates

ODP has just begun to explore the nature of gas hydrates deposits and the range of depositional settings in which they occur. IODP will aim to quantify the rate at which the gas is generated in the sediments, determine its dependence on the detrital organic carbon source material and the microbial community, quantify the rates of gas migration through the sediments and establish the mechanisms of its entrapment in the sediments. IODP will also examine the significance of bottom simulating reflectors (BSRs) and provide a more quantitative relationship between the presence of a BSR, its acoustic character and the amount of gas with which it is associated. In addition to drilling through gas hydrate sections, it will be essential to log the holes, and recover samples at close to ambient temperatures and pressures. Gas hydrates studies will also be closely linked to the more general studies of fluid flow and the deep biosphere, as the existence of many of these deposits may depend on microbial methane producers and methane consumers, their respective rates of growth and on the pathways of fluid migration.

Successful study of gas hydrates will require new approaches and new technologies in scientific drilling. In addition to using the non-riser IODP drillship, mission-specific drilling platforms will be required in several environments. Shallow- and intermediate-depth holes will be drilled, and near-surface samples will be taken, to study the dynamics of the upper portion of marine gas hydrate reservoirs. Mission-specific platforms will be used for studying high-latitude and shallow areas of permafrost that have gas hydrate deposits. Because of their ephemeral nature, gas hydrates sampling and study will need special tools and new technology to make *in situ* and direct measurements.

The Role of Multiple Platforms in Exploring the Deep Biosphere and Subseafloor Ocean

The availability of a wider array of drilling platforms and enhanced sampling technologies in IODP will permit expanded exploration of the deep biosphere and subseafloor ocean. ODP's versatile, non-riser drillship has enabled initial exploration of this realm, and has allowed us to focus on needed experiments and new technologies. New ODP technologies include installation of a microbiology laboratory on board the *JOIDES Resolution*, and continued development of a new pressure sampling tool (HYACE, see p. 84) and an Advanced CORK system for isolating and sampling interstitial waters in multiple zones beneath the seafloor (see p. 82). IODP's non-riser drillship will continue to play a key role in studies of fluid flow, deep biosphere and gas hydrates. The new ship will enable research to expand into the third dimension by drilling networks of holes that sample the relatively shallow sediment column and upper crust. The emplacement of monitoring devices in such networks will enable long time-series data to be recorded so that scientists can evaluate steady-state conditions, and the impact of episodic events on subseafloor processes.

By itself, the non-riser drillship cannot drill the complete range of environments required for exploration of this scientific theme. Although the *JOIDES Resolution* has drilled to about two kilometers below the seafloor, successful drilling to these depths is far from routine. To go beyond a relatively shallow network of holes and to truly explore the three-dimensional aspects of processes that take place in the subseafloor ocean, holes must be drilled deep into the crust itself. To do this on a routine basis, with good sample recovery, deep coring technology and methods for maintaining stable holes provided by the riser drillship is required. This is true for deep penetration into crustal rocks for studies of microbial activity, fluid movement and chemical alteration. It is also true for drilling deep within thick sedimentary sections for similar studies, as well as for studies related to the cycling of organic carbon. To fully realize the potential of the riser-equipped drillship in scientific ocean drilling, the present water depth limits of drilling with well control will continue to be extended. Currently this limit is near 3000 m. IODP is committed to extending these limits to at least 4000 m.

There remain scientific targets associated with this theme that cannot be drilled with either the riser or non-riser ships such as the ice-covered Arctic Ocean. Platforms specifically equipped for missions in ice-covered regions will be required. Drilling is important in these polar latitudes as we know that gas hydrates exist at relatively shallow depths and that a seafloor spreading center (the Gakkel Ridge) disappears into the thick sediments of the northern Siberian margin where permafrost is found on the shelves. These observations point to a potential for near "end-member" conditions for gas hydrates, thermally driven fluid flow and associated microbial environments.

In settings near continental margins, drilling with multiple platforms is essential to studies of fluid flow, gas hydrates, carbon cycling and microbial ecology. In very shallow waters, especially in those sections requiring well control for safety and good sample recovery, mission-specific platforms will be required. In deeper waters, the non-riser ship can provide spatial arrays of holes that can help define processes taking place in the upper part of the section and can also provide information that will help site deeper holes. To drill deeply within both passive and convergent margins, a riser ship with full well control will be required. Riser drilling will be able to overcome the difficulties associated with unstable hole conditions and will enable sample recovery.

Environmental Change, Processes and Effects

The crucial questions of climate change are those of process and response, cause and effect. The instrumental climate record is only about 100 years long, which is insufficient for establishing the extent to which any current climate change is the result of natural variability or anthropogenic atmospheric input. Information contained in marine sedimentary records extends these extremely limited instrumental climate observations into the realm of large-scale, natural climatic variability. Sediment analysis has revealed periods of extremely warm climates comparable to or exceeding those predicted for our immediate future. What forced Earth's environment toward these extremes? How did Earth's system respond, and on what time scales?

A major IODP goal is to address the cause of environment changes on all time scales. This will be accomplished through the synergistic efforts of data collection, analysis and quantitative modeling. The complete recovery of a global array of sedimentary records by scientific ocean drilling is the first step in this effort. Analysis of the recovered marine sediments provides crucial estimates of past environments when average conditions were significantly different from those observed today (i.e., sea-surface temperature, thermocline depths, ocean-surface and deep circulation, atmospheric circulation patterns). General circulation models are well-tuned to replicate the current environment, but we need to know how well these models replicate significantly different past climates. Accurate depictions of past climatic extremes provide crucial scenarios against which model reliability can be tested. Only then, using climate models of proven reliability, can we assess the rates and severity of future environmental changes.

Most observations of environmental change can be grouped into time scales ranging from tectonic (longer than about 500 kyr), to orbital (20 kyr to 400 kyr), to oceanic (hundreds to a few thousand years), and to seasonal-to-centennial. As our goal is to understand processes and, ultimately, to predict climates, we approach questions of climate and environment by considering categories of process, rather than timing of the response. Thus, this section is divided according to the causes of climatic change: those caused by processes internal to Earth, those caused by processes that are external to Earth's climate system, and those representing some interplay between internal and external processes.

Internal Forcing of Environmental Change

One of the most perplexing questions is why Earth's climate varies slowly from very warm conditions, "Greenhouse Earth," to those of bi-polar glaciation, "Icehouse Earth" (Figure 17). How are the polar regions kept cold, and how, at other times, is heat transported poleward under conditions of extreme warmth? Why does change occur sometimes gradually and at other times in discrete steps? Answers to these questions include, at least in part, mechanisms internal to Earth's system such as continental assembly and breakup, elevation and erosion of vast plateaus, opening and closing of oceanic gateways, magmatism, and changing concentrations of CO_2 and other greenhouse gases in the atmosphere. Issues related to such internal forcing of climate change include those of the forcing mechanism (what initiates change), feedbacks that may serve to amplify or reduce the effects of both large and small events, and response (which components of the Earth system are most sensitive and why).

- **Tectonically induced changes:** The uplift of high mountain ranges and plateaus, such as those in the Himalayan-Tibetan region, the Colorado Plateau and the Andes Mountains, contribute to environmental change in a number of ways. The elevations themselves may physically interfere with atmospheric circulation. For example, the uplift of the Himalayan-Tibetan region has altered the path of the northern hemisphere jet stream. It brought monsoons to regions lying south and east of the plateau, and aridity to regions lying to the north. The elevation of the Andes during the Pliocene has resulted in the orographic stripping of moisture from the southern hemisphere tradewinds and the return of that moisture to the Atlantic via the Amazon. Accelerated weathering permitted by the rapid erosion of newly uplifted terranes also draws down atmospheric CO_2 by means of silicate weathering. Furthermore, burial of organic carbon associated with the muds derived from these eroding regions also removes carbon from the climate system. All of these processes lead Earth towards a colder climate. One clear way to evaluate tectonic uplift is to measure the resulting change in terrigenous deposition evidenced in sediment cores recovered by drilling in nearby marine basins. Increases in terrigenous accumulation rates, driven by increased topographic relief and erosion, can be directly tied to a chrono-stratigraphy and to the proxy indicators of climate and unroofing history contained in the relatively complete marine sections recovered by scientific ocean drilling.

  A second mechanism for inducing climate change via tectonic processes results from the large horizontal motions of the plates. These motions rearrange the geography of oceans and continents, and may be associated with large-scale volcanism. Especially critical are the opening and closing of oceanic gateways. For example, during Cenozoic time at low latitudes, the Tethyan and Panamanian seaways have closed and the Indonesian passage has been significantly restricted. The Norwegian-Greenland Sea began to open in earliest Eocene (~55 Ma) time. In the Southern Hemisphere, the Tasman and Drake passages began opening in Late Cretaceous (~80 Ma) and mid-Tertiary (~30 Ma) time, respectively, although timing of the deepening of these southern passages is poorly constrained. This changing configuration of barriers and gateways has altered ocean-surface and deep-water circulation and thus global heat transport. The change from latitudinal to meridional flow at low and mid latitudes, and the opening of the circum-Antarctic ocean, have been tied to the long Cenozoic cooling process. The

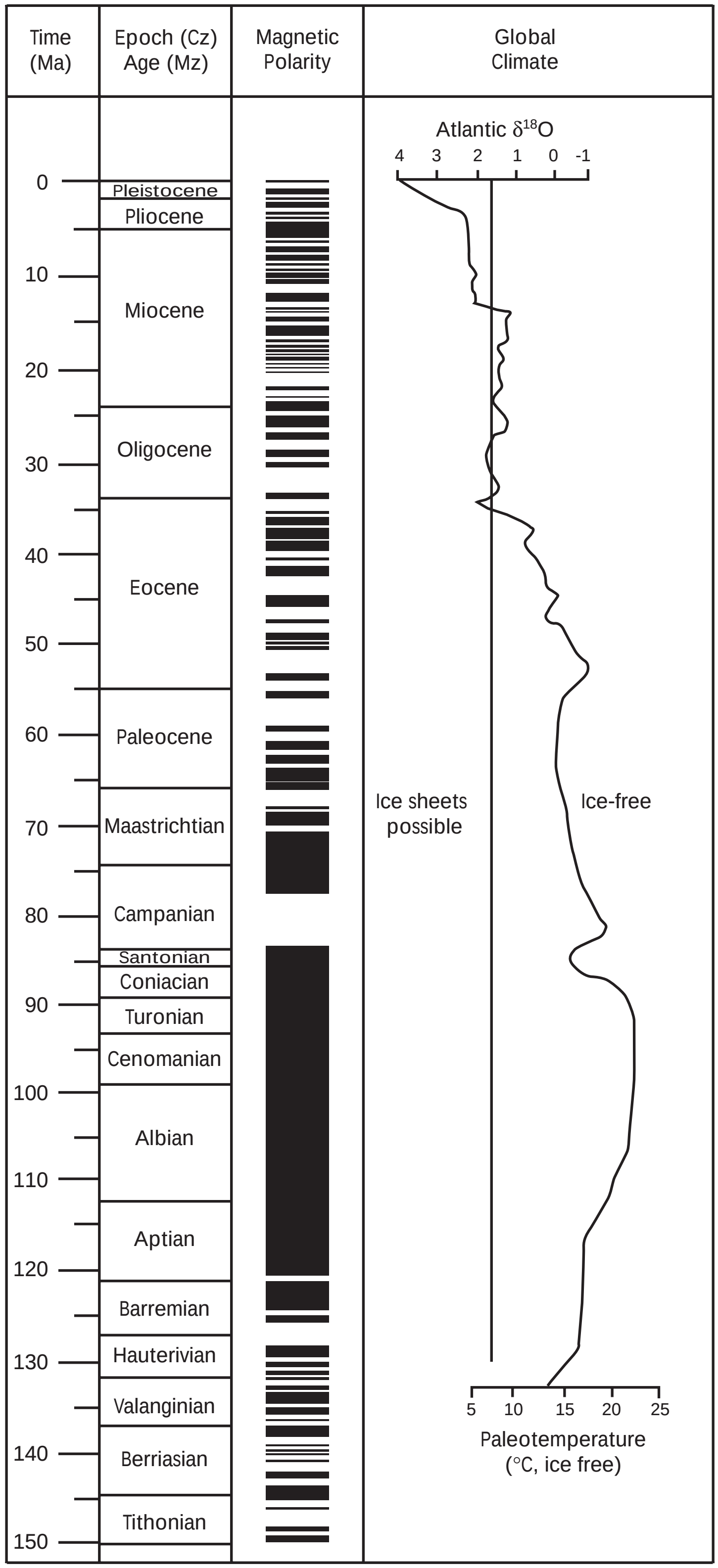


Figure 17. The past 150 m.y. of Earth surface temperatures as indicated by the $\delta^{18}O$ values of marine calcareous sediments. Note the transition from a "Greenhouse" Earth during the Cretaceous to an "Icehouse" Earth today. See also comparison between longer term changes in climate and major tectonic and igneous processes in Figure 28. Figure compiled by Millard F. Coffin, The University of Texas at Austin.

clearest way of defining the timing and the oceanographic impact of these gateway changes is by way of paleoceanographic indicators of deep- and surface-water conditions found in scientific ocean drilling sites that lie within regions affected by these changes.

Another tectonic process that may influence the global environment is plate-boundary rearrangements, especially those occurring along ridge-transform systems. When a new spreading center breaks through older lithosphere, seafloor hydrothermal activity increases by one to two orders of magnitude. Greatly increased rates of seafloor spreading, such as those characterizing mid-Cretaceous time, may also result in enhanced seafloor hydrothermal activity. Significantly enhanced seafloor hydrothermal activity would have a pronounced effect on ocean chemistry, including the silica budget, and possibly on climate. The long-term history of hydrothermal activity is the least well-understood, yet critically important, aspect of the global geochemical budgets of many elements, such as strontium, iron, manganese, silica, magnesium and potassium. Development of better proxy indicators of hydrothermal activity and their use in recovered sections from a variety of ages and locations should allow IODP to better develop this crucial history.

- **Igneous processes and environmental change:** Large igneous province (LIP) formation is characterized by massive basalt extrusion on continents, such as the Siberian, Deccan and Columbia River flood basalts, on nascent continental margins, such as the North Atlantic volcanic margins, or in the oceans, such as Kerguelen Plateau-Broken Ridge and the Ontong Java Plateau. The formation of these LIPs is accompanied by the release of heat, hydrothermal fluid, volatiles and particulates to the environment, which is in turn likely to affect oceanic and atmospheric chemistry, hence the climate and biosphere. The formation of several large Cretaceous (~140-~65 Ma) oceanic plateaus and of the North Atlantic volcanics—marking the opening of the North Atlantic at the end of Paleocene (~55 Ma) time —are accompanied by high sea-level stands and unusually warm climate, perhaps resulting from CO_2 emissions associated with this enormous amount of observed volcanism. Warming that began at the end of Paleocene time led to the early Eocene warm period, the only time during the Cenozoic as warm as the predicted "Greenhouse" world of the near future. This warming may have played a role in the initiation of the Late Paleocene Thermal Maximum event, a relatively short-lived spike in the global temperature record, thought to have resulted from a destabilization of gas hydrates on the continental margins (see Gas Hydrates Initiative). The unusual characteristics of a very warm global climate are of pressing interest to the modern world; the paleoceanographic record of warm climates will be an important early IODP focus (see Extreme Climates Initiative).

In contrast to the environmental effects hypothesized for the bulk of LIP emplacements, the explosive eruptions that characterize subduction zone volcanism may be associated with climatic cooling. ODP has documented significant episodes of volcanic activity in the Caribbean region in late Paleocene (~56 Ma) time and in Central America in earliest Oligocene (~34 Ma) time. Although the former accompanied early Eocene warming, the latter was at the time of early Oligocene cooling. DSDP and ODP drilling has also revealed that during the Neogene, volcanic episodes occurred in the Pacific Rim every five million years or so. A particularly intense volcanic period in the North Pacific began at about 2.6 Ma, at the same time as the sudden onset of major northern hemisphere glaciation. Whether the vol-

Initiative: Extreme Climates

Understanding the mechanisms by which climatic extremes develop, are maintained and end is fundamental to a quantitative description of global change. Earth is now in one of those extremes, the geologically unusual situation of bi-polar glaciation. Our knowledge of how Earth's system operates to maintain the current climate is relatively good, but we are still debating how the climate has reached this state. Changing gateway configuration, elevation of mountains and plateaus, and CO_2 drawdown by chemical weathering are all factors that may contribute to the answer.

Continued global warming could become a serious problem, but the case of extreme global warmth presents a challenge that is beyond human experience. The last time the world was as warm as it is hypothesized to be in the year 2150 was during early Eocene (~50 Ma) time. Such warm climates must be engendered by some combination of an increase in greenhouse gas coupled with changes in atmospheric and oceanic heat transport. In the past, extended periods of naturally warm climate began slowly, over two or three million years, as in the case of late Paleocene to early Eocene (~55-~49 Ma), and possibly longer during the warm climate regime of the Cretaceous (~140-~65 Ma), implying underlying long-term tectonic causes. A question of fundamental importance is how, once established, Earth's climate system operated to maintain the low thermal gradients indicated by warm, high-latitude climates. The paradox in this case is the apparent requirement to transport the great amount of heat needed to warm the poles, versus the sluggish oceanic and atmospheric circulation suggested by low pole-to-equator thermal gradients. The mechanisms for ending periods of extreme warmth are also poorly known, and may involve a combination of both step-wise and gradual change associated with fluctuations in ocean circulation and removal of atmospheric CO_2 by weathering or carbonate deposition.

Much of the inherent climatic variability during "Icehouse" extremes is related to changing ice volume in response to Earth's orbital variability. Neogene (~24-0 Ma) oceans are generally well-ventilated, physical and chemical fluxes of materials from continents to oceans are high, and the calcite compensation depth (CCD) is relatively deep. During extremely warm climate intervals, it is less clear how orbital cycles influenced climate. Oceans may have been less well-ventilated, fluxes of materials from continents to oceans may have been reduced, and the CCD was relatively shallow.

To investigate the nature of fundamentally different conditions on Earth during times of past extreme climate, IODP will drill at locations that will yield critical information about the nature of past oceanic and atmospheric circulation, such as equatorial and sub-polar regions. The Arctic Ocean, which is thought to have been ice-free in Paleogene and Cretaceous times, is also critical to our understanding of these climatic extremes, and will be drilled accordingly. Sites with higher sediment-accumulation rates in Cretaceous or early Eocene times, coupled with reduced overburden, such as are found on some oceanic rises and plateaus, are particularly desirable drilling targets because such sediments will not have been subjected to significant diagenesis and primary isotopic and geochemical signals may still be preserved.

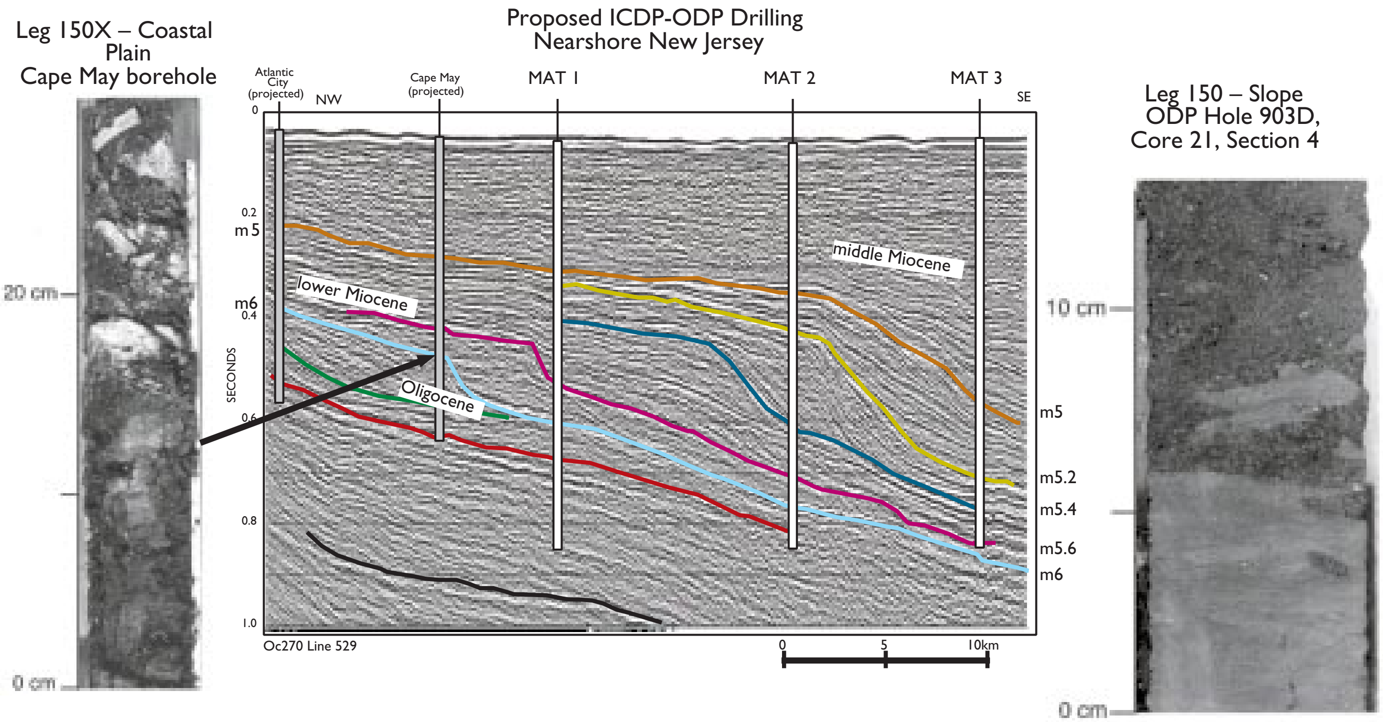


Figure 18. Early Miocene seismic sequences sampled onshore (Leg 150X Cape May) and on the continental slope (Leg 150) of New Jersey showing core and seismic expressions of a basal Miocene (m6) sequence-bounding unconformity. Note that the region most critical to sea-level and sedimentary three-dimensional structure studies (around proposed sites MAT 1-3) has not yet been drilled because the shallow water depths involved require mission-specific drilling platforms. Figure courtesy of Kenneth G. Miller, Rutgers University, and Gregory S. Mountain, Columbia University.

canism is related to the onset of glaciation is unknown. To establish whether there was a volcanic output-climate link then, and at other times throughout Earth's history, IODP will drill downwind from important volcanic centers, and then integrate the information from the drill cores into climate models.

- **Sea-level change:** Sea level divides our planet into fundamentally contrasting realms, land and sea. Change in the position of this dynamic boundary has occurred throughout geologic time, affecting nearshore ecosystems, material and chemical balances between the land and sea, and the global climate system. Sea-level variation has exerted a major control on the three-dimensional sedimentary architecture of continental margins, with important consequences for the occurrence and migration of fluids, including both hydrocarbon and water resources. ODP drilling has provided a chronology of baselevel lowerings for the past ~42 m.y., linked these lowerings to global sea-level drops caused by the growth of ice sheets (glacioeustasy), and has made progress toward estimating the rates of eustatic change.

Despite these advances, amplitudes of sea-level change remain poorly constrained, mechanisms that control sea level globally and regionally are contentious, and the response of sedimentary architecture to sea-level change has been determined only for short time intervals on selected margins. Amplitudes can best be estimated by locating boreholes in critical nearshore locations that have proved difficult to drill with the *JOIDES Resolution*. This inability to drill in shallow water has hampered efforts to evaluate sequence stratigraphic architecture under a variety of tectonic, eustatic and sedimentary settings (Figure 18). Though ODP proved that many sea-level changes have a glacioeustatic origin, the causes of large, rapid global sea-level change prior to ~42 Ma remain speculative. Available data cannot determine whether pre-42 Ma variations occurred synchronously around the globe (implying a mechanism driving planetary sea level) or were the result of local processes (tectonism, sediment supply, etc.). Various studies suggest that tectonism, not ice volume, is the most important control on global and regional sea-level change. Evaluating causal mechanisms requires dating margin sequences in different tectonic and sedimentary settings, a goal that has not been attained because of drilling platform limitations. To address these fundamental scientific issues, IODP will use the non-riser drilling vessel in outer shelf-slope settings and, most importantly, use mission-specific platforms to drill on shallower parts of continental shelves.

- **Organic, carbon-rich sediments and greenhouse anoxia:** Understanding the factors that lead to the development of sediment- and water-column anoxia and the origins of associated organic, carbon-rich sediments has long been a goal of scientific ocean drilling. DSDP and ODP drilling results have provided insights into the influence of climate on marine eutrophication and into the origins of petroleum source rocks. Central to these studies has been a debate as to the relative importance of high marine productivity versus water column stratification and stagnation. Many Mesozoic black shales and

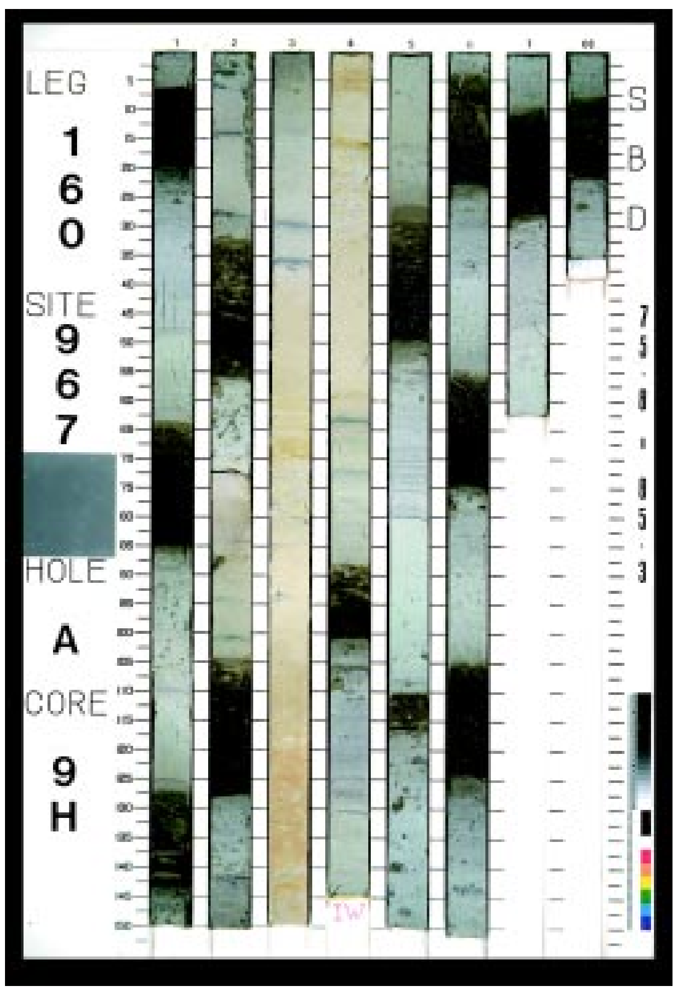


Figure 19. Regular sapropel intervals (black) in background pelagic sediments (white-gray) from eastern Mediterranean ODP Leg 160, Site 967. Photo courtesy of Ocean Drilling Program.

younger anaerobic deposits, such as the sapropels of marginal basins (e.g., the Mediterranean Sea), appear to originate from a combination of enhanced nutrient input, consequent elevated productivity of organic-walled plankton, and water column stratification (Figure 19). A major concern in the modern marine environment is the anthropogenically driven eutrophication of coastal and shelf areas. These conditions lead to anoxia, death of the benthic biota, and significant deterioration of water quality (e.g., anoxia in the Adriatic driven by Po River effluent, and in the Gulf of Mexico resulting from Mississippi River effluent).

Analysis of marine sediments provides information on how anoxic events affect the ocean biota and how areas recover when oxygenated conditions return. The most pervasive of the Cretaceous anoxic events (at 120 and 93 million Ma) were global in extent and imply a whole-ocean process that impedes the breakdown of organic matter and results in abnormally high carbon burial. The most extreme event at the Cenomanian-Turonian boundary (93 Ma) appears to have coincided with maximum Cretaceous temperatures, the highest of the last 115 m.y., and with a positive carbon-isotope excursion associated with excess biogenic carbon burial. Cooling immediately postdating this event was probably initiated by the drawdown of CO_2 associated with this sequestration of organic carbon. These periods of enhanced carbon burial represent extreme behavior of the ocean-atmosphere system during times of exceptional global warmth. IODP will complete a global array of drill sites that sample anoxic events in depth transects, allowing scientists to evaluate their character and cause. IODP samples and analyses will provide needed information about the sensitivity of Earth's system to extreme climate and the processes that drove the world's oceans to anoxia during warm intervals (see Extreme Climates Initiative).

- **Transient climate episodes:** High-resolution climate records obtained from analysis of marine sediments have revealed extreme, "transient" (hundreds to hundreds of thousands of years in duration) climate episodes that likely result from rapid shifts in the climate system in response to an internal feedback or external forcing mechanism. The extreme warm transients include the late Paleocene Thermal Maximum (LPTM, ~55 Ma) and perhaps several events associated with the Cretaceous anoxic events. The cold transients include the early Oligocene (~34 Ma) and Oligocene/Miocene boundary (23.7 Ma) glacial maxima. In several of these cases, these brief climate extremes appear to have triggered major evolutionary pulses in the biota.

At least some of the warm transients appear to have been the result of geochemical feedbacks involving marine carbon reservoirs. For example, the LPTM, which is characterized by a global warming of 2-3°C and 5-7°C of high-latitude warming, was accompanied by a global carbon isotope excursion of -3 per mil over a period of less than 20,000 years. Ocean carbon-isotope values returned to normal in about 170,000 years, approximately the residence time of carbon in the ocean. Methane is greatly depleted in ^{13}C relative to the ocean or atmosphere, and one explanation for the very large isotopic signature of this event is the injection of an immense quantity of CO_2, derived from the oxidization of methane gas hydrates or other hydrocarbon sources, at rates approaching (or exceeding) those of fossil fuel inputs at present. Evidence from benthic foraminifera indicates that at least part of the methane was oxidized within the oceans, causing depletion of dissolved oxygen and the largest deep-ocean extinction event of the Cenozoic.

Regardless of source, such large and sudden inputs of carbon into the ocean/atmosphere system should have profoundly affected both atmospheric CO_2 content and ocean carbon chemistry. In particular, geochemical models show that with such a sudden pulse of CO_2, initially the ocean's pH would drop and calcite shells would dissolve at shallower depths. The ocean pH and alkalinity balance would recover within 170,000 years via chemical weathering of silicate rocks and deposition of inorganic and organic carbon. Part of IODP's Extreme Climates Initiative will seek a better definition of this particular event as well as similar events thought to have occurred in the Cretaceous, as well as a more complete evaluation of their global impact.

External Forcing of Environmental Change

- **Climate system interaction with orbital forcing:** A major ODP achievement has been to document a distinct orbital influence on the oceanic environment through much of the Cenozoic. One new use of this knowledge will be to develop an orbitally tuned time scale for the entire Cenozoic that will significantly enhance the temporal resolution of Earth history and aid in studies of paleoclimate, geochemical cycling and biologic evolution. The importance of this cannot be overstated. Despite a significant and growing understanding of how orbital variability affects the various Earth systems, important questions remain.

About 750,000 years ago, Earth's climate system changed dramatically from a regime of dominant 41,000-year cycles to one of much larger amplitude, 100,000-year cycles (Figure 20). Curiously, the orbital parameters thought to pace climate change (eccentricity, tilt and precession) do not vary significantly across this transition in the climate system. The cause of the observed change in the response

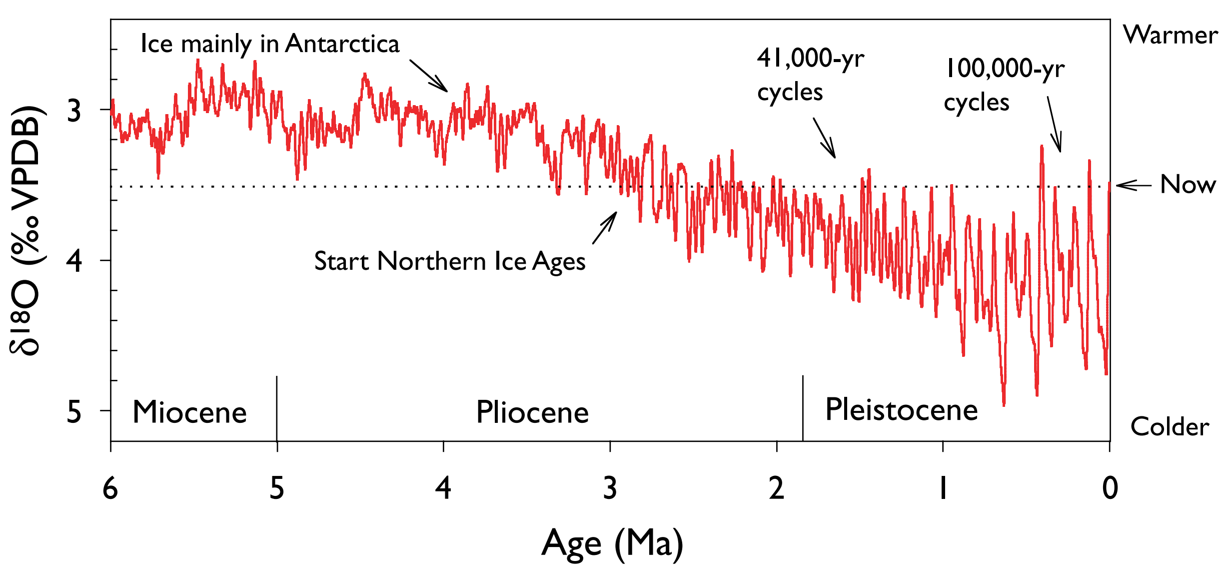


Figure 20. Benthic foraminiferal oxygen isotope record from an eastern equatorial Pacific site (ODP Site 849) for the past 5 m.y. Note the overall trend to more positive values (colder or more ice volume) starting about 4.2 Ma. Changes in the character of variation occur at several places through the record, but especially at about 0.75 Ma. Figure courtesy of Alan C. Mix, Oregon State University.

of Earth's system to orbital forcing remains a mystery, but it must involve a change in sensitivity of, or feedbacks within, the climate system. Thus, this event, in addition to similar ones within the Cenozoic, serve as a natural experiment to help us determine the controls of orbitally induced climate change. Each shift in climate's spectral character represents a separate experiment under differing boundary conditions. Several possible explanations for such spectral shifts have been proposed. When the ice sheets exceeded a certain size, they might have amplified orbitally forced climate oscillations at longer periods. Perhaps other parts of the global system were involved, such as tectonic changes that altered the sensitivity of the system, or changes in the deep sea that modified either the carbon cycle or Earth's heat distribution. IODP will test these hypotheses by using newly developed time-scales, and recovering more complete sections globally.

The earlier Cenozoic record of climate change provides a specific opportunity to test models of climate with and without large polar ice sheets, as well as with substantially different oceanic, atmospheric and orographic boundary conditions. These several different worlds offer a key to understanding how orbital variations interact with a wide range of surface boundary conditions to produce a climatic "state." IODP will recover the continuous sequences of deep-sea sediments from these ancient times that are needed for such tests.

- **Impact Events:** Over 150 impact craters of varying size have been identified on Earth; the largest is the 180-km diameter Chicxulub crater beneath Yucatán. The Cretaceous/Tertiary (~65 Ma) boundary impact event that created this extremely large crater has been intensively investigated (Figure 21), but considerable uncertainty remains as to the environmental and biological perturbations caused by it. We have even less understanding of the environmental effects of smaller events, such as the late Eocene (~35 Ma) Chesapeake Bay impact. Understanding the environmental and biotic effects of impact events must involve investigation on a variety of temporal scales over which the Earth system responds.

There are many related and outstanding questions about the effects of impacts. We do not understand the exact "killing" mechanism for impact events. Why are some species more sensitive to extinction than others? Extinction of a given species could result directly from the environmental perturbation caused by the impact itself, or perhaps that species was just more susceptible to extinction at the time of the impact. Large impacts clearly cause a major change in oceanic and terrestrial biogeochemical cycling that can last for millions of years, but we need to constrain the exact primary and secondary effects of impacts on oceanic nutrient cycling and how these influence the recovery of faunal and floral groups. The highest quality records of these events reside in the ocean. IODP plans to recover the continuous records needed to document the changes in the environment and in marine life forms that occur in response to impact events.

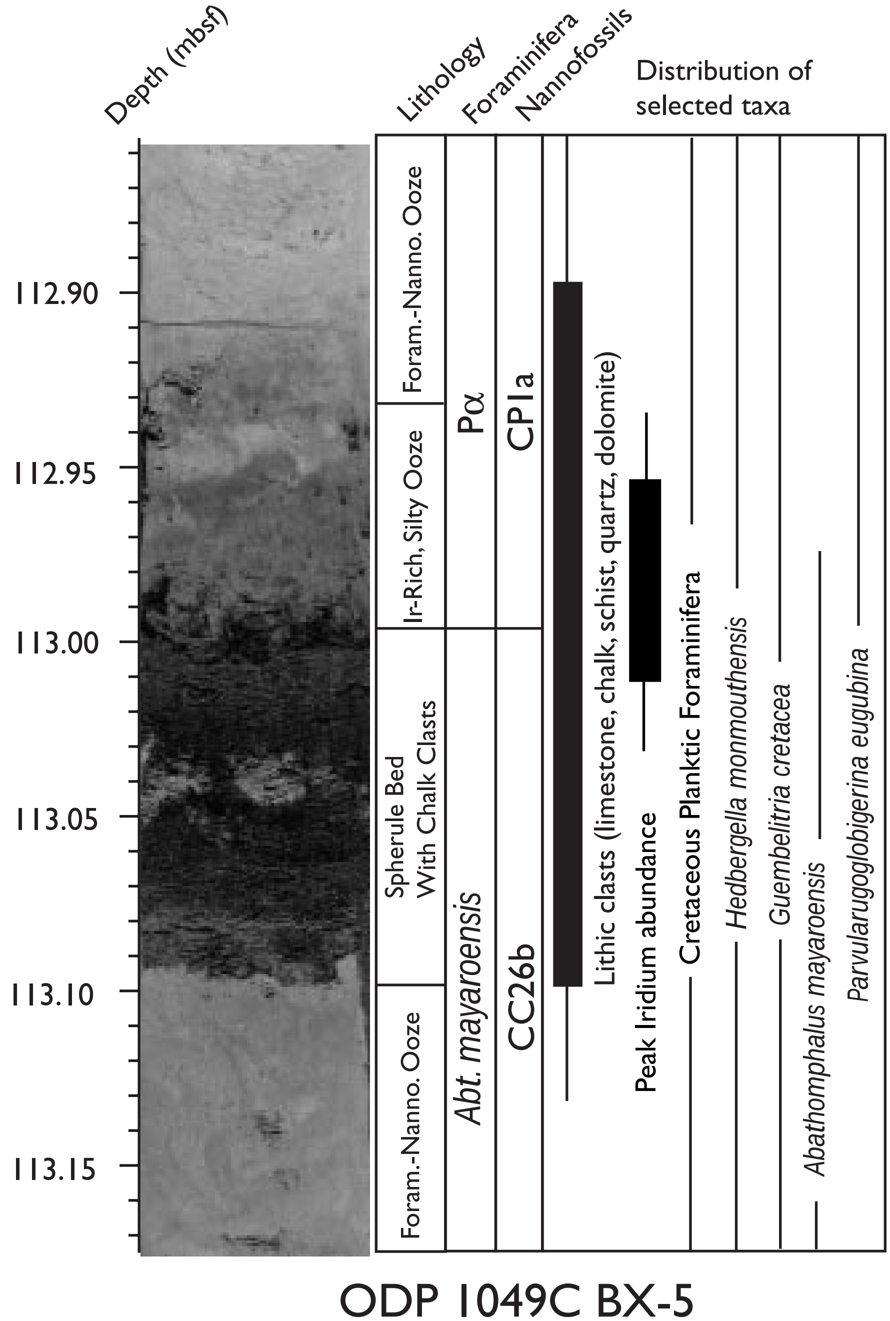


Figure 21. Cretaceous/Tertiary (~65 Ma) boundary at ODP Site 1049 on South Carolina's Blake Nose, ODP Leg 171B. Illustration shows lithology, planktic foraminiferal and nannofossil zones, distribution of impact-derived materials and ranges of critical planktic foraminiferal taxa. This interval represents a well-preserved record of one of the most dramatic events in Earth history. Figure courtesy of Richard Norris, Woods Hole Oceanographic Institution.

Environmental Change Induced by Internal and External Processes

One of the most important scientific discoveries of the past two decades, based initially on ice-coring efforts in Antarctica and Greenland, is that climate is capable of changing very rapidly (within decades) and can remain in the new or altered state for several thousands of years. Ocean drilling has now recovered sections worldwide which record these climatic events with a resolution equal to or better than the ice cores, and which extend much further back in geologic time than ice sheets. With such detailed records we can begin to explore both the temporal and spatial distribution of climate shifts and oscillations, as well as the processes, feedbacks and internal and external forcing mechanisms that lead to relatively short intervals of altered climatic states. We know that the pacing of the shift from full glacial to interglacial climates is driven by changes in Earth's orbital parameters. We suspect that these 20,000 year (and longer) cycles might feed into higher frequencies of climatic fluctuation. Although we suspect that internal processes (e.g., sea level, volcanic activity, mountain building) may alter the way Earth's climate system responds to oscillatory forcing, we do not fully understand why the climatic sensitivity to external process (principally orbital cycles) seems to change, or evolve, with time. Similarly, we know that there are natural, quasi-periodic, internal oscillations in Earth's climate system with periods of one or two decades. We do not know, however, if there are longer periods at which Earth's climate system naturally oscillates. We also have little understanding of the interaction between external forcing mechanisms, such as orbital variability or small changes in the solar constant, and the natural internal oscillations that exist in the climate system.

The multi-proxy record preserved in deep-sea sediments is the key to exploring the nature of climate change. Biological, mineralogical and geochemical components of marine sediments record surface-ocean conditions such as temperature and biologic productivity, as well as deep-ocean conditions such as the chemical "age" of the deep-water mass overlying the seafloor. Within the same samples, the sedimentary components delivered by winds indicate the source region for this dust, its likely degree of aridity, and the strength of the winds that delivered the dust. Many new proxy indicators of the atmosphere's CO_2 content and the ocean's pH are now being developed and tested. All of these components can be tied into a global stratigraphy. Most importantly, as these components of the marine sediments vary with time in response to climate change, we can determine which component changed first, second and so forth through the entire gamut of proxy indicators of climatic and oceanographic conditions. Applied to a global distribution of high-resolution core samples, we can use the order of change in this multi-proxy record to deduce the most likely forcing mechanisms and feedbacks. Only through evaluating the relative timing of these changes and knowing their geographic extent are we going to be able to understand the origin and means by which rapid climate change propagates around the globe. This global multi-proxy approach is made possible only by scientific ocean drilling.

- **Millennial-scale climate events and abrupt ocean circulation change:** Evidence from ice and sediment cores shows that the last glacial cycle was punctuated at 1,000 to 3,000 year intervals by rapid fluctuations in air and sea temperatures in the North Atlantic region, some of which were synchronous with massive melting and iceberg discharges. Recent scientific ocean drilling has shown that over at least the last 500,000 years such rapid events in the ocean are widespread (Figure 22), however, the global and regional impact of events now reasonably well know in the North Atlantic remains uncertain. Rapid transmission of these North Atlantic events beyond the region where icebergs melt implies a strong atmospheric link in the climate change process or abrupt changes in large-scale ocean circulation and associated heat transport. Several mechanisms are now being considered, and the available data allow several hypotheses to be proposed. For example, proxy temperature records show periods of long-term cooling followed by abrupt warming, often within decades. Water freshening at high latitudes by ice-sheet melting or by change in atmospheric water vapor transport may have gradually diminished thermohaline circulation strength, reducing northward, surface-ocean transport of heat. A rapid return to strong thermohaline circulation may have caused the abrupt warming observed in northern Europe; analogous temperature changes are also recorded in the tropics, but it remains unclear whether the trigger for such events lies in the high or low latitudes. The global significance of these events is highlighted by their apparent transmission, within decades, to the North Pacific (Figure 23). Such millennial-scale variability is not just a characteristic of glacial intervals, but also persists into the relatively ice-free Holocene. For example, cooling episodes such as the "Little Ice Age" of the 1600s to 1800s have been linked by some scientists to a change in North Atlantic circulation.

A global array of sites from high-accumulation-rate marine sediments is required to provide multi-proxy records that can advance the understanding of the origins and hemispherical or global transmission of these events (see Rapid Climate Change Initiative). Key targets include basinal deposits that contain the debris from melted icebergs, sediment drifts for which grain size and other physical properties directly record the changing speed and fluctuations of the thermohaline conveyer belt, and remote basins and sequences where sensitivities and thresholds (*e.g.*, to changing temperatures or oxygen content) record the global transmission of the events.

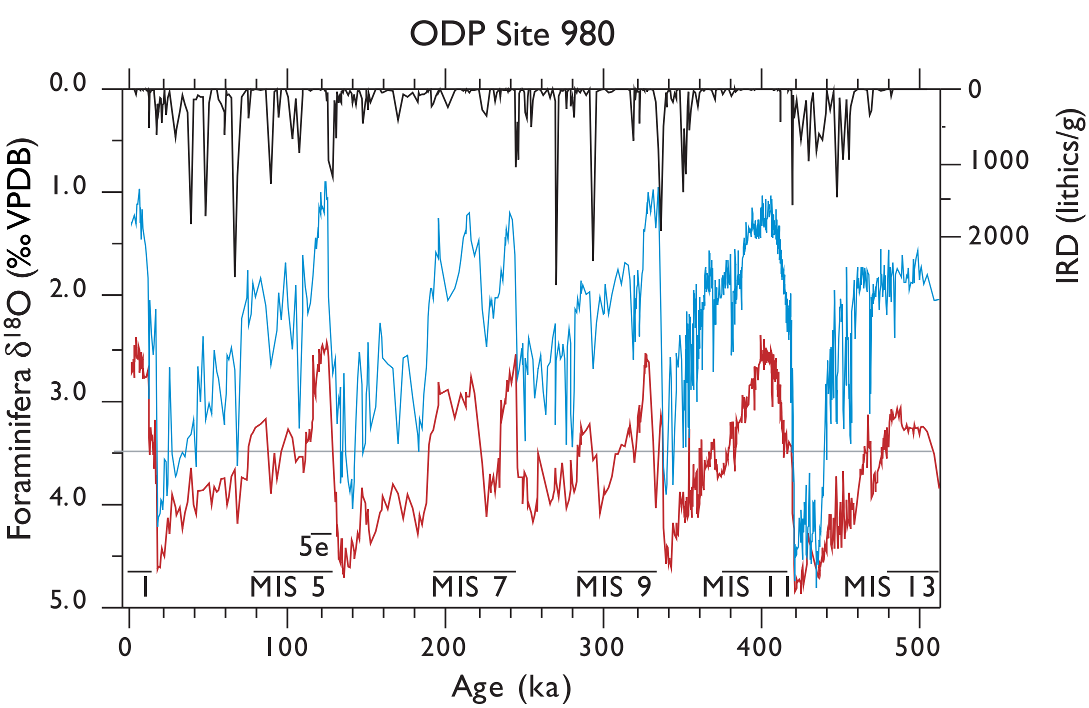


Figure 22. Oxygen isotope data (red and blue lines) and concentration of ice-rafted debris (IRD, black line) from ODP Sites 980 (North Atlantic Ocean) reveal the link between rapid (millennial scale) climate changes and icebergs. Frequent oscillations in iceberg abundance are thought to reflect unstable surges of ice from large ice sheets (similar to those present in Antarctica today). Figure courtesy of Gerald McManus, Woods Hole Oceanographic Institution.

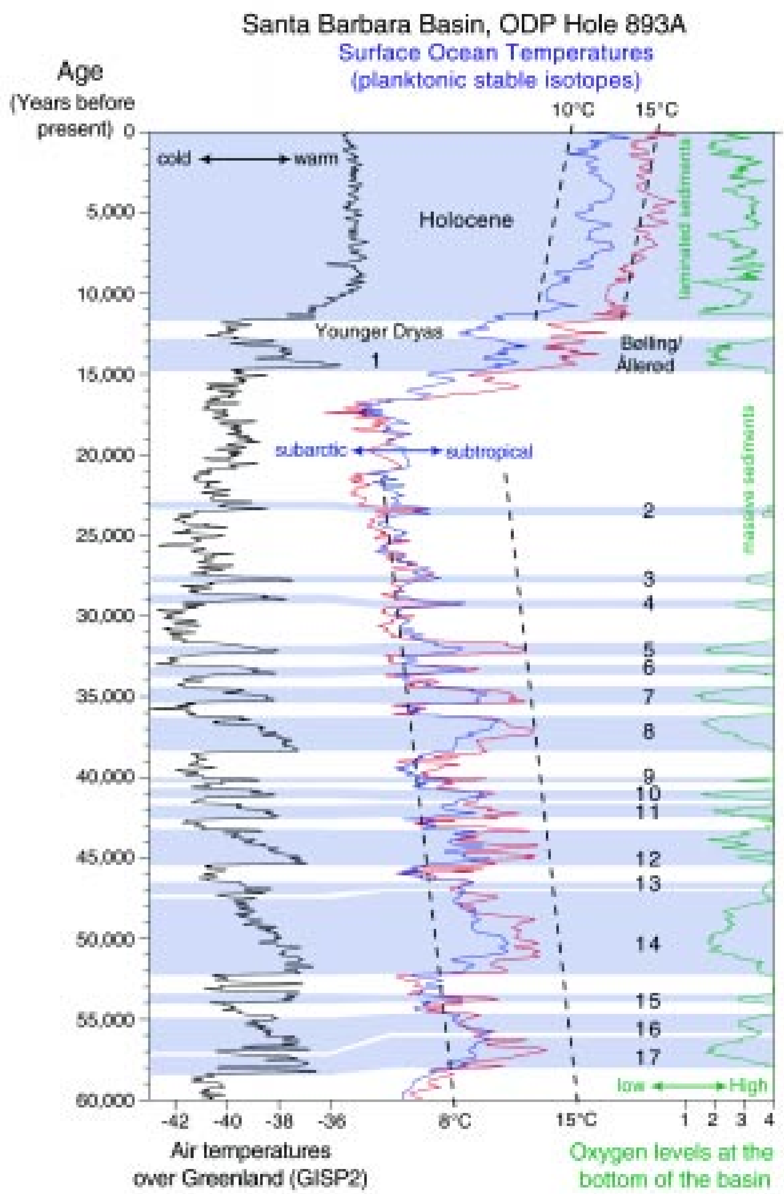


Figure 23. Oxygen isotope, planktonic foraminifera species abundances, and bioturbation index (1 indicates laminated sediment and 4 indicates massively bioturbated sediment) from ODP Site 893 in the Santa Barbara Basin. Data reveal millennial scale climate events in this eastern Pacific site that can be correlated to climate changes recorded in the Greenland ice core (GISP 2) data set and require a direct link between climate events in the high latitudes of the North Atlantic and surface and intermediate waters of the Pacific. Figure courtesy of Ingrid Hendy and James Kennett, University of California, Santa Barbara.

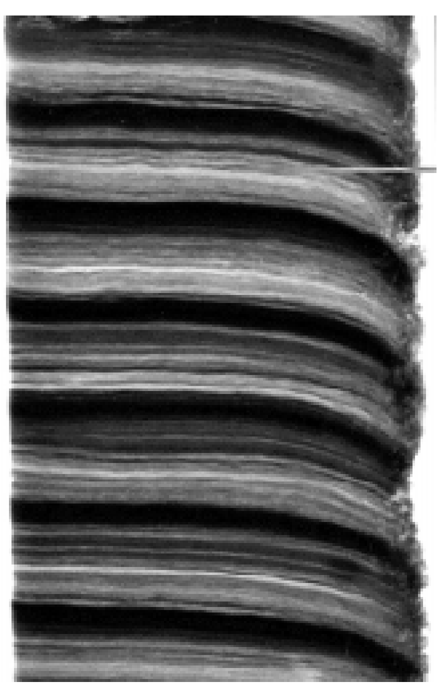
- **Decadal-scale climate variability:** The El Niño-Southern Oscillation (ENSO) dominates ocean and atmosphere inter-annual variability in the tropical and subtropical Pacific and influences global climate. ENSO varies in frequency and strength, and the predictability of this system and its impact on a global scale depend on understanding these variations.

  ENSO is only one of the internal ocean oscillation modes that affects climate. Fluctuations in the North Atlantic Oscillation (NAO) index depict a broadly decadal-scale variation in atmospheric pressure distribution over the North Atlantic, producing changes in the strength of winter westerlies and storm tracks, which result in periods of relatively colder or milder winters. Change in the NAO index is linked to North Atlantic surface circulation and fluctuations in the generation of North Atlantic

Deep Water, the key driver of the global thermohaline circulation. An equally complex oscillation occurs in the North Pacific, however, the period of change is longer at about 20 years. Similarly, observations document decadal-scale oscillatory character in the extent of sea ice around Antarctica. We know very little about how these various internal oscillations of Earth's system interact, nor do we know if they resonate with some of the weaker, external-forcing factors.

Ultrahigh resolution (sub-annual to centennial scale) marine sedimentary records provide an opportunity to evaluate the operation of the ocean-atmosphere system globally, and on human time scales. A particularly fine example of a marine core providing sub-annual climate information is the varved sequence recovered by ODP from Saanich Inlet off Vancouver Island (Figure 24a). Recovery of additional long and complete cores of varved sediments and coral growth-bands (Figure 24b) by drilling may shed light on why and how the whole climate system responds to external and internal forcing and how different oscillation modes may interplay over hundreds to thousands of years (see Rapid Climate Change Initiative). Progress toward a better understanding of decadal-scale climatic change also requires an ability to recover—routinely, safely and completely—laminated sequences where sediments accumulated rapidly, for example, from deep-sea drifts, from shallow continental margins and from marginal basins. Hydraulic piston coring from IODP's non-riser drilling vessel and the use of mission-specific drilling platforms will allow recovery of the requisite high-resolution records.

Figure 24a. An X-ray radiograph of a core from ODP Site 1034 showing the sub-annual detail available from six years of the seven thousand-year Holocene laminated sediment record recovered from Saanich Inlet. Figure courtesy of Brian Bornhold, Geological Survey of Canada, and John Firth, ODP/Texas A&M University.



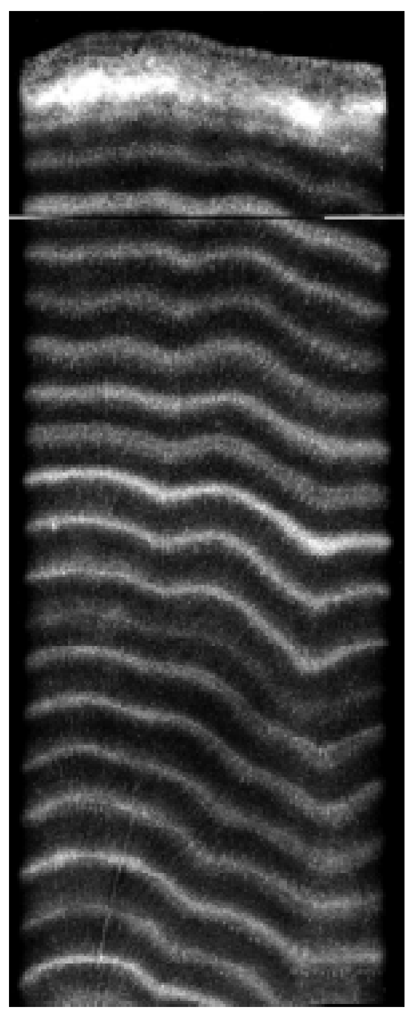


Figure 24b. The image to the left is of a 75 mm core through a massive coral colony from Papua New Guinea. The core was photographed under long-wavelength UV light to reveal annual fluorescent banding (bright bands indicate wet season; dark bands indicate dry seasons). These annual growth rings provide proxy records of tropical climate at sub-annual scale resolution, and are just one type of annual banding in corals. Figure courtesy of Sandy Tudhope, University of Edinburgh.

Initiative: Rapid Climate Change

One of the most striking results of recent paleoclimate research has been the determination that climate can change abruptly across the globe (Figure 23). For example, during the last glacial cycles, jumps between warmer and colder states occurred within decades, and these jumps were often associated with alterations in ocean circulation patterns.

Records of "natural" rapid climate change provide an indispensable context for evaluating contemporary anthropogenic inputs to the environment. The timing and distribution of the present warming trend may match those of previous times, or they may differ in some way explainable only by anthropogenic forcing. Such comparisons are greatly facilitated by recovery and use of detailed marine sedimentary records with resolutions approaching those of instrumental records. Laminated marine sediments may combine histories of seasonally generated productivity and runoff from coastal precipitation, resulting in an ultra-high-resolution, multi-proxy record of past environmental conditions (Figure 24a). Massive corals growing in tropical reef ecosystems represent natural biological climate recorders that contain proxy records at annual resolution, including past sea-surface temperatures (Figure 24b). Deep-sea sediment drift deposits may also provide critical information on changing deep-sea circulation at decadal to centennial resolution. Currently, the sedimentary record of the Arctic Ocean is essentially unknown, yet has the potential to advance our knowledge of rapid climate change processes enormously. Finally, there is an opportunity to cooperate with the International Continental Drilling Program (ICDP) in planning the development of a global array of high-resolution records from marine and lacustrine settings that will provide detailed proxy records of both marine and continental climate change. Records of such high temporal resolution are critical to our appraisal of the relative importance of the atmosphere and ocean in the global transmission of climate change. A full understanding of the causes and consequences of rapid climate change requires recovery of a global array of high-resolution cores spanning different time intervals. Only IODP will have the capability to penetrate far enough into rapidly accumulating sediment piles, with large enough core diameter and high-quality core recovery, to provide the materials needed for study. IODP's new and more flexible drilling strategy, including use of mission-specific drilling platforms, will open previously inaccessible regions to sampling, such as the ice-covered polar oceans and shallow water sites.

The Role of Multiple Platforms in Exploring Environmental Change

The processes that drive environmental change, and effect climates of extreme cold and warmth, take place on a variety of time scales. Their elucidation thus requires sediment recovery using a variety of drilling strategies. At the ultrahigh resolution end of the spectrum, annual layering such as varves or coral growth bands is critical to our understanding of climate change on human time scales. Recovered records should extend back at least to the last glacial interval to capture rapid shifts in climate that have been documented in ice cores and in varved marine records. These high-resolution marine records tend to occur in settings close to continental margins such as anoxic basins (including fjords), and on atolls and carbonate platforms. In deeper water settings, the non-riser drillship with heave compensation can recover relatively complete varved records using ODP's Advanced Piston Coring technology. Recovery of sections in extremely shallow water will require drilling platforms designed specifically for those water depths.

The best records of millennial and even centennial-scale paleoenvironmental events are recovered in rapidly accumulating sediments that are found in a wide variety of water depths, from nearshore deltaic or slope deposits to deep-sea sediment drift deposits. For drift deposits, the non-riser drillship is ideally suited to recover complete sections. In the more shallow water environments close to continental sediment sources, mission-specific platforms are required to recover completely high-resolution records of environmental change, containing both marine and terrestrial proxy indicators. The choice among using the non-riser drillship, the riser drillship or a mission-specific platform to acquire these high resolution records hinges on water depth restrictions and safety considerations (whether or not well control is required). In some cases a combination of platforms may be required to recover fully high-resolution records.

The general characteristics of long-term global climate evolution over the past 100 million years or so have been mapped out with cores recovered by the *JOIDES Resolution*, ODP's non-riser drillship. To go beyond merely refining this global history and to develop more detailed regional histories, other drilling platforms must be brought into play. For example, understanding the relationship between regional tectonic uplift, orography and climate may involve drilling through and recovering thick sections of terrigenous material shed from continents. Such deep holes will require the well control available only with a riser vessel, and will be greatly aided by the development of well control technology to depths of 4 km. The combination of casing and recirculating drilling muds of varying weight will allow the stabilization and cleaning of holes required for penetration far beyond what has been achieved with the *JOIDES Resolution.*

To explore the environmental history of the Arctic Ocean will require mission-specific platforms capable of drilling in ice-covered waters. To date we have recovered only three, relatively short cores that sample Arctic basin sediments which predate Northern Hemisphere glaciation. These cores hint at an ice-free Arctic with intervals of high biological productivity and organic carbon preservation. Other than these two spot samples of climatic extremes, the detailed climate history of this region remains unknown.

The search for a better understanding of eustasy, regional sea-level histories, and the roles they play in developing the depositional architecture of continental margins, has fostered major scientific research efforts over the past few decades. Investigations of this problem using the *JOIDES Resolution* have been only partly successful. Failures have been ascribed to the inability of the *JOIDES Resolution* to drill in very shallow waters, to drill deeply into very thick continental margin sedimentary sections, and to adequately recover the sections drilled. IODP's multiple-platform drilling strategy will permit mission-specific platforms to drill deeply and safely in very shallow waters, the riser-equipped drillship to drill deeply and safely in deeper waters, and the non-riser drillship to drill some of the thinner, deeper water sections. This combination of platforms is an excellent example of an integrated offshore drilling program that can be fully linked to onshore drilling efforts (see Collaborations section).

Solid Earth Cycles and Geodynamics

Convection in Earth's outer core is responsible for generating Earth's magnetic field, and for providing a potentially important source of heat to drive mantle convection, possibly including deep mantle plumes. Mantle convection, in turn, causes motion of the rigid lithospheric plates that form Earth's rigid outer "skin." The plate tectonic processes associated with mobility of the lithospheric plates control creation of new crust and uppermost mantle at both divergent and convergent plate boundaries, and cause recycling of old crust and mantle lithosphere at subduction zones (Figure 1; Figure 25). The relatively steady-state plate tectonic processes coexist with a less-understood group of deep mantle processes that result in massive, episodic magmatism at Earth's surface. These deep-mantle processes in turn might affect the boundary conditions for outer core convection, with possible influences on Earth's magnetic field. Intriguing and as yet unexplained relationships may exist between the frequency of change in the polarity of Earth's magnetic field and major geodynamic events. A more complete understanding of the variability of Earth's magnetic field through time, in both magnitude and direction, is an important component of drilling studies of the Earth system.

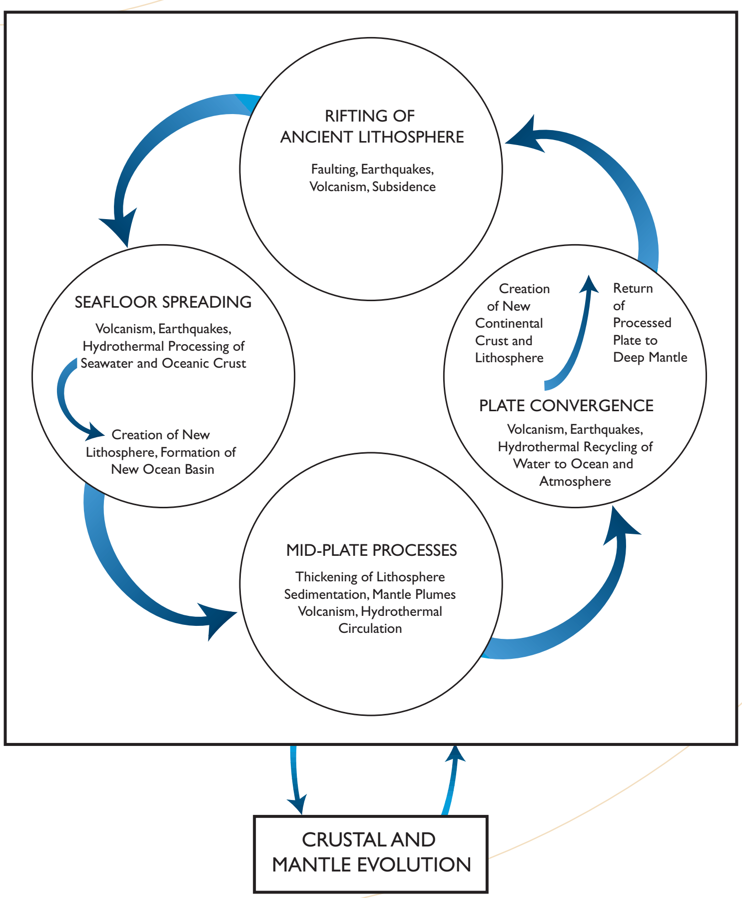


Figure 25. The solid Earth cycle involves the breaking apart of continents and birth of oceans, the creation, evolution and recycling of oceanic and LIP lithosphere, as well as the creation of new continental lithosphere. The recycling of plates in the subduction zone is counterbalanced by the upwelling of mantle plumes, leading to the differentiation of the mantle.

Increasing evidence suggests that mantle dynamics and lithosphere recycling play a role in environmental change and natural resource accumulation. Large-scale magmatism and variations in its nature appear to profoundly affect Earth's environment, but neither the details of this coupling, nor the magnitude, history or cause of variations in mass flux from Earth's interior, are well understood. Solid Earth cycles and their influence on surface processes, including sedimentation, drainage patterns and fluid flow, also largely determine where important resources such as hydrocarbons and mineral deposits form. IODP will use its spectrum of drilling platforms and technologies to address the extent to which solid Earth cycles and geodynamics interact with Earth's environment to induce change and influence mineral deposition.

Understanding solid Earth cycles and geodynamics provides a compelling scientific rationale for the new technology incorporated into IODP's deep-objective, riser-based drilling capabilities, particularly in water depths of 4 km and more. Coordinated efforts between IODP and the International Continental Drilling Program (ICDP) will allow us to undertake studies across continental margins representing depths of 10 km or more, revealing the processes associated with rifting, continental breakup, and volcanic passive margin development. Sampling a complete *in situ* section of oceanic crust into the uppermost mantle for the first time will reveal the anatomy of entire oceanic crustal section and the processes associated with its aging. Drilling into Large Igneous Provinces (LIPs), both along continental margins and in intraoceanic settings, will elucidate the processes controlling episodic mass and energy fluxes from Earth's mantle, resulting in extensive mantle melting under a wide range of pressure and temperature conditions. Drilling LIPs also offers the potential to recover records of Earth's magnetic field that are needed to understand the frequency and nature of paleointensity changes and their possible relation to changes in climate and biological development. On shorter time scales, deep-Earth processes associated with solid-Earth cycles and geodynamics cause major natural hazards—earthquakes, tsunamis and explosive volcanic eruptions. An important initial IODP riser-drilling focus will be to seek answers to the numerous scientific questions involving the nature of and processes associated with the earthquake rupture (seismogenic) zone beneath the heavily populated convergent margin offshore eastern Japan.

Formation of Rifted Continental Margins, Oceanic LIPs and Oceanic Lithosphere

- **Processes of rifted continental margin development:** In principle, the plate tectonic cycle begins with divergence between lithospheric plates, first manifested by rifting and associated thinning of continental lithosphere (Figure 26). As divergence continues, continental lithosphere is traditionally envisioned to eventually thin and weaken to a point at which lithospheric mantle can ascend, decompress and partially melt. Subsidence associated with rifting and breakup results in the formation of sedimentary basins, which develop during the entire interval from earliest rifting to post-breakup. From a geodynamics perspective, rifting and continental breakup represent a large natural experiment involving the rheology of the continental lithosphere and the response of the underlying asthenosphere. By drilling and coring the geological records of deformation patterns, rates of deformation and associated magmatism on both sides of the breakup axis, namely the conjugate margins, we can better understand the processes controlling temporal and spatial variability of rifting, and how rifting ultimately transitions to seafloor spreading. With *in situ* measurements and by long-term monitoring of active rifting and fault mechanics, we can obtain information on rock deformation that applies to shorter time scales and spatially smaller domains than the entire zone of rifting. Then, by combining results from the rock record with *in situ* studies of active processes, we enhance our understanding of long-term rift devel-

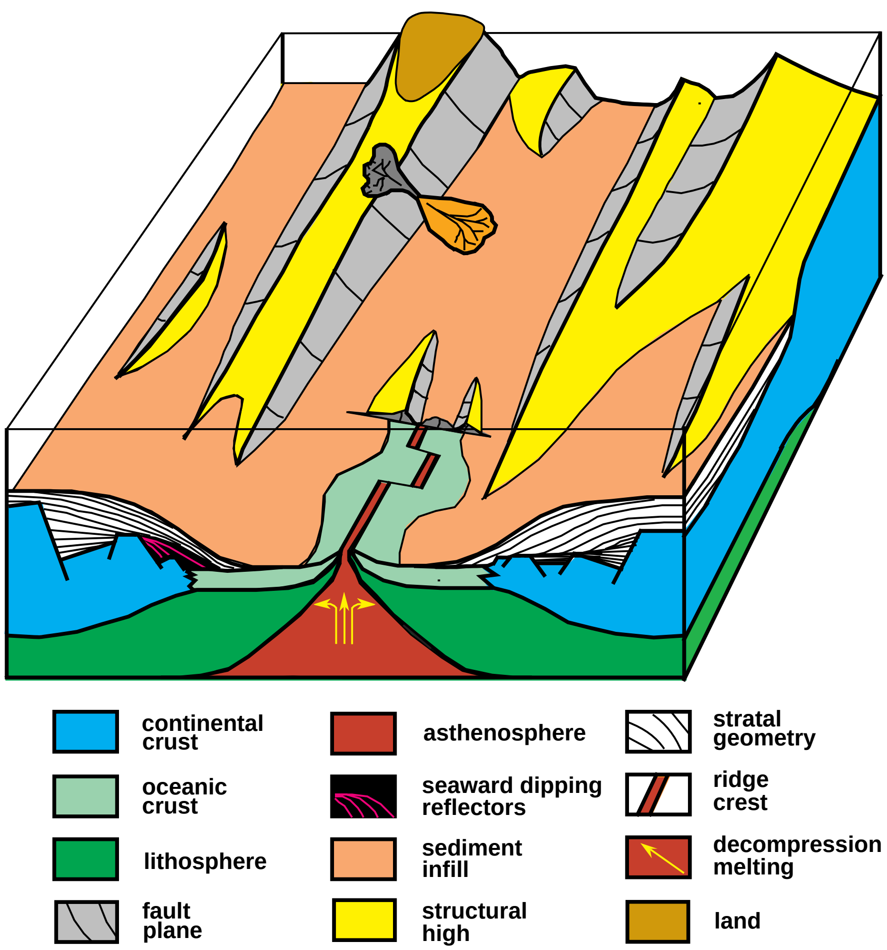


Figure 26. Synthetic view of the processes that rupture continental lithosphere and lead to the formation of rifted margins, associated sedimentary basins, and ultimately to formation of oceanic lithosphere. Drilling at various water depths, at shallow or deep penetration, and with or without a riser is one major component of a full suite of approaches (including 4-D imaging, long-term monitoring, geodetic studies, laboratory experiments, and modeling) that improve our understanding of rifting processes. Figure from Coffin, M. et al., EOS Transactions of the American Geophysical Union, 1998.

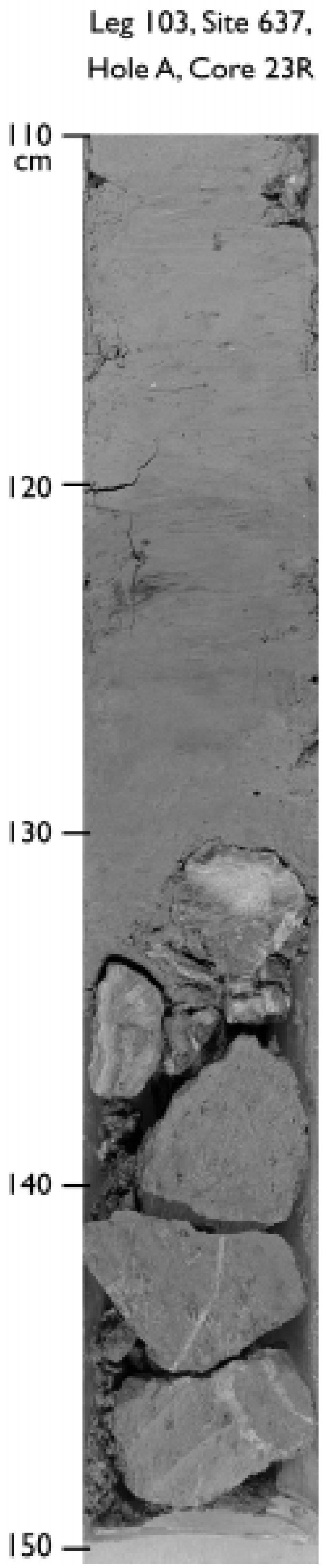


Figure 27. Contact between sediment and peridotite from the Iberian non-volcanic margin, ODP Leg 103, Site 637. This is the extreme end member of amagmatic seafloor spreading; mantle rock apparently forms the entire oceanic crustal section in the absence of partial melting. Figure courtesy of Gilbert Boillot, Observatoire Oceanologique.

opment and dynamics. Furthermore, the effects of tectonic controls on rifted-basin formation, evolving source and drainage areas, and the increasing influence of eustatic sea-level changes as open shelf-slope-rise basins eventually develop are all crucial to basin analysis and assessment of natural resources.

ODP results reveal that when continents break up, new ocean basins begin to develop in two distinctly different ways. Along some divergent continental margins, even moderate extension and thinning of continental lithosphere (original plate thickness ca. 100 km) permit melting of underlying asthenosphere if it is sufficiently warm or wet. Widespread volcanism may develop prior to the final separation of continental lithosphere of the diverging plates. As the plates finally separate, the mantle can ascend to shallower levels, decompress and melt further. Consequently, the initial igneous crust along such margins can form at anomalously shallow levels, at or near ambient sea level, and is two to four times thicker than normal oceanic crust. This thick igneous crust is continuous with adjacent continental flood basalts along many margins, and constitutes the fundamental characteristic of a volcanic rifted margin type of LIP. In sharp contrast, along other rifted margins, continental lithosphere may thin well beyond the point at which ascending normal mantle would begin to melt, but only negligible amounts of asthenosphere melts. Instead, reaction of sea water with mantle exposed at or near the seabed following plate separation transforms the mantle into mechanically weak serpentinite (Figure 27). Along both volcanic and non-volcanic rifted margins, oceanic crust of normal ~7 km thickness eventually forms. IODP's new drilling platforms will allow recovery of sequences that record the tectonic and magmatic processes controlling the development of rifted continental margins. These sequences lie at depth, beneath previously inaccessible shallow water regions and in areas prone to containing hydrocarbons. New IODP long-term monitoring and *in situ* measurement technologies will contribute significantly to the understanding of rifting mechanics and dynamics.

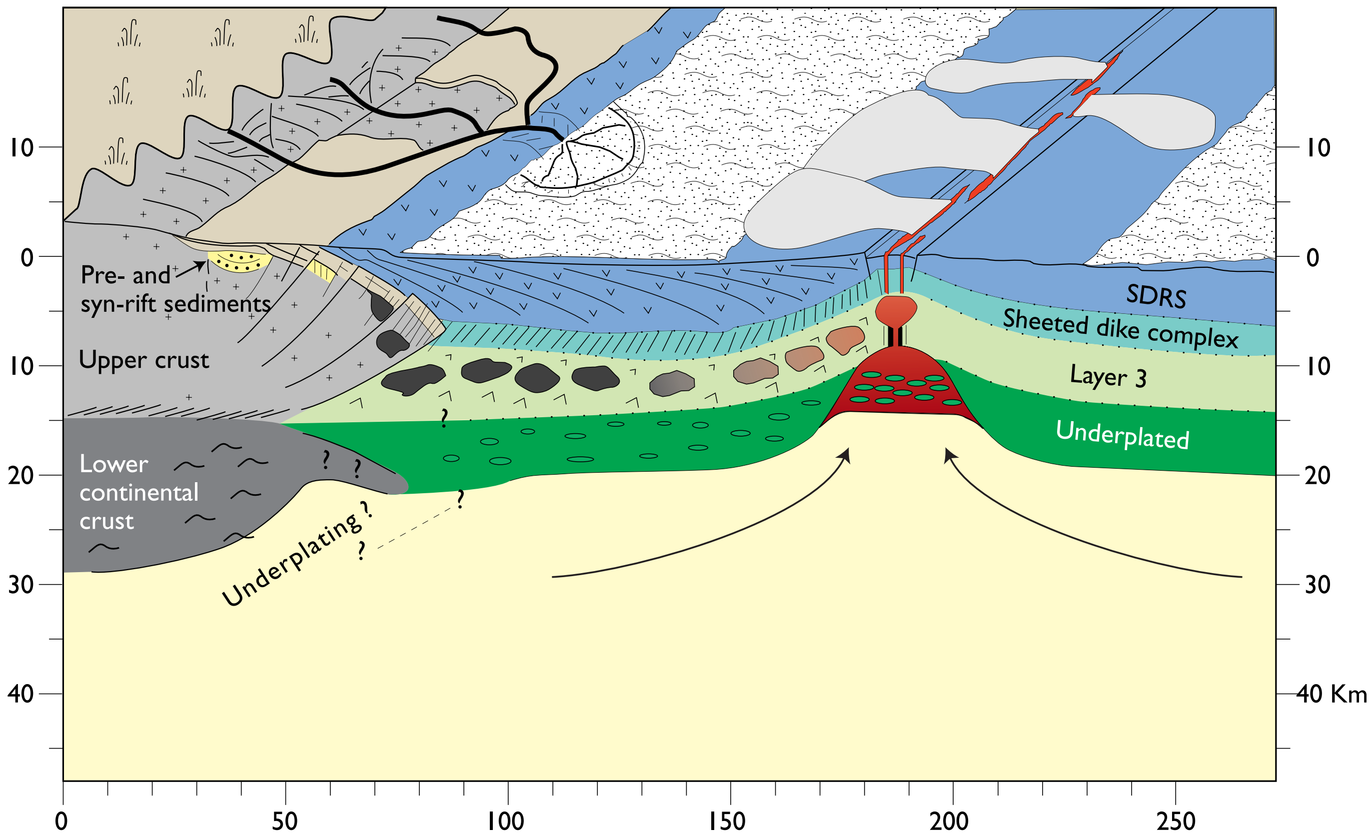
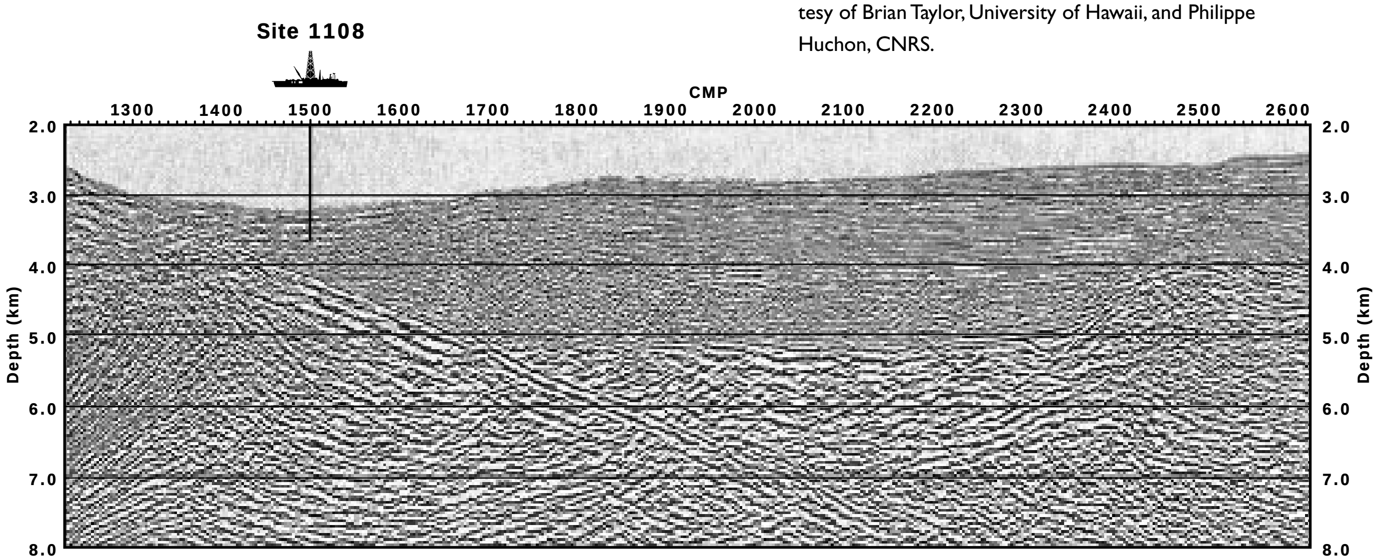


Figure 28. Schematic diagram of the Greenland volcanic margin showing the formation of the seaward-dipping reflector sequence (SDRS) wedge at ~54 Ma. This also shows the underplated layer at the base of Layer 3, which consists of gabbros. Other interpretations have been proposed for the deep structure of the margin, including the continent-ocean transition. These could be tested by deep drilling. Figure courtesy of Hans Christian Larsen, Danish Lithosphære Centre.

Figure 29. Multichannel seismic image of a low-angle normal fault at the western tip of the Woodlark basin, where ODP drilled Site 1108, east of Papua New Guinea. Understanding how such faults slip, as well as elucidating their role in continental extension and possibly in the transition from rifting to spreading, are major targets for future drilling. Figure courtesy of Brian Taylor, University of Hawaii, and Philippe Huchon, CNRS.



Initiative: Continental Breakup and Sedimentary Basin Formation

Volcanic and non-volcanic rifted margins offer insights into continental breakup and sedimentary basin formation. Rock sequences at volcanic margins primarily record the margin's magmatic history, which can yield information about mantle dynamics and lithospheric divergence. In contrast, sequences from non-volcanic margins primarily preserve the history of deformation associated with sedimentary basin formation that lead to continental breakup. To understand all of the processes involved in rifted margin and sedimentary basin development, we need to examine both types of margins by conducting "conjugate margin" studies across the entire width of the former continental lithospheric rift zone. To provide essential complementary data, we will need to install observatories in narrower zones of active rifting.

At volcanic margins, IODP will address the temporal relationship of magmatism to extension. This timing is critically important to resolving whether divergent margins form "passively" as a result of far-field plate forces, that is, subduction, or "actively" as a result of local thinning and weakening of the lithosphere by mantle plumes. Timing relationships are also key to understanding the details of plume-lithosphere interactions. Resolution of these problems requires deep holes into syn-rift sediments buried beneath the volcanic pile (Figure 28). Deep basement holes will be drilled at different margin settings to provide representative stratigraphic sections and geochemical fingerprinting of the main body of seaward-dipping lava flows.

At non-volcanic rifted margins, a major IODP focus will be the role of low-angle faulting in the breakup of continents, sedimentary basin formation, and eventual seafloor spreading (Figure 29). Establishing the presence and geometry of such fault systems on conjugate margin pairs that are fully separated is a high priority. Direct sampling of the fault zone in an active rift, and *in situ* measurements and seafloor observatory monitoring of physical properties, will address the "weak fault" paradox: how do these low-angle faults move under shear stresses that are far smaller than those which are required by experimental and theoretical studies? Other important rifting processes that will be studied include the deformation rate, strain partitioning, shift in both vertical and horizontal location of deformation and in mode of deformation with time, history and role of different fault generations, and nature and rheology of the crust subcropping below the sedimentary rift fill. Penetration of thinned lower continental crust—possibly through the former continental Moho—into presumably serpentinized lithospheric mantle will allow *in situ* examination of the nature, deformation and rheological properties at the base of the continental crust.

The final steps, from the end of continental breakup to the beginning of steady-state seafloor spreading, are poorly known. At volcanic rifted margins away from ridge-centered hot spots, a major decline in magmatic productivity occurs within only a few million years of final plate separation. In contrast, at non-volcanic rifted margins, significant magmatism only seems to initiate within several millions of years following plate separation. To assess how variations in asthenospheric temperature and strain rates determine which highly differing margin type develops, we need to understand both end members. IODP will drill across the continent-ocean transition of conjugate margin pairs, and undertake *in situ* measurements and long-term monitoring of those margins that are actively forming to investigate how lithospheric deformation transitions to steady-state seafloor spreading.

Processes of large igneous province development: Excessive magmatism resulting in volcanic rifted margin LIPs is at least partly linked to one fundamental plate tectonic process, continental breakup. However, LIPs such as oceanic plateaus, submarine ridges, ocean basin flood basalts and seamount groups are commonly found in other plate boundary and intraplate settings, having formed independently of the normal plate tectonic cycle (Figure 30). Oceanic plateaus provide the strongest evidence that at specific times, most recently during the Cretaceous (~140-~65 Ma), significant mass and energy were transferred from Earth's interior to the surface in a mode quite different from that of steady-state plate tectonics. This alternative means of interior energy loss may occur on other terrestrial planets in our solar system, and may have dominated Earth's early history. Understanding the processes that create LIPs thus has particular significance for planetary evolution.

Large and relatively short-lived magmatic events can thicken the igneous crust in locations away from mid-ocean spreading ridges. Some of the LIPs created by these events are nearly continent-sized oceanic plateaus, with crustal thicknesses of 20 to greater than 30 km. The vast dimensions of these major LIPs, and the episodic nature of their formation, indicate major mantle melting events. Understanding the origin and formation of oceanic LIPs will yield insight into mantle dynamics and comparative planetology. We have thus far only scratched the surface of oceanic LIPs because of limited technological capabilities. New IODP drilling technologies will allow us to access the intermediate and deep igneous crust of LIPs, to piece together long stratigraphic sections recording high-frequency variations in plume history and, for the first time, to firmly constrain the timing of entire LIP eruptive events.

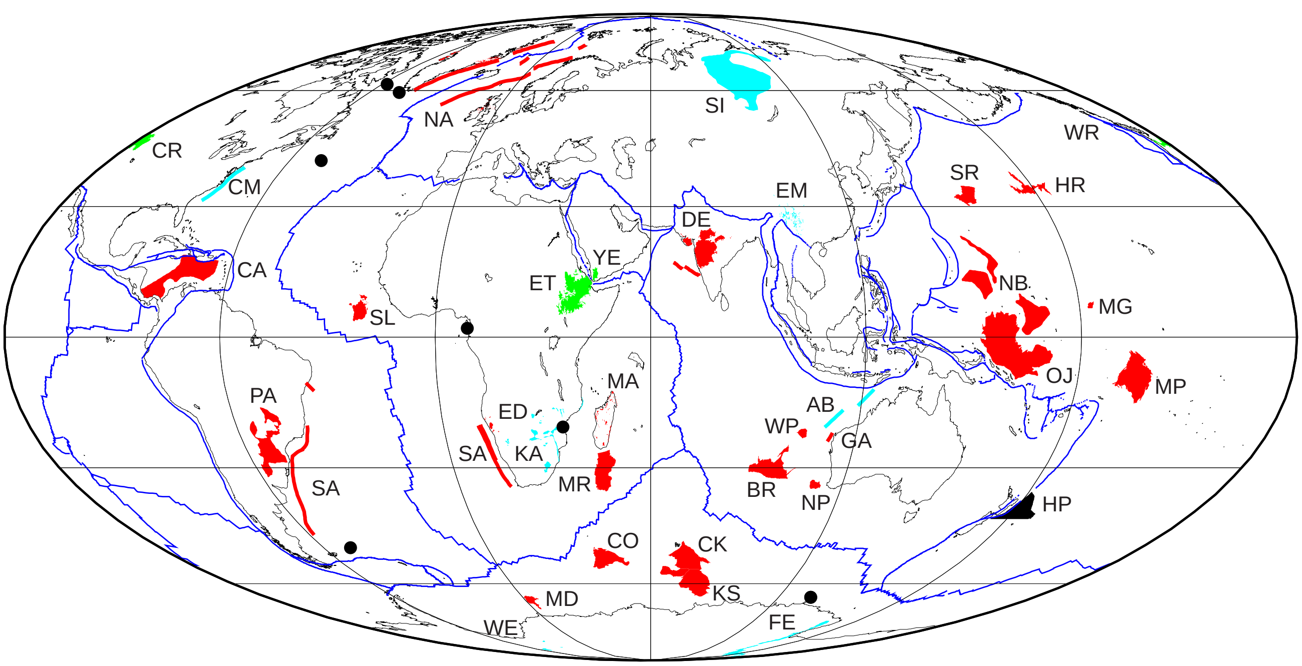


Figure 30. Distribution of major Mesozoic and Cenozoic LIPs, including oceanic plateaus, volcanic rifted margins, continental flood basalt provinces, submarine ridges and seamount chains. Light blue >150 Ma, red 150-50 Ma, green 50-0 Ma, black undated. Volcanic margin LIPs (lineations and circles) are inferred from occurrences of seaward-dipping reflectors in seismic profiles. Current plate boundaries appear in dark blue. Figure from O. Eldholm and M. Coffin, American Geophysical Union Monograph 121, 2000.

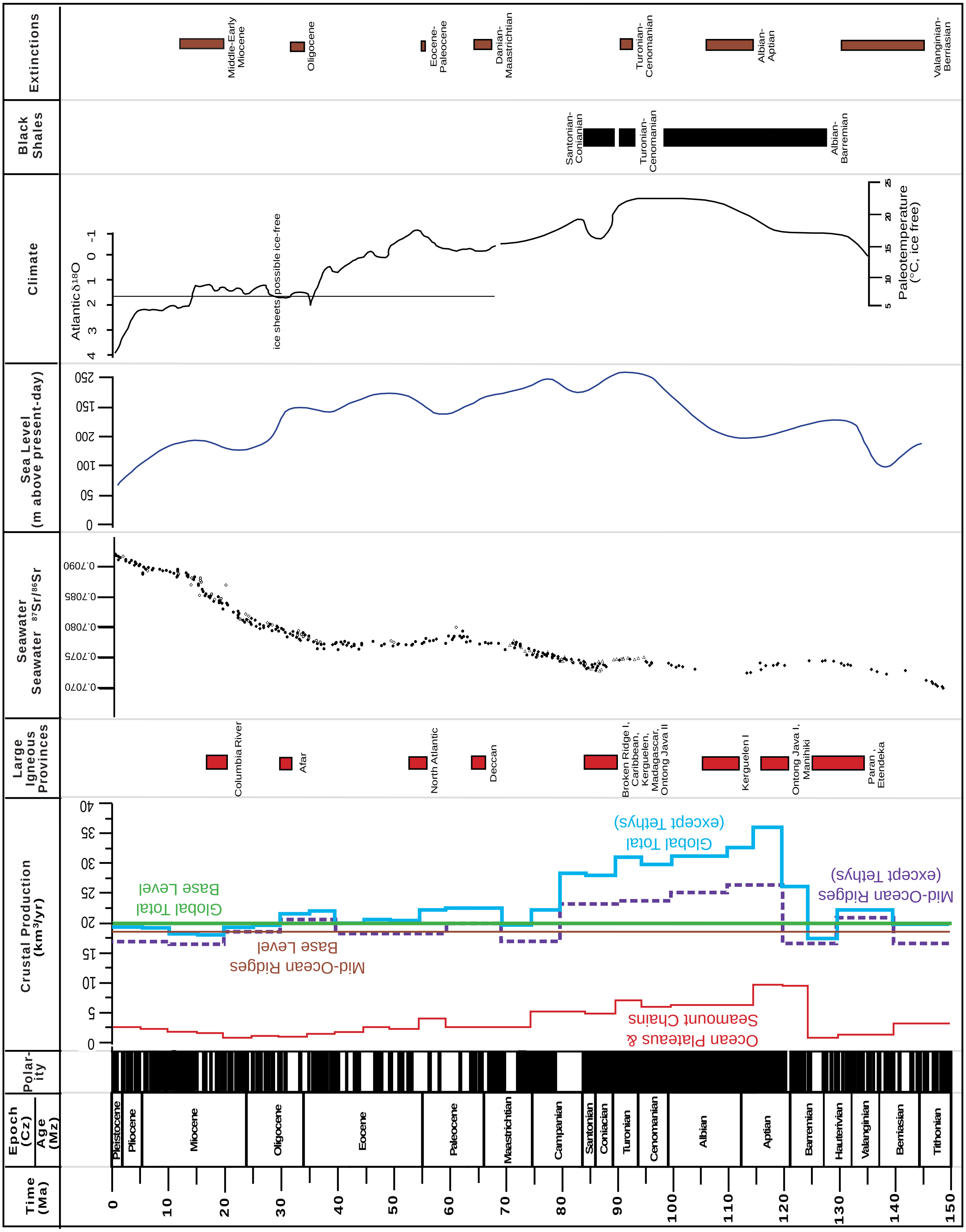


Figure 31. Temporal correlations among geomagnetic polarity, crustal production ages, LIPs, seawater strontium isotope ratio, sea level, climate, black shales and mass extinctions (Figure courtesy of Millard F. Coffin, The University of Texas at Austin).

Scientific drilling of LIPs will investigate mass and energy fluxes from the mantle to the crust and their relationship to LIP genesis, including the nature and relative role of mantle reservoirs and extruded melts, the effect of different dynamic settings on melting, the magmatic and tectonic processes associated with emplacement and post-emplacement, and the impact on the hydrosphere, atmosphere and biosphere. Whereas today's mid-ocean ridge system accounts for ~95% of the mass and energy transfer from mantle to crust, LIPs may have accounted for 50% or more of the mantle mass and energy flux during specific intervals of the Cretaceous period when ~20 major LIPs formed (Figure 30). Such pulses of magmatism may have resulted in significant contemporaneous changes in climate, mass extinctions, changes in the geomagnetic field, higher rates of seafloor spreading and hydrothermal activity, and an increased number of continental breakup events. It seems clear that the Cretaceous LIP episode is closely associated with an interval of extraordinary geomagnetic field behavior. There were no reversals during the period 121-84 Ma, in contrast to about 40 during the last 10 m.y. (Figure 31).

Links among the outer core, mantle and atmosphere lie at the heart of Earth system research. The enormous outpourings of predominantly basaltic magma that characterize LIPs, which commonly cover areas of $\geq 10^5$ km^2 on times scales of 10^6 years, may also have had significant environmental consequences. In the historical record, the environmental effects of even a relatively small basaltic lava flow have been well documented. Iceland's 1783-84 Laki flow, ~1% of the volume of a typical LIP flow, re-

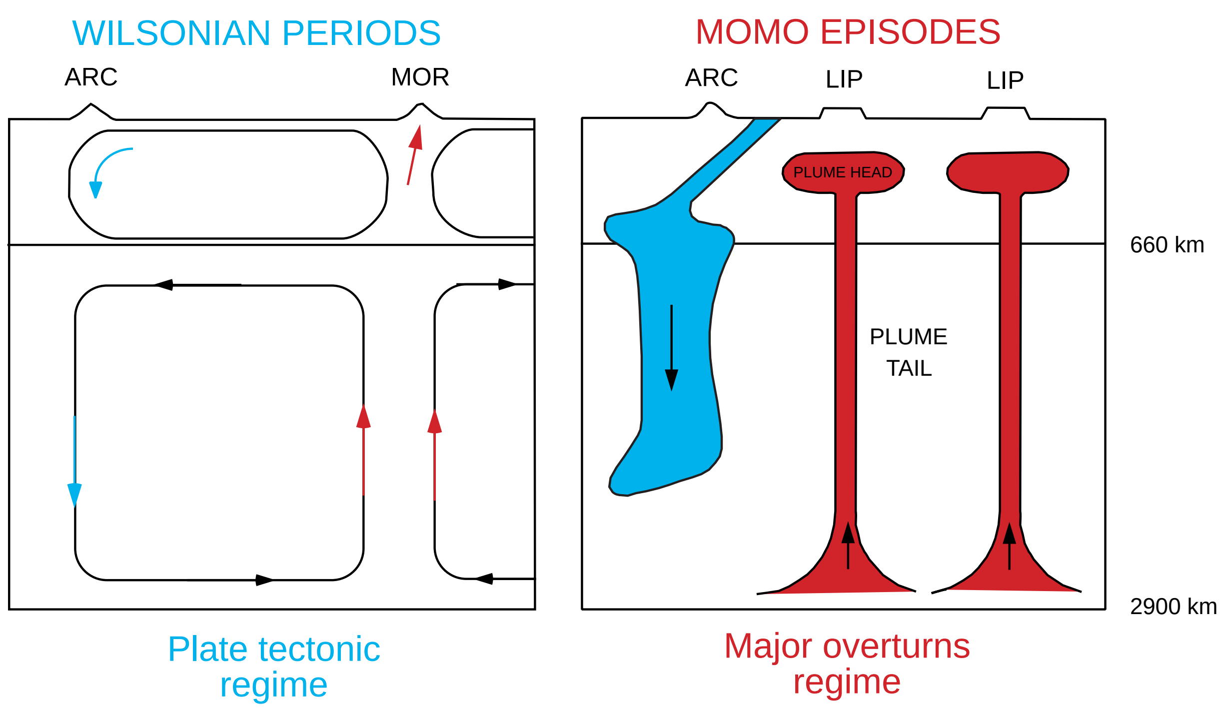


Figure 32. Model of Wilsonian periods and MOMO (Mantle Overturn, Major Orogeny) episodes. During Wilsonian periods (left), the normal mode of plate tectonics prevails, with opening and closing of oceans and mantle convection with isolated upper and lower mantle. Plumes originate predominantly from the base of the upper layer, and continental growth is dominated by arc accretion. During MOMO episodes (right), accumulated cold material descends from the 660-km boundary layer into the lower mantle, and multiple major plumes rise from the core-mantle boundary to form Large Igneous Provinces (LIPs) at the surface, thus creating a major overturn. Figure reprinted by permission from Nature, Stein and Hoffman, Mantle plumes and episodic crustal growth 375, Figure 1, p. 64, copyright 1994 Macmillan Magazines Ltd.

Initiative: Large Igneous Provinces

One outstanding success of scientific ocean drilling has been to establish that oceanic LIPs represent voluminous, episodic magmatic events. We still know far less about oceanic LIPs, however, than about any other type of volcanism on Earth. To date, only the upper 5% of LIP (volcanic rifted margin and oceanic plateau) crust has been penetrated by the ODP. Only small samples of the deeper crust and upper mantle have been recovered, severely limiting our knowledge of the lower 95% of LIP crust. Significant progress in understanding oceanic LIPs almost entirely depends on drilling because most oceanic LIPs are covered by thick sediments, with few or no tectonic exposures of the middle and lower crust.

Two objectives of drilling LIPs are of particular interest to a broad scientific community: (1) to understand mantle behavior during these massive, episodic magmatic events, and (2) to determine potential causal relationships and feedback mechanisms between LIP emplacement and environmental change (Figure 32). To tackle the first problem fully, we need to further investigate Cretaceous (~140-65 Ma) and Cenozoic (~65-0 Ma) LIPs. A prerequisite to understanding past mantle behavior, however, is thorough knowledge of present-day global mantle dynamics, which will provide the "ground truth" for mantle circulation in the past. To achieve that end, IODP will work with the International Ocean Network (ION) to install borehole seismometers to fill gaps in the Global Seismic Network, thereby improving the accuracy and resolution of global mantle tomography. In addition, a better understanding of the behavior of the geomagnetic field is required. To address the second problem, we must drill LIPs and sedimentary sections that correlate temporally with these changes. An overall understanding of the transient processes associated with LIP magmatism and related tectonism requires determining crustal ages and compositions from samples and logging, and characterizing mantle convection patterns by *in situ* monitoring with seafloor observatories in areas with and without plume activity. Only with these data will we be able to characterize LIP emplacement mechanisms and to assess the effect of variables such as magma supply and tectonic factors.

sulted in the deaths of 75% of Iceland's livestock and ensuing starvation of 25% of its human population. Geological studies suggest that LIP formation has caused significant global environmental change. The potential causal and feedback mechanisms, however, are neither proven nor well understood. Sampling and analyses of the extrusive crust of oceanic LIPs and contemporaneously deposited sediments, particularly those formed during the Cretaceous, will reveal environmental effects of these massive volcanic outpourings.

- **Processes of oceanic crustal formation:** Oceanic crust covers more than 50% of Earth's surface, yet the composition of *in situ* lower oceanic crust and the petrological nature of the oceanic Moho remain largely unknown. Knowledge of the structure, physical properties, and alteration history of the lower two-thirds of the oceanic crust is currently limited to geophysical observations, gabbros drilled from shallow crustal levels at one location, dredged rocks from the seafloor and the study of ancient oceanic crust in mountain belts (ophiolites). The ophiolite model associates the lower oceanic crust with a thick plutonic sequence of gabbros, and the oceanic Moho with a transition from these gabbros

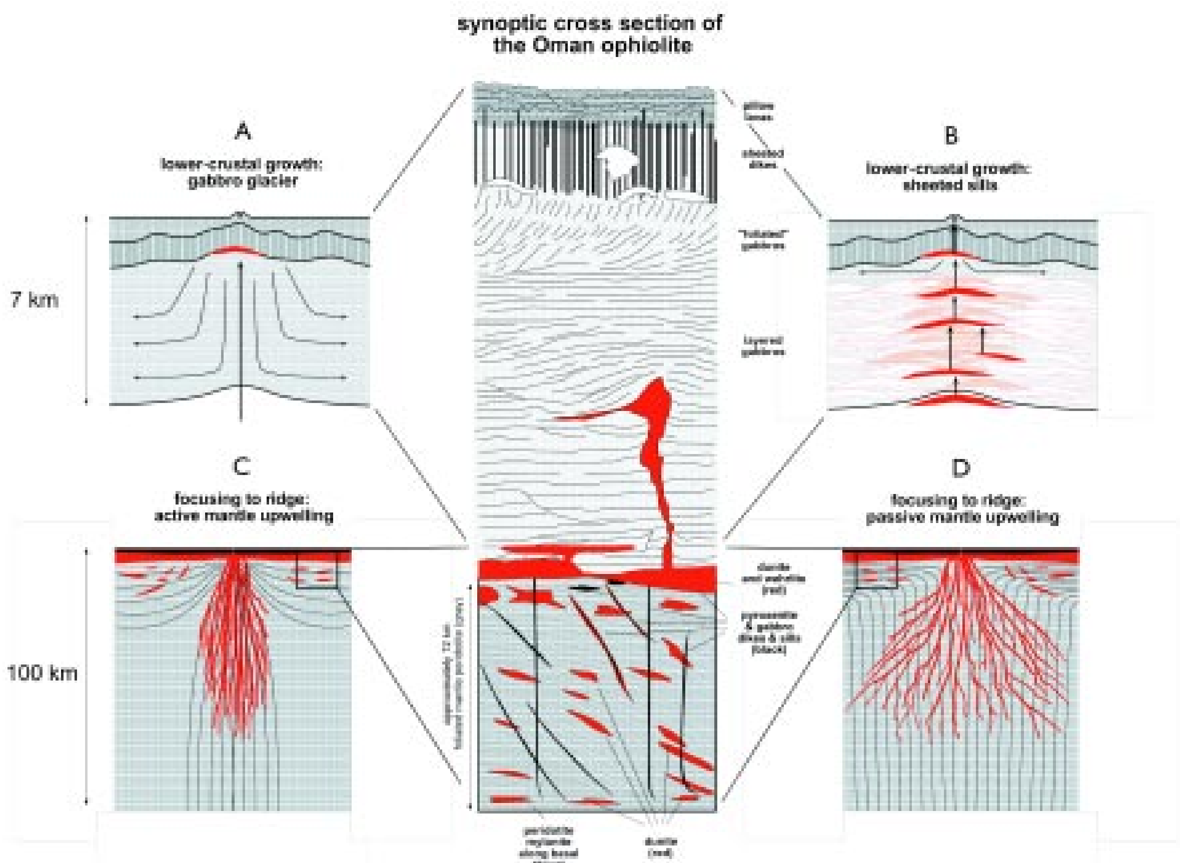


Figure 33. End-member models for igneous accretion of the lower crust at fast-spreading mid-ocean ridges and for focusing of melt extraction in the mantle from a ~100 km wide melting region to a ~10 km wide crustal accretion zone beneath the ridge axis. (A) "Gabbro glacier" model. Ductile flow downward and outward from a single, shallow axial magma chamber forms the entire lower crust. (B) "Sheeted sill" model. Melt transport by hydrofracture and in situ emplacement of the lower crust by sill intrusions. Most gabbros are crystallized at their current depth of emplacement. (C) Focused solid mantle upwelling, resulting from buoyancy driven mantle convection, mainly vertical melt transport. (D) Passive solid mantle upwelling, resulting from plate spreading, with coalescing melt flow conduits. Central panel is a summary cross-section of the Oman ophiolite, where upper mantle and lower crustal exposures allow testing of these hypotheses. Figure reprinted by permission from Nature, Keleman, P.B. et al., Extraction of mid-ocean ridge basalt from the upwelling mantle by focused flow of melt in dunite channels, 375, Figure 1, p.748, copyright 1995 Macmillan Magazines Ltd.

to mantle peridotite. While the ophiolite model has been widely accepted and applied for decades, it has never been directly tested by *in situ* sampling of the lower oceanic crust because of the technological limitations of drilling. The deepest, continuous drill hole into the oceanic crust penetrated just over 2000 m, less than a third of the way through a "typical," geophysically defined oceanic crustal section.

Recent geological studies of mid-ocean ridges revealed structural differences between fast- and slow-spreading ridges that were not foreseen from interpretation of ophiolite sequences (Figure 33). At slow-spreading ridges, ODP recovered much peridotite and basalt, but little gabbro, suggesting that a gabbroic layer is generally attenuated or even absent in the vicinity of transform faults. Such ridges show large, along-strike compositional variations which can span the entire range of rock types from serpentinite to basalt. It is thought that the low rate of mantle upwelling and associated conductive cooling at slow-spreading ridges leads to episodic formation of discrete magma chambers. Higher mantle upwelling rates at fast-spreading ridges reduce the relative role of conductive cooling, however, and may lead to a more uniform crustal structure, with a nearly steady-state melt lens near the top of

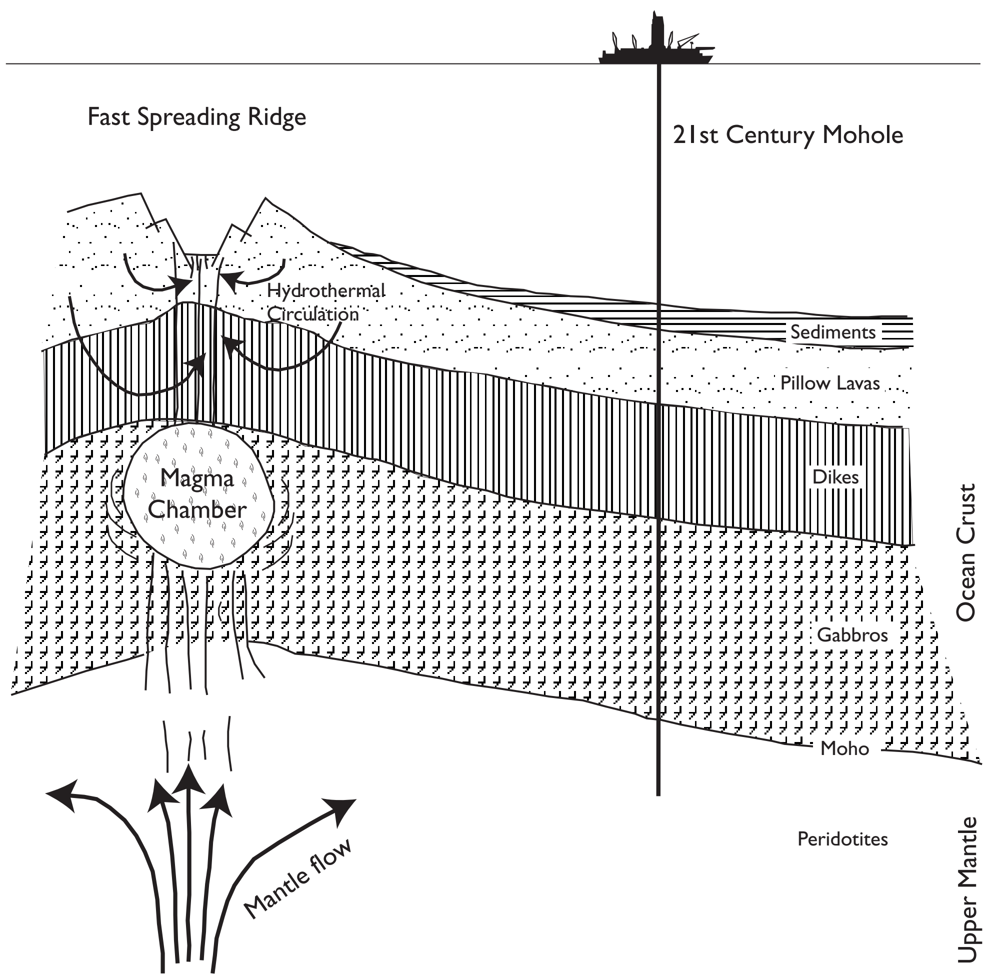


Figure 34. The 21st Century Mohole at a fast-spreading ridge. Direct sampling of rocks from the lower crust and the upper mantle, which has never been achieved, will open a window into Earth's interior and should provide completely new constraints on Earth's evolution. Questions to be addressed by the 21[st] Century Mohole include those related to fundamental processes governing the compositions and the three-dimensional structure of the oceanic crust, the evolution of the oceanic upper mantle, the formation of economically important ore deposits, and the evolution of the deep subseafloor biosphere. Figure courtesy of Yoshiyuki Tatsumi, Kyoto University.

seismic Layer 3. At fast-spreading ridges, the crustal section is expected to be more ophiolitic, consisting of three main components: gabbros forming the lower crust, translating upwards into sheeted dikes, and eventually into pillow lavas comprising the upper crust.

The petrological differences observed to date between shallow oceanic crust at slow- and fast-spreading ridges have revived speculation that the Moho might be an alteration boundary in the shallow mantle between serpentinized and unserpentinized peridotite in some locations (e.g., along slow-spreading ridges), and the boundary between crustal melts and residual mantle at others (e.g., along fast-spreading ridges). We don't know how the two models for the Moho can be reconciled with the fact that magmas vary remarkably little in chemistry no matter what the spreading rate. Furthermore, the depth to the Moho and the seismic velocity of the lower crust, interpreted from geophysical data, appear to be largely independent of spreading rate. This paradox, and the validity of the ophiolite model, will only be addressed by direct, *in situ* sampling of the lower oceanic crust and Moho by drilling (see 21st Century Mohole Initiative). A high priority is to recover intact and tectonically undisrupted sections, with as complete an integrated record of fluid flux and alteration as possible.

Initiative: 21st Century Mohole

To advance significantly our understanding of the processes governing the formation and evolution of oceanic crust, IODP plans to recover a complete section of oceanic crust and uppermost mantle generated at a fast-spreading ridge (Figure 34). Recovery of a complete crustal section has been a goal of Earth scientists since the 1950s, and will help elucidate the structure, composition, mineralogy, and *in situ* physical properties of the oceanic crust and the geological nature of the seismic Moho. Core samples and borehole geophysical data will also allow scientists to establish a standard lithologic section for correlation with major seismic discontinuities in the oceanic crust and upper mantle. One goal is to better constrain estimates of present and past magma production from the oceanic mantle.

Knowledge of the bulk composition and alteration of the oceanic crust is critical to our understanding of solid Earth cycles, and will be derived from the 21st Century Mohole section. This information will be needed to assess geochemical mass balances at ridges and subduction zones. A complete oceanic crustal section will allow us to determine the net and long-term buffering capacity of the oceanic crust in influencing the composition of seawater. Core samples will also be used to constrain the extent of microbial mediation of chemical exchanges between seawater and oceanic crust. Finally, the source of marine magnetic anomalies will be much better understood when a complete section of the lower oceanic crust is available for analysis.

By using riser or advanced non-riser drilling technologies, acquiring downhole geophysical logs, emplacing seafloor observatories, and drilling complementary holes into crustal exposures at tectonic windows and slow-spreading ridges, we anticipate major breakthroughs in understanding the formation and evolution of the lower oceanic crust and upper mantle. The 21st Century Mohole and associated initiatives will be undertaken in close collaboration with the InterRidge program.

Recycling of Oceanic Lithosphere Into the Deeper Mantle and Formation of Continental Crust

Oceanic lithosphere is subducted at convergent plate boundaries, leading to its eventual recycling into the deeper mantle as well the as the formation of volcanic arcs. The subducting plate, along with its sediments, fluids and altered igneous rock, interact with the overriding plate along the subduction zone (Figure 35). Physical and chemical change occur progressively with depth in the subducting plate, and include the release of fluids and volatiles to the overriding plate and mantle wedge. Subduction recycling also contributes to the growth of continental and arc crust and constructs the rock and structural fabric of convergent margins. Subduction influences the geochemical evolution of the oceans and mantle, generates volcanoes, produces hydrocarbon and mineral resources, and provides nutrients for benthic bio-chemosynthesis. During subduction, variations in friction along the shear zone account for much of the structural fabric of convergent margins and control where great earthquakes nucleate (see Seismogenic Zone Initiative).

IODP will address, by drilling, fluid sampling and long-term monitoring, the budget of important fluids and volatiles, such as water, methane and CO_2, as they enter, traverse and exit subduction zones. The subducting plate carries water and other volatiles, within the oceanic crust and sediments, to progressively higher pressures and temperatures. As the plate descends, fluids distilled from it influence and commonly control

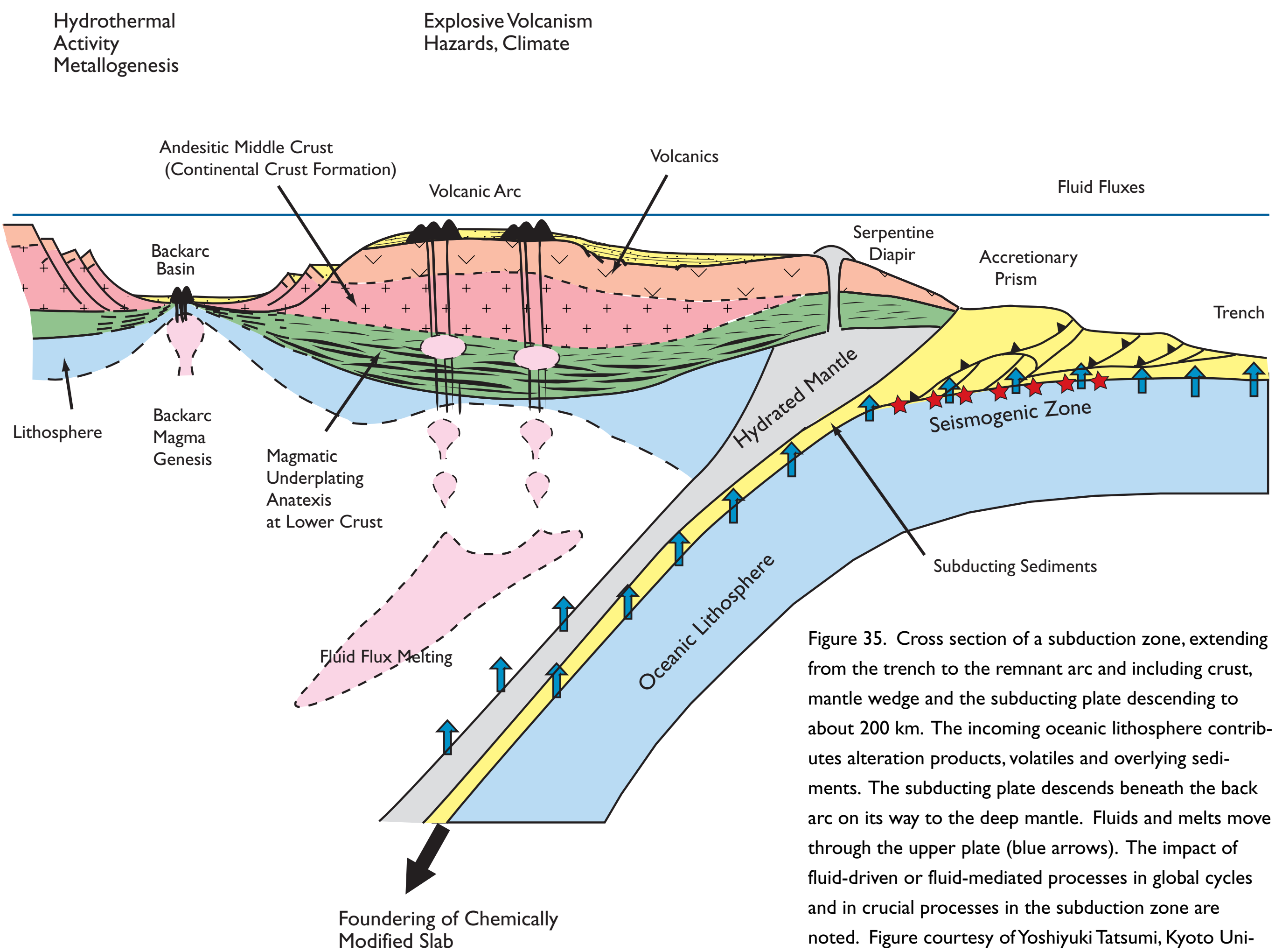


Figure 35. Cross section of a subduction zone, extending from the trench to the remnant arc and including crust, mantle wedge and the subducting plate descending to about 200 km. The incoming oceanic lithosphere contributes alteration products, volatiles and overlying sediments. The subducting plate descends beneath the back arc on its way to the deep mantle. Fluids and melts move through the upper plate (blue arrows). The impact of fluid-driven or fluid-mediated processes in global cycles and in crucial processes in the subduction zone are noted. Figure courtesy of Yoshiyuki Tatsumi, Kyoto University.

fundamental processes in the subduction zone. At shallow levels, water and carbon fluxes influence the formation and destruction of gas hydrates, and may support a deep subseafloor biosphere as well as chemosynthetic vent communities in forearcs. At greater depths, excess pore fluid pressures moderate the strength of faults and influence the hazards associated with great seismogenic-zone earthquakes. Deeper still, water released from the downgoing slab allows partial melting of the overlying mantle wedge, and when incorporated into arc magmas, powers explosive eruptions. CO_2 cycling through the subduction zone is a little known component of Earth's natural carbon cycle. Beneath the arc and back-arc, volatiles derived from the subducting plate promote mantle melting that contributes to the formation of continents. Volatiles also contribute metal-rich fluids to gold- and silver-rich supra-subduction zone hydrothermal deposits hosted in felsic volcanics, thought to be analogous to many Archean gold deposits. Finally, volatiles retained in the subducting plate are thought to be carried down into the mantle, where they may modify mantle rheology, oxygen fugacity and convection.

The changing mineralogy of the downgoing plate controls the composition and flux of fluids moving into the upper plate. Devolatilization, diagenesis and metamorphism control the physical properties of the subduction interface and impact its seismogenic potential. Most subducted material is not recycled in the arc crust. Instead, the material hydrates and modifies the wedge of mantle above the shallow subducting plate (ca 15-200 km depth). Understanding the effects of subduction on the volatile budget, noble gas composition, internal heating capacity, rheology and temperature of the mantle has been an important and long-standing goal in the subdiscipline of mantle geodynamics. IODP's multiple platforms and new technologies will enable geoscientists to assess the contribution of multistage alteration of the oceanic crust, and perhaps active near-trench hydrological circulation, to the volatile content, elemental composition and thermal structure of the incoming plate. Deep riser drilling and sampling will help map how melt from the mantle wedge changes through time, and with distance from the trench.

The creation and growth of continental crust remains one of the fundamental, unsolved problems in Earth science. Arc magmatism is thought to be a principal process in continental creation. Bulk continental crust is andesitic in composition, but the primary melt extracted from the upper mantle in subduction zones is basaltic. We still do not understand what causes this compositional change. IODP will drill into juvenile oceanic arcs, ideal sites for addressing this question, because extensive dredging and seismic surveys suggest that a major part of the middle arc crust is composed of rocks with andesitic compositions. A more mafic lower crust is inferred from more mature oceanic arcs. Probing the possible new "continental root" beneath juvenile oceanic arcs by IODP will be a tremendous step towards understanding the origin of the andesitic continental crust (Figure 35).

Initiative: Seismogenic Zone

More than 90% of all seismic energy worldwide is released in subduction zone earthquakes. Loss of lives and vast amounts of property and infrastructure have resulted from these earthquakes and associated tsunamis. Factors that influence the destructiveness of subduction zone earthquakes are magnitude, position with respect to population, and whether fault displacement propagates to the seafloor, causing sudden generation of tsunamis. The subduction zones of Peru-Chile, Middle America, Cascadia, Northeast Japan, Nankai, Java-Sumatra and the Mediterranean all pose significant earthquake and tsunami hazards to major population centers.

Most earthquakes are generated in the Seismogenic Zone, a relatively small portion of the subduction zone where subducting and overriding plates are coupled to some degree so that elastic strain accumulates and is eventually released as an earthquake. Despite the current quantitative knowledge of plate motions monitored by an array of geodetic measurements and the Global Positioning System, the sudden release of long-term accumulation of strain in the Seismogenic Zone is not predictable. Advances in far-field observations are revealing more details about how a large earthquake rupture nucleates and propagates over a fault with asperities, where microearthquakes occur, and what heterogeneities (e.g., acoustic impedance contrasts, Poisson's ratio anomalies, or anisotropies) exist near the fault. Various physical and chemical changes before and after large earthquakes have been recorded. Physical models of earthquakes are being developed and tested by laboratory experiments and modeling. No simple model, however, explains the wide variety of seismogenesis at convergent plate boundaries in relation to geology and tectonic setting. Fluids may control the fault mechanics, somehow interacting with the complex structure surrounding the Seismogenic Zone, but models of the behavior of these areas remain highly speculative.

The Seismogenic Zone initiative is a comprehensive, multidisciplinary project focused on the behavior of rocks, sediments and fluids in the fault zone region to understand better the nature of this zone and the mechanics of the earthquake cycle. This initiative will be integrated with studies of earthquake mechanics, past records exhumed from seismogenic zones, laboratory experiments and modeling efforts. In trying to understand how, when and where devastating earthquakes occur, we lack fundamental knowledge of the physical and chemical conditions within the seismogenic zone that change over time and lead up to sudden rupture. As one of its inaugural activities, IODP will drill through a seismogenic fault zone to characterize the composition, deformation microstructures and physical properties of the rocks at *in situ* conditions (Figure 36). As the faults must slip repeatedly, thermo-chemical imprints on these rocks may be scrutinized to infer localized fluid fluxes, including co-seismic melting events. Downhole logging will augment the characterization of *in situ* physical conditions across the fault. Borehole observatories able to record high-temperature conditions will be placed across the seismogenic zone and will provide time-series records of *in situ* fault conditions including pore pressure, temperature, stress changes (from micro- earthquake mechanisms), fluid chemistry and changes in tilt and strain. Collaboration with International Continental Drilling Program (ICDP) investigations of seismogenic zones at both convergent and transform (e.g., San Andreas fault) plate boundaries will also be critical in developing an improved understanding of earthquake generation mechanisms.

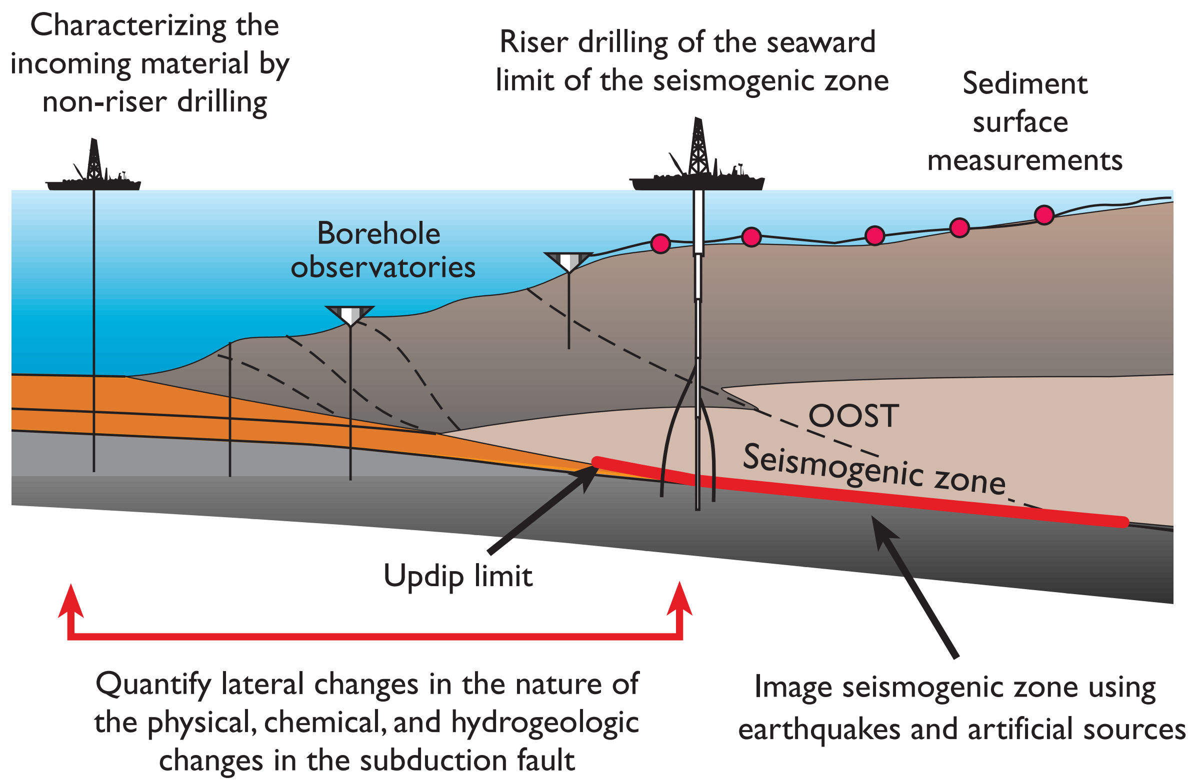


Figure 36. Integrated strategy to study earthquake processes at the seismogenic zone. Direct access to the seismic fault and implantation of sensors are the keys to understanding how plate motion is dynamically accommodated and plates are coupled at the seismogenic zone. OOST is an out-of-sequence thrust fault, which may slip to generate tsunamis. Figure reprinted from the COMPLEX report, JOI Inc., May 1999.

The Role of Multiple Platforms in Exploring Solid Earth Cycles and Geodynamics

The processes driving solid Earth cycles and geodynamics extend across a broad spectrum of space and time. Fault zones can be less than a meter wide, whereas mountain belts and LIP crusts span several tens of kilometers. Earthquakes and volcanic eruptions are nearly instantaneous in a geological sense, whereas rifting and plate subduction occur over millions to hundreds of millions of years. In addition, rifting, basin formation, seafloor spreading and subduction are active over a wide range of water depths, in both ice-covered and ice-free areas. The complementary capabilities of riser, non-riser and mission-specific drilling platforms are crucial to successfully pursue this area of research within the IODP. Significant drilling challenges must be overcome, and the IODP riser drillship capability must be increased to operating in at least to 4 km of water depth as soon as technically feasible.

With few notable exceptions, DSDP and ODP have largely avoided drilling into sedimentary basins on divergent continental margins because of safety considerations associated with the possible presence of hydrocarbons. Hole stability problems or hydrocarbon risks have resulted in unsatisfactory results when drilling and coring with non-riser technology in important target regions such as syn-rift sedimentary sections and low-angle detachment faults. In both convergent and divergent margin settings, application of riser drilling technology and mission-specific platforms for shallow water drilling, in combination with on-land drilling, will assure that complete margin transects can be recovered.

ODP non-riser technology has permitted only reconnaissance sampling of the uppermost basaltic carapace of LIPs. Maximum penetrations have been only 1.0 km on a volcanic margin and only 0.2 km on an oceanic plateau. These represent minor fractions of total crustal thickness, which range from 15 to 35 km, and unsatisfactorily short time series for any given location. Riser technology is required to penetrate deeper into LIPs to elucidate temporal development. In combination with stratigraphically offset sections, deeper drilling will also provide much improved crustal coverage. Mission-specific platforms are necessary to access related crustal sections from shallow water in the vicinity of islands and atolls and in ice-covered regions. In certain areas along rifted margins and LIPS, non-riser drilling will be a cost-effective way to produce arrays of moderately deep holes, and will be critical for sampling water depths currently inaccessible by riser drilling.

Another long-standing scientific goal is to understand the structure, composition, alteration history and *in situ* physical properties of the oceanic crust, and the nature of the seismic Moho. To achieve this goal, IODP must recover complete crustal sections, as described in the 21st Century Mohole Initiative of this Initial Science Plan. Using non-riser technology, ODP has only succeeded in penetrating 2 km into oceanic crust, far from the 5-6 km needed in order reach the seismic Moho. Riser technology is required to drill deeply into the oceanic crust so that mud circulation could continuously clean and stabilize the hole. The non-riser platform will be able to drill the offset sections, slow-spreading ridges, and pilot holes for the 21st Century Mohole.

Understanding Seismogenic Zone processes requires direct access to the deep (>5 km), seismically active part of the décollement and emplacement of sensors for monitoring *in situ* changes in pore pressure, temperature, stress, fluid chemistry, tilt and strain. Non-riser technology has successfully permitted characterization of the subducting plate above the shallow part of the décollement and sampling of shallow fault systems splaying off the deeper décollement. However, even at fairly shallow depths and seaward of the Seismogenic Zone, non-riser technology has proven insufficient to maintain hole stability to permit penetration through, and direct sampling of, the main detachment. The very deep drilling required to reach the seismically active zone makes riser drilling mandatory, and will challenge the limits of present-day technology. In the near term, non-riser drilling will continue to serve as a time-effective supplement to riser drilling in this complex environment, and will make it possible to design experiments involving an array of holes at a wide range of water depths and crustal penetrations.

Implementation Plan

Three broad IODP research themes are presented in this Initial Science Plan:

- The Deep Biosphere and the Subseafloor Ocean
- Environmental Change, Processes and Effects
- Solid Earth Cycles and Geodynamics

Within these three themes, eight initiatives are identified that are ready to be addressed within the first decade of IODP drilling, and are based on either broad, community-based workshop results or strong proposal pressure within ODP. The initiatives include:

- Deep Biosphere
- Gas Hydrates
- Extreme Climates
- Rapid Climate Change
- Continental Breakup and Sedimentary Basin Formation
- Large Igneous Provinces
- 21st Century Mohole
- Seismogenic Zone

Although these themes and initiatives are the main components of this Initial Science Plan, IODP's science planning structure will be flexible enough to allow the international scientific ocean drilling community to pursue new opportunities and approaches as they emerge.

The implementation plan presented here describes the various facets of IODP's proposed infrastructure, including drilling platforms, observatories, scientific databases and publications, education and public affairs, and innovations and technology development. A transition strategy from ODP to IODP is also proposed, as is a scientific management and advisory structure.

Principles of Implementation

1 Coordinated Use of Multiple Platforms Within a Single Program

IODP will be a single scientific program that will primarily use two dynamically positioned drilling vessels, and occasionally use mission-specific platforms. Japan will supply the riser-equipped vessel, and the US will supply the non-riser vessel. The use of all of these platforms will be carefully coordinated by the successor to the JOIDES Advisory Structure and by IODP management in order to maximize the program's operational efficiency and scientific return.

2 Engineering Development and Use of Special Measurement and Sampling Tools

IODP's ambitious Science Plan will be supported by a strong program of engineering development. New drilling techniques will be developed and new measurement and sampling tools will be deployed, some of which will be coordinated with industry. There will be an emphasis on sample recovery at close to *in situ* temperature and pressure conditions, with a minimum degree of contamination. Close coordination between engineering development, and science planning and operation will be required.

3 New Logging Program

ODP has consistently used state-of-the-art downhole logging tools to allow scientists to more completely relate the recovered cores to the *in situ* section and to the site survey data, and to characterize a drilled section when sample recovery is minimal. ODP has pushed the limit of existing technology and has used newly developed tools to measure more precisely downhole magnetic and geochemical properties. IODP's downhole measurements program will strive to integrate logging data collected from various platforms and assure their uniformity and comparability. Deep riser holes in high pressure and temperature conditions will provide further challenges for downhole measurements. An IODP priority is to develop an advanced logging program that will successfully operate tools in extreme environments and will also better capture the chemical, biological and physical state of the section being drilled. These challenges will necessitate continued consultation with industry.

4

Coordination with Observatory Sciences

IODP plans to continue the productive collaboration with seafloor observatory science programs, especially in the long-term monitoring of subseafloor physical parameters and seismicity, in active experiments and in regional-scale characterizations of subseafloor conditions. Future collaboration efforts will likely include instrument development, site selection, data transmission via fiber optic cables and data archiving. A firm foundation of observatory science both, as part of IODP and in coordination with other international programs, is a priority.

5

Establishing a Site Survey Program

To maximize the links among IODP's coring and sampling results, downhole measurements and observatory installation, and to put all site-specific activities into a regional context for both scientific and safety reasons, IODP must have a well-thought out program of pre- and post-drilling geophysical characterization. Obtaining the needed high-quality data is an expensive undertaking and may be greatly facilitated by close cooperation with the hydrocarbon exploration industry. Ideally, an international program will be developed to delineate regional/global settings of planned drilling targets, and to produce high-resolution, site-specific images in support of downhole measurements and to site downhole instrumentation locations. Depending upon the scientific target, both relatively shallow imaging of the section as well as deep crustal and mantle imaging will be required. In shallow-water and/or ice-covered areas, new imaging techniques and strategies in support of IODP may also have to be developed.

6

Cooperation with Other Initiatives and Industry

Although drilling is a powerful tool with which to study Earth systems, it is not the only tool. IODP will coordinate closely with various other science initiatives to broaden the scope of drilling science, as well as involve additional scientific communities. Strong ties will also be developed with industry scientists and engineers in fields of mutual interests.

Implementation Plan for Initiatives

Table 1 illustrates the relationships between IODP scientific opportunities and initiatives, including coordinated use of drilling platforms, tools and observatories, and cooperation with other initiatives and industry.

Further implementation details for each IODP initiative are presented in Appendix 1. Each figure includes the IODP time line, use of platforms, tools and observatories, predrilling geophysical requirements and co-operation with other initiatives and industry. For the non-riser vessel, a two-month cruise constitutes standard practice, based upon historical experience with the *JOIDES Resolution*. Approximately 60% of the non-riser vessel's total number of drilling expeditions are assigned to an activity directly related to the scientific initiatives presented in this Initial Science Plan. We anticipate that mobilization of one mission-specific drilling platform per year will be standard operating procedure in IODP. These numbers are still tentative and depend greatly upon on proposal development and evaluation by the successor to the JOIDES Advisory Structure.

Infrastructure

Drilling Platforms

IODP's goal is to be able to drill and continuously core at almost any location in the world's oceans. To achieve this goal, the international community has consistently emphasized the use of multiple drilling platforms, including a riser (well-control) vessel, a non-riser vessel and mission-specific vessels. In response to this requirement, Japan, through its Marine Science and Technology Center (JAMSTEC), is building a riser vessel so that IODP can meet its deep objectives, and also drill targets in potentially overpressured subseafloor environments such as the Seismogenic Zone. The US National Science Foundation will supply an upgraded replacement for ODP's *JOIDES Resolution* to enable IODP to drill in a wide range of water depths and lithologies where a riser is not needed. Mission-specific drilling platforms will be mobilized in environments not suitable for either of IODP's two primary vessels.

The dynamically positioned, riser-equipped ship currently being built under the direction of JAMSTEC (Figure 37) will incorporate the cutting-edge technology of deep water, riser-controlled drilling now available in the oil industry. Core quality will be improved over that of the *JOIDES Resolution,* drill cuttings will be able to be retrieved for additional stratigraphic control and, above all, overpressures can be contained when encountered in continental-margin settings. The ship will initially be able to conduct riser drilling in water depths up to 2500 m (Table 2 and 3). Plans to increase this capability to 4000 m is underway. At these con-

IODP Implementation Framework

Scientific Opportunities	Initiatives	Coordinated Use of Platforms, Tools and Observatories	Site Survey Requirements	Cooperation
The Deep Biosphere and the Subseafloor Ocean				
• The Subseafloor Ocean in Various Geological Settings - Mid-ocean ridges - Ridge flanks, large igneous provinces and old ocean basins - Subduction zones - Passive rifted margins and carbonate platforms • The Deep Biosphere • Gas Hydrates	• Deep Biosphere • Gas Hydrates	• Riser: Sampling for deep-seated fluid and biosphere • Non-riser: 3-D sampling and measurement of fluid and biosphere • Mission-specific: Shallow shelf, Artic Ocean and permafrost zone • Tools: *In-situ* sampling and measurement critical • Observatory: Long-term monitoring and active experiments	• High-resolution site characterization required, including swath mapping, submersible dives and 3-D seismic in many cases	• Close cooperation with other international programs related to deep biosphere, fluids in the crust and gas hydrates. • Cooperation with oil/gas, geotechnical and biotechnology industries
Environmental Change, Processes and Effects				
• Internal Forcing of Environmental Change - Tectonically induced change - Igneous processes and environmental change - Sea-level change - Organic carbon-rich sediments and Greenhouse anoxia - Transient climate episodes • External Forcing of Environmental Change - Climate system interaction with orbital forcing - Impact events • Environmental Changes Induced by Internal and External Processes - Millennial-scale climate events and abrupt ocean circulation change - Decadal-scale climate variability	• Extreme Climates • Rapid Climate Change	• Riser: Drilling of thick and continuous sedimentary records • Non-riser: Global array and transects • Mission-specific: Reefs, atolls, shallow shelf and Arctic Ocean • Tools: Recovery of undisturbed section and high-resolution logging • Observatory: No particular requirement	• High-resolution seismic survey to delineate stratigraphic context of transect array	• Close cooperation with other international programs related to climatic research • Cooperation with oil/gas and geotechnical industries in the field of source-rock studies
Solid Earth Cycles and Geodynamics				
• Formation of Rifted Continental Margins, Oceanic Large Igneous Provinces and Oceanic Lithosphere - Processes of rifted continental margin development - Processes of large igneous province development - Processes of oceanic crustal formation • Recycling of Oceanic Lithosphere into the Deeper Mantle and Formation of Continental Crust	• Continental Breakup and Sedimentary Basin Formation • Large Igneous Provinces (LIPs) • 21st Century Mohole • Seismogenic Zone	• Riser: Very deep drilling (6-7km below seafloor) • Non-riser: 3-D sampling and measurement • Mission-specific: Transect with riser/non-riser platform. Shallow shelf zone • Tools: Logging program critical (Logging-While-Drilling and Logging-While-Coring) • Observatory: Long-term monitoring especially in Seismogenic Zone initiative	• 3-D seismic survey targeted for relatively shallow level. • Imaging of deep crustal structure using OBSs and other refraction techniques. Enhanced mantle tomography may be required for LIPs and oceanic lithosphere sites	• Close cooperation with other international programs related to continental margin study, mid-ocean ridge study, Earth tomography and earthquake studies • Cooperation with oil industry

Table 1. Summary of planned drilling activities associated with the Initial Science Plan, including platform use, site survey needs, and areas of potential cooperative effort. Detailed plans are shown in Appendix 1.

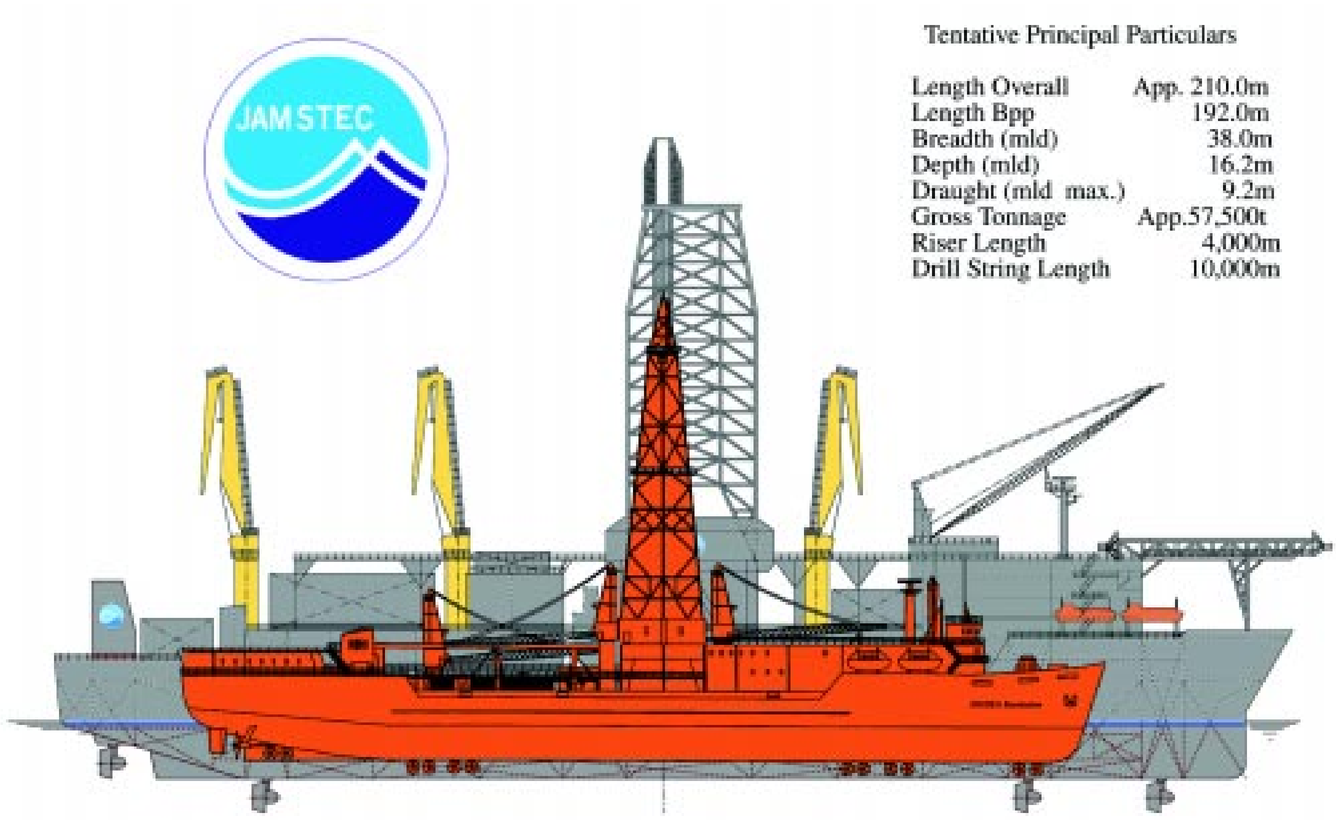


Figure 37. Silhouettes of ships representing the two primary drilling platforms to be used in the IODP. In the foreground is a silhouette of the *JOIDES Resolution*. A comparable ship, with enhanced capabilities, will be part of the new program. In the background is the present general design of a deep-water riser drilling ship produced by JAMSTEC in consultation with the international community. General design specifications for this new ship are shown in the upper right corner. Detailed design of this ship has been completed and construction began in 2000.

siderable water depths, IODP will be able to address high-priority scientific objectives that require safe and deep drilling into thick sedimentary sections along continental margins and into the oceanic crust. This riser ship will begin sea trials in ~2004 and will be available for international IODP scientific ocean drilling in ~2006. In 2000, the US Science Advisory Committee's Conceptual Design Committee (CDC) provided design specifications for a new, versatile US-supplied, non-riser drillship for IODP. The drilling vessel design (Table 2) was based on optimal recovery of sections for high-priority IODP drilling targets as well as general improvements in laboratory, office and living conditions over those of the *JOIDES Resolution*. Key ship design recommendations include: (1) a 50% increase in available laboratory space over that in the *JOIDES Resolution*, allowing the capture of all important core-based properties at-sea, an increase in office space and conference facilities, and improved access to downhole logging and geophysical visualization, (2) an ability to operate in shallower waters (< 20 m), which should allow sampling of important inner continental shelf sedimentary sections worldwide, (3) improvements in heave compensation, which should improve core quality in all geologic environments, and (4) improvements in habitability. Non-riser drilling will offer the widest possible range of sampling and coring techniques, from advanced hydraulic piston coring (APC), to extended and diamond core barrel technologies (XCB/DCB), to rotary coring (RCB).

	JOIDES Resolution (Non-Riser Drilling)	CDC vision (Non-Riser Drilling)	OD21 Riser Drillship (Riser Mode)	OD21 Riser Drillship (Non-Riser Mode)
Specification of Ship				
Station Keeping	DP in Beaufort 10	DP in Beaufort 8	DP in Beaufort 9	
Anchoring	No	Yes for Shallow Water	No	
Standard Leg Duration	Up to 8 weeks without Resupply or Port Call	Up to 8 weeks without Resupply or Port Call; fresh water resupply needed when working in coastal limits	6 months with Resupply and Crew Change every 2 weeks	Up to 10 weeks without Resupply or Port Call
Laboratory	1245 m^2	1800 m^2	2118 m^2	
Core Storage	8000 m cores in hull	10-20' Container on Deck Space (8000 m Cores)	10-20' Container on Roof Deck (8000 m Cores)	
Container Lab	No	5-20' Container on Deck Space	3-20' Container or 1-20' Container + RI Lab	
Geophysics Doghouse	32.5 m^2 at Stern	50 m^2 at Stern	None	
Accommodation	25 Scientists+26 Technical Staff 2-4 person/room Shower/Head per 2-8 person	60 Scientists 2 person/room Shower/Head per < 4 persons	51 Scientists 1 person/room Shower/Head per room	
Heave Compensation	In-Line Active	Active	Active Crown Mount	
Drilling/Coring Capability				
Coring Tools	APC, RCB, XCB, DCB	APC, RCB, XCB, DCB	APC, RCB, XCB, DCB	
Maximum Deployable Drillstring Length	7659 m	11000 m	10,000 m for Initial Phase 12,000 m for Next Phase	
Water Depth – Operational Limits	76-6000 m	< 20 to 7000 m	500-2500 m for Initial Phase 500-4000 m+ for Next Phase	500-7000 m
Water Depth in Extreme Conditions	Shallow: 50 m (record) Deep: 5980 m (record)	Shallow: < 20 m by Anchoring Deep: 7000 m	----------------	----------------
Penetration Depth	Max.: 2111 m (record)	> 2000 m	7000 m targeted	-------------
Well Control	Limited	Limited	Full	Limited

Table 2.

JOIDES Resolution	CDC vision	OD21 Riser Drillship
Laboratory		
Core Description Laboratory	The CDC report does not specify each of the required laboratories. The report says, however, that the non-riser ship's laboratory facilities must be comparable to those of the *JOIDES Resolution*, with 50% more laboratory space, enhanced multi-sensor tracks, improved databases and networking, and better ship-to-shore data communication. The ship must also have sufficient exterior space for standard 20' containers for "as needed" scientific lab modules and for core storage.	Core Laboratory (includes Physical Property Laboratory and XRF/XRD Laboratory)
Paleomagnetics Laboratory		Paleomagnetics Laboratory (Magnetic Shielded Room)
Physical Properties Laboratory		*Included in Core Laboratory
Chemistry Laboratory		Geochemistry Laboratory
Paleontology Laboratory		Sample Preparation Laboratory
Microscope Laboratory		Paleontology/Petrology Laboratory (Microscope)
Thin Section Laboratory		Thin Section Laboratory
X-Ray Laboratory		* Included in Core Laboratory
Photography Laboratory		None, because of digitization in Core Laboratory
Underway Geophysics Laboratory		Core Viewing Area
Downhole Measurements Laboratory		Downhole Measurements Laboratory
Microbiology Laboratory		Microbiology Laboratory
		X-Ray CT Scanning Laboratory
		Core Sample QA/QC Laboratory
		Mission Specific Container Laboratories
		RI Laboratory (future installation)

Table 3.

These two primary platforms represent powerful tools for exploring Earth and conducting scientific experiments at sea. No other research vessels in operation will be capable of the extremely sophisticated drilling, sampling, logging and emplacement of measurement devices, while carrying on board a diverse contingent of scientists and technicians to oversee drilling operations, conduct *in situ* experiments and evaluate the recovered samples and data in real time. The tremendous synergy that develops among onboard scientists and their high degree of productivity are the hallmarks of scientific ocean drilling. The additional laboratory space available on the two new drillships will provide even greater flexibility in developing shipboard research and training programs, and options to set up specialized shipboard scientific activities that may be needed as we explore new environments. Regular resupply of the Japanese riser ship at sea will also provide flexibility in its scientific, technical and operational staffing. Special teams of scientists and engineers will be able to come on board and address specific scientific opportunities or technological challenges as they are encountered.

While the Japanese and US ships allow IODP to address most of the high-priority scientific goals mapped out in this Initial Science Plan, there remain drilling objectives that cannot be met by either vessel. Other drilling platforms will be required for IODP to investigate high-priority regions such as the Arctic Ocean, and to drill in shallow water (< 20 m) environments that contain detailed records of climate and sea-level change. The nature of the scientific problem and the location of the proposed drilling will define the exact nature of the required platforms. Shallow-water drilling and coring are well within present-day technological capabilities, and platforms that can meet most of our scientific needs are available on a commercial basis. Currently, drilling in ice-covered Arctic waters offers a substantial technological challenge, and represents an opportunity for IODP to make both scientific and technological breakthroughs. It is possible that icebreakers and specially designed drilling barges, in concert, can conduct drilling operations in deep-water, ice-covered regions, although long, continuous sections from the deep Arctic Ocean have never been recovered. The international community continues to assess the development of technology required to achieve IODP objectives in Arctic waters. As part of IODP's mission-specific drilling efforts, portable laboratories will be needed that can be placed onboard and/or at a nearby location on shore. These laboratories will be capable of carrying out critical measurements of the ephemeral properties of sediments and pore fluids that are routinely carried out on IODP's primary platforms. They will provide the minimum necessary capabilities for initial processing of cores, and for on-site scientific and technical measurements.

Observatories

Long-term monitoring of oceanic processes is becoming increasingly important in ocean sciences as more sophisticated monitoring devices are being developed. These devices have greater data-gathering capacity and require little servicing, less space and less power. The scale of the monitoring effort needed depends on the scale of the process studied. For example, to image Earth's interior more accurately, seismometers need to be emplaced worldwide in seafloor boreholes at selected locations. To monitor processes such as fluid flow in the crust, scientists need a network of sealed boreholes with multiple packers and related instrument packages.

ODP has already successfully installed several monitoring devices in seafloor boreholes that can measure physical properties, such as fluid flow and temperature, record seismicity, and obtain water or biological samples over months to years. This technology has been developed and provided by individual scientists in close collaboration with ODP engineers and the JOIDES scientific community.

This productive collaboration will continue because new observatories will be needed to address the goals outlined in this Initial Science Plan, especially those associated with the deep biosphere and subseafloor ocean, and with solid Earth cycles and geodynamics. IODP will drill the holes required for these new observatories, and where necessary, service older ones. In some observatories, data will be collected in computer memory chips and recovered by submersibles. Where observatories are located in the vicinity of seafloor fiber optic cables, data will be transmitted in real time to scientists and laboratories worldwide. At present, there are more than 30 drilled "Legacy Holes" equipped with reentry cones, which are available for emplacement of monitoring devices. IODP will consider these "Legacy Holes," and newly drilled holes, as opportunities to expand deep-ocean observatory science, often in partnership with other seafloor observatory programs.

Scientific Data Bases and Publications

The scientific ocean drilling community has vast experience in collecting and archiving large amounts of data, and publishing them, and associated research results, in paper form. Because of the enormous value of drilling data and scientific results, the community has recently taken advantage of new hardware and software and that make ODP's legacy both more accessible to scientists and educators and cheaper to maintain and publish.

As more and more data are collected on samples in real time through multi-sensor track measurements and automated sampling and measurement techniques, the size of the data repository for scientific drilling and the rate of its growth continue to increase. Currently, each two-month ODP cruise generates approximately 1 gigabyte of laboratory data, though when digital core images are added, approximately 10 gigabytes of data are generated per leg. We can only expect these figures to increase significantly with simultaneous drilling on multiple platforms, additional and more complex observatories continuously recording data for long periods, capture of digital core images, input of post-cruise laboratory analyses into the database, and a larger number of scientists and laboratories involved in the IODP.

An important first step for IODP, prior to when the first core comes on deck, is to establish an independent data management center (DMC) that is responsible for collecting, archiving and updating all laboratory data generated by the program, and by the research community, over the years following an IODP field activity. This DMC would also maintain, or be linked to, ODP and DSDP databases. All newly captured data would be stored in a relational database, and would be accessible over the Internet in a variety of ways. This relational database would have links to other databases through individual site numbers and geographic location. At a minimum, these ancillary databases would include a logging database, an observatories database and a site-survey database containing records of the seismic section drilled. The DMC would also be responsible for providing some basic tools for plotting and visualizing the data. Help desk support for IODP data would be provided by the DMC.

The data and the collected samples are invaluable legacies of scientific ocean drilling, but the evaluation and interpretation of these data are the essence of our science. Scientific papers and syntheses of individual project results will continue to be important products of IODP. IODP's web site, possibly maintained at the IODP DMC, will contain lists and links to this literature, which can be searched and sorted. When practical, electronic literature can also be hot-linked to the IODP databases. With the rapid advances now taking place in electronic publishing, data storage, and Internet access, we cannot possibly predict all the tools that might be available when IODP data begin to flow. Even a conservative extrapolation beyond what is currently available suggests that the international scientific community will have ready access to a comprehensive IODP scientific literature, linked to a vast array of ocean drilling data and data products.

Curatorial Facilities and Shore-Based Laboratories

Four shore-based core repositories, three in the US and one in Germany, currently provide curatorial and sampling facilities for all DSDP and ODP drill cores. These core respositories serve the community by providing scientists with samples for further study long after operations at sea are complete. Scientists may visit repositories and take their own samples, or submit a sample request form and have a curator sample the core(s) for them. There are limited laboratory facilities available at these core repositories for sample analysis. To date, scientists have taken over 1.5 million samples from more than 190 km of ODP core.

At the end of ODP, all of the current four core repositories will be at or near capacity. If new facilities are not built for IODP cores, one or more of the current facilities will have to be significantly expanded. Based on current figures from the *JOIDES Resolution*, we can anticipate a minimum of about 10-20 km of core recovery per year from the non-riser vessel that will need to be stored and curated. In addition, there will be a significant amount of core material recovered by the riser vessel, perhaps as much as another 10-20 km per year. Core recovery from mission-specific platforms can also be significant depending on the lithologies being drilled. Based on ODP repository capacity, a minimum of about 20,000 square feet of storage space will be required over the first ten years of the program, with about 95% of that refrigerated to maintain core quality.

IODP will require shore-based laboratories because of some of the special staffing or deck-space circumstances related to riser drillship and mission-specific platforms. Riser technology will permit drilling and recovery of very thick sedimentary and crustal sections. Drilling times for any single site may last months to a year or more. These long stays on a single site, the thick sections that are recovered and logged, and the diversity of experiments that will take place during the drilling operations will require cooperative efforts of multiple teams of scientists. These teams will probably not all be on the ship, and certainly not all at one time. Therefore, a central facility will be required for these teams to meet, where recovered cores can be viewed, described, and more completely analyzed, where all data from the site can be compared and integrated, and where results of drilling, logging, coring and monitoring efforts can be discussed. Such meeting and laboratory facilities must be located close to core repositories, so that handling, transport, and potential damage to samples are minimized. We expect that shore-based laboratories will be built by individual countries participating in IODP, though laboratory operation may, at least in part, be a program function.

To maximize the usefulness of cores for subsequent scientific investigations, shore-based laboratory facilities will also be required to make standard measurements on cores recovered by mission-specific platforms. Costs, space constraints and logistical difficulties will prevent IODP from having a complete suite of analytical equipment and scientific and technical expertise onboard such leased platforms. Thus, laboratory facilities that permit sample measurements and descriptions comparable to those carried out on IODP's primary drilling platforms must be made available on shore.

Education and Public Affairs

While IODP's central mission focuses on fundamental scientific research, there is an important role for educational outreach. Today, as never before, there are many opportunities to convey the excitement of scientific discovery to teachers and their students, as well as the media, through a variety of programs, including those that exploit the Internet and other distance-learning technologies or offer firsthand research experience at sea.

IODP can most effectively influence science education by serving as a resource for educators, and by facilitating, and coordinating education projects that complement program goals. Projects in which IODP takes a lead will be conducted in partnership with experts in the field of science education. Experts may include university science education professors, teachers who are officially designated as science education specialists within their respective state or national systems, academic institutions, elementary and secondary school science education research centers, teaching museums, and/or coordinating agencies whose primary mandate is education. The possibility for collaboration with other existing science programs, government agencies and professional organizations that have already launched educational outreach programs will be explored.

Public affairs is another important form of educational outreach, but the audience here includes not only educators, but journalists, other scientists, government representatives and the general public. Public affairs activities include promotional activities, news conferences, and coordinating port call activities where the public can tour the ship and learn about IODP's scientific research. IODP's public affairs program will also include developing materials, such as descriptive brochures and pamphlets, fact sheets, and designing and updating an IODP web site dedicated to outreach. The web site might contain, for example, a virtual ship tour, scientist profiles, a daily log of ship activities, scientific highlights and links to ODP education-related activities sponsored by IODP member countries or developed by individuals outside of IODP.

Advice on which education and public affairs projects merit IODP support and with whom to collaborate could be obtained by establishing an IODP education and public affairs advisory panel, charged with project and/or proposal evaluation. This committee may also recommend development of new projects and web site content, and other materials. Recommendations from this panel would go forward to the IODP Science Committee (SCICOM) for final project recommendation. IODP educational project support could be in the form of matching funds or "in kind" contributions such as personnel time, ship space (berths), travel, satellite transmission costs for distance learning, and materials (CD ROM's, web-based learning activities, videos, museum displays, posters, etc). IODP involvement in, and support of, particular education projects will be contingent on the principal investigators being able to secure matching funds for projects from sources other than IODP. An open, competitive process will help ensure that IODP science is linked to the most innovative education projects with clearly defined objectives and the greatest likelihood of success.

Innovations and Technology Development

ODP has continually expanded the frontier of sampling and measurement technologies for ocean drilling science. IODP will maintain this innovative and developmental approach, especially with respect to deep water drilling technology, sample recovery and downhole measurements, which play an increasingly important role as we probe deeper into ocean sediments and crust in ever more challenging settings. JOIDES has advised ODP on technology needed to achieve its scientific goals. Some tools critical to IODP scientific objectives already exist within ODP, and others are under development. These tools are described below. All ODP tools and technology will be transferred to IODP for use by scientists in the program.

Proven Technology

Core Analyses: ODP is a leader in onboard specialized sediment analyses, particularly applied to the study of Earth's climate and ocean-circulation history. This leadership stems from the successful development of the wireline-deployed hydraulic piston corer that recovers high-quality, continuous sediment sections to depths of 200 to 300 meters below the seafloor. To extract the climate record from recovered sediments, ODP has developed the multi-sensor track (MST) tool, which measures physical properties, geochemical indicators and proxy climate data nearly continuously and non-destructively. We anticipate that additional geochemical sensors will be added to the MST as they become technically feasible. ODP has also expanded its capabilities to include microbiological analyses on a routine basis. This new initiative includes shipboard labs, quality assurance procedures and special sampling schemes for microbiology.

Borehole Observatories: Seismic and Strain Observatories, Circulation Obviation Retrofit Kits (CORKs) and Advanced CORKs: In support of its initiative for *in situ* monitoring of geological processes, ODP has developed the capability to install long-term instrumentation in selected reentry holes. In comparison with most other tools historically used in scientific ocean drilling, these observatories represent a major paradigm shift in technology because they are designed to record physical and chemical processes over long time periods. Two primary classes of such observatories were developed during ODP: (1) downhole broadband seismic stations, sometimes with strainmeters, as deployed in several sites around Japan, and (2) sealed-hole hydrogeological observatories called CORKs, as deployed in many sites since 1991. CORKs seal reentry holes at the seafloor, allowing deployment of various instruments to measure *in situ* physical, chemical and biological properties over periods of years. Advanced CORKs (ACORKs, Figure 2) incorporate multiple seals to allow instrumentation to record time-series observations in several isolated zones within the formation, for example, above, below and across permeable fault zones. These observatories represent a significant advance in the manner in which Earth systems are studied with scientific ocean drilling because this approach directly addresses process dynamics. Such observatories also represent a major commitment to allied geoscience initiatives such as the International Ocean Network, or ION (see Collaborations section).

New Technology

Advanced Diamond Core Barrel: Diamond coring tools are routinely used in the mining and geotechnical industries to recover high-quality cores. ODP, in collaboration with JAMSTEC, is modifying and adapting this technology. During standard operations, ODP uses larger diameter bits than the mining and geotechnical industries, but smaller diameter bits are better suited to recovery of high-quality core. One of the most important factors in core quality, the kerf, is a measure of the ratio of the diameter of the borehole drilled with respect to the diameter of the sample recovered. The new Advanced Diamond Core Barrel reduces the standard kerf ratio and thus will improve core quality and recovery in ODP and IODP.

Active Heave Compensation (AHC): Following a recommendation of JOIDES Technology and Engineering Development Committee, ODP procured an "Active Heave Compensator" system in addition to the Passive Heave Compensator now on the *JOIDES Resolution*. The existing Passive Heave Compensator on the *JOIDES Resolution* can only remove up to 75% of the drillstring movement. The residual motion can cause weight-on-bit fluctuations severe enough to effect core quality and rates of recovery. We anticipate that the recently installed Active Heave Compensator will reduce weight on bit fluctuation by a factor of 10 or more. Testing and refinement of the Active Heave Compensator is currently underway. The provision of more efficient heave compensation provided by this system will improve tool and bit life, core quality and core recovery for all sampling systems deployed. It will also allow deployment of precision coring and monitoring tools.

Hard Rock Reentry System: One of the most difficult and persistent challenges in scientific ocean drilling continues to be starting a borehole in bare-rock settings, for example, at the axis of mid-ocean ridges. This difficulty stems from both the formation characteristics and ODP's need to rely on a long flexible drillpipe that hangs, in tension, from the derrick. When lowered through the water column, sometimes to depths of 5 km or more, in a bare-rock seafloor setting, the drillpipe and bit slip sideways without cutting into the rock, and thus boreholes cannot be started. The Hard Rock Reentry System (HRRS) is under development by ODP to establish a guide base on the seafloor so that the bit can be advanced in bare hard rock. The reentry system is a massive template that allows for easy entry of the drillpipe because it is wide at the top, above the seafloor, and narrows at the seafloor, thus acting like a guiding funnel. Results of initial ODP trials indicate that the system shows real promise.

Fly-in Borehole Reentry System: IODP objectives require various types of sensors in a borehole to measure relevant parameters for long duration, or to get samples for analysis. Typical sensors include seismometers, strainmeters, thermisters, pressure meters and water samplers. During ODP, a submersible-based reentry system was developed in France, and a remotely operated vehicle (ROV)-based system was developed in the US. Recently, another ROV-based borehole reentry system was developed, and sea trials are being conducted by JAMSTEC in 2001. The ROV is suspended by a tether cable from a surface ship.

The ROV is controlled from the surface and is guided to the borehole where it enables the lowering of a sensor string deep in the borehole. Both the ROV and sensor unit are connected to the surface ship with optical fiber cable. The measured data are sent to the surface vessel in real time. For long-term measurements, the optical fiber is terminated, the ROV returns to the surface vessel, and the measured data are stored in memory in the monitoring package left behind. Another ROV or manned submersible is used to return to the borehole and retrieve the long-term records.

Technology Under Development

Hyperbaric (Gas Hydrate) Autoclave Coring Equipment (HYACE): This tool is a wireline-deployed coring system that will sample and maintain cores at *in situ* temperatures and pressure. The system will include a variety of coring tools to sample a full range of lithologies (soft sediment to hard rock). It will also include a system for nondestructive physical and chemical analyses with sampling under pressure and at controlled temperatures, once the samples are returned to the ship from below the seafloor. HYACE is a European Marine Science and Technology (MAST)-supported project, with eight supporting partners (six European countries and two industry partners). ODP is a collaborator in the HYACE project, providing shiptime and engineering support for prototype testing. HYACE will be completed in time for IODP. The system is ideally suited for studying gas hydrates and microbiology of the deep biosphere.

Vibra-core sampling tool: Fugro, Inc. has recently adapted a Russian-designed vibra-corer for the marine geotechnical industry. This tool, when used in ODP, will recover difficult formations (corals, hard/soft sequences, silty sands) that have not been successfully sampled with the standard suite of ODP tools. ODP is now adapting and testing this tool.

ODP – IODP Transition Strategy

ODP phaseout will overlap with the planning and implementation of IODP, and will be undertaken in close consultation with IODP planning groups, taking into account the following principles:

- ODP drilling proposals which are seen by the transition-period IODP Advisory Structure as potential IODP drilling proposals will be mentored and nurtured until they become officially part of the IODP science planning process.
- ODP data bases, repositories and equipment will be made available to IODP as required.
- Components of the JOIDES Advisory Structure that are required for IODP will be transferred to the IODP Advisory Structure in a timely fashion.

As soon as the last of the ODP drilling legs have been scheduled, a new IODP Interim Science Advisory Structure (iSAS) will be put in place. Initially the IODP panels and committees will mentor, help develop and evaluate submitted proposals that address the major thematic areas. It is anticipated that planning for riser drilling will require five years to complete, thus detailed plans will begin to be developed for the first riser site prior to the actual start of IODP. These plans will be drafted by a Detailed Planning Group (DPG) to be named by the iSAS.

Program Operations and Management

The operation and management of IODP represents a significant challenge for the international scientific community. The members of the IODP International Working Group (IWG) are developing international Memorandums of Understanding (MOUs) that will define their representation and their roles in IODP. Until these MOUs have been approved by the parties concerned, the exact operation and management structure of IODP cannot be defined. However, as with the Science Advisory Structure, the scientific community can offer some guiding principles derived from our long and successful experience of working together in ODP and DSDP:

- IODP funds received by the management structure should be commingled at as high a level as possible commensurate with international agreements.
- IODP management structure should be as simple and as streamlined as possible, consistent with functional effectiveness of multiple platform operations and with the constraints imposed by international Memorandums of Understanding.
- Considerable effort should be made to assure good communications at the operational level.
- IODP operations should strive for uniformity and standardization of tools, equipment and procedures used on all platforms and in all laboratories.

Given these principles, we can also define several levels of management and management tasks needed in IODP, without having to specify how individual programmatic units will ultimately be linked in the final management structure. This linkage will depend, at least in part, on the final MOUs developed by the IODP member nations, and in part on the responses to requests for proposals that are made once the initial formation of IODP is underway. These levels are listed and briefly described below:

- **Level 1.** International Program Management Office. This office would receive input from the Science Advisory Structure and oversee the overall management and operations of IODP. An annual budget for drilling operations proposed by this office will be submitted to the management council of the IODP partner nations.
- **Level 2.** Science Operator (riser) would manage the operations of the riser vessel including science staffing of that ship. Similarly, the Science Operator (non-riser) would operate and staff the non-riser vessel. A Ship Operations administrator is likely to be needed to coordinate ship operations and assure good communication between operations subcontractors.

  Science Services managers will represent several different offices providing specific services. These are likely to include Data Management Services (networks, telemetered data, site survey and IODP databases, publications, industry databank, etc.), Logging Services, Curatorial and Shore Laboratory Services, and possibly Observatory services.

- **Level 2/3.** There may be some specific science services that lie at either Level 2 or Level 3 depending on the complexity of their final charge and their ultimate position in the management structure. These could include managers of the Site Safety and Pollution, Engineering Development and Delivery (programmatic tools) and Education and Public Affairs.

- **Level 3.** This level would include Drilling Operations and Rig managers, and any platform-specific Technical Support managers. It would also include a large number of lower level (but very necessary) managers associated with rig-specific drilling and operation services.

IODP Science Advice

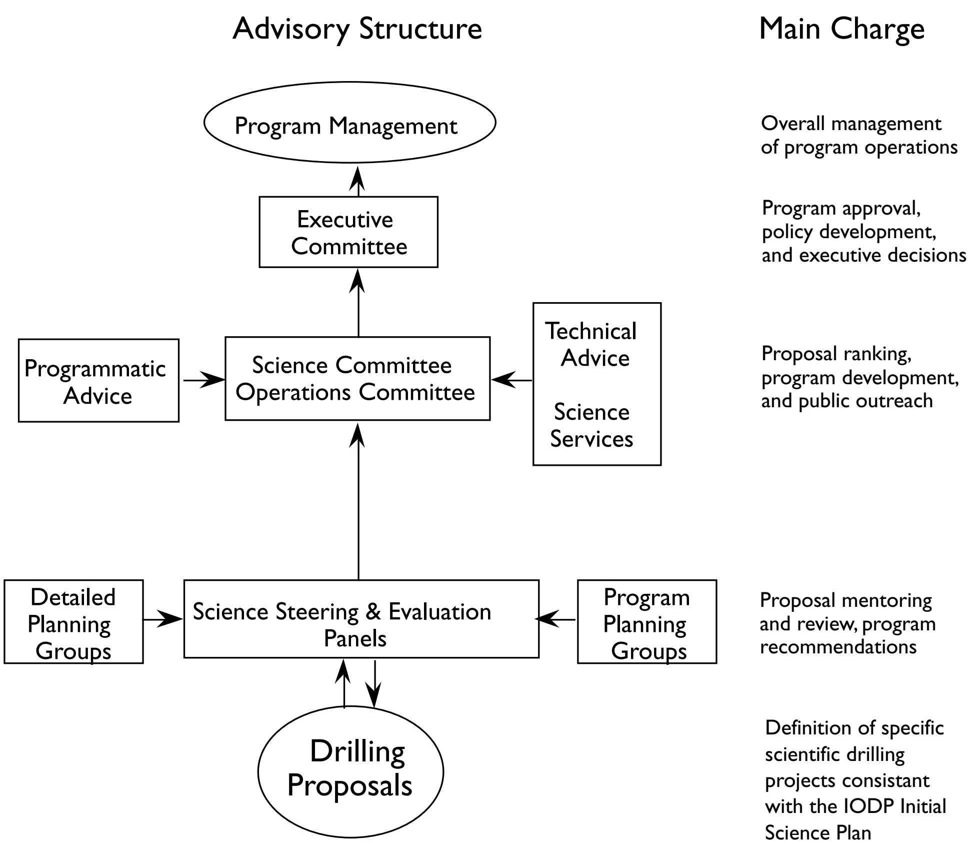


Figure 38. Diagram of proposed scientific advisory structure of IODP. This structure is based primarily on the present JOIDES Science Advisory Structure. It is recognized that some elements of this older structure must be augmented to deal with the increased demands of an integrated, multi-platform program and it is understood that representation in the new IODP Advisory Structure will reflect new international agreements. However, there are two key elements of this structure that will remained unchanged : (1) IODP will be a program driven by proponents who develop scientific drilling proposals which will be peer-reviewed and ranked by the international community, and (2) The advisory structure will review all proposals and, with expert technical advice, determine the most appropriate drilling platform to use in addressing the scientific objectives.

Science Advice and Coordination

With the advice of the scientific community, the IWG member countries will ultimately decide on the exact nature of the Science Advisory Structure and the proportional membership on advisory committees. The very successful nature of the past international scientific drilling programs shows that the community has learned how to: (1) define important scientific objectives, (2) develop specific drilling proposals to address these objectives, (3) fairly rank these proposals in a peer-review process and (4) recommend a drilling plan that addresses high-priority ocean drilling science. Thus, the recommended Science Advisory Structure seen in Figure 38 reflects this experience and is based on the current JOIDES Advisory Structure.

IODP will be a much larger program than ODP and DSDP, and with the increase in the number of operating platforms there comes an increase in complexity that needs consideration and planning. We have two primary guiding principles:

- IODP should always look like, and function as, a single international scientific program.
- IODP should receive scientific advice by an advisory structure that reviews all proposals, no matter what drilling platform is appropriate to accomplish the proposed science.

Having said this, there are some obvious corollaries to these principles that derive from the complexity of the planned program. For example, the Operations Committee (OPCOM), which currently defines the drillship schedule, will have a much larger task than in ODP. They will have to work closely with the IODP Program Manager, the Science Operators, and the Science Service Operators to assure that individual expeditions and drilling programs operating on different platforms and over different time scales are scheduled in an efficient and cost-effective manner. At the next level down in the advisory structure (Figure 38), the Science Steering and Evaluation Panels (SSEP) will rely more heavily on Detailed Planning Groups (DPGs) in developing specific science and drilling plans for the very deep holes drilled by the riser ship. They will need to define in great detail the scientific objectives, drilling, coring and logging strategies, and needs for downhole measurements and observatories throughout the multiple kilometers of section drilled. These recommendations must be carefully reviewed and evaluated not only by the scientists, but also by the safety and pollution-prevention advisors, the technical advisors and drilling engineers, and the science operator representatives.

Programmatic advice on issues of publications and data base management, educational and public affairs efforts, and improved coordination with resource exploration industries will also play a role of increased importance in the new program. The exact mandates and makeup of individual committees, panels and groups will be reviewed and revised as the IODP develops over the next few years.

Collaborations

Partnering with Other Research Programs

There are a large number of international programs with scientific goals that are complementary to those of IODP and where collaboration would be advantageous. These include the International Continental Drilling Program (ICDP), International Ocean Network (ION), seafloor fiber optic networks such as NEPTUNE, the International Geosphere-Biosphere Program, Past Global Climate Changes (PAGES), International Marine Past Global Changes Study (IMAGES), InterMargins, InterRidge and Nansen Arctic Drilling (NAD). Collaboration might include establishing IODP Program Planning Groups or Detailed Planning Groups, cosponsoring workshops, sharing of drilling expertise, technologies and equipment, or developing specific drilling experiments. In some cases IODP will make significant contributions to these programs by supplying cored material, establishing holes or "observatories" needed for long-term instrumentation, and providing core description and curatorial facilities. Other programs might enhance IODP's research capabilities by contributing specialized tools such as borehole seismometers, or providing detailed site survey data. The primary goal is to make the most of the diverse resources available to all of these programs.

In cases where there are clear overlaps in scientific objectives or where proposed site locations could serve more than one scientific purpose, IODP may establish Program Planning Groups (to help plan research strategy) and/or Detailed Planning Groups (to develop specific drilling plans) with representation from both the IODP and allied research communities. These groups are designed to facilitate the planning and execution of drilling programs and maximize the scientific payoff for both IODP and the other cooperating national or international research programs. ODP used this strategy to optimize drilling objectives in the Arctic, for example, where members of the Nansen Arctic Drilling Program participated on ODP's Arctic DPG.

To foster close cooperation with other research programs, there will be a continuous exchange of ideas through jointly sponsored workshops and conferences. Themes of common interest can be followed up by joint Detailed Planning Groups that develop specific drilling proposals. Such a partnership of scientists is a fundamental requirement of proposal-driven programs such as IODP, ICDP and others.

One outstanding example of ongoing collaboration is the drilling of the coastal plain portion of the New Jersey (onshore-offshore) sea level transect. For this project, ODP has supplied drilling expertise, archived and stored the cores and coordinated publications. ICDP, along with NSF and the New Jersey State Geological Survey, has funded and carried out the onshore drilling. ICDP has also committed to help support the inner-shelf portion of that transect. Such a cooperative approach precludes development of artificial boundaries between studies, and encourages a thoughtful definition of the scientific problems to be addressed. Other examples of possible cooperative efforts are outlined in Appendix 3.

While the benefits of collaboration are numerous, there are also some challenges faced by cooperative efforts, including: (1) joint planning and coordination, (2) consensus-building in ranking high-priority science, and (3) coordinating scheduling of science activities and facilities within and among the different programs. These challenges will be addressed by formal liaison between the IODP advisory structure, such as Program Planning Groups, and equivalent structures of the partner programs.

Partnering with Industry

At the same time as the scientific ocean drilling community is expanding its research interests and its technical capabilities through the development of IODP, the drilling and oil exploration industries have been undergoing significant changes. These industries are now exploring for hydrocarbons in deeper water settings where much of the primary experience and information base comes from past scientific ocean drilling efforts, but large oil exploration company mergers have tended to diminish the relative size of their individual research efforts. These new and parallel trends in ocean research and oil exploration have resulted in larger areas of overlap in both the scientific interests and capabilities of the two communities. Consequently there now is an unprecedented opportunity for the scientific ocean drilling community to develop close cooperative partnerships with industry in order to advance our knowledge of settings that generate and host hydrocarbon resources.

The strategy for developing IODP partnerships with industry is focused in two areas. The first is to begin working with industry researchers to develop drilling proposals that address the high priority science objectives of IODP as well as meeting industry's high priority research needs. The second is to establish regular communications with the executive levels of industry to ensure a long term and sustainable participation of industry researchers in IODP. This will be achieved by working with industry associations that already have established industrial executive links, and by delivering regular (semiannual) briefings to industry executives at national and international industry forums. New joint research initiatives will be encouraged by sponsoring special forums with industry on a regular basis. Similar partnerships are planned for the mining and biotechnology industries.

IODP Funding

The US and Japan intend to be equal partners in funding the operation of IODP, and up to one-third of program costs may be provided by other international partners. The degree of support and participation levels of other nationals and consortia of nations is currently under discussion by the International Working Group. Initially Japan, through the Japan Marine Science and Technology Center (JAMSTEC), is funding the construction of a state-of-the-art, deep-water riser drilling ship. This ship will be built, tested and ready for scientific drilling operations in ~2006. The US National Science Foundation (NSF) will underwrite conversion of a commercial non-riser drillship, to be available for IODP drilling operations by ~2005. Mission-specific platforms will be mobilized when specified as necessary by the IODP science advisory structure.

The estimated annual IODP program costs of $140 million (in 1999 dollars) are based on expenditure plans developed by administrative and technical personnel from JAMSTEC, and on current program plans for the operation of ODP, including JOI and its subcontractors. They include estimated program costs derived from existing FY 1999-2000 budgets, as well as forecasts based on 1999 industry market price lists for equipment and technical services, estimates for drilling and logging operations, and for ancillary operations such as hole planning, core curation, science advice and data management.

The annual cost estimates for operating the new riser vessel are based on calculated project costs for completing two potential riser holes off the east coast of Japan at 2500 m and 2000 m water depth with drilling penetration of 4000 m and 3500 m below seafloor, respectively. The estimate was calculated based on industry market price information available in the second quarter, 1999 or earlier. It was prepared with the advice and support of Japanese industry and academic science communities and was reviewed by the IODP Planning Subcommittee (IPSC) Technology Advice Working Group. Although riser drilling costs will largely depend on geological/geostructural conditions of individual sites and distances from supply ports, the estimates do not include contingency and/or cost impacts arising from potential drilling hazards (serious mud loss, side tracking, etc). Subcommittees of IODP's interim science advisory structure continue to seek and assess hazard predictions and associated cost estimates, and well as drilling cost estimates for additional potential riser sites, including some in more remote locations.

Cost estimates for operating the non-riser vessel and program administration were extrapolated from ODP's FY 1999 and 2000 operating budgets, including non-riser ship operations, logging operations and associated ancillary operations. Budget estimates for the Science Advisory Structure and overall Program management were derived from FY 2000 ODP expenditures, taking into account the anticipated increase in program complexity. Cost estimates have been reviewed and assessed as reasonable by the IODP Planning Subcommittee working groups and advisors.

The estimated operational costs summarized in Figure 39 do not include several items that are viewed as important parts of the new program. These include:

- operation of mission-specific drilling platforms and the need for associated containerized laboratories;
- expanded database management and publications efforts;
- expanded shore-based facilities for processing and analysis of samples.

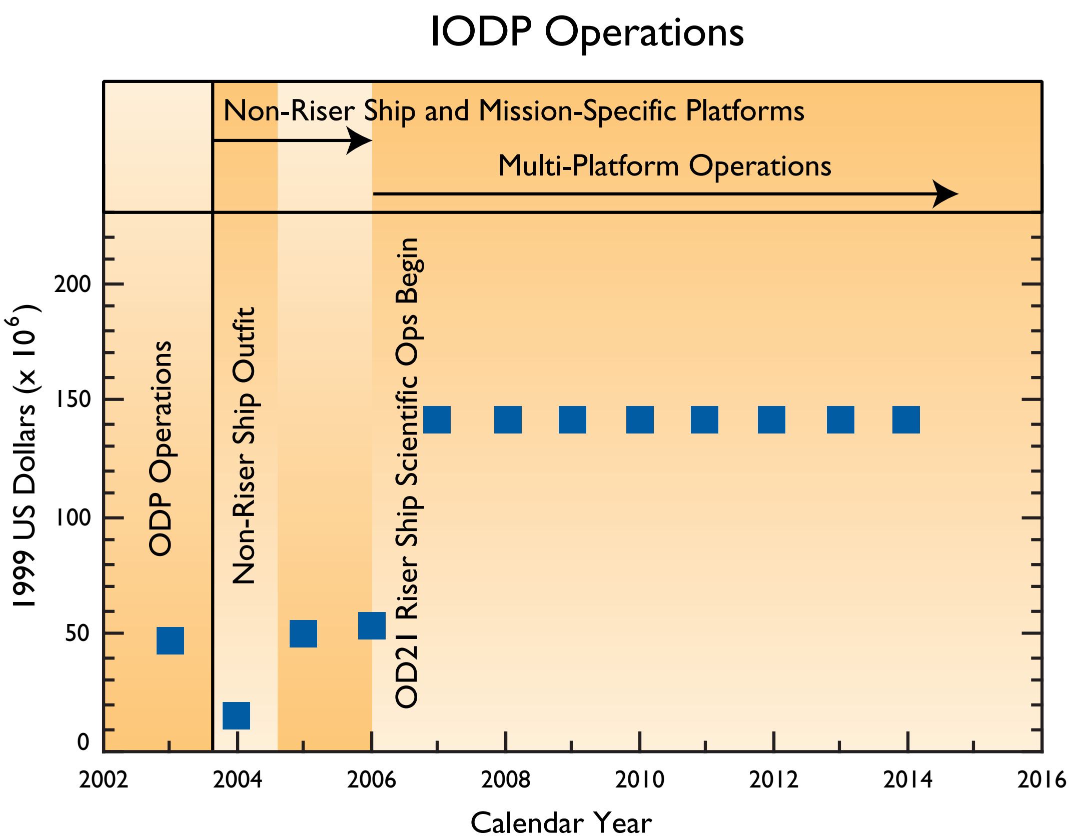


Figure 39. Estimated IODP operational costs (in 1999 US dollars). These estimates are derived from cost estimates of operating of the OD21 riser ship as presented by JAMSTEC and evaluated by the IPSC. The non-riser ship costs and basic program operation cost are based on ODP's fiscal year budget. The costs shown in this graph assumes the operation of two primary drilling ships and the basic operation of IODP. It does not include costs of mission-specific platforms and other elements of the IODP described in the text.

Cost estimates for operating mission-specific platforms are not yet available for several reasons. First, the exact operational limits of the non-riser drilling ship have yet to be determined, so the extent of the scientific needs not addressed by this ship are not known at this time. Second, much as the Japanese and the US are capitalizing the costs of building or converting the two primary drilling ships for IODP, other IODP members may yet come forward to capitalize the costs of missions-specific drilling equipment or platforms for the broader community. There has as yet been insufficient time for the development of a large number of specific scientific drilling proposals that require mission-specific platforms. However, we believe that the heaviest demand for such platforms will be in ice-covered regions and in very shallow waters. Mobilization costs, locations of the drilling areas, readily available facilities and other logistical considerations could have a significant impact on total costs.

An important item not included in the budget is travel costs for participation in the ocean drilling program science advisory structure, which is likely to expand due to the increased complexity of the new program. Costs for scientists to attend ODP science advisory panels and committee meetings have traditionally been funded by member-country national programs, and we expect that participation will continue to be supported in this manner.

Appendix 1

Community Consultation in the Development of the IODP Initial Science Plan

The international ocean drilling community has a long and distinguished history of seeking community consensus on important scientific objectives. Near the end of DSDP (1983), and soon after the beginning of ODP (1985), large international Conferences on Scientific Ocean Drilling (COSOD I, Austin, TX, 1981; COSOD II, Strasbourg, France, 1987) considered the state of knowledge and charted new courses for the future of drilling science. During the course of ODP, two long-range plans (1992, 1996) have been produced, each preceded by significant national and international planning efforts in the form of large numbers of meetings and workshops.

The IODP Initial Science Plan has specifically benefited from two large, international planning meetings over the past four years (see table A-1). The first, CONCORD (Tokyo, 1997), was charged with defining the important science to be achieved from riser-drilling operations. The second, COMPLEX (Vancouver, 1999), complemented CONCORD by describing the scientific objectives linked most strongly to non-riser drilling. Both conferences have also considered, in a variety of ways, the scientific goals and technology inherent in mission-specific drilling activities.

As in the past, the international drilling community will continue to examine its scientific progress and prospects, using new scientific planning efforts and contributions of its member nations as a primary guide, and producing new planning documents as necessary.

Table A-1: Participants in Major IODP Planning Workshops

Participation by Country	CONCORD	COMPLEX
Australia	3	13
Belgium	1	2
Canada	3	16
Chinese Taipei	2	5
Denmark	3	2
France	9	26
Germany	6	35
Iceland	2	1
India		2
Italy	1	5
Japan	79	24
Korea	2	2
Netherlands		1
New Zealand		1
Norway		3
Panama		1
Peoples Republic of China	1	6
Portugal		1
Russia	1	2
South Africa		1
Spain	1	3
Sweden		4
Switzerland	1	3
UK	7	18
USA	34	224
Totals	156*	401**

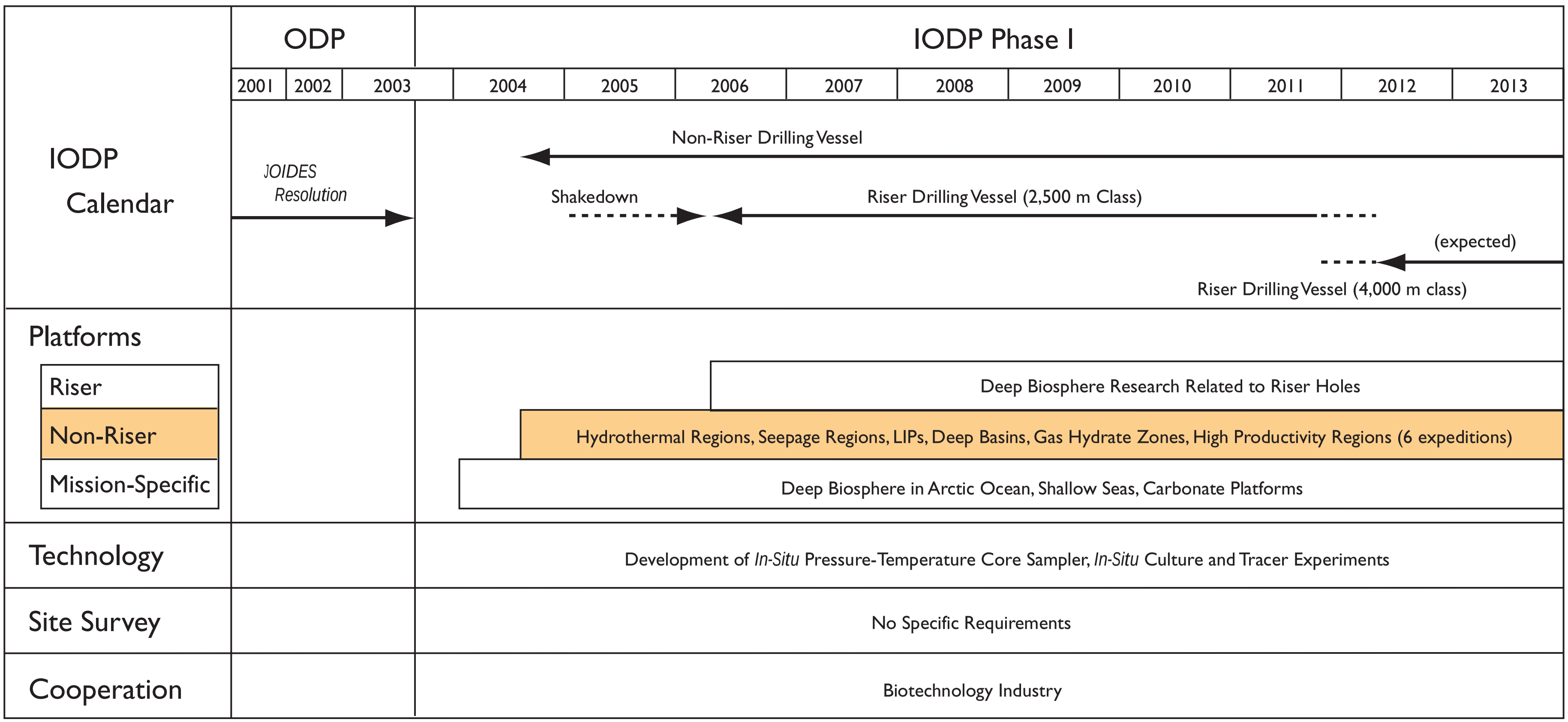
* In addition, 18 others (2-Canada, 2-France, 10-Japan, 1-Spain, 2-U.S.A., 1-Chinese Taipei) submitted vision statements. A total of 74 officials and observers also attended. From Japan: STA/JAMSTEC (36), ORI-U. Tokyo (11), Japan Drilling Co. (6), M&J (2), Geological Survey of Japan (2), Kobe U. (1), Frontier Research Promotion Office (1), NASDA (1), Maritime Safety Agency (1), Marine Works Japan (1), Monbusho (1), Mitsubishi Heavy Industries, Ltd. (1), Mitsui Engineering and Shipbuilding, Ltd. (1), and Marine Works Japan(1). From the U.S.A.: NSF (5), JOI (1)., and USSAC (1). From the U.K.: NERC (1).

** In addition, 27 other scientists attended from the Ocean Drilling Program, JOI., NSF and JAMSTEC/STA. Table A-1 Participants in major IODP Planning Workshops

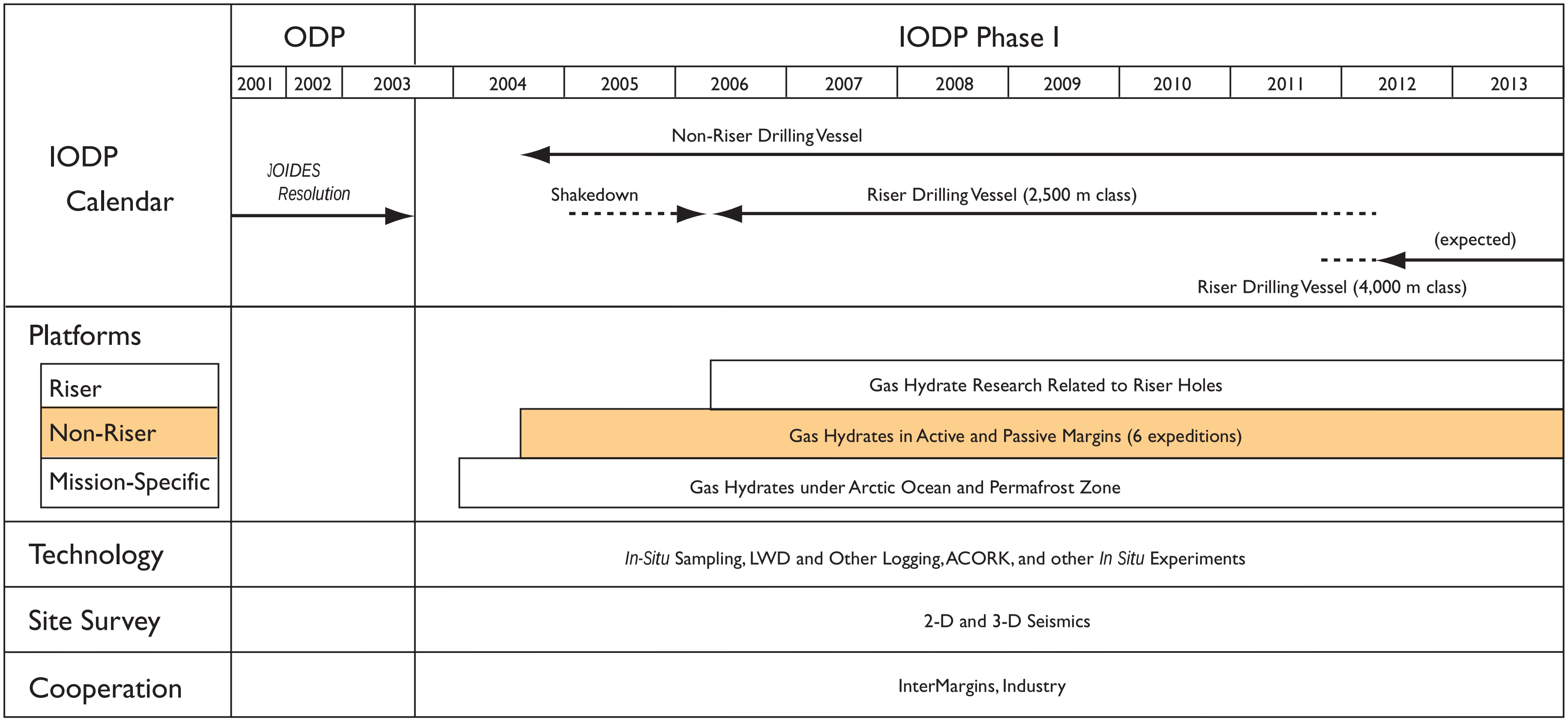
Appendix 2

IODP Implementation Plans

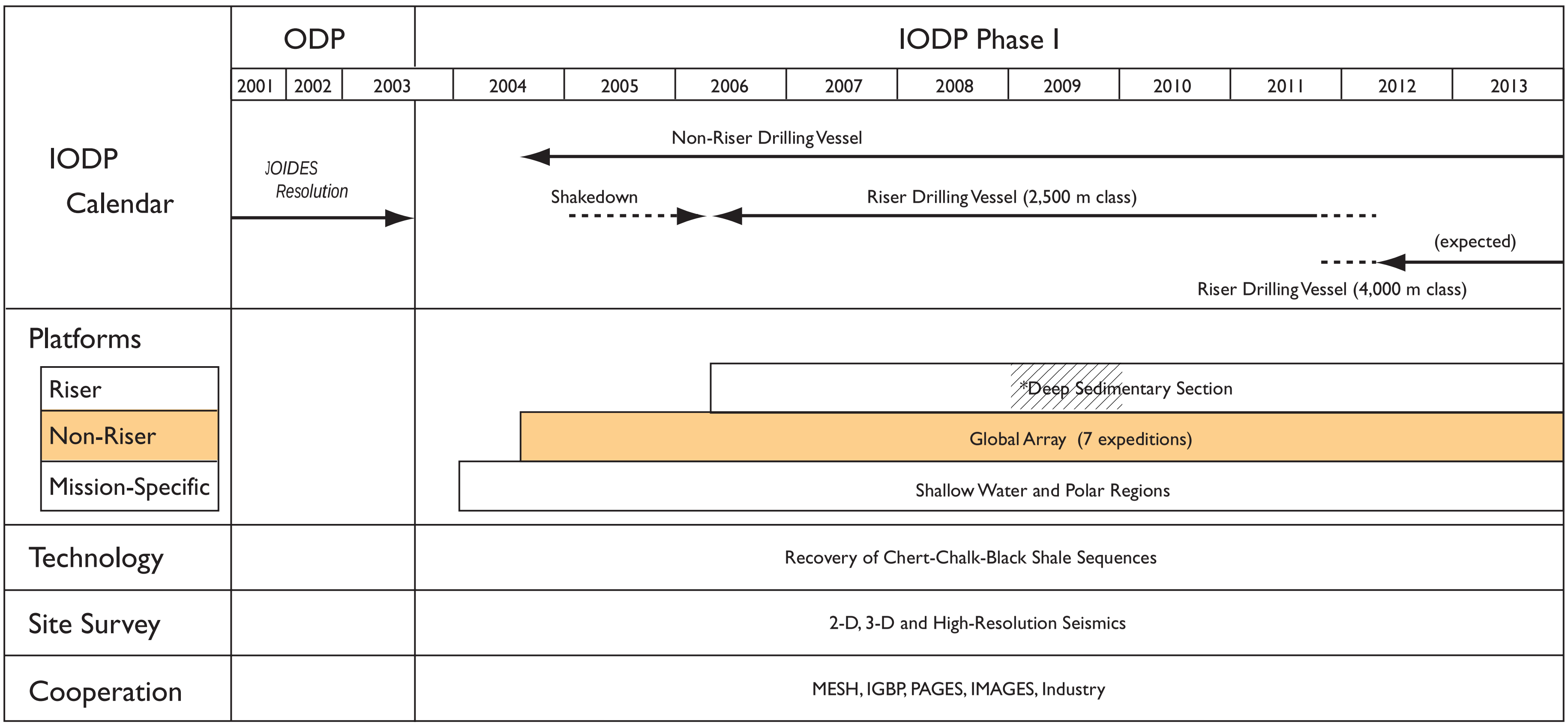
Scientific Initiative: Deep Biosphere



Scientific Initiative: Gas Hydrates

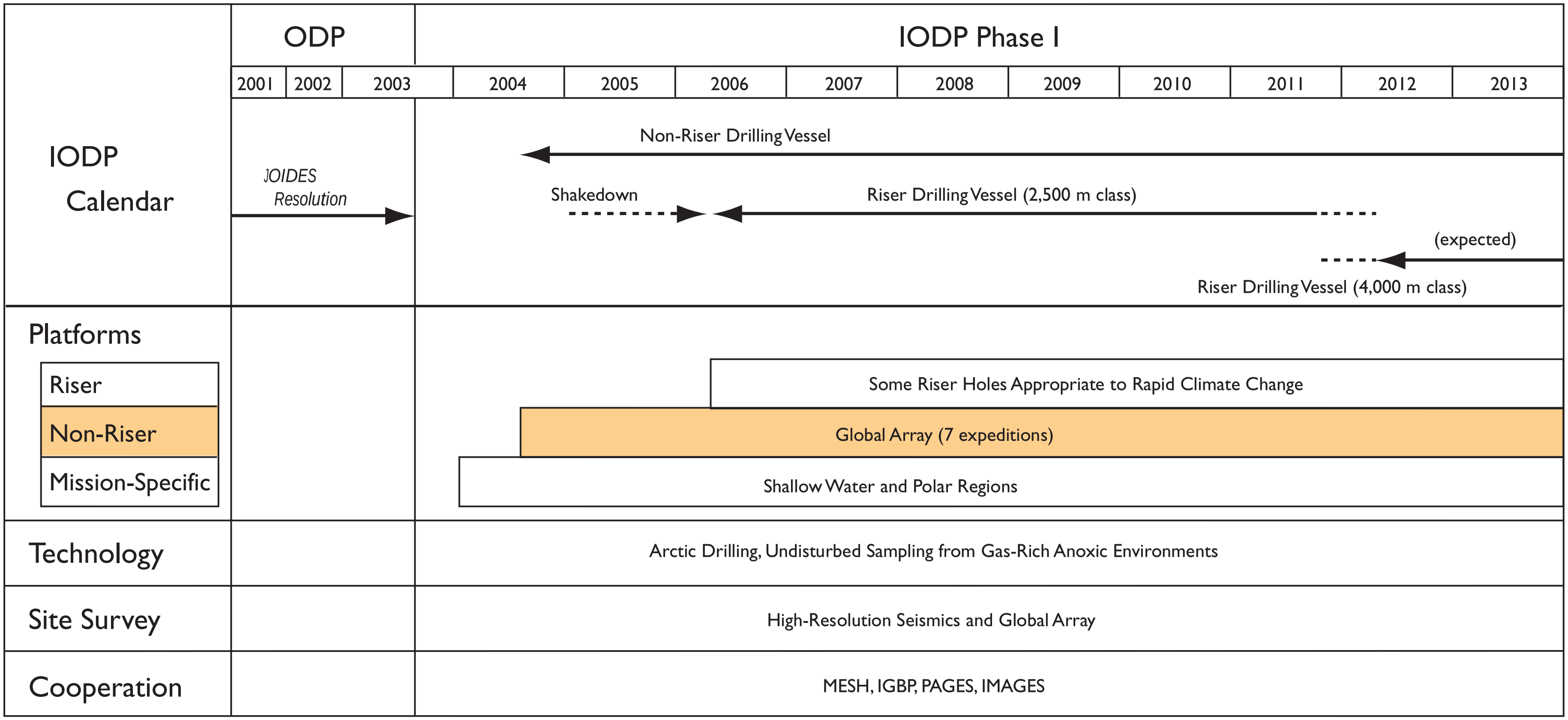


Scientific Initiative: Extreme Climates

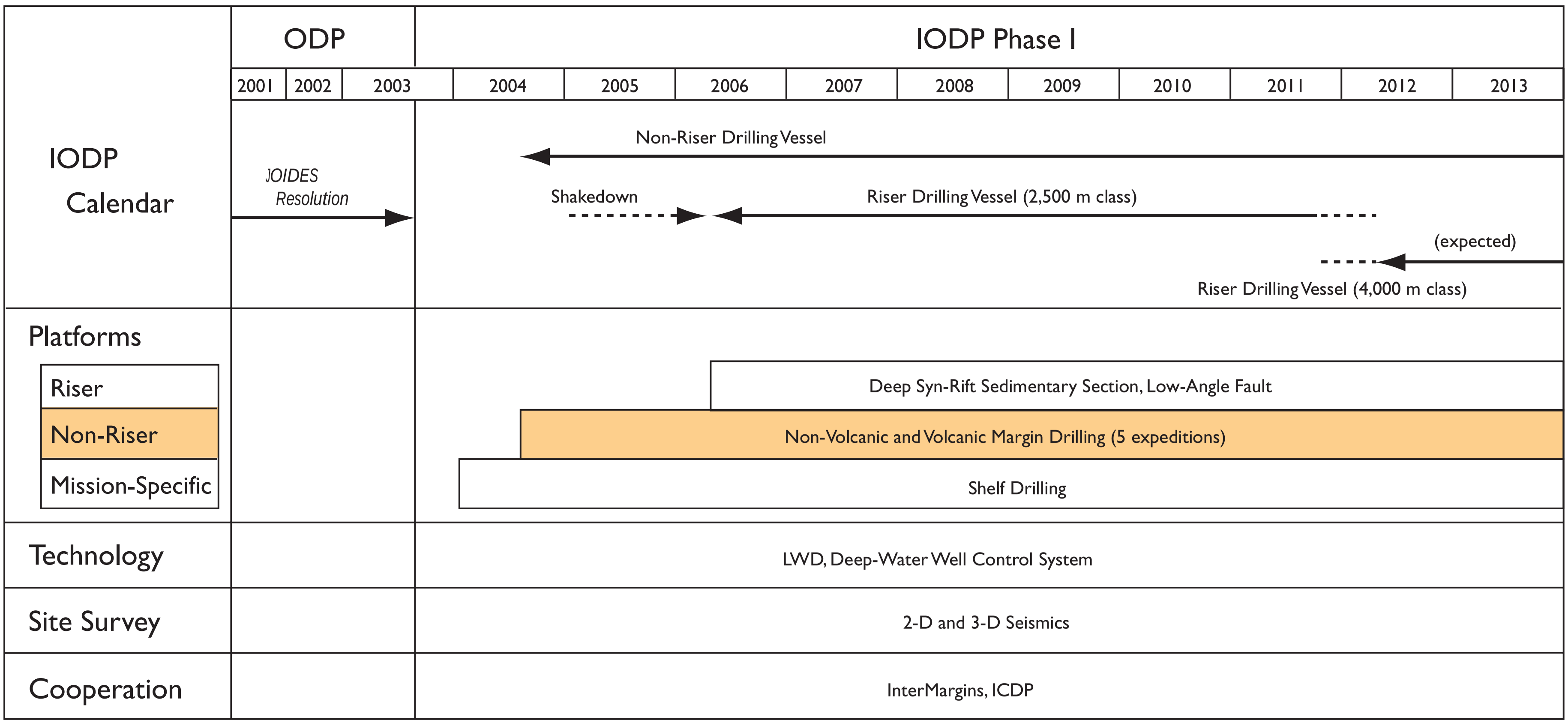


*The hachured area in "Riser" represents an expected peak drilling period.

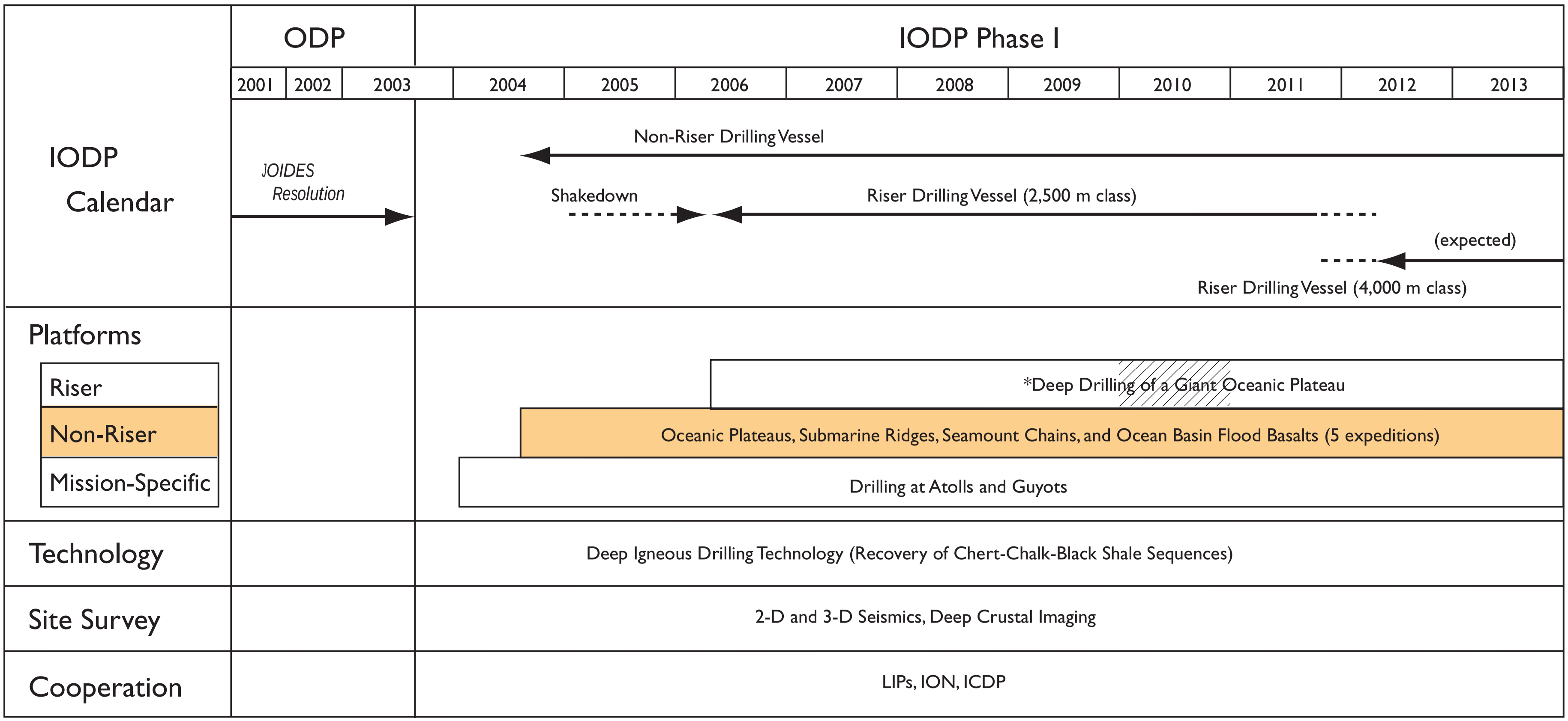
Scientific Initiative: Rapid Climate Change



Scientific Initiative: Continental Breakup and Sedimentary Basin Formation

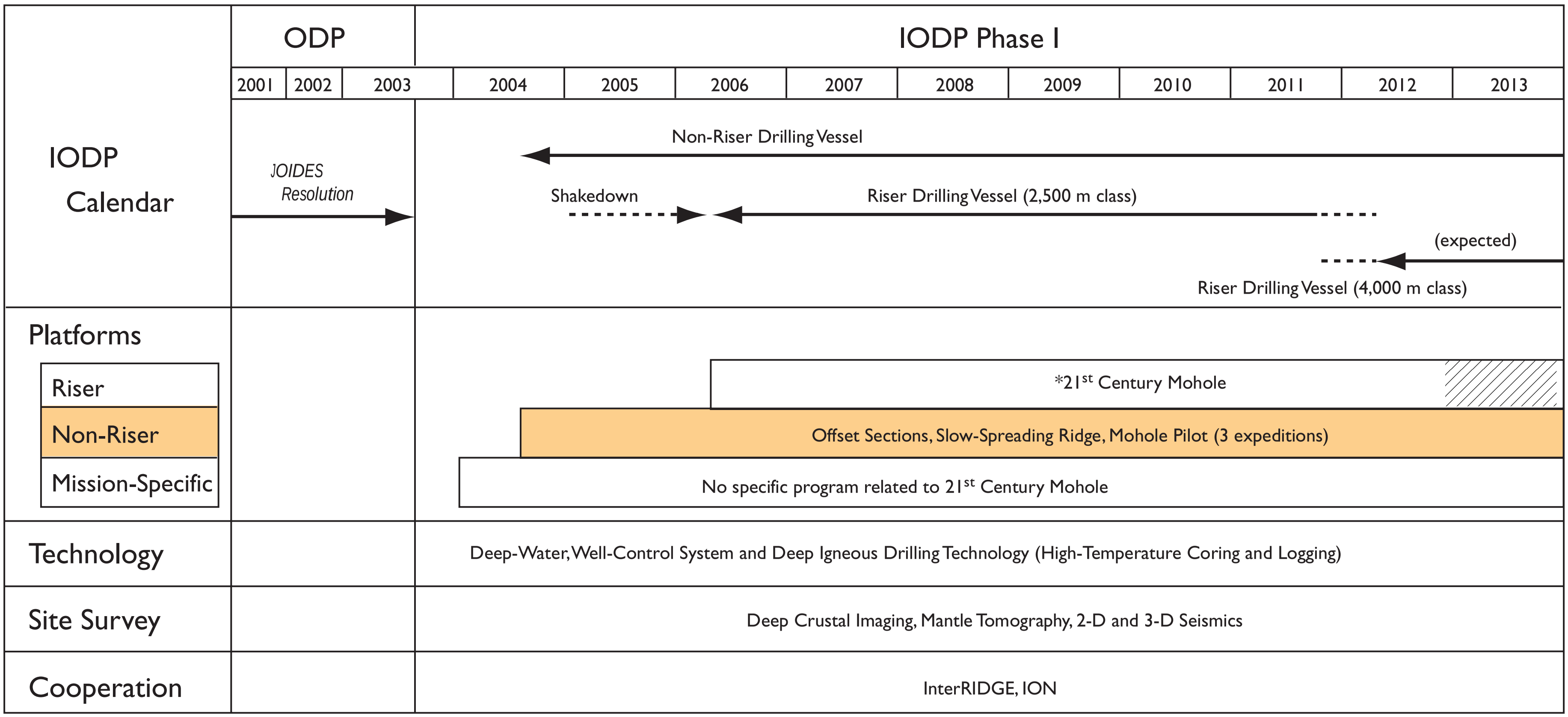


Scientific Initiative: Large Igneous Provinces



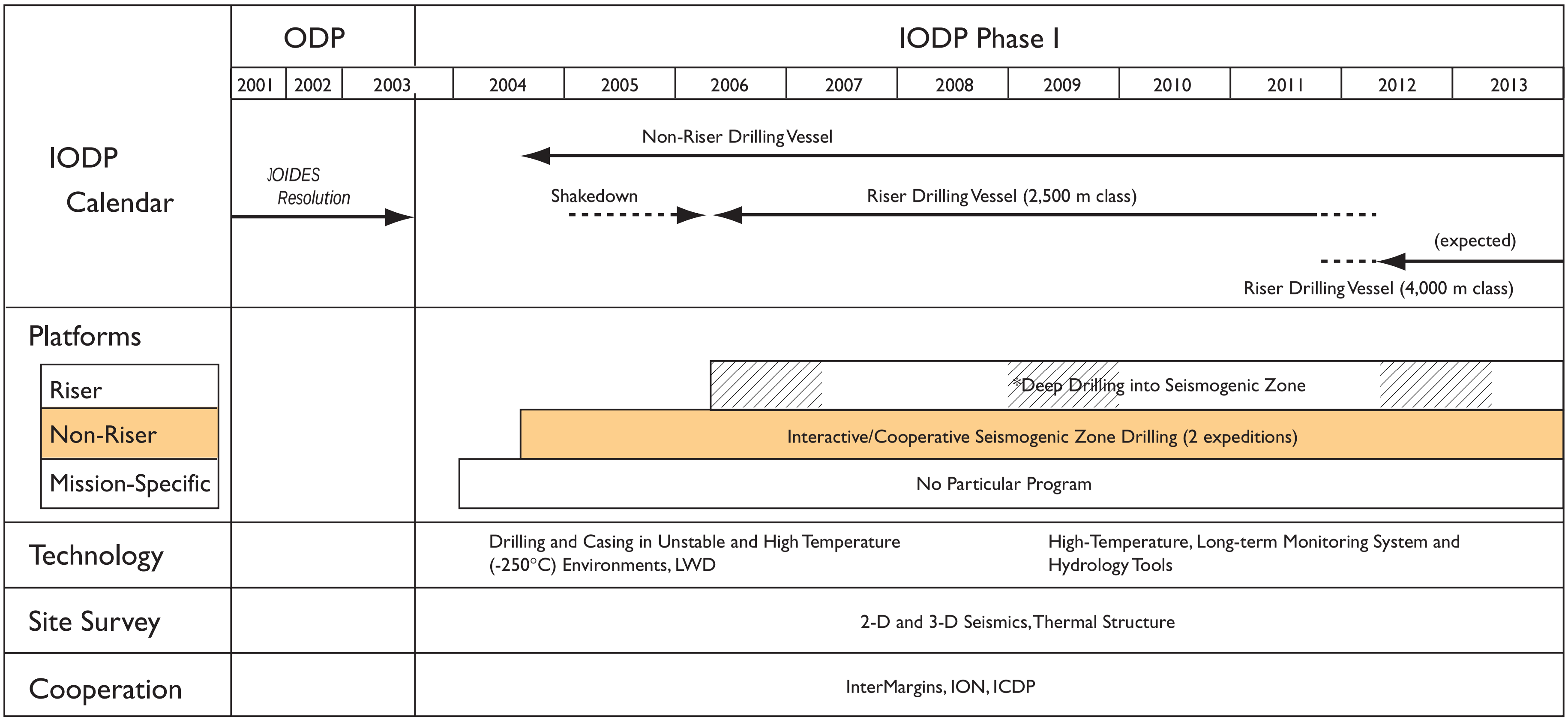
* The hachured area in "Riser" represents an expected peak drilling peirod.

Scientific Initiative: 21st Century Mohole



*The hachured area in "Riser" represents an expected peak drilling period.

Scientific Initiative: Seismogenic Zone



* The hachured area in "Riser" represents an expected peak drilling period.

Appendix 3

IODP Synergies with Marine Geoscience Programs

In the decadal program envisioned in this Science Plan, there will inevitably be substantial scientific overlaps with ongoing and new marine geoscience initiatives around the world. The IODP Science Advisory Structure will remain open to interaction with these initiatives as they develop, both through direct interactions at the level of advisory structure committees and through submission of collaborative proposals to use IODP drilling platforms and related technologies. The spirit of this cooperation is described in the Implementation Plan (p. 71). Here we provide some examples of specific programs that have already successful collaborated with ODP and should continue to interact productively with IODP in the years following 2003.

The Deep Biosphere and the Subseafloor Ocean

As IODP pursues the study of gas hydrates worldwide, there should be productive interaction in the US with the NOAA-National Undersea Research Program (NURP), which oversees the asset DSV *Johnson Sealink.* NURP seeks to identify complementary scientific goals of NOAA, NSF, DOE (e.g., National Methane Hydrate Multi-Year R&D Program Plan) and scientific ocean drilling in the study of hydrates. Similar programs exist in Europe, Canada and Japan, many of which are tied to continuing industry interests in hydrates as a potential economic resource, and bacterial activity as it relates to the maturation and biodegradation of hydrocarbons in thick sedimentary sections.

The COMPLEX report and the Industrial Liaison Working Group of the IODP Planning Subcommittee (IPSC) have each identified the study of fluid flow in sedimentary and crustal sections as being of primary scientific importance. Collaborative proposals from academia and the international hydrocarbon industry are already in review within ODP; more are planned for IODP. Likely areas of specific geographic interest include the Gulf of Mexico, the Niger Delta and Atlantic Canada. InterRIDGE (RIDGE 2000 in the US) continues to focus on the study of hydrothermal processes, biogeochemical reactions and the biosphere in young oceanic crust; observatories (e.g., the DEOS program) planned as part of InterRIDGE and NEPTUNE will likely use IODP drilling capabilities.

In the US, new focus areas for NSF funding include different aspects of biocomplexity. IODP is likely to interact with ongoing investigations embodied in the multi-year initiatives, "Life in Extreme Environments (LExEn)" and "Biocomplexity in the Environment." In Japan, JAMSTEC expanded its microbial research program (Frontier Research Program on Extremophiles) in 2001 and is anticipating closer cooperation with IODP in the future.

Environmental Change, Processes and Effects

Many of the world's developed nations now have domestic and collaborative programs grouped under the broad rubric of "global change" research. In the US, these programs include Earth Systems History (ESH) and Marine Aspects of Earth Systems History (MESH). ESH and MESH concentrate on intervals of extreme climate and the rates of climate change through time, both central to IODP. Margins is now developing a "Source-to-Sink" component which will study entire depositional systems off New Zealand, New Guinea and Alaska over the next several years. Drilling has already been identified as a fundamental component of these proposed studies. InterMARGINS will concentrate on similar process-oriented systems. One current funded example is EuroSTRATAFORM, an outgrowth of ONR's STRATAFORM (Stratal Formation on Margins) Initiative, which will focus on the Adriatic Sea and the Rhone Fan areas of the Mediterranean.

Proposed IODP Arctic drilling will tap into a large number of ongoing scientific initiatives, including Arctic Natural Sciences (US/NSF) and the Nansen Arctic Drilling (NAD) program (international). Arctic drilling is also likely to need to develop new mission-specific drilling technologies, which will benefit from collaborative efforts within those parts of the hydrocarbon industry that have worked in Arctic, including Russian companies.

The ongoing Mid-Atlantic Sea-Level transect on the inner continental shelf off New Jersey has already received a financial commitment from the International Continental Drilling Program (ICDP). It is an example of cooperative scientific efforts aimed at establishing links between on-land drilling, shallow water drilling and drilling deep into the marginal sections in a truly integrated approach to investigating this region. Other commitments from ICDP are likely as IODP efforts to sample continuously and extract the climate and depositional records preserved in continental margin sedimentary sections develop.

JAMSTEC's initiative of establishing a new research institution for earth sciences (IFREE: Institute for Frontier Research on Earth Evolution) will allow further international involvement on paleoenvironmental research related to IODP. A division of IFREE will focus on the study of extreme climate and catastrophic events.

Solid Earth Cycle and Geodynamics

The centerpiece for riser-based drilling in the early part of IODP will be a multidisciplinary, multi-year examination of the seismogenic zone off eastern Japan. Planning for that activity has been and will continue to be one of Japan's highest marine geoscience priority. NSF's SEIZE program plan incorporates seismogenic zone planning in the US; SEIZE is one of the four components of the developing Margins program. Another area of focused study, for both the Seismogenic Zone and the Subduction Factory components of Margins, will be Central America. ODP proposals for Costa Rica/Nicaragua already exist, and more planning for that area within IODP is underway. Potential collaborations with ICDP in these Subduction Factory activities are likely.

IODP will continue to be sympathetic to placing holes for seismic observatories in the world's oceans as part of the Global Seismic Network (GSN)/International Ocean Network (ION) programs. That record of collaboration within ODP over the past five years is clear.

The "21st Century Mohole" Initiative has always been one of the "holy grails" of the international research community that is interested in drilling deeply into the oceanic crust . This project remains an important long-term goal, complementing the active, process-oriented studies of the oceanic crust, as embodied in the NEPTUNE, DEOS and InterRIDGE programs.

JAMSTEC's IFREE is expected to develop integrated research on solid earth cycles and geodynamics including mantle-core dynamics, chemical evolution of mantel and crust, plate dynamics and seismogenesis.

The key to all of these interactions will be a willingness of the IODP scientific community to engage in such collaborations, and the flexibility to plan, schedule, and execute them, using joint fiscal and technical resources from the programs involved.

Glossary

ACORK .... Advanced Circulation Obviating Retrofit Kits (borehole seal)
AHC .... Active Heave Compensation
APC .... Advanced Piston Corer
BHA .... Bottom Hole Assembly
BRG .... ODP's Borehole Research Group
BSR .... Bottom Simulating Reflector
CCD .... Calcite Compensation Depth
COMPLEX .... Conference on Multi-Platform Exploration of the Ocean
CONCORD .... Conference on Cooperative Ocean Riser Drilling
CORK .... Circulation Obviating Retrofit Kits (borehole seal)
DCB .... Diamond Core Barrel
DEOS .... Dynamics of Earth and Ocean Systems
DOE .... US Department of Energy
DP .... Dynamic Positioning
DPG .... JOIDES Detailed Planning Group
DSDP .... Deep Sea Drilling Project
ENSO .... El Niño-Southern Oscillation
ESH .... US program studying Earth System History
EXCOM .... JOIDES Executive Committee
GSN .... Global Seismic Network
HYACE .... HYperbaric Autoclave Coring Equipment
ICDP .... International Continental Drilling Program
IFREE .... JAMSTEC's Institute for Frontier Research on Earth Evolution
IMAGES .... International Marine Past Global Changes Study
InterRidge .... An international geology and geophysics program studying mid-ocean ridges
InterMargins .... An international geology and geophysics program studying continental margins
IODP .... Integrated Ocean Drilling Program
ION .... International Ocean Network
IPSC .... Integrated Ocean Drilling Program Planning Sub-Committee
iSAS .... Interim Science Advisory Structure
JAMSTEC .... Japan Marine Science and Technology Center

JOI .... Joint Oceanographic Institutions, Inc.

JOIDES .... Joint Oceanographic Institutions for Deep Earth Sampling (ODP's science advisory structure)

LExEn .... Life in Extreme Environments

LIPs .... Large Igneous Provinces

LPTM .... Late Paleocene Thermal Maximum

Margins .... A US geology and geophysics program studying continental margins

MAST .... European Marine Science and Technology Programme

mbsf .... meters below the seafloor

MESH .... Marine Aspects of Earth System History

MEXT .... Japan's Ministry of Education, Culture, Sports, Science and Technology

MOU .... Memorandum of Understanding

NAD .... Nansen Arctic Drilling

NAO .... North Atlantic Oscillation

NEPTUNE .... Northeast Pacific Time-Series Undersea Networked Experiments

NOAA .... US National Oceanic and Atmospheric Administration

NSF .... US National Science Foundation

NURP .... NOAA's National Undersea Research Program

ODP .... Ocean Drilling Program

OPCOM .... JOIDES Operations Committee

PAGES .... International Geosphere-Biosphere Program Past Global Changes

PPG .... JOIDES Program Planning Group

RCB .... Rotary Core Barrel

RIDGE .... Ridge Interdisciplinary Global Experiments

ROV .... Remotely Operated Vehicle

SEIZE .... Seismogenic Zone Experiment

SSEP .... JOIDES Science Steering and Evaluation Panel

STA .... Science and Technology Agency of Japan

STRATAFORM ..... Research program studying STRATA FORMation

TEDCOM .... JOIDES Technical Development Committee

XCB .... Extended Core Barrel

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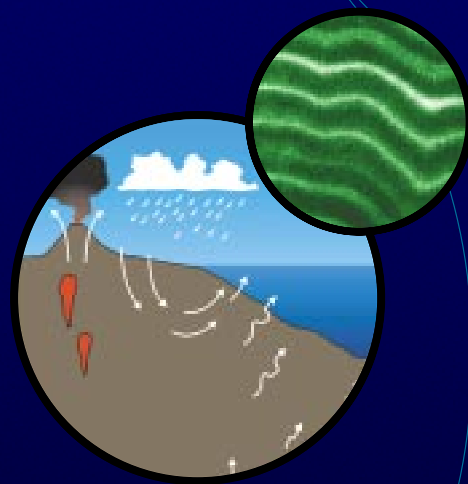

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