COMPLEX

Conference on Multiple Platform Exploration of the Ocean

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May 1999
Vancouver, British Columbia

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Prologue

We seek scientific knowledge for many reasons, but one of the noblest motivations is the pursuit of science in service to humanity. We cannot, however, just create societally relevant science; rather, science must be built on a solid foundation of basic knowledge. During the first 30 years of scientific ocean drilling, our knowledge base has grown and the technology we use has advanced. We are now establishing a global framework for understanding critical Earth processes, and we have seen many refinements in our abilities to formulate key Earth science questions and to develop new strategies to answer these questions. Concurrently—and, in many ways, specifically aided by drilling results—quantitative models have been developed for many components of the Earth system. The confluence of these growing knowledge streams has brought us to the point where scientific ocean drilling can now directly address fundamental questions of great relevance to humankind. These questions—categorized under the broad themes of resources, natural hazards, and global change—provide an overarching and compelling framework within which to plan scientific drilling beyond 2003.

"...scientific ocean drilling can now directly address fundamental questions of great relevance to humankind."

Executive Summary

Introduction

Planet Earth can be viewed as a complex system in which various components—such as the atmosphere, hydrosphere, lithosphere, and biosphere—interact with each other and to transfer energy and material at various scales of time and space. Anthropogenic impact on these subsystems is becoming increasingly important as major perturbations are produced in the "natural" behavior of the Earth system. Understanding how the dynamics of the Earth system work and how perturbations affect the Earth system is therefore vitally important for the future design of our society.

For more than 30 years the international scientific community has demonstrated unprecedented levels of cooperation and collaboration in the establishment of a series of coordinated programs for scientific ocean drilling. Through this drilling, our knowledge base has grown and technology has advanced. We have seen many refinements in our ability to formulate key Earth science questions and to develop new strategies to answer these questions. Concurrently, and in many ways directly aided by drilling results, quantitative models have been developed for many components of the Earth system. The confluence of these growing knowledge streams has brought us to the point where scientific ocean drilling can now directly address fundamental scientific questions of immediate relevance to humankind.

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As our conceptual understanding of the various components that drive our dynamic Earth is rapidly increasing, the nature of scientific drilling is becoming more focused. But we are still at a point where scientific drilling can lead to unexpected major new discoveries. Two recent drilling-related discoveries have forced us to rethink our current understanding of the Earth system. The first and probably most exciting finding from recent drilling has been the discovery of living organisms at great depths below the Earth's surface. This discovery thus extends the biosphere into the upper lithosphere and raises fundamental questions about the origins of life. The second finding has been the recent recognition of the far-reaching ramifications that the vast deposits of subsurface frozen methane (gas hydrates) can have on the global carbon budget.

As our strategies evolve, however, it is becoming increasingly clear that we are often limited in our ability to address these questions by the current capabilities of our drilling platform—in terms of both drilling and sampling limitations—and by our very approach to scientific drilling. Nevertheless, as we near the conclusion of the Ocean Drilling Program, we find that it has put us in a strong position from which to define a new phase of scientific ocean drilling that integrates new technologies and new approaches. On this basis, we propose the development of an innovative scientific drilling strategy that will directly address many of the remaining fundamental Earth system problems yet will be flexible enough to tackle problems so far undefined.

Recognizing the opportunity and the potential presented by this confluence of events, the Earth science community has been proactive in creating a new vision for future scientific ocean drilling. The Japanese have brought forth a bold plan for a riser-equipped drilling platform capable of drilling very deep boreholes in previously inaccessible environments. The international scientific community has already gathered together to explore the scientific opportunities presented by this new platform (CONCORD, 1998), but a large number of scientific problems still remain for which platforms without risers are better suited. In light of this, the Conference on Multiple Platform Exploration—COMPLEX—was held in May 1999 in Vancouver, British Columbia, Canada, to define the scientific frontiers and to develop strategies.

More than 350 scientists came to Vancouver and with phenomenal enthusiasm and consensus planned an exciting future for scientific drilling. The results of this meeting, summarized here, outline a new approach to planning global Earth science experiments that integrates a variety of tools that best meet the needs of specific questions. These tools range from deep or standard drilling platforms to small coring rigs deployed in special environments where other sampling tools cannot go. The experiments articulate tests of specific hypotheses posed by modeling and integrate scientific ocean drilling with other tools like ocean observatories and continental drilling. The key to this approach is a clear vision of primary scientific questions and research strategies, long-term and global strategic concepts for addressing these problems, and most critically, a program that makes the most appropriate tools accessible to the Earth science community.

In this summary we highlight some of the most exciting new initiatives to be addressed by a pioneering integrated ocean drilling program and briefly present the technological approaches and strategies needed to carry them out. Scientific challenges lie in understanding newly discovered Earth subsystems like the deep biosphere and the potentially economic gas hydrate deposits. Investigating the Arctic Ocean, which remains the last largely unexplored region of Earth, is certain to yield scientific and technological benefits to society. New insights into the sensitivity of the Earth system will be provided by the study of the changing circulation and biogeochemistry of the oceans, the solid Earth cycles, the processes occurring in the seismogenic zones along oceanic plate boundaries, and core and mantle dynamics, including the rapid eruption of voluminous quantities of igneous rock. Perturbation and recovery processes of the Earth system, including adaptation strategies of the biosphere, will be studied through examination of catastrophic events and rates of biologic evolution.

Deep Biosphere

Recent results from scientific ocean drilling have revealed a huge and previously unknown microbial biomass. This biomass, buried deep in sediments and the crust of the ocean, may be as much as two-thirds of Earth's microbial population. Fundamental issues such as the environmental conditions that support and limit this subsurface biosphere and its geographic extent need to be understood. What role do these communities play in determining atmospheric composition (and thus climate), and what is their potential as indicators of subsurface oil and gas deposits? Finally, an understanding of how these organisms can survive in these harsh environments and their potential for preserving genetic codes from millions of years ago may enhance our comprehension of the origins and evolution of life.

Thorough investigation of the deep biosphere requires a global sample collection from drill sites in a range of tectonic and environmental settings that will call upon the full suite of platforms available to an integrated ocean drilling program. Newly developed as well as refocused existing technologies will be needed to permit contamination-free drilling and clean-lab sampling techniques. NASA (the U.S. National Aeronautics and Space Administration) and other international organizations charged with planetary exploration can serve as valuable resources for collaboration and exchange in this realm.

GAS HYDRATES

Since the 1960s, we have known about the presence in marine sediments of "gas hydrates"—a frozen form of gas (mostly methane). Although, for safety reasons, scientific drilling programs judiciously avoided these deposits in the past, recent advances in scientific drilling and survey technology have allowed us to begin to sample gas hydrate deposits. The initial results have raised important questions about the role of gas hydrates in the global carbon system. In particular, current estimates of the size of the hydrate deposits suggest that they constitute a very large storehouse of carbon, but the rates of hydrate formation and dissociation, as well as the periods over which the deposits have formed, are not understood. Without such an understanding, it is impossible to accurately model the global carbon cycle. The destabilization (i.e., melting) of hydrates may be associated with geohazards such as submarine slope failure, possibly generating tsunamis and/or the release of massive amounts of greenhouse gases into the atmosphere. Such releases could explain the extreme climate excursions recorded in Earth's history. Though the details are unresolved, hydrates must also be an important energy source for benthic organisms. Finally, the potential of marine hydrates as a natural gas resource needs to be explored.

An integrated ocean drilling program is ideally suited to address the critically important issues regarding gas hydrates. High-quality geophysical surveys are needed initially to carefully characterize the extent and nature of the hydrate fields. Settings with different rates of gas hydrate formation and dissociation and different modes of methane transport must then be drilled. A full suite of drilling platforms—including shallow-drilling rigs and deep-drilling ships as well as ice barges—

will be needed. New technology will have to be developed to improve our ability to collect in situ samples and make direct measurements of gas hydrate properties. Finally, there will be a need for experiments that seal the borehole (i.e., using corks) and allow for the long-term and long-range monitoring of in situ pressure, temperature, and fluid flow.

Mare Incognitum—The Arctic Ocean

The Arctic Ocean and its marginal seas play a critical role in the global ocean–climate system. The dense, cold, bottom waters of most of the world's ocean, which originate in the Arctic, strongly influence global thermohaline circulation, driving world climate. The permanent Arctic sea-ice cover has a tremendous influence on the Earth's albedo and the distribution of fresh water. The sea-ice variation both seasonally and over longer time periods thus has a direct influence on global heat distribution and climate. Despite this, the logistical difficulties associated with the work in this remote and harsh region have prevented us from gathering the critical data needed to document the Arctic's role in the development and maintenance of the global climate system. Only about 2% of the Cenozoic stratigraphic record is represented in the existing core material. The Arctic Ocean, despite its critical role in global climate evolution, is the only ocean basin whose history is virtually unknown.

Drilling in the high Arctic presents a difficult logistical challenge. To fully understand the Arctic Ocean, we will not only need to drill in ice with deep-water drilling vessels but will also need specialized platforms to drill in the extensive shallow continental shelf regions of the Arctic. Recent developments, however, have created circumstances that may, for the first time, allow scientific drilling to come to fruition there. For example, the feasibility of station keeping in the high Arctic has been demonstrated. In addition, high-quality surveys have been made to guide the selection of specific drilling sites in critical areas, and the Swedish Polar Research Secretariat has expressed a willingness to provide support to a high Arctic drilling effort. The coincidence of these events has created a situation that may finally allow successful scientific drilling in the high Arctic.

Probing Global-Change Processes—Processes That Control the Variability of the Earth's Environment

With recent advances in data acquisition and Earth system modeling, we are now poised to use the marine geologic record of climate and ocean change to address two fundamental questions about the Earth's climate system: (1) What processes set the sensitivity of the climate system to change? (2) What controls the long-term evolution of this sensitivity?

Complex linkages between tectonic, global biota, ocean chemistry and circulation, and atmospheric composition create the feedbacks both negative and positive that set the sensitivity of the ocean system to change. Understanding the processes that control climate sensitivity to change is an essential prerequisite to making useful predictions about future climate. The study of long-term records of climate preserved in marine stratigraphic sequences offers two unique strategies for addressing our two fundamental questions.

Changes in Earth's orbital parameters provide a known forcing to the climate system. Deciphering how oceanic biogeochemistry and the climate system respond to this forcing and how this response changes with time provides a unique "experiment" for understanding climate sensitivity. Past climates provide an opportunity to study the response of the climate system to significant changes in atmospheric greenhouse gases. The fact that Earth has sometimes had very warm polar regions lacking glacial ice sheets leads to fundamental questions about the Earth system and strains our understanding of processes of global heat transport. A systematic study of these extreme conditions, using both ocean drilling and Earth system modeling of climate, ocean circulation, and biogeochemistry, will greatly advance our understanding of climate change.

Understanding the sensitivity of climate also requires improved documentation of oceanic and biogeochemical processes that can act as positive and negative feedbacks to change. Key feedback mechanisms include a suite of high-latitude processes including glacial ice-sheet and sea-ice dynamics, ocean thermohaline circulation, and ocean and atmosphere heat-transport dynamics. Ultimate understanding of climate change demands a more complete documentation of the interaction of these processes.

Thus, answers to our fundamental climate and oceanic biogeochemistry questions demand documentation of climate-system variability on a wide range of time scales and under significantly different boundary conditions. Advances in our understanding require an integrated sampling strategy with improved modeling of the Earth system. This integration will allow us to test specific hypotheses and greatly advance our understanding of climate change.

Optimized sampling in sometimes difficult environments will require greater attention to predrilling surveys. Improvements in drilling and coring methods are needed to improve core quality and remove current limits to high-resolution sampling. We need to extend our ability to sample the geologic record completely and continuously throughout the sediment column. New and more flexible drilling strategies will open previously inaccessible regions, such as the polar oceans and shallow-water sites. High-resolution spatial arrays of sites of special interest will penetrate the seafloor from 50 to 150 m.

SOLID EARTH CYCLES AND THE SEISMOGENIC ZONE

Motion of Earth's lithosphere is a fundamental driving force for Earth system dynamics on the geologic to human time scale. The lithospheric plates move relative to each other, breaking apart continents, making new oceans and sedimentary basins, and building new mountain belts. The resulting solid Earth cycles generate the transportation of material and energy through parts of Earth's interior and at its surface. Energy and material transfer occurs on various time scales, from relatively slow, as in the rise of mountain ranges, to instantaneously, as in explosive volcanic eruptions and destructive earthquakes.

The significant recent advance in our understanding of the plate-tectonic cycle is our increased awareness of the importance of the role of fluids that reside at almost every level within the lithosphere. Fluids are now considered to play a major role in driving or mediating all the critical processes of plate tectonics. These include major aspects of Earth as a unique planet, such as plate-scale faulting and deformation, the nature of the crust-mantle boundary, and the creation of continental crust. Intimately related are the formation of ore deposits and hydrocarbon resources, hazardous explosive volcanic eruptions, and devastating earthquakes and tsunamis at subduction zones. Volatile cycles related to plate tectonics are a major factor controlling climatic variability, the biological processes of the deep biosphere, and gas hydrate formation.

Critical processes related to solid Earth cycles occur in the ocean. These include tectonic and sedimentary processes on passive continental margins, creation and evolution oceanic lithosphere, and material cycles in the subduction zones—here called the subduction factory because of its obvious reflection of, and often its contribution to, the material cycles of our industrialized society. The theory of plate tectonics provides the underlying kinematic explanation for destructive earthquakes, yet the reason why only a small part of the area of plate contact, called the seismogenic zone, generates earthquakes remains enigmatic. Although it is considered that fluids play a major role in these critical processes, many aspects of the state of fluids such as pressure, flow rate, and chemical reactivity are virtually unknown.

Oceanic boreholes provide direct access to the regions where fluid processes are concentrated. Uncontaminated fluid sampling, in situ measurements, and long-term monitoring of the variability of the state of fluids can only be done through drilling.

Core and Mantle Dynamics

Ocean drilling also has the potential to make unique contributions to elucidating processes occurring beneath the plates, deep within Earth's dynamic interior. In this region, internal heat that makes Earth a living planet is released via radioactive decay of long-lived radioisotopes. Chemical elements are differentiated in highly reactive zones such as the core-mantle boundary as the planet evolves toward some final, lower-energy state. Within Earth's core, the magnetic field, with all of its implications for cosmic-ray shielding, chronological dating, and navigation, is generated. All of the volcanic, tectonic, and hydrothermal activity we experience on Earth's surface is indirectly the result of the functioning of this hot chemical reactor.

A grand challenge of the twenty-first century will be to map the structural geology of Earth's deep interior and characterize how this dynamic region has functioned throughout geologic time. To what extent are hotspot island chains produced by plumes rising from the core-mantle boundary? Do subducting slabs end up ponding at the base of the mantle? Although the convecting mantle and core are inaccessible to the drill bit, ocean drilling will be essential for the installation of subseafloor seismic observatories needed to create a globally complete image of the lateral heterogeneity of the interior. Furthermore, drilling volcanic rocks that are products of the deep interior but are now found within a well-defined stratigraphic context is the best way to determine the geochemical evolution of the mantle and the complexities of the time-varying components of the magnetic field, including events leading up to entire field reversals.

With technology currently available to the drilling program, it is possible to drill the boreholes necessary to install seismic observatories. In order to obtain global coverage, some of these boreholes will need to be in the extreme high latitudes of the Southern Ocean, where operations are very difficult. Furthermore, in order to exploit the potential of observatories, operations will need to be carefully coordinated with those of international groups planning and maintaining those observatories. A more difficult challenge for the future drilling program will be obtaining the deep-crustal penetration and continuous core recovery necessary for mapping out the spatial and temporal geochemical heterogeneity of the mantle and the oriented cores that reveal magnetic field history. Although riser-style drilling holds great promise for attaining depths never before drilled in hard-rock lithologies, it will be simply too expensive and time consuming to obtain the required sampling if there is no capability for excellent recovery of oriented cores in shallow basement boreholes from a more conventional drilling ship.

Paleobiology and Evolution—The Marine Biosphere

Among the most pressing challenges facing modern-day research in the Earth, ocean, and atmospheric sciences is the need to understand the causes and effects of rapid major perturbations of the carbon cycle, especially the effects on global climate and on the biodiversity of the planet. Ocean drilling is particularly important to addressing this challenge because of its proven potential to yield truly global records of the history of life in the oceans. These records allow us to address three important scientific goals: (1) We aim to understand evolutionary processes that have given rise to the great variety of marine life and to acquire fundamental knowledge of our own origins. (2) We need to evaluate the sensitivity of marine ecosystems to large perturbations such as abrupt climate change, massive release of greenhouse gases, and removal of key parts of the oceanic food chain—issues we face as a result of human-induced climate change and exploitation of ocean resources. (3) We seek to decipher the ecologies of marine organisms and their critical, but poorly understood, roles in the cycling and uptake of greenhouse gases, major nutrients, and carbon. We are only just beginning to appreciate the feedback processes between life and the regulation of Earth's climate and inventories of many nutrients, gases, and chemical species.

Catastrophic Events

In addition to the all-too-familiar hazards associated with the movement of the plates, such as earthquakes and volcanic eruptions, Earth has experienced less common but potentially more deadly catastrophes, such as asteroid impacts, massive outpourings of flood basalts in plate interiors, giant landslides, and sudden ice-sheet collapse. The human experience with these rare events is so limited that we must turn to the seafloor record for information on the frequency of and conditions surrounding their occurrence and on their short- and long-term consequences for life and the environment. What are the effects of catastrophic events on primary productivity in the ocean and on the evolution of life? How long do the effects persist? Although we will for the most part be powerless to prevent such catastrophes, we may be able to mitigate their effects if we understand what to expect. Furthermore, by observing Earth's response to sudden, natural perturbations, we can better model the likely result of large and geologically instantaneous anthropogenic forcing of the Earth system.

Drilling is the only proven technique for accessing the record of catastrophic events as recorded in ocean sediments. Complementary land records are useful, but often poorly preserved. A complete strategy involves drilling both in the vicinity of former catastrophic events and in more distal locations, perhaps primarily for other reasons. Catastrophic events commonly result in major signatures in the sediments near the shoreline, caused by sudden sea-level changes or tsunamis. For this reason, the capability to drill in very shallow waters is important. On account of the short time scale of the catastrophe itself, collections of high-resolution records in regions of excellent preservation are essential. Complete core recovery, at least in targeted intervals, is required.

TECHNICAL NEEDS

One of the goals of COMPLEX was to define the scientific objectives of the post-2003 drilling program in the context of multiple platforms. At the end of this report, we describe the scientific objectives of COMPLEX in terms of three platform capabilities:

1. Scientific objectives that would be addressed by a riserless vessel of the *JOIDES Resolution* class with significantly enhanced capabilities

2. Scientific objectives that would be addressed by a vessel with expanded, riser-style capabilities such as envisioned for the new riser-equipped vessel (see CONCORD Report)

3. Scientific objectives that would be most efficiently addressed by other platforms or that cannot be addressed by either a riserless vessel with enhanced capabilities or the new riser-equipped vessel

We discuss the drilling, sampling, logging, in situ measurement, and enhanced laboratory needs identified in the different initiatives.

Table 1. Multiple Platforms for COMPLEX Objectives, Records Sought, and Strategies and Additional Needs

Ocean Exploration Objectives	Riserless Vessel (Enhanced Capabilities Relative to the *JOIDES Resolution*)*	Mission-Specific Platforms	Riser-Equipped Drilling Vessel	Strategies and Additional Needs
Deep Biosphere	Global sampling arrays in a range of tectonic environments	Sampling of shallow-water environments	Sampling in deep-water environments and in hydrocarbon-bearing zones	Microbial sampling during contamination-free drilling Specially designed shipboard laboratory
Gas Hydrate	Sampling of key environments	Shallow-water drilling Ice barge for high-latitude sites	Sampling on ocean margins in hydrocarbon-bearing and subduction zones	In situ, pressure-controlled sampling techniques and instrumented borehole corks
***Mare Incognitum*—The Arctic**	Drilling in ice-covered regions	Ice barge with drilling capabilities Need to drill in both deep and shallow regions of Arctic		Ice-breaker support
Global Change Processes and Climate	Deep (>150 m) drilling in regions of laminated sediments and in environments with ultra-high sedimentation rates to examine annual to interannual variability High-latitude paleoceanographic records in regions of deep-water formation Continental ice-sheet records (e.g., ice-rafted debris) Long-term, high-sedimentation-rate regions to document surface- and deep-water circulation processes Pelagic records of extreme climates	Ice barge with drilling capabilities (Arctic drilling) Shallow-water drilling targets in coral systems of the tropical ocean Pressure control in areas of high sedimentation rate, hydrocarbon-rich sections, or laminated sections	Pressure control in areas of high sedimentation rate, hydrocarbon-rich sections, or laminated sections	Drilling of deeply buried marine sections in continental sedimentary basins

Solid Earth Cycles	Sediment stratigraphy, slope stability, tectonic windows, volcaniclastic sections, serpentine seamounts, incoming plate, and shallow fore-arc sections Drilling on bare fractured rock Intact sections, offset drilling, and paired holes and shallow-hole arrays	Sea-level sequence stratigraphy (jack-up rigs, semisubmersibles) Ore deposits (hard-rock, e.g., portable, remotely operated drills and jack-up rigs)	Rift-history determination, deep fault penetration, total crustal section, high-temperature reaction zone, total fore-arc section, seismogenic zone Blow-out preventers in thick sedimentary prism Test of ophiolite model and delineation of protocontinents and arc history	
Seismogenic Zone	Transect of holes for studying lateral variations and installation of observatories		Deep penetration into out-of-sequence thrusts and seismogenic zones	Laboratory experimental studies Geology of paleo–seismogenic zone Long-term monitoring of critical parameters such as fluid pressure, strain, and seismicity
Core and Mantle Dynamics	Globally distributed arrays of remotely operated observatories Selected active-process observatories in areas of active surface systems Arrays of boreholes through high-sedimentation-rate sections containing suitable paleomagnetic signatures Samples from >500 m depth into igneous basement		Deep-crustal sampling	Long-term maintenance and monitoring of observatories Further development of long-term monitoring systems
Large Igneous Provinces	Transects of shallow (approximately 150 m) boreholes on key LIPs Drilling in tectonically exposed deeper sections		Deep-crustal reference sections	On-land drilling in obducted sections
Paleobiology and Evolution	Arrays of boreholes through high-sedimentation-rate sections in a wide variety of marine environments			
Catastrophic Events	Drilling in areas of impacts and explosive volcanic events	Shallow sites in areas of unstable slope conditions to examine mass-wasting events High-latitude drilling at ice margins to document ice-sheet instability	Study of mass-wasting events requires drilling through highly unstable regions of continental margins	Mass-wasting studies require development of in situ monitoring of possible triggering mechanisms, e.g., earthquakes, pore-pressure changes, and dissociation of gas hydrates

Part 1

Scientific Ocean Drilling

in the Twenty-First Century

Lessons from Twentieth Century Scientific Ocean Drilling

> **With advances in technology came new capabilities, new approaches, and new insights.**

More than 30 years ago, in the Gulf of Mexico, the *Glomar Challenger* retrieved its first samples from the seafloor, initiating a new era of scientific ocean drilling. The early days of drilling provided our first direct access to seafloor materials beyond the reach of conventional sediment corers and rock dredges. Drilling was exploratory as we sought answers to the most basic questions of the nature and age of the seafloor in different regions. Despite relatively limited capabilities, early drilling led to a number of new and fundamental discoveries, including confirmation of the theory of plate tectonics, identification of the repeated isolation and subsequent desiccation of the Mediterranean, and documentation that ocean circulation was fundamentally different in the geologic past.

With advances in technology came new capabilities, new approaches, and new insights. For example, the development of the hydraulic and advanced piston corers allowed the recovery of long, continuous stratigraphic sections that have permitted us to look at climate variability and dynamics over a wide range of timescales. As we acquired detailed, multiple-parameter climatic records, we began to document the nature of climatic forcing (i.e., the actions of the forces, both external and internal to the Earth system, that affect climate) over many timescales and, more important, Earth's response (both linear and nonlinear) to this forcing. Additions to these data combined with the future development of better climate models will revolutionize our understanding of the nature of past oceanographic and climatic variability.

Drilling in continental margins and ocean crust has greatly expanded our definition of Earth's hydrosphere. Fluid flow and associated chemical reactions alter the physical and chemical properties of Earth's ocean crust and sediments and thus play a key role in controlling ocean and atmospheric chemistry, both vital to human existence. Ocean drilling has demonstrated that fluid flow through seafloor

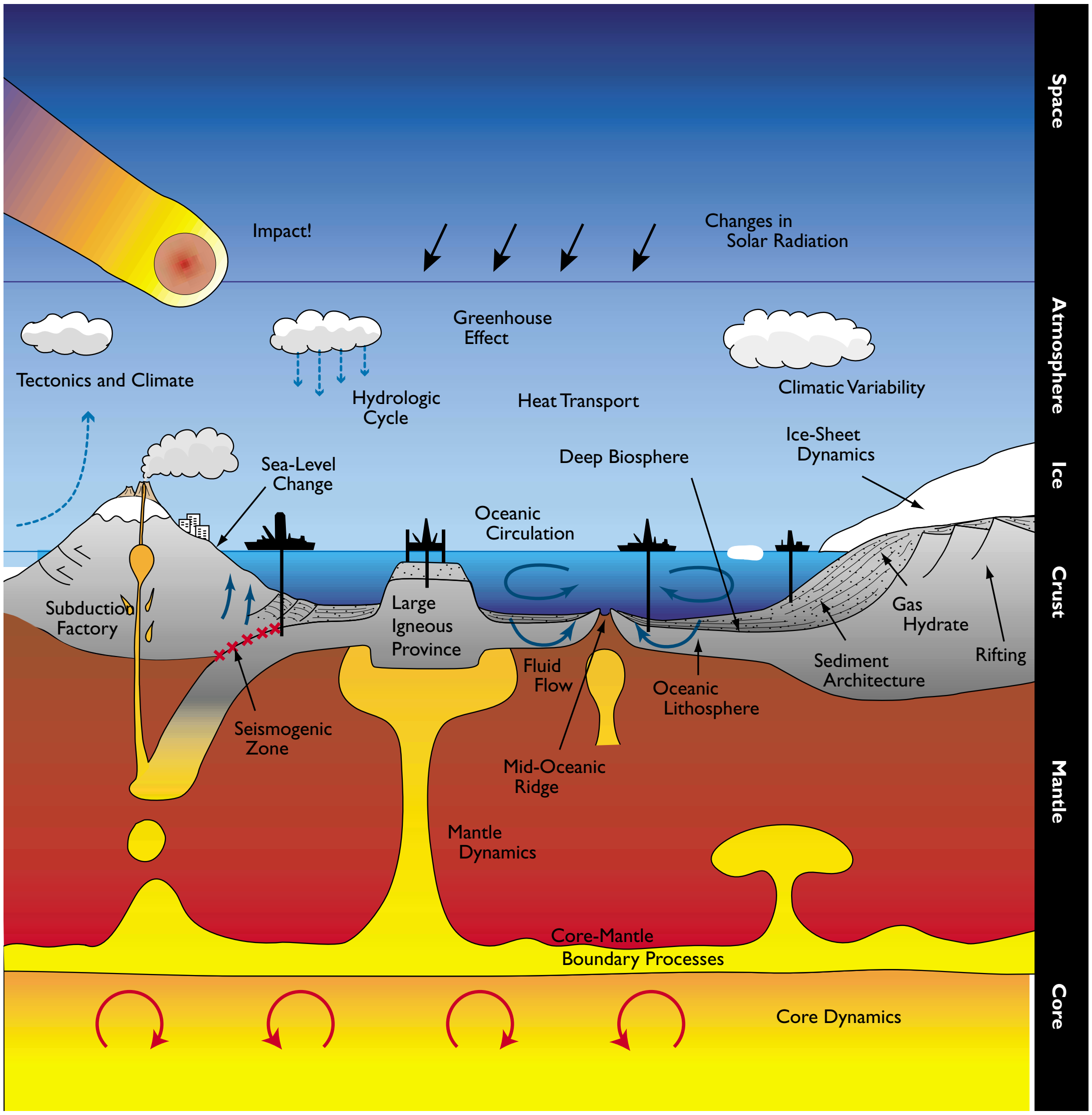

Figure 1. Complex linkages in the Earth system.

sediments and within the ocean crust allows biological processes that mediate many of the chemical reactions in the hydrosphere. Indeed, ocean drilling has afforded a new insight into the role and extent of biological life on planet Earth.

Paralleling these developments in scientific ocean drilling—and often directly resulting from them—has come an increasing recognition that Earth is a large, complex, interactive, and interconnected system, the parts of which are dynamically linked on timescales much shorter than previously believed. The individual components of the system, which often are subjects of discrete fields of study, are inextricably linked through complex and still poorly understood pathways and feedback mechanisms (Fig. 1).

> **Our understanding of the various components that drive our dynamic Earth is rapidly increasing, and the nature of scientific drilling is becoming more focused.**

With this growing observational database and a recognition of these complex Earth system links have come rapid conceptual and computational advances in our ability to model various components of the system. These models, though far from perfect, add an important new dimension to our ability to formulate scientific questions and test hypotheses; they add a powerful new tool for our quest to understand the nature of Earth system variability.

Our understanding of the various components that drive our dynamic Earth is rapidly increasing, and the nature of scientific drilling is becoming more focused. But we are still at a point where scientific drilling can lead to unexpected new and exciting major discoveries. Probably the most important example, already alluded to, is the recent drilling-related discovery of living organisms at great depths below Earth's surface. This discovery extended the biosphere into the upper lithosphere and raised fundamental questions about the origins of life. A second example involves the recent recognition of the vast subsurface frozen methane deposits (gas hydrates) in seafloor sediments; these methane deposits can have far-reaching ramifications for the global carbon budget and thus for climate.

With these new discoveries, our growing observational database, evolving new conceptual paradigms, and more sophisticated Earth system models, we have greatly enhanced our ability to formulate key Earth science questions and to develop new strategies to answer these questions. As these strategies evolve, however, it is becoming increasingly clear that we are often limited in our ability to address these questions by both the current capabilities of our drilling platform and by our approach to scientific drilling. Just as astronomers learned at the end of the first 30 years of their exploration of space with orbiting, light-collecting telescopes, new questions demand new approaches. In the Earth sciences, new sampling technologies—our "bigger telescopes"—as well as our improved sampling strategies and enhanced ability to model Earth systems now set the stage for new investigations probing even further into Earth's secrets.

Thus as we near the end of the Ocean Drilling Program, we find ourselves well-positioned to define a fresh phase of scientific ocean drilling that integrates modern technologies and approaches to develop a new scientific drilling strategy that will directly address many of the remaining fundamental Earth system problems already defined as well as many yet undiscovered. Recognizing the opportunity and the potential presented by this confluence of events, the Earth science community has been proactive in creating a new vision for future scientific ocean drilling.

The Japanese have brought forth a bold plan for a riser-equipped drilling platform capable of drilling very deep boreholes in previously inaccessible environments. (A riser is basically a long pipe big enough to have the drill string pass through it. It connects the ship to the borehole with a sealed connection so that if drilling mud is pumped down the borehole, the cuttings return to the ship. In the *JOIDES Resolution* mode of drilling, if mud is pumped down the drill string, the waste flows out onto the seafloor. Having the riser allows drilling in areas bearing gas and oil since the borehole can be sealed for the safety of personnel and to prevent environmental problems; otherwise, any hydrocarbons drilled into would flow straight into the ocean. A 2.5-km-long riser is very heavy, and there is the associated problem of pumping a column of mud and cuttings that is >2,500 m tall.) The international scientific community has already gathered together to explore the scientific opportunities presented by this new drilling platform (Conference on Cooperative Ocean Riser Drilling [CONCORD], July 22–24, 1997, National Olympics Memorial Youth Center, Tokyo, Japan). However, a large number of scientific problems still remain for which riserless drilling, from a vessel of the *JOIDES Resolution* class or other riserless platforms as appropriate, are better suited. In light of this, the Conference on Multiple Platform Exploration (COMPLEX) was held in May 1999 in Vancouver, British Columbia, Canada, to develop strategies that address these problems.

Lest there be any doubt of the importance of scientific drilling to the international Earth science community, the response to the COMPLEX meeting was remarkable. More than 350 scientists came to Vancouver (more wished to come but the attendance was limited by the venue) and with phenomenal enthusiasm and consensus planned an exciting future for scientific drilling. Drilling strategies and scientific issues were discussed free of many of the constraints that have limited previous programs. The discussions were aimed at the development of a truly integrated approach to planning global experiments; the participants defined riserless ocean platforms needed for drilling and conducting multiple-strategy programs. The results of this meeting, summarized here, outline a new approach to planning global Earth science experiments; this approach integrates a variety of tools that best meet the needs of scientists who are trying to answer specific questions. These tools range from deep or standard drilling platforms to small coring rigs deployed in special environments where other sampling tools cannot go. The proposed experiments articulate tests of specific hypotheses supported by modeling and integrate scientific ocean drilling with other approaches like ocean observatories and continental drilling. The key to success is a clear vision of the primary scientific questions and research strategies, the long-term and global strategic concepts for answering these questions, and most critically, a program that makes the most appropriate tools accessible to the Earth science community.

Scientific Overview

Ocean drilling is the most successful internationally coordinated scientific program studying the history of the entire Earth system. More important, because it is a coordinated program, ocean drilling is providing first-order observations and analyses of the linkages between these Earth processes. In this report we present the scientific questions that we are poised to answer with a new program of ocean drilling.

Many of the questions discussed later in this report have faced Earth scientists for a long time. Past ocean drilling and associated studies have greatly added to our understanding of Earth. At the same time, our ability to more precisely model Earth processes has greatly improved. Thus, we stand ready to combine new and better techniques for sampling with our ability to predict system behavior and test our understanding of Earth. For example, our discoveries of the warm climates of the Early Cretaceous, some 120 million years ago, have led us to pose fundamental questions on how climate and its integral components, such as atmospheric- and ocean-heat transport, operate under conditions fundamentally different from today's. Oceanic anoxic events (OAEs) occurred repeatedly during these warm climate intervals and record rapid changes in the global carbon cycle in association with major marine and terrestrial biotic turnovers. The fact that OAEs are missing from the later geologic record implies causal links among climates of extreme warmth, carbon cycling, evolution, and ocean circulation. The late Paleocene thermal maximum (LPTM), some 55 million years ago, is notable for its rapid increase in deep-ocean, high-latitude, and continental temperatures. A marked negative carbon isotope anomaly points to a possible massive release of methane into the atmosphere from gas hydrates in the ocean at rates similar to present-day anthropogenic inputs of CO_2 from fossil fuel burning. The LPTM thus potentially presents an example in the geologic record that could be used for predicting responses of the carbon cycle and climate to rapid and massive input of fossil fuel CO_2.

As with all scientific endeavors, new discoveries lead geologic research into uncharted territory. For future ocean drilling, we present three new research foci—the study of the deep biosphere, the study of gas hydrates, and the study of the Arctic Ocean. It has been estimated that two-thirds of the microbial population of Earth is found buried deep in the crust and sediment column of the ocean. How this huge biomass survives in an environment of such meager resources raises fundamental questions for biochemistry, microbial physiology, and microbial ecology.

We have known about the presence of gas hydrate deposits in marine sediments for a long time, at least since deep-ocean sampling by the Russians in the late 1960s. The stability field (i.e., the temperature and pressure conditions) in which methane gas plus water can be frozen into a gas-water ice—called a gas hydrate—is found at relatively shallow depths in the marine sediment column. The stability field often intersects the sediment-water interface. Until recently, scientific ocean drilling has avoided regions of gas hydrates for safety reasons (the vessel *JOIDES Resolution* was not equipped to handle large volumes of gas in the sediment column). With advances in technologies combined with better experimental strategies, gas hydrates have now been safely sampled by scientific drilling. Continued advances in new technologies will allow us to retrieve gas hydrates at in situ seafloor hydrostatic pressures and to examine processes associated with the formation, stability, and disassociation of these deposits.

But why study gas hydrates? Only recently has the volume of these deposits become fully appreciated. *Even the most conservative figures estimate gas hydrates to contain twice as much energy as all other hydrocarbon sources combined.* They thus form a major pool of carbon that is closely linked to the ocean-atmosphere carbon cycle. Are major changes in Earth's carbon cycle observed in the geologic past a reflection of changes in the gas hydrate pool? Recent drilling results suggest that this is the case. The presence of large hydrate deposits in tectonically active regions poses a new climate-tectonic linkage that can operate on timescales much faster than our traditional view of tectonic impacts on Earth's climate. Can tectonic seismic events and associated continental-slope failures unroof large hydrate reservoirs and catastrophically release large volumes of carbon to the ocean and atmosphere? This aspect of the carbon cycle, which can only be studied through scientific ocean drilling, has added to the list of important short-term climate linkages that we must understand if we are to understand climate variability.

But why study gas hydrates?

Are major changes in Earth's carbon cycle observed in the geologic past a reflection of changes in the gas hydrate pool?

Can tectonic seismic events and associated continental-slope failures unroof large hydrate reservoirs and catastrophically release large volumes of carbon to the ocean and atmosphere?

In this report, we discuss exploring the last *mare incognitum* of Earth's oceans—the Arctic. The geologic record of the Arctic Ocean remains essentially unexplored. Given the importance of this region to global climate and to ocean circulation, our ultimate understanding of many Earth processes will remain incomplete until we are able to fully sample the Arctic seafloor.

We also describe new integrated strategies to address fundamental Earth system questions. These include the study of changing circulation and biogeochemistry of the oceans, the solid Earth cycles, the processes occurring in seismogenic zones along oceanic plate boundaries, core and mantle dynamics, large igneous provinces, the paleobiology and evolution of the marine biosphere, and catastrophic events.

How to Read This Report

The COMPLEX meeting was organized from the 315 abstracts submitted to the Joint Oceanographic Institutions for Deep Earth Sampling (JOIDES). These abstracts are available from JOI Inc., Washington, D.C. (http://www.oceandrilling.org/COMPLEX). Presentations based on these abstracts were grouped into fourteen primary scientific sessions:

- Understanding Extreme Climates
- Documenting Climate Variability
- Constructing the Lithosphere
- Subduction Factory and Convergent-Margin Processes
- Geologic Processes Related to Rifting
- Climate Forcing on Long Timescales—Tectonics and Climate
- Climate Forcing on Short Timescales—External and Internal Mechanisms
- Evolution of the Crust and Lithosphere
- Seismogenic Zones
- Basin and Passive-Margin Evolution
- Dynamics of Earth's Interior
- Catastrophic Events
- Understanding Earth's Biosphere
- Gas Hydrates

The goal of the meeting's organization was to provide an opportunity for all participants to participate fully in the discussions. As expected from the multidisciplinary nature of scientific ocean drilling, there was considerable overlap between sessions. Indeed, any division of the scientific discussions into themes or report sections is artificial and is done here only for presentation purposes. The results of the scientific discussions of COMPLEX cover the following topics:

- The Deep Biosphere
- Gas Hydrates
- Mare Incognitum—The Arctic Ocean
- Climate and Ocean Biogeochemistry
- Solid Earth Cycle
- Seismogenic Zone
- Core and Mantle Dynamics
- Large Igneous Provinces
- The Marine Biosphere
- Catastrophic Events
- Summary of Technology Needs

In the COMPLEX report, all sections cover both state-of-the-art knowledge gained by ocean drilling in the past and new, exciting discoveries made by recent drilling campaigns. Many of the research areas that evolved from these discoveries are still in an exploratory phase and raise fundamental questions that must be addressed by future ocean drilling.

The New Foci
for Scientific Ocean Drilling

Ocean Drilling and the Deep Biosphere

Subsurface Communities: An Overview

In the near-subsurface layers of the seafloor, we find an orderly sequence of organisms that utilize the organic fluxes descending from the overlying water column to the seafloor. Depending on the strength of the organic input, the communities supported can be highly organized. The near-subsurface microbiota supported by organic input from the water column populate three more-or-less distinct zones:

> **Through continued deep sampling, it is becoming increasingly obvious that microbiotic communities play an active role in elemental cycling even at great depths within the seafloor.**

1. Near the sediment-water interface live aerobic-respiring heterotrophs.
2. Somewhat deeper are anaerobic-respiring heterotrophs (nitrate- and sulfate-reducing bacteria).
3. The microbiota that live deepest within the seafloor sediments are fermentative organisms.

It has been found that, although the nearly all of the organic input for the near-subsurface zones comes initially from the overlying water column, the biomass is complexly recycled by the microbiota in the seafloor. For example, the zones of sulfate reduction and fermentation overlap, and the fermenters act as a "front end" for the sulfate reducers. Furthermore, throughout the three near-subsurface zones, as methane and sulfide from great depths diffuse upward toward the sediment-water interface, they are commonly intercepted by methane- and sulfide-oxidizing organisms that act as local sources of biomass within the sedimentary communities. The structures of and interactions within these communities have been studied for many years. Fundamental questions remain, but the microbiota that live near the sediment-water interface are by far the best known.

Through continued deep sampling, it is becoming increasingly obvious that microbiotic communities play an active role in elemental cycling even at great depths within the seafloor. At the sediment–hard-rock interface, bacteria interact strongly with hard-rock mineral phases and thus catalyze "weathering reactions" that have been traditionally viewed as abiotic (Fig. 2). In even lower sediment zones formerly thought to be unpopulated by active microorganisms, a community now known as the "deep bacterial biosphere" has been discovered. These organisms can be detected visually through various staining techniques. Their viability has been demonstrated by uptake and turnover of isotopically labeled substrates. Sulfate-reducing bacteria are among the most numerous. In some settings it has been shown that acetate is the main substrate, but sources of acetate (either thermogenic or biogenic) are poorly known. The integrated size of this microbial population is enormous. Conservatively, it constitutes two thirds of Earth's bacterial

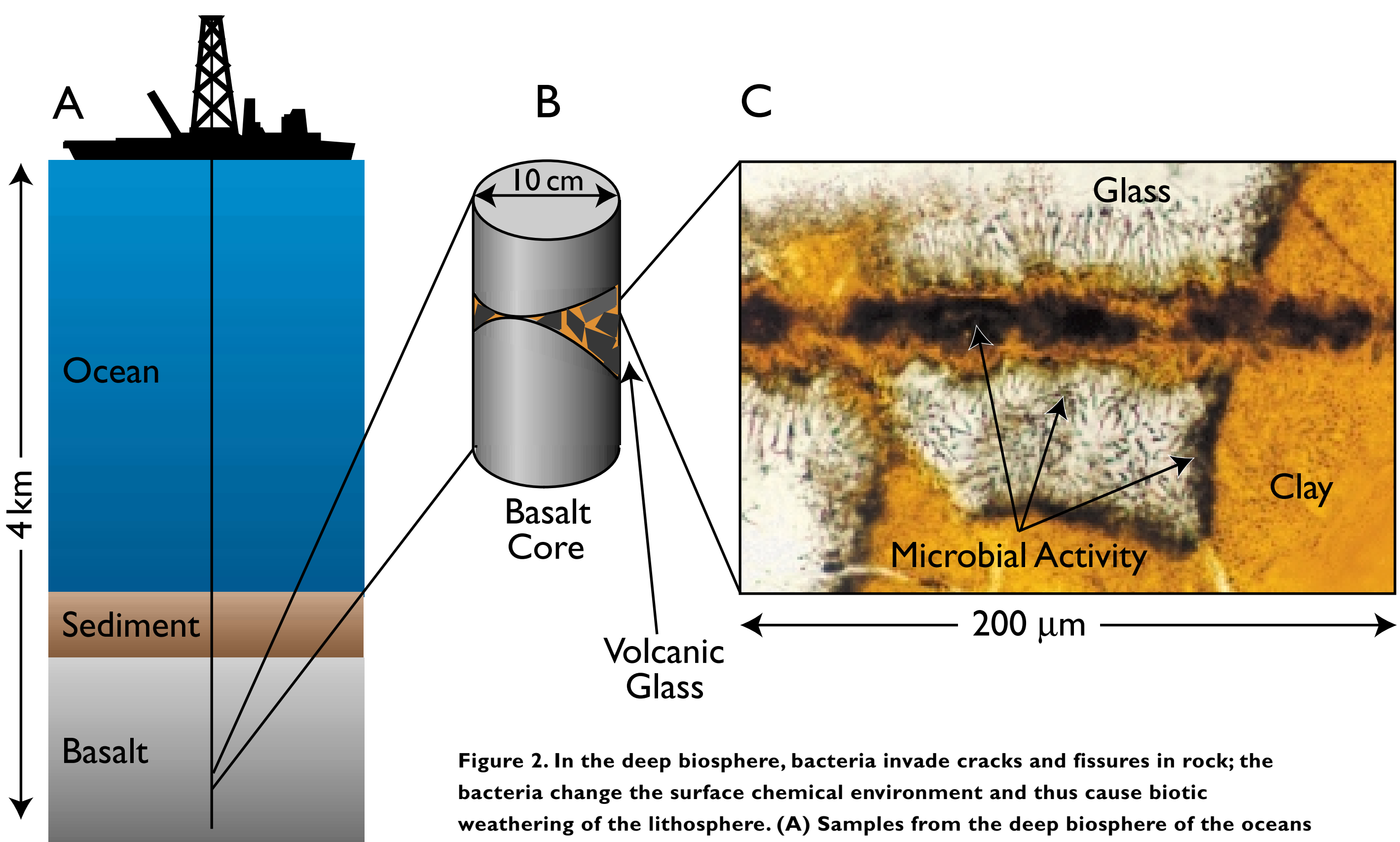

Figure 2. In the deep biosphere, bacteria invade cracks and fissures in rock; the bacteria change the surface chemical environment and thus cause biotic weathering of the lithosphere. (A) Samples from the deep biosphere of the oceans are obtained by drilling. (B) Volcanic glass is common in basalt cores from the seafloor and contains abundant microbial life. (C) Paper-thin slices from basaltic drill core show clear (i.e., white) volcanic glass, orange clay, and dark, iron-rich minerals along surfaces where microbes have been transforming the glass to clay.

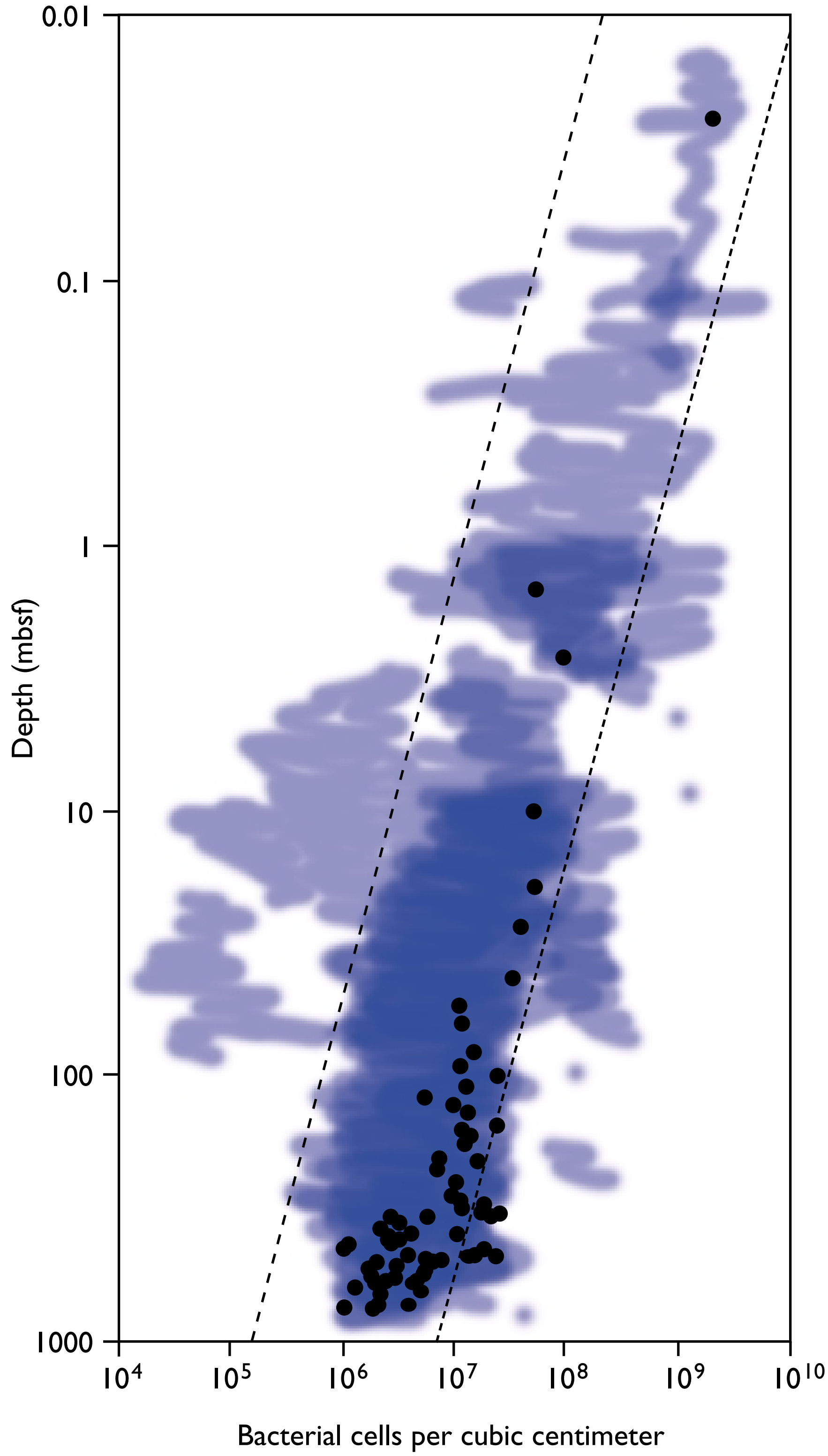

Figure 3. The abundance of bacterial cells in deep-ocean sediments and the effect of the presence of gas hydrates. The depth scale is logarithmic, and so is the horizontal scale that plots the numbers of bacterial cells found. The blue shading summarizes all observations prior to Leg 164 (October–December 1995); darker shading indicates more observations of the particular number of bacterial cells at the plotted depth. The broken lines mark the usual abundance trend with increasing depth; they indicate the 95% confidences intervals on either side of the mean. The heavy points represent observations at Hole 997, at a water depth of 2,780 m on the Blake Ridge (in the Atlantic, approximately 600 km east of Savannah, Georgia). The cluster of observations at and above (i.e., to the right of) the usual trend at sediment depths near 500 m is associated with the presence of methane hydrates, which certain bacteria use as a nutrient source.

biomass. The synthesis and maintenance of this huge biomass from the presumably restricted resources that exist at these great sedimentary depths are remarkable and raise major questions for biochemistry, microbial physiology, and microbial ecology.

Opportunities for Ocean Drilling to Answer Fundamental Questions

Environmental boundary conditions that support and limit the existence of the deep-subsurface biosphere are of primary importance to future research, and defining them requires well-designed deep Earth sampling strategies. Limits to be evaluated comprise temperature, pH, and redox potential. Influences of lithology and porosity are of interest, as are effects of organic carbon content and rates of sediment accumulation and burial. A tight network of carefully chosen drill sites will allow global mapping of these populations, with respect to both depth (Fig. 3) and geographic extent; such mapping is needed to refine our present estimates of the integrated global biomass in the deep bacterial biosphere. Integration of such a global assessment initiative with tectonically oriented drilling programs will make it possible to examine the influence of tectonic settings at passive vs. active margins and spreading centers on the structure and size of subsurface communities and rates of species change within them.

Biogeochemical impacts of the subsurface microbiota are another topic central to future deep biosphere research. Although carbon and redox budgets for the near-surface assemblages are reasonably well known, those for the deep bacterial community are completely unknown. If, as appears likely, members of this community intercept reduced substances ascending from the sediment-hard rock interface, modulation of the community's activities could have substantial effects on climate and atmospheric composition. Effects of the subsurface microbial community on sedimentary geologic and geochemical records are apparent but very incompletely studied. Examples are provided by authigenic minerals such as carbonate cements that are precipitated through bacterial oxidation of organic fluids, by the formation of biomagnetic minerals, and by hydrocarbon-related diagenetic zones that are potential indicators of subsurface oil and gas deposits. Future deep sampling will be aimed at providing more robust constraints on the perspective that the deep bacterial biosphere is being nourished by hydrogen or organic compounds produced abiotically at the sediment–hard-rock interface rather than depending entirely on organic fluxes coming from the overlying water column.

Trophic strategies used by subsurface communities and their means of survival through molecular, cellular, and ecological mechanisms are another focus of deep biosphere research. Energy-producing reactions and sources of carbon, nitrogen, and phosphorus are largely unknown and must be determined. 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—i.e., numbers of species present and their relative abundances—are essentially unknown. In most bacterial communities, metabolites are transferred very intricately between species. The same is likely to be true within the deep bacterial biosphere. No information is currently available about systematic differences in microbial populations in carbonate sediments vs. those in siliceous or siliciclastic sediments, nor is it understood how these populations can successfully adapt to wide variations in the availability of energy sources, e.g., between the nutrient-rich hydrothermal vents and the nutrient-poor 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 genetic codes that would offer unique opportunities to trace evolutionary patterns and processes.

Research Focus

Studies of microbial populations, of pore-water chemistry, and of organic chemistry over very substantial ranges of subbottom depths at different environmental and tectonic settings are paramount to enhance our understanding of how and to what extent the deep biosphere takes part in global biogeochemical cycling. Drilling in diffuse-flow zones at spreading centers will provide information on deep bacterial communities growing over a wide range of temperatures at readily accessible depths in the sediment column and lithosphere. 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 would provide information about the role of bacteria as sinks for fossil fuels. For contrast, hydrothermal sites with both high and low fluid flow should be studied. Studies at boundaries of gas hydrate deposits would provide information about the long-term stability of such deposits and about global budgets for methane, an important greenhouse gas. Studies at organic-rich–organic-poor interfaces (i.e., where turbidity currents have covered organic-rich strata or where terrigenous coals or lignites have been buried by marine sediments) would provide new information about mechanisms of remineralization of organic carbon (i.e., incorporation of previously organic carbon in an inorganic substance, such as calcium carbonate), a major process within the carbon cycle.

Technological Requirements for Reaching Scientific Goals

Methods for the study of microorganisms are being developed very rapidly because of their importance in biotechnology. Continuing assimilation of new techniques into ocean drilling to study the deep bacterial biosphere is of the highest importance. Contamination-free drilling and clean-lab sampling constitute challenges for future scientific ocean drilling. Exchanges of technology with National Aeronautics and Space Administration planetary exploration programs that involve development of robust and clean sampling techniques are deemed potentially beneficial in this endeavor.

“Continuing assimilation of new techniques into ocean drilling to study the deep bacterial biosphere is of the highest importance.”

As part of a global assessment initiative to map the distribution and structure of subsurface communities, it is envisioned that monitoring of microbial populations will be implemented in future ocean drilling as part of a routine procedure similar to, e.g., pore-water chemistry and head-space gas determination. A major future ocean-drilling commitment to deep biosphere research will warrant the establishment of a permanent microbiology working group with full access to planning and operating bodies. Establishment of a full-time position for a dedicated shipboard microbiologist is most desirable to serve the needs of clean sampling and state-of-the-art shipboard and postcruise microbiological research. Shipboard facilities for preparation of growth media are needed to enable investigators to react to unexpected observations. Sampling and incubation of microorganisms at in situ temperatures and pressures are essential prerequisites to recover and handle deep bacterial samples under natural conditions. In situ downhole measurements of sedimentary and geochemical parameters that are relevant to shipboard and shore-based microbiological research need to be compiled into global databases. Establishment of in situ biochemical tracer experiments requires shipboard facilities and procedures allowing for the safe use of radionuclides.

Significance of Projected Studies

Reliable estimates of the full extent and global scale of biochemical cycling require knowledge of the wide range of processes involved in the cycling of carbon and its redox partners. This knowledge is paramount to any attempt to interpret geochemical and geologic records. It is also indispensable for applied geotechnological developments that are relying on accurate predictions about how the Earth system will respond to changes affecting the delivery of reactive materials to the seafloor.

Deep subsurface communities and, in particular, the deep bacterial biosphere constitute a new world entailing a new form of life, previously hidden. Full appreciation of its biomass and its role in global biogeochemical cycling is currently beyond our grasp. Any satisfactory understanding of these biota and processes will alter our views of our dynamic Earth and, undoubtedly, of life itself.

Quantifying the Gas Hydrate Cycle

In the 1990s, considerable evidence has accumulated that huge quantities of carbon are stored in ocean sediments in the forms of free and dissolved gas as well as gas hydrates (Fig. 4), a solid phase made of "cages" of water molecules that hold gas molecules, primarily thought to be methane. Gas hydrates form when sufficient quantities of methane or other hydrate-forming gases are present at temperatures typical of ocean bottom water (i.e., a few degrees above the freezing temperature of water) and at pressures above about 50 bars (equivalent to water depths of somewhat more than 500 m). *Some estimates suggest that twice as much carbon is stored in hydrate form as is contained in all known hydrocarbon resources including petroleum, natural gas, and coal as well as the less economic concentrations in tar sands and oil shale.*

Ocean drilling revealed the hydrate system and will continue to provide crucial evidence about it. For example, Legs 146 and 164, on the Oregon and New Jersey Margins, recovered hydrates, fluids, and gas as well as tantalizing evidence of their effects on the subsurface environment. However, most drilling efforts so far have deliberately avoided hydrate systems for safety reasons. Thus, there is a challenging new opportunity for a future integrated program of ocean drilling to establish an ocean-wide network of hydrate sampling sites. This is the only avenue for us to gain insight into how the processes of hydrate formation and release affect the global biogeochemical cycle and how they are related to tectonic processes.

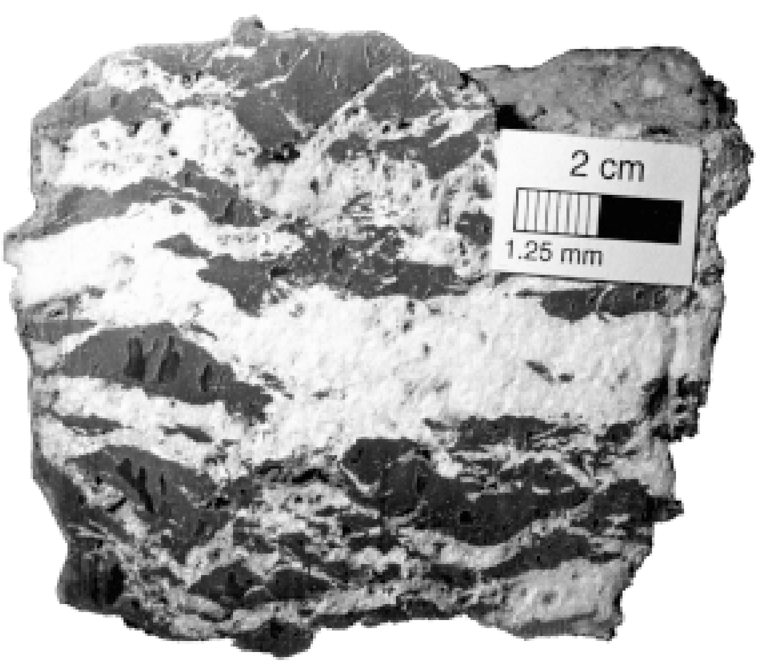

Figure 4. Specimen of interlayered gas hydrate (white layers) and sediment from the Cascadia accretionary ridge, Northeast Pacific margin. Solid gas hydrates form on the seafloor in near-surface sediments where methane ascends in gaseous or dissolved form along the thrusts and folds of the ridge. Hydrates occur in discrete layers pushing the sediment fabric apart parallel to bedding planes. (Photograph courtesy of J. Greinert and G. Bohrmann.)

Hydrates present in today's ocean sediments are but a part of a complex dynamic system in which hydrate is created and consumed continuously (Fig. 5). New methane is generated by metabolic pathways as ubiquitous methanogenic bacteria consume organic matter present in the sediments; when this methane moves into the zone where gas hydrates are stable, it will form additional hydrate. In some settings, thermogenic gas being expelled from deeper formations is added to the mix of hydrate-forming gases. Hydrate is consumed (actually dissociates back into water plus methane, or other gas) when it is exposed to unsaturated seawater because the ocean and the sedimentary environment above the hydrate zone are not saturated with respect to methane (the bulk of the hydrate-forming gas). Indeed, methane that makes its way up into the water column is an important energy and carbon source for benthic and mid-water organisms. Thus, hydrates constitute a large carbon reservoir that has not so far been adequately accounted for in our formulations of the global carbon cycle. The role of hydrates in—and contributions of hydrates to—biogeochemical, hydrologic, sediment, and carbon fluxes and the links of hydrates to other carbon reservoirs are largely unknown.

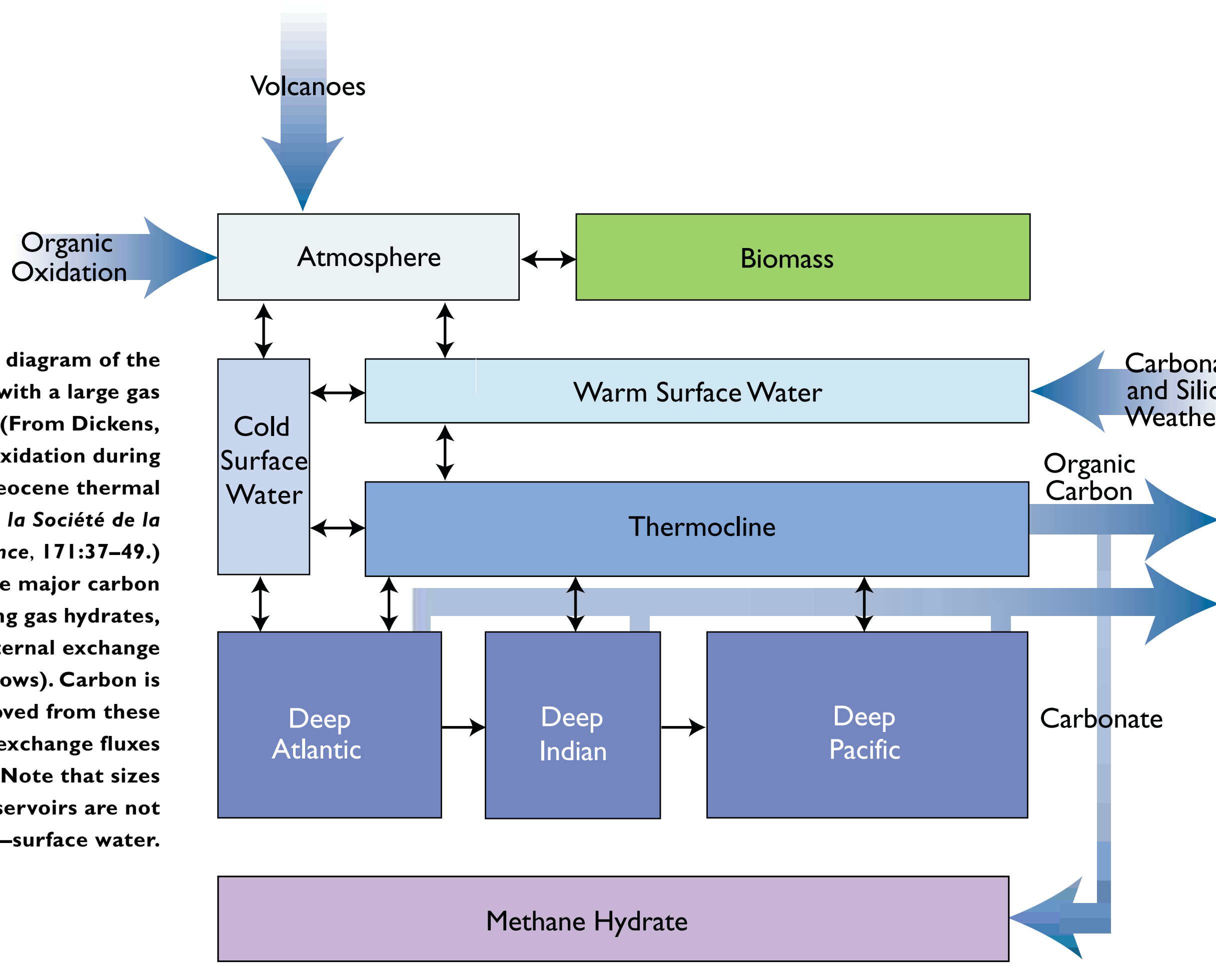

Figure 5. Schematic diagram of the exogenic carbon cycle with a large gas hydrate capacitor. (From Dickens, G.R., 2000. Methane oxidation during the late Palaeocene thermal maximum. *Bulletin de la Société de la Géologique de France*, 171:37–49.) There are nine major carbon reservoirs, including gas hydrates, with a series of internal exchange fluxes (small, black arrows). Carbon is added to and removed from these reservoirs by external exchange fluxes (large, blue arrows). Note that sizes (i.e., masses) of reservoirs are not drawn to scale. S.W.—surface water.

While it is now apparent that the gas 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 gas hydrate reservoir of carbon. Ocean drilling using advanced geotechnologies will play a crucial role in building a well-grounded understanding of the formation and destruction of gas hydrates and their role in the global carbon cycle. The primary scientific objective of gas hydrate research in future ocean drilling is to provide means for answering the question. What are the dynamics and global consequences of carbon cycling through the ocean's gas hydrate system?

What are the dynamics and global consequences of carbon cycling through the ocean's gas hydrate system?

Why Study the Gas Hydrate Cycle?

Quantification of the role of gas hydrates will address significant problems in the Earth and environmental sciences. The current estimates of the size of the hydrate reservoir suggest that it is a very large storehouse of the carbon that participates in—and, more important, modulates—the global carbon cycle. However, the size and flows of carbon in and out of the storehouse are not well understood, nor are the timescales over which the fluxes are active. Thus a significant component of the global carbon cycle is currently unaccounted for in the quantitative discussion of carbon flows. Carbon moves out of the hydrate reservoir in the form of methane or carbon dioxide gases or by precipitating as carbonate minerals. This part of the carbon cycle may constitute an important feedback mechanism in greenhouse transients that influence climate. Destabilization of hydrates and the subsequent release of greenhouse gases form one possible explanation for significant extreme climate excursions evidenced by very strong carbon isotope anomalies in the geologic record. Whether or not hydrates have played a crucial role in climate excursions, it is very likely that hydrates interact in important ways with the deep biosphere. The methane and other gases present in hydrates are an important energy source and substrate for the benthic biota. Formation and destabilization of hydrates helps shape continental margins and may provide a trigger mechanism for geohazards associated with slope instability. Finally, marine gas hydrates may become a future natural gas resource. Thus, there are many important consequences for both the marine hydrosphere and the biosphere, as well as important societal issues for which a well-grounded understanding of the processes that create and destroy hydrates will be crucial.

Research Questions

Fluxes, transfer pathways, and rates must be determined in order to delineate the functioning of the gas hydrate system. Organic matter, sediment, heat, and fluids are added to gas hydrate systems. Rates and magnitudes of these inputs must be quantified as well as the amount and composition of organic matter. Complex consortia of microbes likely contribute to this biomass conversion, and diverse communities of methanotropes and symbionts are known to dwell on methane reservoirs above and below hydrate zones. Additional information about specific locations and rates of each biomass conversion is required to construct a quantitative model with testable predictions.

A primary assumption in gas hydrate studies is that the gas in the hydrate cage is mostly methane. This assumption, based on the dominance of methane in experimental hydrate systems in the laboratory, needs to be verified (or rectified) through direct measurements of the gas composition of natural hydrates. Which gas is bonded with water determines the resulting hydrate's molecular structure. In addition, determination of the physical properties of natural hydrate samples is needed. Data on acoustic properties will be particularly useful so that we can more reliably interpret existing and newly acquired geophysical data—both from seismic surveys and downhole logging. A growing geophysical database, in turn, will make possible more accurate regional and global estimates of the size of the gas hydrate reservoir.

Gas hydrate forms when pore water becomes saturated with gas and the required temperature and pressure conditions prevail. The rate of hydrate formation in the natural environment is largely unknown. Conversely, an increase in temperature or a decrease in pressure should cause hydrates to dissociate, but the rate of dissociation is unknown. Heat and fluids circulate inside the hydrate stability zone (Fig. 6), causing a redistribution of methane of completely unknown proportions. Constraints on these fluxes and their variability on a variety of scales are needed. The formation and dissociation of hydrate in the pore space affects sediment properties and pore-water chemistry. Similarly, pore-water and sediment compositions affect the amount, composition, and distribution of hydrate. Current knowledge of this geochemical coupling is rudimentary at best.

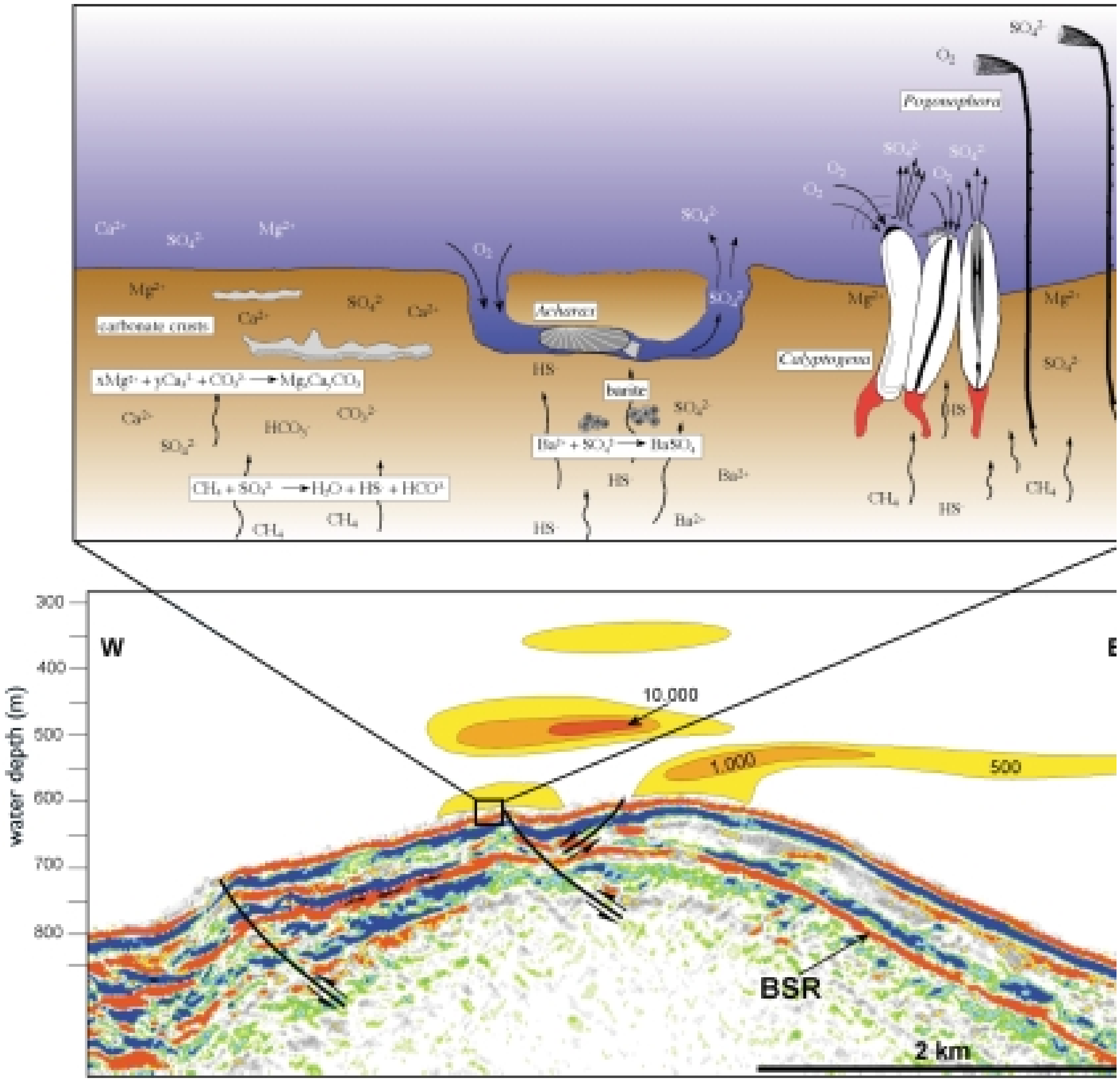

Figure 6. Gas plumes, a bottom-simulating reflector (BSR), and various vent fauna at the Hydrate Ridge of the Cascadia accretionary complex. (From Suess, E., Torres, M.E., Bohrmann, G., Collier, R.W., Greinert, J., Linke, P., Rehder, G., Trehu, A., Wallmann, K., Winckler, G., and Zuleger, E., 1999. Gas hydrate destabilization: enhanced dewatering, benthic material turnover and large methane plumes at the Cascadia convergent margin. *Earth and Planetary Science Letters,* 170:1–15.) The BSR marks 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 in which the methane concentration (contoured values in nanoliters per liter of seawater) exceeds 1,000 times the saturation value of methane in the atmosphere. The gas emanations support specific ecosystems with chemoautotrophic biota and authigenic mineral precipitates. The close-up of the accretionary complex depicts *Calyptogena* sp., *Acharax* sp., and *Pogonophora* sp. as well as carbonate and barite precipitates.

Research Focus

Improved quantification of the gas hydrate contribution to and role in the carbon cycle critically depends on designing integrated research strategies. Several coordinated series of drilling operations are needed in which individual drilling campaigns build on the experience and results of previous ones. Ideally, drill sites are selected so that the scientific objectives of gas hydrate drilling are complementary to those of other site investigations. This ideal requires identification of a spectrum of key locations representing seafloor settings with different flux rates and different fluid and gas transport modes such as focused or diffuse venting, gas escape from pockmarks, and exposures created by slope failure. High-quality geophysical surveys and acquisition of a comprehensive data set that characterizes the hydrate-sediment-water system as a whole will complement hydrate sampling and help in mapping areal extent of hydrate fields. Active and passive in-hole experiments including sensor deployment and tracer injection will help in monitoring fluid and gas propagation through and interconnection between plumbing pathways.

Probing the pore-water–hydrate–sediment system under in situ conditions is the foremost prerequisite of future gas hydrate research. Progress in hydrate research in the "field" as opposed to the laboratory has long been hampered by the lack of adequate tools for recovery of in situ samples. For example, gas hydrates have often been detected only through the diluting effect of hydrate water on pore-water salinity or the temperature effect of endothermic hydrate dissociation on core temperature. Upon attempting to sample these environments, however, equilibria between gaseous and solid phases of methane were disturbed to an extent that made monitoring or reconstruction of in situ conditions impossible. The ultimate solution involves using borehole seals called "corks" that are instrumented to monitor borehole conditions and allow sampling of borehole fluids as well as reentry of the borehole with instruments or, if the corks are completely removed, a drill string. The resulting long-term observations of gas hydrate deposits and their response to deliberate perturbations will complement in situ sampling and geophysical mapping programs.

Technology and Platform Needs

The ephemeral nature of gas hydrates makes special tools and radically new technology necessary to allow in situ sampling and direct measurements of gas hydrate properties. Obtaining the chemical composition of in situ pore waters is critical for assessing volumes and composition of gas hydrates. Existing technologies such as the pressurized core barrel can only recover total gas at subsurface pressure. Moreover, it is unclear whether this tool will recover a good and continuous core in sediments other than claystone. Development of new and better technology and tools is required to achieve the scientific objectives of gas hydrate drilling. Primary geotechnological needs for gas hydrate research in future ocean drilling include the following:

- Recovery and handling of cores at in situ conditions. Pressurized coring systems are needed to obtain water, gas volumes, and hydrate distribution. Recently developed tools such as hydrate autoclave coring equipment (HYACE) with in situ transfer chambers will help by enabling close inspection and property measurements of gas hydrates at in situ conditions. Gas hydrate and microbiological sampling and experiments need custom-designed shipboard and shore-based microbiology laboratory facilities. Temperature-pressure-conductivity sensors, adapted to an advanced piston core (APC) coring system, are needed to monitor whether and at what depth gas was evolved from sediment cores; the sensors must record gas saturation routinely and continuously within cores.

- Deployment of instrumented corks with multiple-packer systems that can seal and isolate a series of discrete zones in the sediment column. These corks have a great potential for long-range monitoring to accurately define in situ pressure and temperature and to monitor for fluid flow and transient effects, e.g., from tidal loading. A particular need will be in situ fluid sampling during controlled experiments where the fluid regime is perturbed.
- Improved logging techniques to yield in situ parameters for hydrate characterization. Downhole temperature tools will enable us to obtain more accurate in situ temperature recording. Downhole measurements using Raman spectroscopy are indispensable for determining in situ mineralogy, structure, and stability condition of gas hydrate. Logging while drilling (LWD), resistivity at bit (RAB), nuclear magnetic resonance (NMR) logging, and new shear-wave tools are relevant and desirable for gas hydrate drilling. RAB appears especially promising for obtaining in situ resistivity because measurements are made very close to the drill bit.

Fit-to-mission platforms will play a central role in future gas hydrate research as they will make the wide range of environments in which gas hydrates occur accessible for drilling. Medium-length boreholes and sampling of surface exposures are necessary to gain insight into the dynamics of the upper part of gas hydrate reservoirs. Alternative platforms such as shallow-water drill rigs and ice barges are needed to sample gas hydrates in permafrost settings of high-latitude coastal zones. Such investigations will ultimately allow us to develop robust knowledge about physical boundary conditions under which gas hydrates occur and disintegrate. We can then document and predict the effects of the gas hydrate formation and disintegration processes on the marine and, in fact, the global environment, in the geologic past and in response to future global change.

"Fit-to-mission platforms will play a central role in future gas hydrate research as they will make the wide range of environments in which gas hydrates occur accessible for drilling."

Mare Incognitum—The Arctic Ocean

The Arctic Ocean and its marginal seas play a fundamental role in the global ocean-climate system. The dense cold bottom waters of most of the world's ocean, which originate in the Arctic, strongly influence global thermohaline circulation, driving world climate. The permanent Arctic sea-ice cover has a tremendous influence on Earth's albedo and the distribution of fresh water. Its variation both seasonally and over longer time periods thus has a direct influence on global heat distribution and climate. Despite this importance, the logistical difficulties associated with work in this remote and harsh region have prevented us from gathering the critical data needed to document the role of this key region in the development and maintenance of the global climate system.

To illustrate the extent of stratigraphic information missing from the Arctic Ocean, we have plotted an estimate of the number of available Arctic Ocean cores versus age (i.e., the stratigraphic coverage; Fig. 7). Although the exact ages of the four very short pre-Pleistocene cores available (one from the Eocene and three from the Cretaceous) are uncertain, it is clear from Figure 7 that only about 2% of the Cenozoic is represented in the existing core material. The Arctic Ocean, despite its critical role in global climate evolution, is the only ocean basin whose history is virtually unknown.

The complexity of this basin—which receives surface water from the North Pacific, the North Atlantic, and the various large rivers that drain northern Eurasia and North America, where water exists in all three phases year round—can only be examined by direct sampling of sediments that record its history. In the condensed sections preserved on the basinal highs is a record of the development of the Fram and Bering Straits, varying fluxes of fresh water into the basin, the devel-

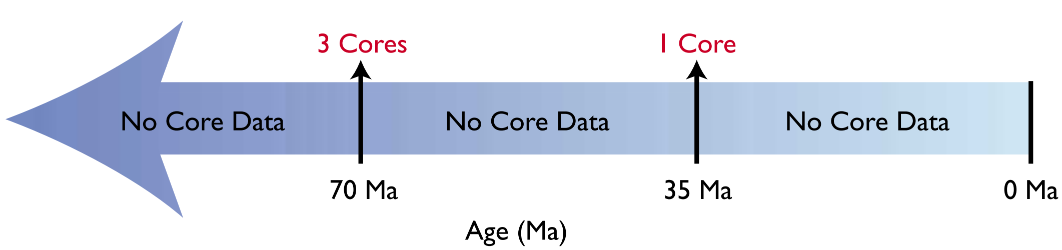

Figure 7. Stratigraphic coverage of existing cores, central Arctic Ocean.

opment of the ice pack, and the history of the high-latitude effects of the Pleistocene glaciations. This information is necessary to fully understand the climate of the Northern Hemisphere, providing a data set that complements ice and sediment cores collected at lower latitudes.

Recent developments have created circumstances that may, for the first time, allow scientific drilling to come to fruition in the high Arctic. These developments include the demonstration of the feasibility of station keeping while drilling in the high Arctic, the accumulation of high-quality site survey data to guide the selection of specific drill sites in critical areas, and the expression of a willingness to provide support of a high Arctic drilling effort on the part of the Swedish Polar Research Secretariat. The coincidence of these events has created a situation that may finally allow successful scientific drilling in the high Arctic.

The History of the Arctic Ocean—The Scientific Challenges

The history of the Arctic basin is so poorly known that we can look at the recovery of any material as a true exploration that will, by definition, increase our knowledge and understanding of this critical region. Indeed a question as fundamental as the nature (continental or oceanic) of one of its major tectonic features—the Lomonosov Ridge—needs only a single well-placed borehole to resolve, yet none exists. Nevertheless, it is still possible to offer a number of Cenozoic paleoceanographic objectives for which we think there are testable hypotheses.

"The history of the Arctic basin is so poorly known that we can look at the recovery of any material as a true exploration..."

Evolution of Cenozoic Environments

A major element in the evolution of Cenozoic environments has been the transformation from warm Eocene oceans with low latitudinal and bathymetric thermal gradients into the more recent type of oceans characterized by strong thermal gradients, oceanic fronts, cold deep oceans, and cold high-latitude surface waters. About 92% of all water in today's oceans are colder than ~10 ∞C. In the Eocene, 50 million years ago, *all* water in the oceans was warmer than 10 ∞C. Bottom water temperatures in the early Eocene, the time of maximum Cenozoic warmth, were on the order of 13–15 ∞C. Large-scale continental ice sheets did not exist because Earth's climate condition inhibited their growth.

The transition to today's world—in which Antarctica is covered by a continental glacier and the Arctic is covered by seasonally variable but persistent sea ice—is linked to both the change in climate that increased latitudinal gradients and to oceanographic changes that connected surface and deep-sea circulation between high- and low-latitude oceans. It is not yet known what role the Arctic played in this transformation, or how and when climatic, tectonic, and oceanographic changes in the Arctic contributed to the global ocean cooling and increased thermal (horizontal and vertical) gradients. In order to understand the evolution of the global climate system, it is necessary to determine when the Arctic Ocean became ice covered and to study the variability in terms of frequency, extent, and magnitude.

Ocean Circulation

The series of interconnected basins composing the Nordic Seas contain about 0.7% of the volume of the world's ocean, excluding the Amerasia Basin of the Arctic Ocean. Despite the small volume of these areas, they nevertheless act as a primary source of a large volume of deep, ventilated waters in the world's ocean. Also, the export of ventilated deep waters to the Atlantic via the Fram Strait is compensated by a corresponding import of relatively warm and saline surface waters of Atlantic origin. The Arctic Ocean is hence commonly described as one of the lungs of the deep global ocean (the other being the Weddell Sea in the Southern Ocean). The tectonic development and opening of the Fram Strait has determined the history of water-mass exchange between the Arctic Ocean and the balance of the world's ocean, as this strait represents the only deep connection between the Arctic and all other oceans. The opening of the Fram Strait may have occurred as early as late Eocene, some 35 million years ago.

An understanding of the exchange of water masses between the Arctic Ocean and the balance of the world's ocean is a key factor for modeling the change in global oceanographic conditions over the past 30–40 million years. Such models require knowledge about, for example, when bottom water formation began in the Arctic, how chemical and physical characters of this water mass varied through time, and which cause-and-effect relationships governed the development of the Arctic water masses. This knowledge is not attainable with the currently available geologic samples.

Rapid Climate Change During the Late Pleistocene

Recent studies of Greenland ice cores and sediment cores from the North Atlantic and Nordic Seas have demonstrated the occurrence of rapid changes in climate, in surface-water conditions, and in the formation of deep water by thermohaline processes during the late Pleistocene (i.e., the past 800,000 years). Evidence is accumulating that suggests that these changes are interconnected and that they may have been caused by a switching off and on of the Atlantic's conveyor circulation system in which dense, cold North Atlantic surface water sinks and flows south and is replaced by northward flow of less dense, warm surface water. Surface-water conditions in the North Atlantic generally are considered to play a critical role within the system, although the exact forcing (i.e., driving) mechanisms involved are still the subject of much debate. Shutting off the flow of North Atlantic surface water into the ice-covered Arctic Ocean must have had profound effects on the density structure of water masses in the Arctic Ocean and on its role as a source region for deep-water formation. The paleoenvironmental effects of such an oscillating ocean-climate system presumably were amplified in the central Arctic Ocean; therefore, the central Arctic hemipelagic sedimentary record should be an excellent monitor of the history of the North Atlantic conveyor system.

Fluxes of Material into the Oceans

Finally, ascertaining the rates at which both the biogenic and abiogenic sediment components accumulate in the deep Arctic Ocean basins is essential to deciphering the global geochemical balances. Accumulation rates of biogenic and abiogenic sediment components determine the internal material cycling in the oceans and affect the microbiota in the seafloor; these rates are therefore linked to the chemical state of both the oceans and the atmosphere. Today's knowledge about sediment fluxes in the Arctic Ocean is seriously limited simply because the currently available stratigraphic sections represent only a few percent of the past 50 million years.

Part 2

New Integrated Strategies

to address

Fundamental Earth System Questions

Probing
Global Change Processes

Processes that Control the Variability of Earth's Environment

Lessons from a Changing Earth

How sensitive is Earth's climate to change? Will we be able to predict future changes, perhaps influenced by greenhouse gases, in the environments that sustain life? Can knowledge of past global changes, recorded in the rich archives of marine sediments, offer insight into such questions?

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Advances in understanding past global change have resulted from the Ocean Drilling Program's extraordinary success at recovering ancient sediments from the seafloor. We know that Earth's past environments were vastly different from today's. We know its climate passed from global warmth 100 million years ago, through a number of rapid cooling and warming events, to global refrigeration in which much of the high latitudes were inundated by ice. We know that catastrophic excursions, both warm and cold, occurred many times along the way. But we don't yet understand why.

Throughout this long and tortuous history, climate oscillations were paced by the same primary external forcing: The tilt of Earth's axis drives the familiar seasons, but on longer timescales of 20,000 and even 40,000 and 100,000 years, discrete oscillations in Earth's orbit affect the seasonal distribution of solar heating at any given latitude. Such timescales imply that the actions of these driving forces have a relatively narrow range of frequencies. However, the climate system also responds to other driving forces that have a broad range of frequencies from annual to many tens of millions of years. Some of these climate oscillations arise from interactions among climatic subsystems. For example, on the scale of years to decades, the well-known El Niño and North Atlantic Oscillation (NAO) climate effects arise within the climate system from complex coupling of winds, ocean currents, and heat transport. In the tropical oceans, dipole modes of the sea-surface temperatures form in specific paired water bodies, one of which warms while the other cools (or vice versa). Such dipole modes appear to be actively involved in setting the stage for anomalous ocean and atmospheric circulation patterns. Rapid climate shifts and oscillations observed in the geologic record may reflect similar interactions of climate subsystems or may respond to as yet unknown driving forces, such as variations in solar intensity or geologic events caused by tectonics or volcanism.

An opportunity is at hand to extend our understanding of the broad array of feedback mechanisms within Earth's climate system that set its sensitivity to various driving forces. This opportunity arises from several accomplishments and developments of the Ocean Drilling Program:

- The ability to document continuous recovery of long sediment sequences has allowed the establishment of a high-fidelity astronomical timescale for the past 30 million years and has given us the capacity to extend this framework further into the past.
- The application of multiple, sophisticated, climate and biogeochemistry proxies to these long records has permitted us to identify rapid variability on all timescales and has given us an appreciation of the complex interconnectedness of Earth's subsystems.
- Continuous improvements in computing technologies facilitate new uses of quantitative models that help to interpret rich data archives.

A primary goal in the new integrated program of ocean drilling will be to understand the complex responses to what appear to be straightforward forcing, e.g., Earth-Sun orbital changes. In so doing, we will take a large step toward understanding the workings of the climate system. We will address two fundamental questions about Earth's climate system: What processes set the sensitivity of the climate system to change? What controls the long-term evolution of this sensitivity?

What processes set the sensitivity of the climate system to change?

What controls the long-term evolution of this sensitivity?

Answers to such questions demand documentation of climate-system and ocean biogeochemistry variability on a wide range of timescales and under significantly different boundary conditions. Specific research questions derive from the current state of understanding as expressed in Earth system models. New technologies will facilitate sampling in previously inaccessible locations and with the highest possible resolution, testing such models in a way that has not been possible before. The rich archives of climate change that await discovery will allow us to sample and explore interactions among different subsystems of Earth's climate system and thus to probe the internal workings of the feedback processes that set the sensitivity of Earth to change. In the following, we provide examples of accomplishments and new questions arising from recent findings that will lead to focused research goals in a new program of ocean drilling.

Feedbacks and Global Change

What are the important feedbacks that are likely to affect climate sensitivity?

How do they operate on the wide variety of timescales observed in the geologic record?

How has the climate system responded to forcing vastly different from that influencing the pre-industrial state?

What are the important feedbacks that are likely to affect climate sensitivity? How do they operate on the wide variety of timescales observed in the geologic record? How has the climate system responded to forcing vastly different from that influencing the pre-industrial state? The geologic record presents an opportunity to observe the sensitivity of the climate system to many Earth processes that affect our ability to predict future climate. Through exploring the past history of climate sensitivity we will be able to gain an understanding of the range of variability in climate we are likely to experience in the future.

The geologic record of atmospheric carbon dioxide is an excellent example. Gases trapped in ice cores reveal oscillations in atmospheric CO_2 concentrations of ~100 ppm during the past 400,000 years. Changes of this magnitude are comparable to the anthropogenic rise in atmospheric CO_2 since the beginning of the Industrial Revolution. Evidence of these dramatic changes in atmospheric CO_2 is recorded not only in the terrestrial ice archive, but in the deep sea as well, indicating the global ramification of these events. These records present an opportunity to understand the complex interaction of ocean chemistry and physics with the marine and terrestrial biosphere—which form climate subsystems that must have played important roles in causing these variations. Recently developed approaches use biomarkers that are sensitive to surface-ocean CO_2 concentrations; these approaches have been applied to strata recovered in ODP drill cores and have yielded data to trace atmospheric CO_2 concentrations back into the Miocene. These and similar approaches, provided that they show robustness against diagenetic alteration effects, will help in documenting the variability of atmospheric CO_2 and its relationship to Cenozoic and longer-term climate evolution.

The atmospheric content of CO_2, a primary greenhouse gas, is affected by several feedback mechanisms. CO_2 is transferred between the atmosphere and ocean by a variety of processes (Fig. 8). Its solubility in seawater increases as temperature drops, so when the surface ocean cools, additional CO_2 is transferred from the atmosphere to the ocean, further amplifying the cooling of Earth's climate. Its concentration in the atmosphere is directly affected by interactions between the biosphere and climate. On longer timescales, climate-related feedbacks also affect the rate of continental weathering, which controls the long-term concentration of atmospheric CO_2. Understanding CO_2 availability in the geologic past will help to evaluate the importance of atmospheric CO_2 in long-term climate change, including the role it plays in natural climate oscillations.

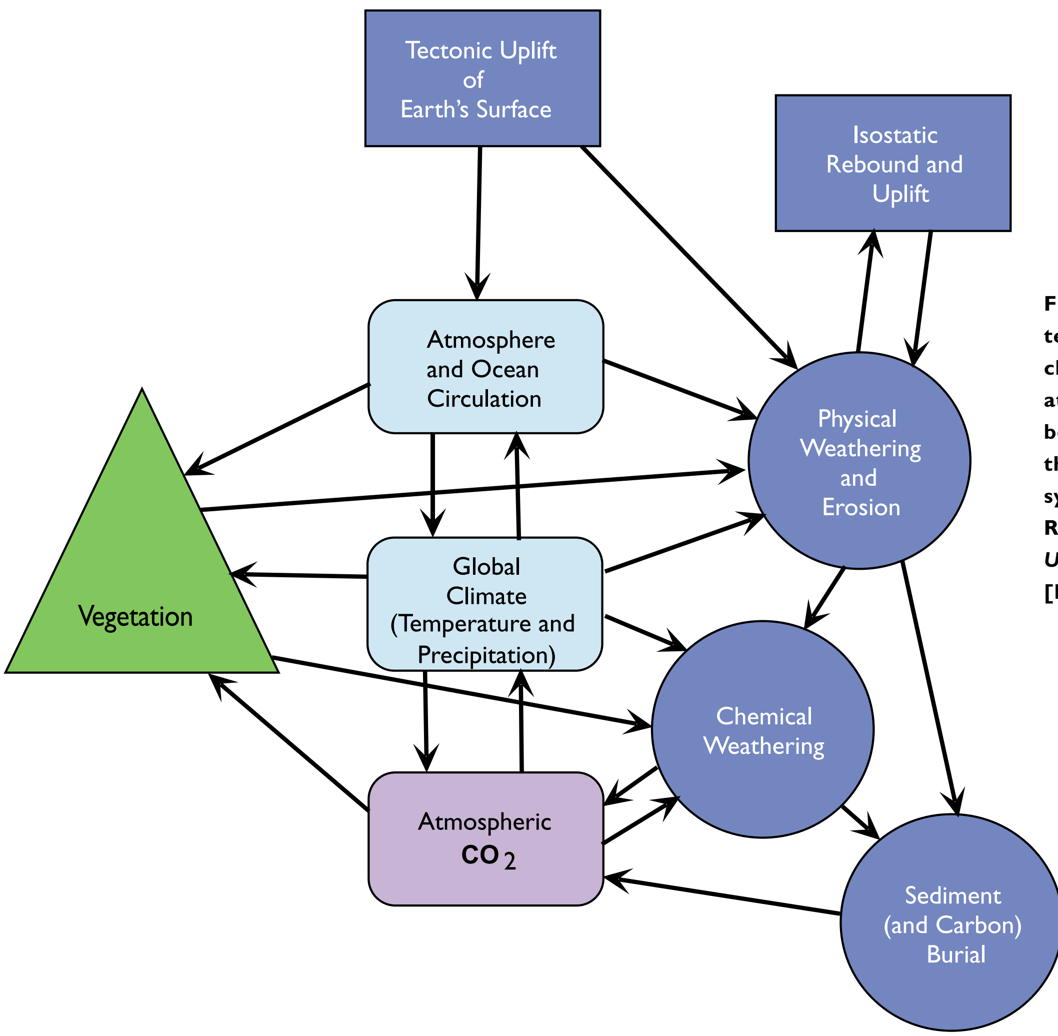


Figure 8. Complex linkages among tectonics, the global biota, ocean chemistry, circulation, and atmospheric CO_2 create feedbacks, both positive and negative, that set the sensitivity of the global climate system to change. (Modified from Ruddiman, W.F. [Ed.], 1997. *Tectonic Uplift and Climate Change*. New York [Plenum Press].)

Few substances influence climate in as many ways as water. In liquid form, it provides immense thermal inertial to the world's ocean. As ice, its bright surface raises the planetary albedo, efficiently reflecting the Sun's energy back to space. In vapor form, water is a potent greenhouse gas. Because of its biological importance, water mediates vegetation type and biomass and thus plays a role in the terrestrial carbon cycle. In turn, plant evapotranspiration influences atmospheric water-vapor content and hydrologic cycling. Water thus plays a role in a variety of climate feedback processes.

Models and data provide a means of elucidating these feedback processes. For instance, geologic data suggest major shrinkage of the Sahara desert during intervals of a strengthened African monsoon. Models can only simulate the reach of moisture into the desert by including global vegetation, which effectively pumps water into the atmosphere and strengthens the monsoon. This is an example of a positive feedback system; it involves interaction between the biota and the physical atmospheric circulation and was first discovered in geologic data—including deep-sea sediments—and understood through the use of process models.

Many other feedbacks are involved in the climate system. Variations in continental ice affect Earth's albedo and global thermohaline circulation; tropical surface-water temperatures influence atmospheric moisture content and the greenhouse efficiency of the atmosphere; variations in thermohaline circulation affect heat transport, latitudinal temperature gradients, and ocean chemistry; soil moisture and plant evapotranspiration influence atmospheric water vapor and continental-surface albedo. Next we outline several drilling and research strategies for an integrated program of ocean drilling that are designed to provide deeper insight into these fundamental climate processes and interactions.

Polar Processes Involving Ice, Sea Level, and the Thermohaline Heat Pump

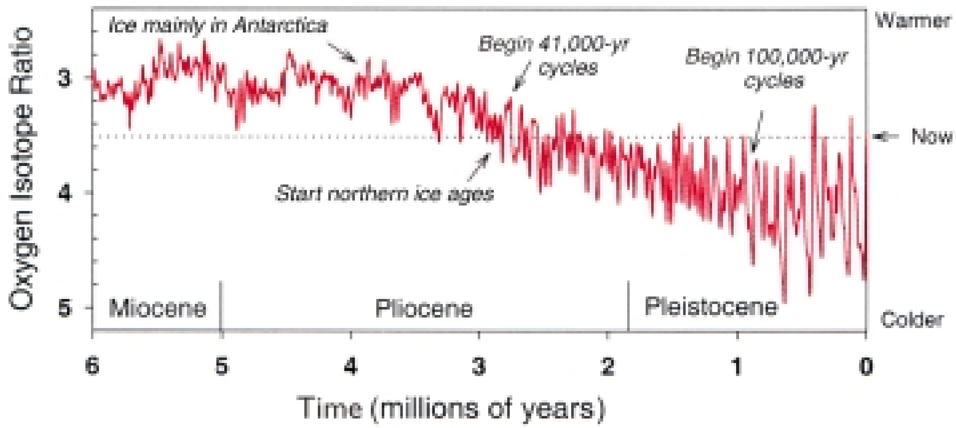
High-latitude systems provide potentially sensitive feedbacks with global consequences. In intervals of cool climate, expanded ice sheets at high latitudes reflect solar energy, leading to more cooling—a positive-feedback mechanism. Lower sea level induced by storage of water in ice sheets opens new land areas for vegetation and restricts shallow oceanic passages, potentially modifying global currents. Melting of ice sheets may cap high-latitude source regions for deep-sea water masses with buoyant fresh water, altering ventilation of the ocean interior. How these critical polar systems will behave in the future under conditions of greenhouse warming remains largely unknown. At the highest latitudes, harsh conditions such as ice cover have so far limited sampling of the geologic record. The proposed integrated program of future ocean drilling will acquire important high-latitude samples, with a goal of better understanding polar processes and their role in changing Earth environments.

"The proposed integrated program of future ocean drilling will acquire important high-latitude samples, with a goal of better understanding polar processes and their role in changing Earth environments."

Middle Pleistocene Revolution—Changes in Earth's Response to Orbital Forcing

During Cenozoic time until about 3 million years ago, there were no large continental ice sheets in the Northern Hemisphere. Between 3 and 1 million years ago, continental ice sheets periodically advanced and retreated, and Earth's climate system was subject to a regime whose dominant cycle had a 41,000-year frequency. About 900,000 years ago, Earth's climate system changed dramatically to a regime of dominant cycles of 100,000-year frequency and much greater amplitude (Fig. 9). Curiously, the calculated orbital parameters thought to pace climate change (eccentricity, obliquity, and precession) do not show any significant difference in their variability across the transition 900,000 years ago. The cause of the observed change remains a mystery, but it must have involved a change in sensitivity of the climate system and thus serves as a natural experiment to help determine the controls of long-term climate change.

Figure 9. Oxygen isotope data from ODP Sites 846 and 849 (tropical Pacific Ocean) define long-term climatic shifts from a regime without Northern Hemisphere ice ages (prior to approximately 3 million years ago), to a regime of rapid oscillations dominated by a 41,000-year cycle (3 to 1 million years ago), and then to a regime of large-amplitude ice-age climate oscillations dominated by 100,000-year cycles.



Several possible explanations have been proposed. Perhaps when the ice sheets exceeded a certain size, they amplified orbitally forced climate oscillations at longer periods. Perhaps gradual erosion caused by a succession of early ice ages changed the conditions underlying residual ice sheets and thus changed their subsequent responses. Perhaps other parts of the global system were involved such as tectonic changes that affected the sensitivity of the system or changes in the deep sea that modified either the carbon cycle or heat distributions on Earth.

The earlier Cenozoic record of climate change provides us with the opportunity to test models of climate with and without polar ice sheets. We know that in geologic time intervals lacking large ice sheets, there are climate records that contain large-amplitude 100,000-year climate cycles. Only ocean drilling can recover globally distributed, continuous sequences of deep-sea sediments deposited during these ancient times. Improved sample recovery and research strategies that employ high-frequency sampling now permit us to develop climate records from the distant past with the same temporal resolution as in Pleistocene sediments. The key development making this feasible is the very real possibility of not only an absolute, orbitally paced chronology for the Cenozoic and perhaps the Cretaceous but also relative, orbitally paced chronologies for sedimentary rocks of all ages. A published chronology is complete for the past 16 million years and, in several locations, chronologies for the past 30 million years are under development. These chronologies will make it possible to develop climate records on the scale of orbital changes for intervals of Earth's history with significantly different boundary conditions. By constructing multiple proxy climate records and observing how previous Earth climates responded to orbital forcing, we will unravel and identify the complex interactions that directly affect the climate system's sensitivity to change.

Millennial-Scale Events— Ice-Sheet Dynamics or Ocean-Heat Transport?

We also seek to understand why significant variations in Earth's climate occur on the shorter timescale of millennia, in the absence of direct external forcing. Internal systems such as the cryosphere and ocean circulation are likely candidates to account for variability on these timescales, perhaps independently, but more likely through interactions with each other and with varying solar insolation.

Current successes in addressing this climatic puzzle include the documentation of the persistent millennial climate variability during the climate oscillations of the ice ages. Such variability is so far best documented in the high latitudes of the world's ocean, for example, in the North Atlantic where the oscillations are associated with evidence for iceberg discharges (Fig. 10). The close association of sea-surface temperature changes and deposition of ice-rafted debris, as well as the link between ice-sheet size and the magnitude of the climate response, clearly demonstrates the importance of ocean-ice-atmospheric feedbacks on millennial timescales. Deep drilling of rapidly accumulating sedimentary sequences is the key strategy to understand these linkages.

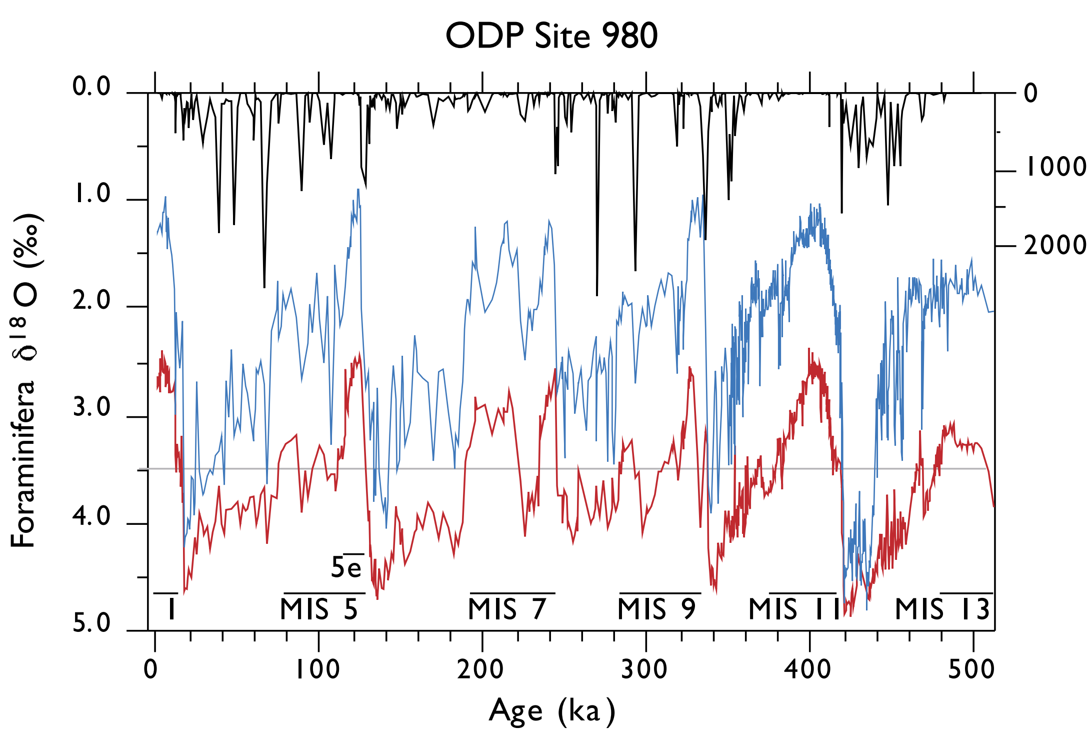


Figure 10. Oxygen isotope data from the benthic foraminiferan *Cibicides* sp. (red) and the planktic foraminiferan *Neogloboquadrina pachyderma* (blue) and concentration of ice-rafted debris (IRD, black line) from ODP Site 980 (North Atlantic Ocean) reveal linkage between rapid (millennial-scale) climate changes and iceberg production. Rapid oscillations in iceberg production are thought to reflect purges of ice from large ice sheets similar to those present in Antarctica today. Higher rock or lithic component contents per gram of sediment indicates a greater quantity of ice-rafted debris. MIS = marine isotope stage, based on oxygen isotopes.

At the same time, drilling successes at low latitudes indicate that polar processes may not offer a complete explanation for the observed variability. In the tropical Atlantic, sea-surface temperatures also vary on millennial timescales. At marginal sites in the subtropics of both the Atlantic and Pacific, extremely high resolution records show that the properties of the surface- and intermediate-depth water masses varied at similar timescales, and perhaps even in phase with, the dramatic oscillations in the high-latitude North Atlantic (Fig. 11).

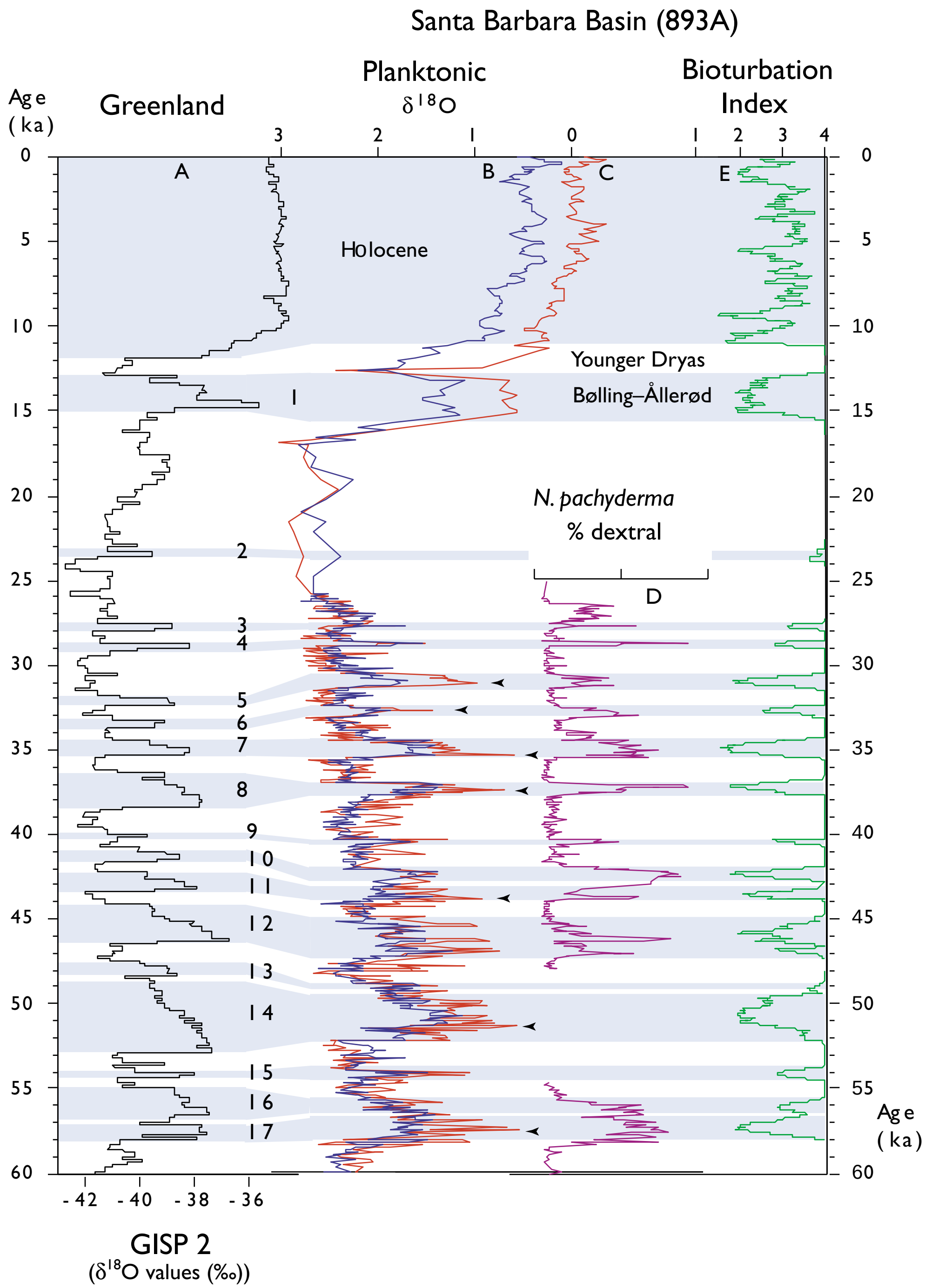


Figure 11. Comparison of oxygen isotope data (numbers refer to interstadial [warmer] intervals) from (A) Greenland Ice Sheet Project ice core 2 (GISP 2) with (B–E) data from the Santa Barbara Basin (ODP Site 893A). (B and C) Oxygen isotope values ($d^{18}O$) in planktonic foraminifera, (D) the abundance of dextral *N. pachyderma*, and (E) the bioturbation index. The comparison reveals millennial-scale climate events in the eastern Pacific basin that can be correlated to climate changes recorded in the Greenland GISP 2 data set; such a correlation requires a direct link between climate events in the high latitudes of the North Atlantic and surface and intermediate waters of the Pacific. (From Hendy, I.L., and Kennett, J.P. , 1999. Latest Quaternary North Pacific surface-water responses imply atmospheric-driven climate instability. *Geology,* 24:291–294.)

The global nature of these climate oscillations and the possibility that they persist through relatively ice-free time intervals raise the likelihood that mechanisms other than ice melting are important. Available data suggest that ocean circulation, from low to high latitudes and from the surface to the deep sea, is involved. Yet what remains to be demonstrated is the exact nature of that role, why the ocean circulation should oscillate at all, and the relative importance of tropical and polar influences on ocean variability. Iceberg or other fresh-water discharges may perturb the density-driven circulation, and changes in ocean-heat transport may influence the size and behavior of ice sheets. Putting these pieces of the climate puzzle together appears to be right on the horizon, but will require a major, additional effort of targeted drilling of high-sedimentation, ocean-margin, and high-latitude locations, coupled to modeling studies that build on data to test hypotheses.

New Approaches and New Drilling Platforms to Clarify the Workings of the Tropical Heat Engine

The tropical ocean is the primary source of energy and water vapor to the atmosphere. Interactions between the ocean and atmosphere in the tropics have global ramifications for climate on all scales. For example, on interannual scales, the El Niño climate oscillations, once thought to be restricted to the eastern equatorial Pacific region, are now recognized as a global phenomenon. On longer timescales, transport of heat from the tropical oceans to high latitudes may set up hemispheric thermal gradients and thus control the dynamics of the atmosphere. Though its influence on atmospheric water vapor, the tropical oceans may influence water budgets. Past efforts in ocean drilling were concerned mainly with long-term changes in tropical climate. New approaches and new platforms for an integrated program of future ocean drilling will extend such efforts both to shorter (interannual) and longer (tectonic) timescales, allowing creation of an integrated view of tropical systems on all scales.

Interannual Variability of the Tropics

Instrumental climate records from the tropics, especially continuously recorded time series, are scarce and short. The limited number of realizations available in the instrumental record to study interannual climate phenomena, much less decadal-to-centennial climate phenomena, means that proxy records must be used to characterize the nature of tropical climate variability in the pre-instrumental period. Understanding the nature and variability of pre-industrial age global climate requires the use of proxy records, and corals are the most promising proxy to study the tropical ocean-atmosphere component of the global climate system on seasonal, annual, decadal, and centennial timescales.

Massive corals growing in the reef ecosystems of the tropics provide some of the richest paleoclimate archives in the world. Corals are particularly useful paleoclimate recorders because they are widely distributed, can be accurately dated, and contain a remarkable array of geochemical tracers within their skeletons. Massive corals from the tropical ocean are the only paleoclimate archive that offer both the annual resolution and multiple-century record length needed for quantification of both seasonal and centennial changes in the tropical surface ocean. Coral records have provided new information on environmental changes in surface-ocean waters over the past several centuries in many regions of the tropics.

Techniques and approaches developed for use with living corals are directly applicable to fossil corals, especially those that have remained submerged in seawater for all of their history. One of the classical problems in paleoceanography is the reconstruction of past sea-surface temperatures; this problem can be particularly well investigated by using fossil corals. Measurements of a suite of coral-based paleothermometers (temperature proxies, e.g., d^{18}O, Sr/Ca, Mg/Ca, U/Ca) permit the identification of both thermal and hydrologic components of past surface-ocean conditions. For example, it is possible to determine sea-surface d^{18}O values by removal of the temperature component of the coral d^{18}O signature. Maps of sea-surface d^{18}O values could be produced to estimate variations in the volume of the planetary ice caps. It may also be possible to produce sea-surface salinity maps, if the strong correlation between seawater d^{18}O and salinity holds through time; such a correlation can be used to recover past patterns of rainfall and evaporation over the tropical oceans.

ENSO—Instability Under Altered Boundary Conditions

The El Niño–Southern Oscillation (ENSO) climate pattern dominates interannual variability of the ocean and atmosphere in the tropical and subtropical Pacific and influences climate throughout the globe. It affects planetary systems as diverse as polar sea ice, maize growth in Africa, drought in the United States, and hurricane intensity and frequency in the Atlantic. ENSO rainfall, sea-surface temperatures, and wind-field changes associated with ENSO events (both "warm" and "cool") differ strongly from event to event. Clearly, the interannual ENSO phenomenon undergoes significant variations from its typical state, and the predictability of this system and its impacts on a global scale depends on understanding these variations.

Although ENSO variability is defined on an interannual scale, decadal and longer variations in ENSO-related parameters are clear in paleoclimate records that reveal intriguing links across timescales and variability exceeding that seen during the era of instrument measurements. Recent work on early to middle Holocene variability highlights the possibilities of both a semipermanent ENSO warm condition as well as an ENSO-free world. Reconstructions of the last glacial maximum in the tropics are roughly similar to those of ENSO cold-ocean conditions, suggesting that ENSO-like processes may play a role in long-term climate changes.

These new insights suggest that a better understanding of this system will require much longer records of ENSO activity than are currently available. For example, how these newly recognized longer-term changes modulate ENSO's extratropical influences remains unknown. The sensitivity of ENSO and its teleconnections to rising greenhouse gas concentrations also requires further investigation. Acquisition of previously unobtainable drill cores from ultra-high-resolution sediment sequences and carbonate reefs and margins to answer key questions about ENSO is a first-order target for the new integrated program in scientific ocean drilling.

Monsoons—Setting the Sensitivity to Orbital Forcing and Tectonics

Understanding the evolution and variability of monsoonal climates across a variety of timescales requires understanding a number of climate responses and feedbacks. These include the sensitivity to changes in solar radiation (Milankovitch forcing), changes in continent-ocean thermal and elevation contrasts, atmosphere-ocean feedback processes that determine sea-surface temperatures and extract and transport latent heat from the ocean to the continents, and vegetation and soil moisture feedbacks.

Previous ODP drilling of the Bengal Fan, the Arabian Sea, the Ninetyeast Ridge, and recently the South China Sea have led to contrasting hypotheses about the late Neogene evolution of the monsoon system, especially as it relates to changes in the Himalayan and Tibetan orography. The collision of India with Asia and the ensuing uplift of the Tibetan plateau represent a significant change in the global boundary conditions that control climate, especially the Asian monsoon system. The relationship of this uplift-erosion-monsoon system to the extraction of carbon from the atmosphere, as functions of silicate weathering and/or organic carbon burial, is poorly known but clearly has a large impact on changes in atmospheric CO_2. Relief generation during uplift and valley incision has the potential to influence monsoonal climate through increasing mountain peak height and concomitant albedo feedbacks. However, the timing and magnitude of the monsoon response and the erosional flux generated by the combined uplift and orographic precipitation remain unclear, in part because different basins and different depositional settings appear to yield different records.

What is the time history of uplift of the Himalayas and Tibet and how does it control the Neogene evolution of the seasonal monsoon and atmospheric CO_2 levels through erosion, weathering, and burial fluxes?

To test hypotheses concerning the role of mountains and monsoons on weathering and changes in CO_2 requires that we develop records with better chronology and multiple independent indices of changes in monsoon strength, sediment weathering, and erosion fluxes. These records must be developed from a variety of depositional environments, including the Indus and Bengal Fans, the marginal basins, and oceanic sites, because the spatial and temporal distribution of both monsoon effects and sediment deposition is highly variable. The fan sites will require better recovery of clastic sequences than has been accomplished in the past. Similarly, better-quality recovery in sections that cannot be recovered with a piston corer is required to generate the complete Neogene stratigraphy of pelagic sediments. Only the replication of long-term trends and short-term variations from a variety of depositional regimes and independent proxies will build a reliable history of climate change that will help answer the central question: What is the time history of uplift of the Himalayas and Tibet and how does it control the Neogene evolution of the seasonal monsoon and atmospheric CO_2 levels through erosion, weathering, and burial fluxes?

A Greenhouse World

Earth is a greenhouse world. The environments that sustain life all depend on the capture of solar energy and the maintenance of Earth's thermal state by the atmosphere. Without greenhouse gases to capture outgoing radiation, Earth would be a frozen and inhospitable planet. With too great a concentration of greenhouse gases, heat could build up to the point of no return. Keeping Earth's climate within bounds requires a delicate balance of atmospheric gases, controlled by complex linkages between the biosphere and ocean circulation and, on long timescales, by tectonics, mountain building, and rock weathering (see Fig. 8).

Productivity, Circulation, Reefs, and CO_2

The state of ocean chemistry is controlled two ways: (1) externally by changing patterns of chemical fluxes between oceans and continents and (2) internally by ocean circulation and processes that result in transformations between different chemical phases. The biota respond to nutrient supplies, which in the long term are controlled by the balance of inputs from continents and outputs buried as organic remains in sediments. There is little doubt that such cycles within the oceans modify the greenhouse gas composition of the atmosphere, but the feedbacks that link the ocean and atmosphere are poorly understood.

We know from ice cores that atmospheric CO_2 has varied on the scale of orbital changes as climate has oscillated from glacial to interglacial states. The change in atmospheric CO_2 on this scale is most probably caused by a variety of interacting reservoirs, including the terrestrial biosphere, the marine biosphere, dissolved oceanic reservoirs (deep and surface), and the sedimentary reservoir. As an example, $CaCO_3$ is either stored in or released from reefs and other shallow-marine systems as sea level falls and rises.

Massive, rapid accumulations of shallow-water carbonates at low latitudes in barrier reefs and carbonate platforms can lead to increases in atmospheric CO_2, which through positive feedback as a greenhouse gas would amplify global warming and sea-level rise. About 400,000 years ago, Earth witnessed a worldwide establishment of modern barrier reefs (such as the Great Barrier Reef in Australia, the Belize Barrier Reef, and the Florida Keys) and optimum production of carbonate banks (Bahamas, Maldives, Queensland Plateau). Anomalously warm climates and flooding of previously exposed areas at these times were associated with high-amplitude sea-level changes.

To explore the feedbacks that link climate and biogeochemical processes, we need to understand past changes in the size of chemical reservoirs and their rates of change, the history of ocean chemistry, and the rates of delivery of biogeochemically important constituents from land to ocean. For example, arrays of drill sites through carbonate reservoirs and coastal regions of high biological productivity, including shelf and bank margins, are needed to quantify rates of and links between biogeochemical cycling and sea-level change. Drilling strategies need to be fully integrated with biogeochemical modeling studies that can predict the size and rates of changes in Earth's biogeochemical reservoirs.

Mountain Building, CO_2, and Climate

The collision of India with Asia and the ensuing uplift of the Tibetan plateau may have had a significant influence on global climate in the Cenozoic as well as the development of the Asian monsoon system. The uplift of this major topographic feature represents a significant change in the global boundary conditions that control climate, but we are still working to understand the direct and indirect influences of uplift on climate. If we can more clearly reconstruct the history of these systems, we will have a deeper understanding of the way changes in atmospheric dynamics and climate interact with large-scale topographic features. A second important element of this study—the erosion generated by the combined uplift and orographic precipitation in the near-mountain regions—affects the global climate via the carbon cycle as silicate weathering and organic carbon burial both tend to take up CO_2 from the atmosphere. The rates and magnitudes of these processes must be better determined through the recovery of the records from deep-sea drilling.

Sediment accumulation records both of these processes. For instance, the study of Bengal Fan sediments has demonstrated the existence of the Himalayas as a major topographic barrier since early Miocene time. By comparing Himalayan source rocks with the eroded sediments now forming the Bengal Fan, we have documented the intensity of both silicate weathering and organic carbon burial. The Bengal Fan also shows complex but systematic relationships between erosion and environmental changes such as C4 plant expansion (i.e., the grasses). And more recently obtained results from Pacific ODP cores have shown important increases in the input of dust to Pacific sediments beginning 3.6 million years ago, perhaps related to the uplift of the Tibetan plateau and the drying of the basins north of the Tibetan plateau.

To test hypotheses concerning the role of mountains and the importance of CO_2 changes for long-term climate change, we need to answer a number of questions that span the fields of tectonics, climatology, geochemistry, and paleontology, such as the following:

- What is the time history of uplift of the Himalayas and Tibet?
- What is the long-term history of monsoon strength in the Asian region, and what does this say about the sensitivity of the seasonal monsoon to elevation changes?
- What are the erosion and weathering history and the sedimentary fluxes of this region, and how have changes in the silicate and organic carbon weathering and sedimentary fluxes influenced atmospheric CO_2 levels?
- How did the uplift and monsoon development influence the evolution of regional biota, including hominids?

Answers to such questions are recorded in the sedimentary archives of basins surrounding the Himalayas and Tibet. None of these questions will be resolved by the study of a single basin. The uplift history of the Himalayas and the Karakorum Range is only accessible via the combined sedimentary records of the Indus and Bengal Fans. The uplift of the Tibetan plateau is more complex to document as it has been less actively eroded than the Himalayas. Drill-core data from ocean basins surrounding China to determine dust accumulation in the oceans will be needed. Although the Himalayan side of the orogen is dominated by physical erosion and plays a major role in organic carbon burial, the eastern margin of Tibet is the source of several major rivers that contribute to a high rate of silicate weathering. The resulting sediments will yield key records for testing the global importance of the uptake of atmospheric CO_2 by the Himalayan-Tibet system.

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Oceanic Gateways

Marine gateways, such as the modern Drake Passage or the once-open Panama gateway, act as critical thresholds in the global climate system. Global cooling over the past 50 million years was associated with the opening of marine gateways around Antarctica, the closing of low-latitude gateways, and the initiation of meridional flow in the Atlantic and possibly the Pacific through its connection to the Arctic. Few ODP legs have been drilled that provide suitable high-resolution stratigraphic sections and, thus, an accurate timing of major steps in gateway displacements (width, sill depths). Hence, the effects of gateways on oceanic circulation and climate have remained mostly qualitative and speculative.

The power of understanding the influence of marine gateways on climate is illustrated by the recent drilling in the Caribbean and eastern Pacific on either side of the Isthmus of Panama. These efforts provide a concrete understanding of the oceanographic effects associated with the uplift of the isthmus. A simple strategy of monitoring the oceanographic conditions on either side of this gateway as it emerged shows that oceanic response occurred nearly 2 million years before the final connection between the Atlantic and Pacific Oceans was severed. Closure of this gateway fundamentally altered the global-heat and fresh-water fluxes and resulted in the onset of a permanent Northern Hemisphere glaciation during the late Pliocene.

This strategy of monitoring the oceanographic and climate changes on both the upstream and downstream sides of a gateway can be adopted for many other regions. In particular, study of the opening of the Drake Passage will benefit from a similar approach. The importance of understanding this gateway is that today, the Antarctic Circum-Polar Current (ACC) is the clearinghouse for the world's ocean, integrating waters from the Atlantic, Pacific, and Indian Oceans and then redistributing bottom and intermediate waters back into each of these oceans. In addition to its role in the interocean exchange of water, the development of the ACC is postulated as the critical step that led to the thermal isolation of Antarctica and its subsequent glaciation. Hence, understanding the history of the Drake Passage and its link to climate forcing is important because the glacial history of Antarctica is one of the requisite records for understanding long-term climate change and provides a needed mechanism to understand and reconstruct glacio-eustatic changes.

Extremes in Climate

Past Deep Sea Drilling Project (DSDP) and ODP drilling has demonstrated that the global climate system is characterized by significant long- and short-term variability over the past approximately 130 million years. This variability has not always been regular in terms of magnitude or rate. At times, the climate system has drifted either gradually or rapidly toward "extremes," including periods of long-term warmth and long-term cold intervals.

High-resolution records have revealed brief but extreme climate states ("transient" climatic events), threshold events that involve rapid shifts in the climate system in response to more gradual forcing. Geochemical feedbacks involving marine carbon reservoirs appear to be amplifying the climatic shifts. The extreme warm transients include the late Paleocene thermal maximum (LPTM, approximately 55 million years ago). The extreme cold transients include the early Oligocene (approximately 34 million years ago) and glacial maximum at the Oligocene/Miocene boundary (23.7 million years ago). In several cases, it appears that these climate extremes triggered major evolutionary pulses in the biota.

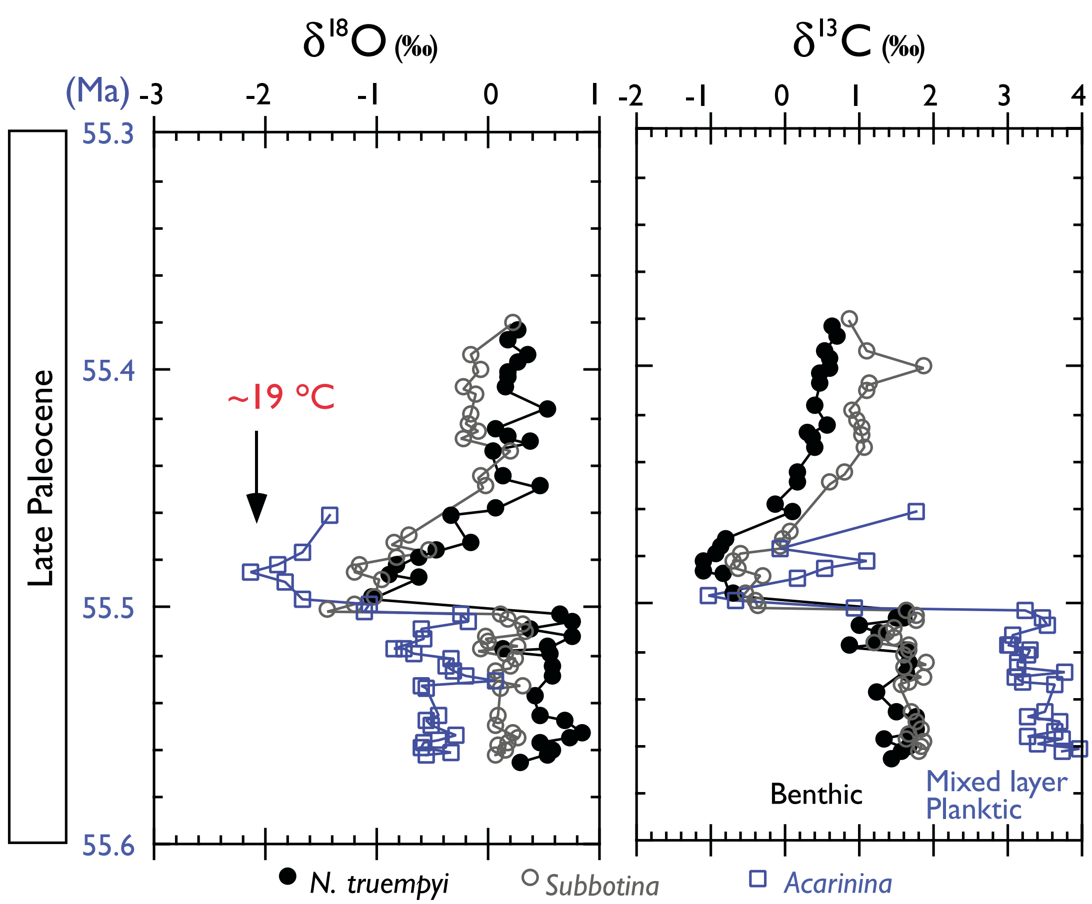

Figure 12. Late Paleocene stable isotopic records from Ocean Drilling Program Site 690 on the Maud Rise. (Data from Kennett, J., and Stott, L., 1991. Abrupt deep-sea warming, paleoceanographic changes and benthic extinctions at the end of the Paleocene. *Nature*, 353:225–229.)

The warm intervals, particularly the transients, appear to be the result of greenhouse gas forcing. For example, the LPTM, which was characterized by 5–8 ∞C of warming, was also accompanied by a worldwide carbon isotope excursion of –3.0‰ over a period of less than 20 thousand years (Fig. 12). Ocean carbon values returned to normal in less than 150 thousand years, or the residence time of carbon in the ocean. An explanation of this anomaly is the injection of an immense quantity of CO_2 greatly enriched in ^{12}C to the ocean or atmosphere at rates approaching (or exceeding) those of today's fossil fuel inputs. A catastrophic release of roughly 1,100 gigatons of methane gas hydrates from the continental margins would do the job. A switch in the source of intermediate to deep water, most likely after the passage of some critical threshold condition, caused significant warming of intermediate to deep water during the LPTM. This warming resulted in steeper sediment geotherms on continental slopes and thermal dissociation (melting) of gas hydrate. Methane released from gas hydrate and underlying free-gas zones then escaped to the ocean or atmosphere (presumably through sediment failure) where it was oxidized to CO_2. Benthic foraminiferal evidence indicates that at least part of the methane was oxidized within the oceans, causing depletion of dissolved oxygen and the largest extinction in the deep ocean of the Cenozoic.

These and other hypotheses can be tested with deep-sea drilling. Regardless of source, such large and sudden inputs of carbon into the ocean-atmosphere system should have had profound effects on ocean carbon chemistry. In particular, geochemical models show that initially the pH would drop and the depth at which calcite shells dissolve would shoal. Ocean pH versus alkalinity balance would eventually recover, within 150 thousand years, via chemical weathering of silicate rocks and inorganic and organic carbon deposition. The vigor of such oceanic transients would depend on the source of carbon. In principle, deep-sea sediments spanning a wide depth range should show evidence of systematic changes in the depths of carbonate dissolution.

Climatic extremes are of interest to a broad segment of the Earth science community including paleoclimatologists, paleoceanographers, biogeochemists, and paleobiologists. The periods of exceptional warmth, particularly the transients, provide natural experiments for testing our current understanding of how climate and biogeochemical systems and the biosphere respond to and operate under extreme greenhouse conditions. They also help to examine fundamental theories on mechanisms of climate change, particularly theories on the role of greenhouse gas forcing.

The Cretaceous "greenhouse worlds" provide additional information about the potential mechanisms and consequences of global warming over long to short timescales. During specific times (e.g., the Aptian [121–113 million years ago] and the Cenomanian–early Turonian [99–92.5 million years ago]), the climate appears to have undergone repeated sudden warming episodes. The latest stable isotope studies show that the maximum temperatures in the Cretaceous were established around the Cenomanian/Turonian boundary (about 93.5 million years ago) and in the middle Turonian (about 91 million years ago). The initiation of the Cenomanian/Turonian boundary oceanic anoxic event (OAE) appears to have been broadly coincident with a paleotemperature maximum (sea-surface temperatures in excess of 19 ∞C at the poles). Cooling, immediately postdating this event, was initiated by an inverse greenhouse effect due to sequestration of atmospheric CO_2 as sedimentary organic carbon. A positive carbon isotope excursion broadly corresponds in time to the period of excess organic carbon burial that defines the anoxic event. Possible causes of these unusual fluctuations include massive dissociation of gas hydrates, mantle degassing, or feedbacks from orbital forcing. Some of these hypotheses, particularly those calling for large changes in the carbon budget, are testable with drilling. With just a few well-coordinated spatial and vertical transects of Cretaceous strata in key areas (e.g., contrasting latitude and depth transects), it should possible to address several of these issues. Primary time intervals to target include the Aptian (OAE 1a: Selli event) and Cenomanian/Turonian boundary (OAE 2: Bonarelli event) oceanic anoxic events. Some key scientific questions include the following:

- To what extent were changes in greenhouse gases responsible for the transient (shorter than 0.5 million years) episodes of global warmth in the Cenozoic and Cretaceous?
- Are the short-term climate-forcing mechanisms similar to the long-term (more than 1 million years) forcing mechanisms?
- Was there a mechanistic link between the long-term warmings and transients?
- How did the ocean-atmosphere system operate during intervals of exceptional global warmth?

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What processes repeatedly drove the ocean toward extreme anoxia during the Late Cretaceous warm intervals?

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New Directions for an Integrated Drilling Program

Advancing our understanding of the feedback processes that set the sensitivity of Earth's climate and biogeochemical systems to change demands a new and unified research strategy that cuts across scales of time and space. We build on the ongoing success of the ODP in examining climate linkages on the scale of orbital changes in an array of sites with continuous recovery and high-resolution sampling. New technologies in surveying, drilling, measurement, data analysis, and modeling will remove current limits to progress and allow us to extend such strategies to both longer and shorter timescales, where specific global feedback mechanisms are best expressed and amenable to meaningful study.

The integration of global, coupled atmosphere-ocean-biogeochemistry models with ocean-drilling records of environmental change represents a new and powerful strategy. We have an exciting and unique opportunity to use both modeling and scientific drilling to design specific experiments to test hypotheses about the impact of gateways and mountain belts, orbital forcing, variations in thermohaline circulation, and greenhouse gases upon climate. Models serve as one strategy to infer spatial gradients between drill sites, to predict both near-field and especially far-field effects of changes in boundary conditions, and to estimate sensitivity and feedbacks between different parts of the climate system. The integration of model experiments, facilitated by improved computer capabilities, enables the design of better drilling experiments and more rigorous interpretation of drilling results. Such integration will be done on many levels and will help to bridge analyses of past climate processes with modern and future predictions. Such integration will be most effective when carried out interactively with continuously improving insights from data collection.

Improvements in drilling and coring methods with increased core diameter or other means of providing greater sample volume will improve core quality and remove current limits to high-resolution sampling. Tests of climate feedback mechanisms under altered conditions of the distant past demand that we extend the ability to sample the geologic record completely and continuously throughout the sediment column. New and more flexible drilling strategies will open previously inaccessible regions, such as the polar oceans and shallow-water sites. Progress on rapid climatic change demands an ability to safely and completely recover high-accumulation-rate sediments (in some cases laminated) from deep-sea drifts, shallow continental margins, and marginal basins on a regular basis. Routine complete recovery of annually banded corals from submerged reefs will require special technologies in both shallow and deep water. High-resolution spatial arrays of sites that penetrate the seafloor from 50 to 150 m will be facilitated by new, cost-effective approaches that can be deployed rapidly and routinely from a variety of vessels in response to continuously improving information as well as to developing scientific questions about the seafloor.

Opening access to the as-yet-untapped archives in such environments demands research strategies that extend beyond the drill bit. Optimized sampling in sometimes difficult environments will require greater attention to predrilling surveys. In most studies of climate change, field sampling is just the beginning of the scientific endeavor. Extracting the needed information from the recovered archives at the resolution required to answer new questions implies a new commitment to postcruise studies. Capitalizing on the detailed information provided by these rich geologic archives extends beyond generation of data to new structures that encompass process modeling and linkage to the climatic archives preserved on land and in polar ice sheets.

Introduction to Solid Earth Cycles

Processes that Govern the Shape of Earth's Surface

Motion of Earth's lithosphere is a fundamental driving force for global change, on geologic to human timescales. The ~100-km-thick lithospheric plates that form Earth's surface move relative to each other, breaking apart continents, making new oceans and sedimentary basins, and building new mountain belts. In addition to creating the rock framework of Earth's surface, plate tectonics establishes thermal gradients near the surface. Together, these provide the matrix and much of the driving force for the movement of fluids (aqueous, carbon rich, or magmatic) through the lithosphere. These fluids carry a message of processes operating at depth and are the mechanism for exchange between the solid Earth and its oceans, atmosphere, and biosphere. The fluids also yield economically valuable resources (e.g., hydrocarbons and ore deposits) on which modern civilization depends.

The physical, chemical, and biological consequences of the tectonically driven interplay among fluids, sediments, and rocks are a common theme in the three chapters that follow. Whether discussing the rifting of continents and development of passive margins, the creation and evolution of oceanic lithosphere, or the dynamics of convergent margins, we must return frequently to the role of fluids in driving or mediating critical processes. These include major aspects of Earth as a planet, such as plate-scale faulting and deformation, the nature of the Moho, and the creation of new continental crust. Intimately related are the nature and extent of the deep biosphere, the localization of hydrocarbon resources, the formation of ore deposits, the distribution of potable water reservoirs, the earthquake hazards of the seismogenic zone, and the nature of climate-modifying and hazardous explosive volcanic eruptions.

Each of the next three chapters deals with a separate tectonic setting and focuses on the role of drilling as part of an integrated plan to address, in that particular tectonic setting, major questions in the Earth sciences. All three chapters have the overall goal of assessing the cycling and feedbacks of plate tectonics, the driver that makes Earth such a unique planet in our solar system. Each of the chapters ends with a brief discussion of technological needs common to all.

The level of planning apparent in the following chapters has been made possible, in part, through a series of workshops that have brought together an international and diverse group of scientists (both participants and nonparticipants in the ODP) to identify critical science questions, to develop integrated strategies for answering them, and to achieve community discussion and consensus. Facilitated in part by the Inter-RIDGE and the developing Inter-MARGINS programs, the COMPLEX workshop participants recognize that deployment of the full battery of techniques and approaches needed to answer the questions posed may require geographic focus. (In the United States, "RIDGE" is "Ridge Interdisciplinary Global Experiments" and Inter-RIDGE is "International RIDGE," referring to RIDGE programs at the international level; Inter-MARGINS is the international effort associated with the U.S. MARGINS [i.e., continental margins] studies.) COMPLEX and future workshops will be essential for fully integrating drilling with other aspects of international Earth science, in the context of developing and agreeing upon candidate sites for such technological focus.

Motion of Earth's lithosphere is a fundamental driving force for global change, on geologic to human timescales.

An integrated program for scientific ocean drilling will have many aspects; some will be totally new to scientific ocean drilling, despite its more than 30 years of history. To understand solid Earth cycles, multiple-platform drilling is an essential and unique aspect of the integrated, coordinated, and interdisciplinary science plans that are presented.

In the studies of the passive continental margins, the successor ship to the *JOIDES Resolution* will focus on shallow arrays of boreholes to determine sediment stratigraphy and slope stability. That drilling platform will also support the study of the formation and evolution of the oceanic lithosphere by the ship's capabilities for penetrating bare, fractured rock, which will be particularly useful in drilling tectonic windows into exposed deeper crust and upper mantle. This ship will produce intact sections and allow offset drilling, paired boreholes, and borehole arrays. Finally, it will be used in exploration near oceanic trenches—the subduction factory—by drilling through volcaniclastic sections, serpentinite seamounts, and the crust of the incoming plate and shallow fore arc.

Various "fit-to-mission" platforms will be employed. Jack-up rigs and semisubmersibles will have roles in deciphering sea-level sequence stratigraphy of passive continental margins. Hard-rock, portable, remotely operated drills will be used along with jack-up rigs to study seafloor ore deposits along the mid-ocean ridges and near trenches, where oceanic lithosphere is created and destroyed, respectively.

A riser-equipped drilling platform will allow access to parts of the seafloor that have not been within the reach of the *JOIDES Resolution.* Along continental margins, rift-history studies and deep fault penetration will be possible because the riser-equipped ship will have a blow-out preventer, which allows safer drilling in thick sedimentary prisms that might be gas bearing. In the mid-ocean ridge and abyssal-plain environments, the riser-equipped ship can collect total crustal sections. Even the high-temperature reaction zones along the ridges themselves could be drilled for study. And the subduction factory knowledge will be enhanced by the riser-equipped ship's capability to acquire total fore-arc sections and drill in the seismogenic zone. Among other goals detailed in the separate chapters, the ophiolite model of oceanic crust formation will be tested as will theories concerning protocontinents and arc history.

The ocean platform–based research will be complemented by continental drilling and undersea remote observatories. In particular, the shallowest sedimentary sequences will be drilled for coastal-plain sea-level studies and land and sea correlations. Ophiolites will be further investigated to flesh out the ophiolite model. Drilling fore-arc islands could yield a deep arc section, and drilling continental collisional terranes could elucidate collisional processes. On the seafloor and within the seabed, remotely operated observatories will provide real-time data access and instrument control. Multidisciplinary experiments involving high-temperature sensors and samplers as well as borehole corks and advanced corks hold great promise for solving some of the perplexing questions that remain.

Processes on Passive Continental Margins

Continental margins, particularly passive continental margins, form the largest repository of geologic resources on Earth. Because of their proximity to major population centers, these continent-ocean transitions constitute one of the most critical regions for societally relevant geologic investigations. Drilling with continuous sampling, logging, and monitoring of boreholes provides the only means of evaluating physical processes operating on passive continental margins that otherwise can be interpreted only from remote-sensing data at various bandwidths. However, until now, continuous sampling by scientific ocean drilling has been largely limited to deeper-water (generally >200 m) regions of continental edges.

"Because of their proximity to major population centers, these continent-ocean transitions constitute one of the most critical regions for societally relevant geologic investigations."

Participants in COMPLEX recognized that future scientific drilling of passive margins, particularly in shallow- and intermediate-water depths, can address fundamental questions in four interrelated areas: (1) geologic processes of rifting and passive-margin evolution, (2) sedimentation processes, (3) sedimentary architecture and sea-level history, and (4) fluid-flow regimes.

To address these areas, the scientific community requires concentrated drilling efforts using "fit-to-mission" drilling-platforms-of-opportunity in shallow-water depths (0 m to shallow water range of riser-equipped vessel) and a riserless vessel of the *JOIDES Resolution* class in intermediate water depths (to approximately 2000 m). Such drilling will greatly benefit from close ties between the international academic community and industrial consortia.

Geologic Processes Related to Rifting, Rift-Basin Formation, and Passive-Margin Evolution

Rifting of continental lithosphere, one of the fundamental processes of plate tectonics, can culminate in the formation of ocean basins. Continental rifting also leads to the formation of rift and postrift sedimentary basins, a primary component of passive or divergent continental margins. These basins are large reservoirs containing resources critical to society, e.g., hydrocarbons, minerals, and potable water. Therefore, a primary goal of an integrated program in ocean drilling should be *to understand the processes and mechanisms by which continents break apart and influence the subsequent evolution of rift and postrift basins.* Scientific questions abound:

- How and where are rifts initiated?
- How do rifts evolve in terms of deformation, sedimentation, magmatism, and structural style?
- What controls the temporal and spatial variability of these factors?
- How does the transition from rifting to seafloor spreading occur?
- How does the rift and breakup history affect resource potential (petroleum, minerals, water)?

Potential tectonic forcing agents that lead to rifting and that may be tested by drilling include variation in horizontal lithospheric stress, especially insofar as it may represent a complementary process to glacial eustasy; mantle flow driven by either slab subduction or upwelling; thermomechanical effects of plumes; and geologic loads, such as prograding sedimentary systems. Therefore, a secondary goal is *to test the relative importance of each of these tectonic forcing agents to the modification of basin and passive-margin stratigraphy.* Examples of the effects of these agents are regional tilting (for an example, see Fig. 13) and local structural inversion (Fig. 14). Questions to be answered include the following:

- What is the timing of basin inversion and of tilting on both local and regional scales?
- How do crustal structure and basin geometry affect the form of inversion and tilting?
- What are the timing and duration of variations in the forcing function?

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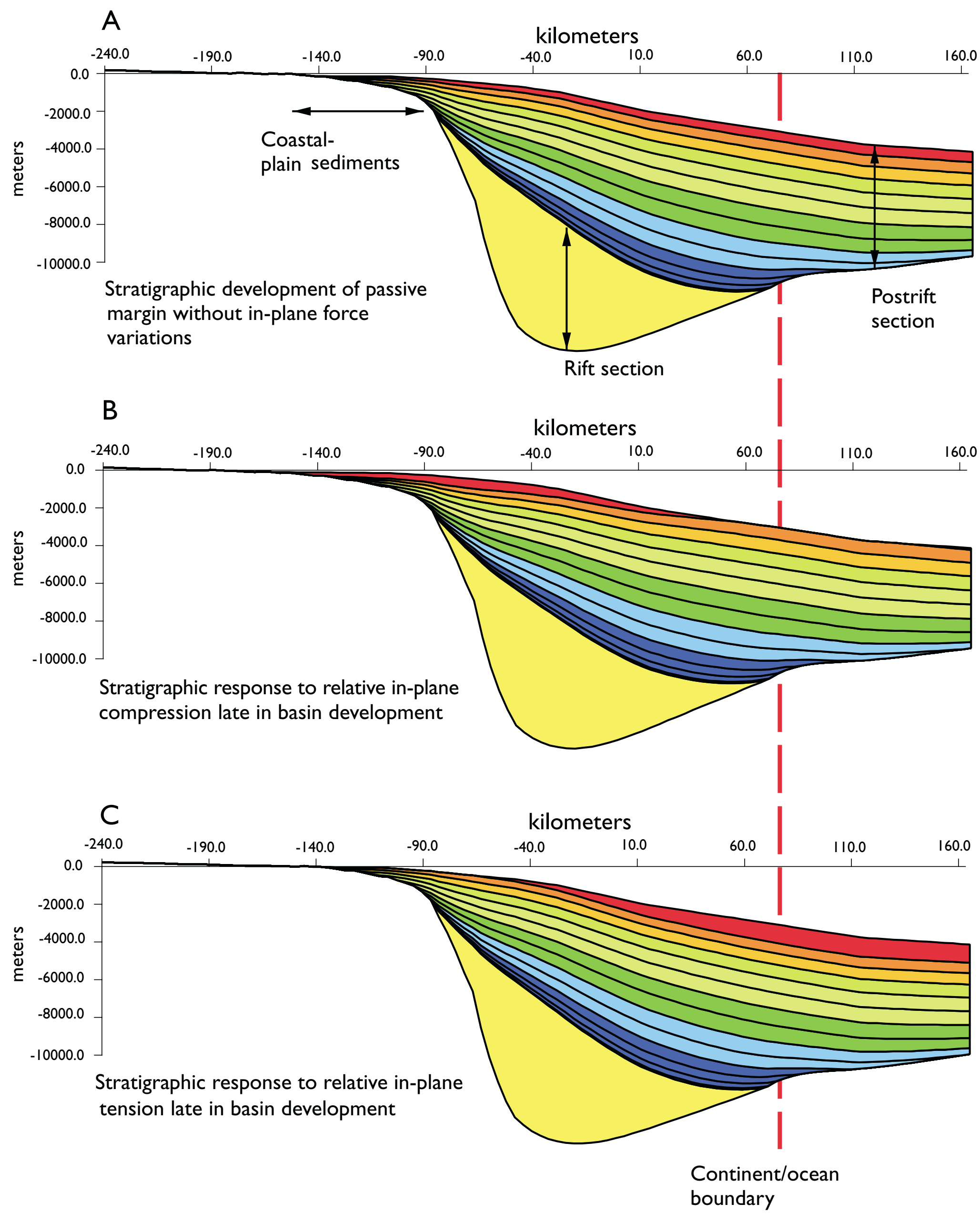


Figure 13. Modeled passive-margin stratigraphy. The postrift time lines show the progressive development of the margin, with the time lines (shown by the colored strata) ranging in age from 1 to 196 million years and following a progression of n^2, where $n = 1, 2, \ldots, 14$, i.e., there are 14 time lines and the ages are the line-number squared). Because of the regional nature of these deformations, in-plane force variations may offer a tectonic alternative to glacio-eustasy in explaining third-order sea-level cycles and/or a mechanism to either enhance or diminish the effects of glacio-eustasy within continental-margin sedimentary prisms. (A) Stratigraphic development in the absence of in-plane force variations. The result is characterized by the usual two-phase development of extensional systems: a rapid, initial subsidence associated with brittle deformation of the lithosphere and a slower, postrift subsidence associated with the cooling of the lithosphere. (B) Margin response to late-stage, in-plane compression. Compression tends to enhance subsidence across the hinge zone, leading to a landward shift in marine onlap. (C) Margin response to late-stage, in-plane tension. Relative tension results in uplift and sediment by-pass of the hinge-zone region, leading to a seaward shift in marine onlap. (Modified from Karner, G.D., Driscoll, N.W., and Weissel, J.K., 1992. Response of the lithosphere to in-plane force variations. *Earth and Planetary Science Letters,* 114:397–416.)

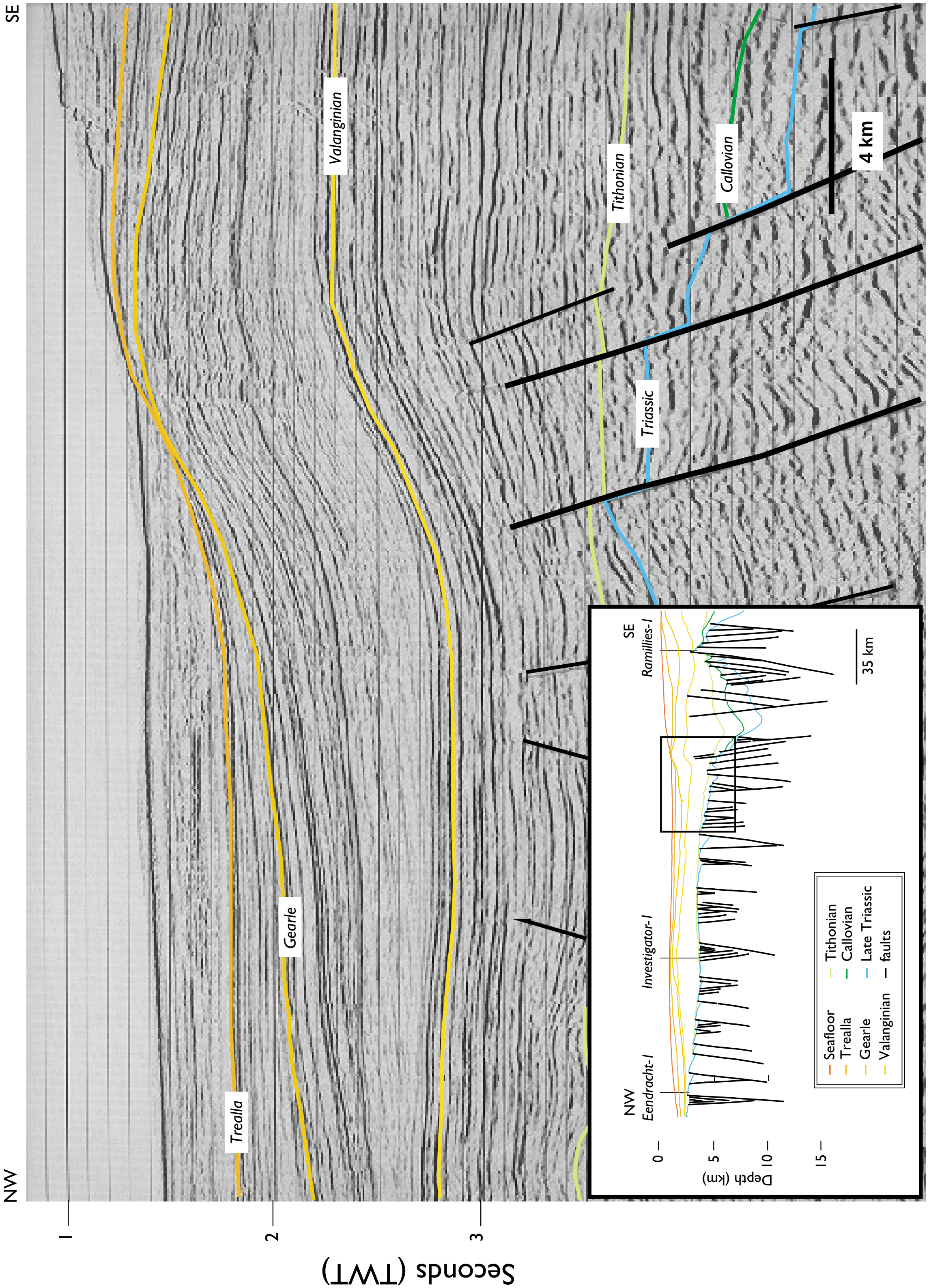
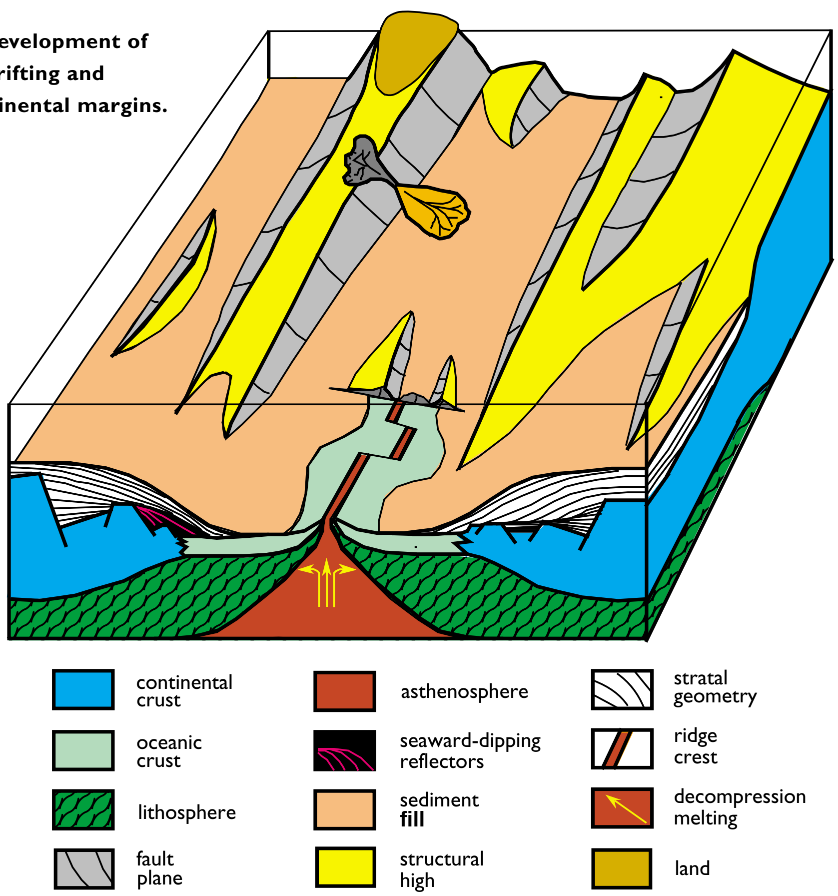


Figure 14. Interpreted seismic reflection profile illustrating localized brittle inversion of the underlying rift structure and the formation of a forced fold within the overlying strata. Seismic line is a dip section across the northwest margin of the Exmouth subbasin, offshore Australia. (From Karner, G.D., and Driscoll, N.W., 1999. Style, timing, and distribution of tectonic deformation across the Exmouth Plateau, northwest Australia, determined from stratal architecture and quantitative basin modelling. *In* Mac Niocaill, C., and Ryan, P.D. [Eds.] *Continental Tectonics*: Geological Society [London] Special Publication, 164:271–311.)

In order to characterize the physical boundary conditions responsible for deformation, it is necessary to study regions—e.g., propagating rifts and loci of structural inversion—in which the processes remain active. In other cases, studying ancient analogues (e.g., failed rift systems and old passive margins) may be advantageous. For both approaches, new strategies are required. First among these are advanced drilling, logging, and sampling technologies, including shallow-water capabilities. From both boreholes and seafloor observatories, we need to make studies of active processes in four dimensions—4-D: three dimensions plus time—especially extension along faults and fluid flow in various environments. Resources must be focused into a limited number of studies on currently active and ancient rifts, including an example covering an entire sedimentary-tectonic-magmatic rift-basin system (Fig. 15). A closer integration of observational data with numerical and laboratory modeling as well as access to ODP digital data sets will yield valuable results. And to study petroleum reservoirs effectively and comprehensively, new alliances between scientific ocean drilling and industry will be essential, as discussed at the end of this chapter.

Figure 15. Development of continental rifting and passive continental margins.



The new mode of focused studies on the passive continental margins will benefit from certain site-selection criteria. For example, if extension has culminated in sea-floor spreading, we must know the timing of breakup. The stratal geometry should not be obscured by postdepositional deformation (e.g., no salt tectonics). We should be able to image and sample postrift and synrift packages and to determine the full crustal thickness across the rift system. We need to have identifiable conjugate-margin segments. Finally, access to quality data sets is required (e.g., two- and three-dimensional seismic, potential-field, drilling, and logging data, in addition to field and/or land observations and mapping), and the study area should be logistically and politically accessible.

Sedimentary Processes: Making Sense of Margin Complexities

Another primary goal of an integrated program in ocean drilling should be *to unlock the great store of information about Earth's response to changes in sea level, climate, and tectonics recorded in sediments deposited in the transition zone between the coastal plain and the deep sea.*

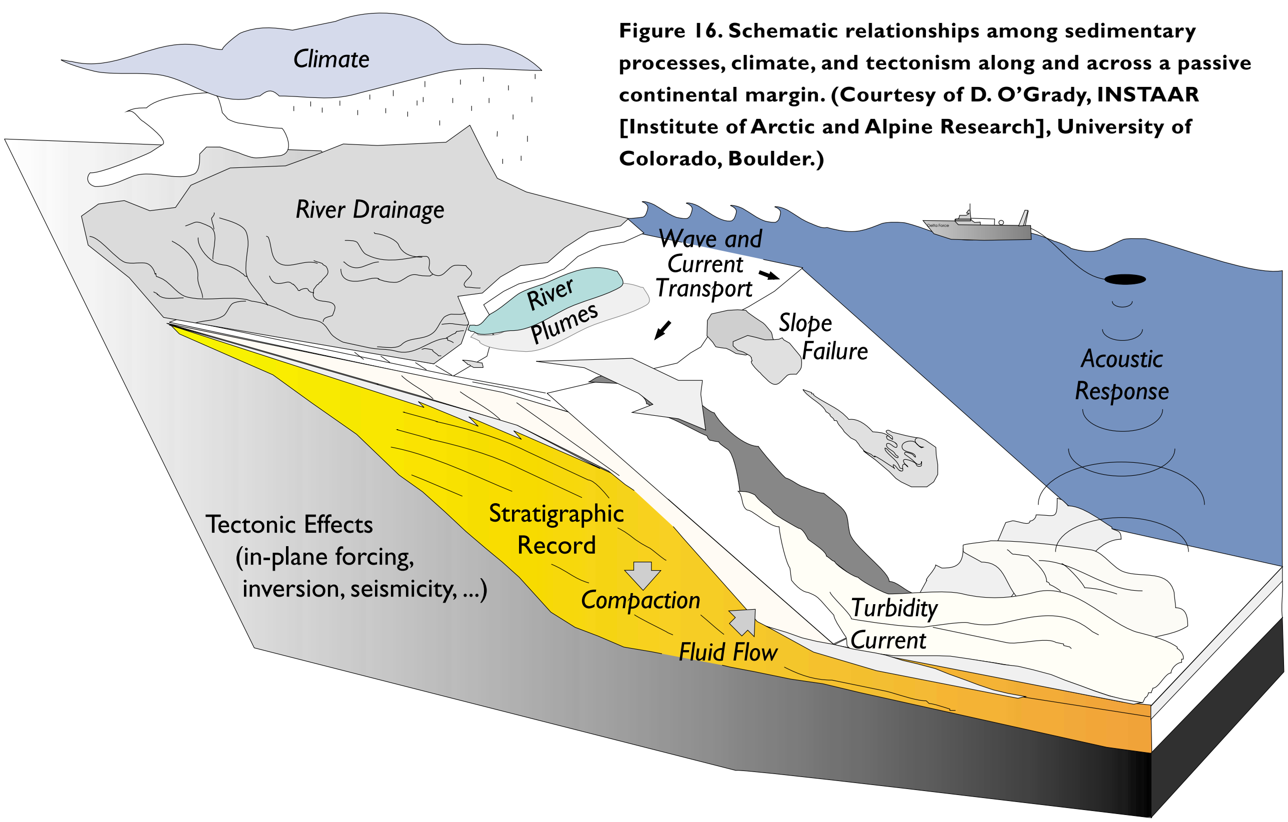


Figure 16. Schematic relationships among sedimentary processes, climate, and tectonism along and across a passive continental margin. (Courtesy of D. O'Grady, INSTAAR [Institute of Arctic and Alpine Research], University of Colorado, Boulder.)

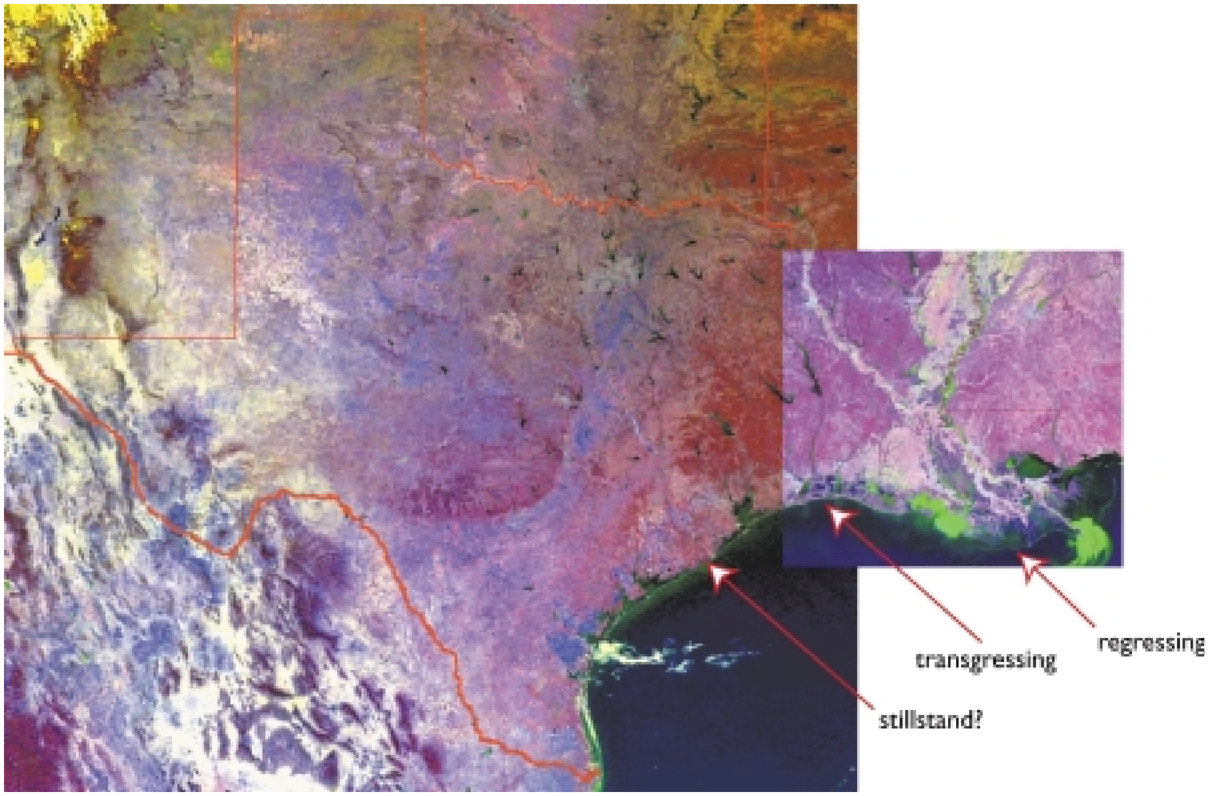


Figure 17. Satellite imagery of the Texas-Louisiana coast showing where the shoreline is moving seaward (i.e., the sea is regressing), landward (i.e., the sea is transgressing), and perhaps stationary (i.e., the sea is at stillstand). Such differences in shoreline response illustrate the spatial variability in the processes that shape continental margins. These processes also vary over time. The consequence is a complex, three-dimensional (four-dimensional, including time) stratigraphic architecture that can only be fully interpreted in the context of sedimentary processes. (Satellite imagery courtesy of Ray Sterner, Johns Hopkins University.)

Continental margins contain expanded, high-resolution records of Earth history. However, interpreting these critical sediment-borne environmental records in terms of the causative tectonic, erosional, depositional, and diagenetic processes is the future challenge. Our ability to fully exploit this information and to identify and recover resources preserved in margin strata depends on understanding the stratigraphic record's temporal and spatial variability and the physical processes that created it.

Passive or divergent continental margins, extending from the coastal plain to the abyssal plain, are natural zones of transition, subject to fluctuations in sea level, climate, and tectonism (Fig. 16). These processes in turn produce temporal and spatial fluctuations in sediment supply, sediment types (e.g., clastic vs. carbonate sediments), oceanographic current regimes, subsurface fluids (from fresh water and salt water to hydrocarbons), nutrients, and biota. The timing, magnitudes, and rates of such fluctuations often differ, both along and across continental margins. For example, along-shore variability in margin sedimentation processes creates along-shore variability in the record of sea-level rise (Fig. 17) and leads to a complex, three-dimensional variability in margin stratigraphy that is pervasive over a range of temporal and spatial scales.

However, this variability can be deciphered. Seismic stratigraphy provides one means of evaluating variability between bounding stratal discontinuities (as described in the next section). The challenge is to predict reliably how and why stratigraphy varies in three dimensions, from the general scale of sequences (tens to hundreds of meters in thickness) down to the scale of individual recovered sediment sections (Fig. 18). To meet this challenge, we must first identify and document systematic changes and next relate these changes to the processes that created them. These relationships can then be refined and tested iteratively through modeling and comparison with observations.

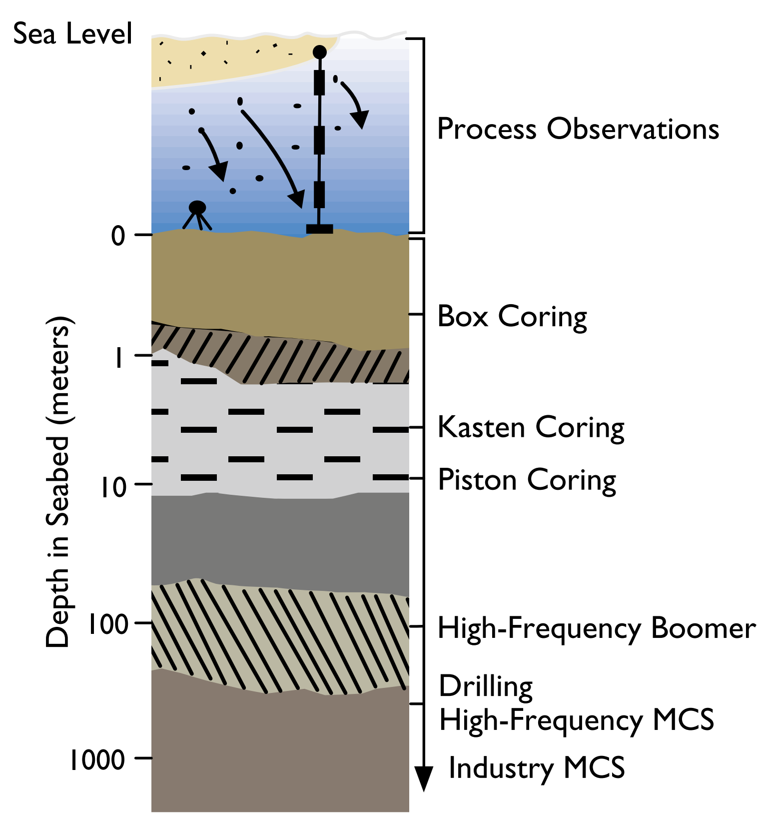


Figure 18. Schematic representation of the depths to which various scientific techniques may be applied to help decipher the formation of the stratigraphic record on continental margins. The techniques shown range from shallow box coring (which can penetrate about 0.5 m) to multichannel seismic (MCS) studies for progressively deeper observations of seabed strata. Spatial scaling of sedimentary processes and products requires a comparable scaling of techniques to study them. (Courtesy of C.A. Nittrouer and J. P. Walsh, University of Washington, Seattle [Nittrouer, C.A., and Kravitz, J.H., 1996. STRATAFORM: a program to study the creation and interpretation of sedimentary strata on continental margins. *Oceanography,* 9(3)146–152.])

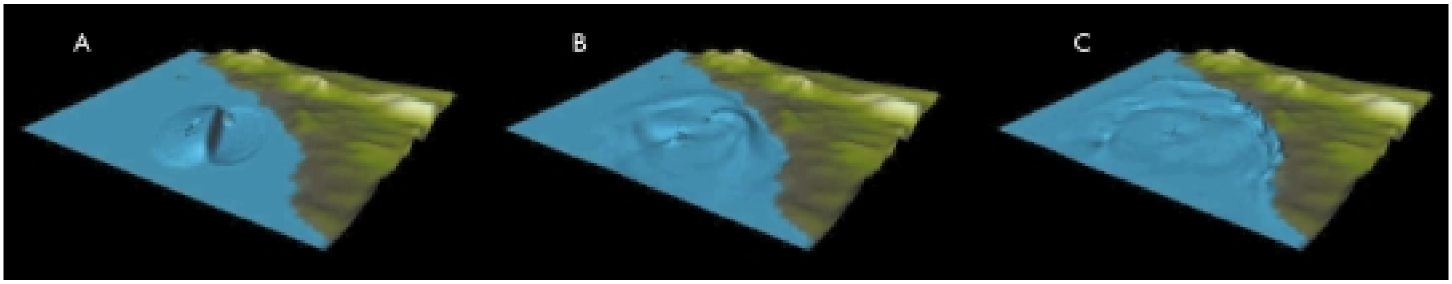


Figure 19. (A–C) Simulation of a tsunami generated by a large, instantaneous seafloor displacement off the coast of southern California, in the vicinity of Los Angeles. (Simulation created by Sean Shevlin, University of Southern California, Los Angeles. Courtesy of the Tsunami Research Program, Costas Synolakis, and the University of Southern California Tsunami Research Team.)

A major component of the passive-margin sedimentary cycle is sediment failure and downslope flow, which erode the shelf and slope to build the continental rise and abyssal plain. An important secondary goal pertinent to comprehending the details of sedimentary processes is *to understand the mechanisms of sediment failure, the forms of sediment transport, and the nature of sediment deposition, as critical factors in margin development.* Related to this goal is the need to investigate roles of fluid flow, sediment supply, and tectonics in enhancing failure, altering stratigraphy and potentially even stabilizing the seafloor. Thus the need for an integrated study becomes apparent.

The benefits that will result from an improved understanding of the spatial variability of passive-margin deposits are immense and involve a variety of related fields. In terms of immediate benefits to society, such knowledge will aid assessments of submarine slope instabilities and their attendant tsunamis, both of which threaten marine and coastal installations (Fig. 19). Exploration for and recovery of passive-margin resources, including oil, gas, minerals, and fresh water, will also be enhanced; the distribution of *all* of these resources is controlled by sediment architecture and its relationship with the "container," that is, the basin architecture (Fig. 15).

Another substantial benefit of understanding the spatial variability of margin stratigraphy will come from being able to properly site a multiple-borehole assemblage of nearly continuous, high-resolution records of passive-margin sediment accumulation for paleoclimate studies. Such high-resolution records have already been

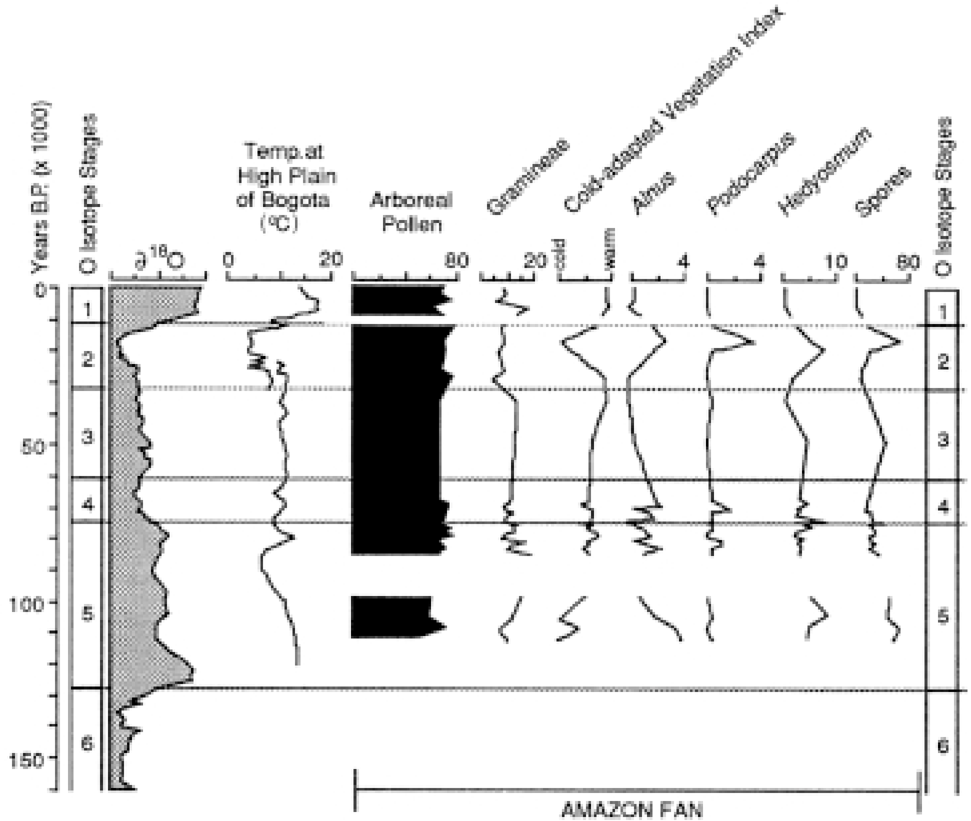


Figure 20. A high-resolution climate record recovered from the Amazon Fan (ODP Leg 155) showing a cool climate in the Amazon River drainage basin during the last glacial period (oxygen isotope stage 2). This record, which is difficult to recover on land, was collected as part of a study of fan sedimentation. (From Haberle, S., 1997. Upper Quaternary vegetation and climate history of the Amazon Basin: correlating marine and terrestrial pollen records. *In* Flood, R.D., Piper, D.J.W., Klaus, A., and Peterson, L.C. [Eds.], *Proceedings of the Ocean Drilling Program, Scientific Results,* 155: College Station, Texas [Ocean Drilling Program], 381–396.)

shown by the ODP to be available in margin settings, although such records have not yet been systematically exploited. These records, which contain both terrestrial and marine signatures, will provide valuable information on past climate and tectonic events, by showing specifically how the linked continent-ocean system has responded to short- and long-term climate fluctuations (Fig. 20). Acquiring high-resolution records in these transitional environments is particularly important, because climate signals (e.g., evidence for sea-level changes) along margins can be enhanced relative to those preserved in the deep sea. Margin records could also be used to help interpret marine deposits now exposed on land or in the subsurface; the combination of modern passive-margin deposits and ancient marine deposits now part of the rock record provides a longer record of Earth's history than is contained in deep-sea sediments alone. Applying our understanding of sedimentary processes from the modern ocean (where geometry and oceanographic setting are known) to the study of older margin deposits (where geometry and oceanographic setting are of interest but unknown) can potentially yield the only possible detailed, long-term record of the response of Earth's surface to environmental change.

New approaches to sampling will be needed to advance our understanding of how sedimentary processes create and preserve stratigraphy over time:

- The complexity of the passive-margin sediment pattern requires a three-dimensional distribution of sites, in both deep and shallow water, and in certain regions requires both riserless and riser capabilities, i.e., a multiple-platform drilling strategy.
- Multiple boreholes will be needed to sample seismically imaged strata, to determine changes in sediment facies—responsible for the seismic images of sedimentary architecture—both laterally and with depth, and to study the climate record these sediments contain. These boreholes must be selected to provide the pertinent information needed for qualitative and quantitative models of sediment transport and depositional processes and to allow for the verification of high-resolution seismic images by downhole measurements and core analysis; single boreholes may not be sufficient to define important facies. Furthermore, site spacing should be sufficient to capture all important stratigraphic transitions.
- High-quality two- and three-dimensional seismic imaging of sedimentary units and basin structure is a necessary prerequisite for determining optimal drilling sites.
- Drilling for sedimentary-process objectives should be linked, where appropriate, with drilling for sea-level and fluid-flow objectives (as discussed next), perhaps requiring additional boreholes.
- Drilling projects should be linked with other programs, such as STRATAFORM (U.S. Office of Naval Research) and MARGINS (U.S. National Science Foundation), that emphasize sedimentary-process modeling and a need for high-resolution climate records to complement process-based studies.

SEDIMENTARY ARCHITECTURE AND SEA LEVEL

Sea level divides the planet Earth into two fundamentally contrasting realms, land vs. ocean. Changes in sea level, both global and regional, are a primary behavioral feature of the Earth system. Multiple-platform scientific ocean drilling will provide unique opportunities to understand factors that control changes in this dynamic boundary, as well as to understand the complex influences these changes have on the planet's biogeochemical system.

The vast accumulations of sediments deposited adjacent to the shoreline along passive continental margins are replete with stratal discontinuities on all spatial scales (Fig. 21). Stratal discontinuities allow an objective and fundamental subdivision of the preserved stratigraphic record, providing the basis for evaluating controls on sedimentary architecture and for predicting sedimentary facies and soci-

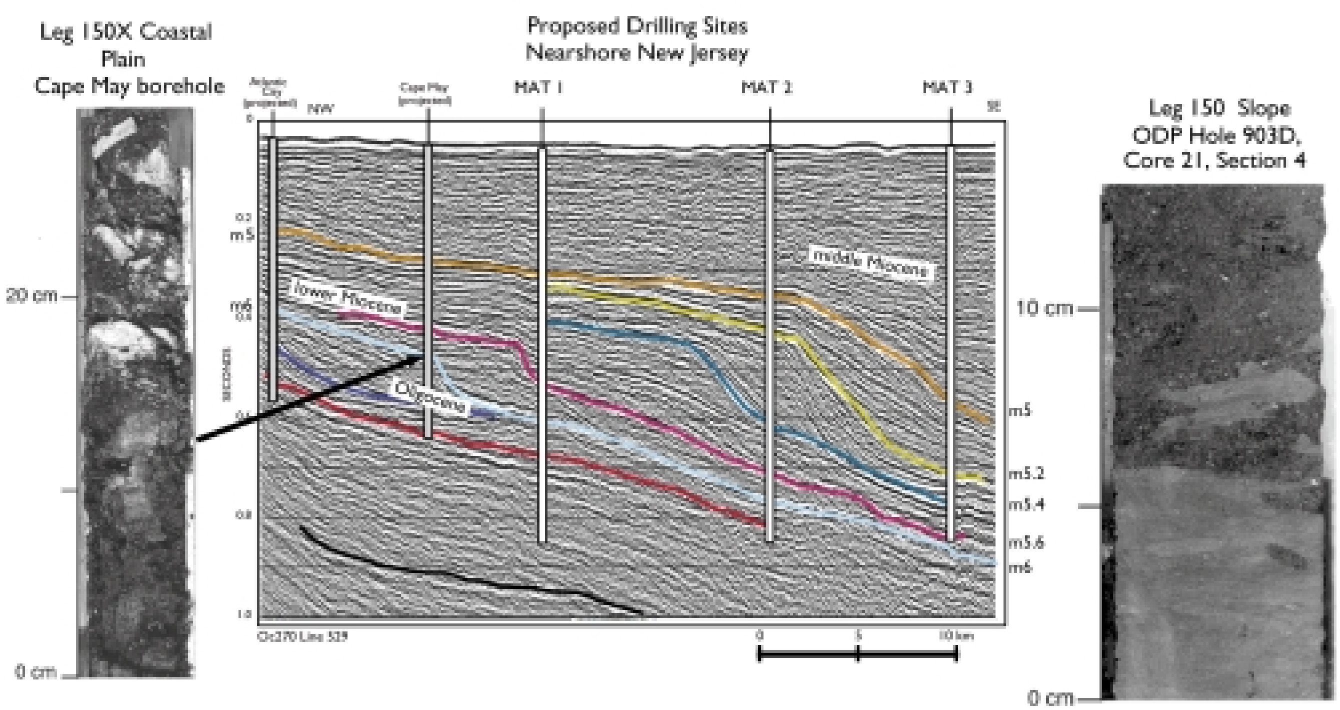


Figure 21. Lower Miocene seismic sequences sampled onshore (Leg 150X, Cape May) and offshore on the continental slope (Leg 150) of New Jersey, showing core and seismic expressions of a basal Miocene (m6) sequence-bounding unconformity. Note that the region most critical to sea-level and sedimentary architecture studies (around proposed sites MAT 1–MAT 3) has not been drilled because the shallow water depths involved (<40 m) require a "fit-to-mission" platform. (Seismic profile from G. S. Mountain et al., unpublished; core photographs after Miller, K.G., Mountain, G.S., Browning, J.V., Kominz, M., Sugarman, P.J., Christie-Blick, N., Katz, M.E., and Wright, J.D., 1998. Cenozoic global sea-level, sequences, and the New Jersey Transect: results from coastal plain and slope drilling. *Reviews of Geophysics* 36:569–601.)

etally important resource distributions (e.g., hydrocarbons and potable water). Similar sedimentary architectures are observed on margins having widely contrasting tectonic and sedimentary histories, thereby emphasizing eustasy as a fundamental control on the stratigraphic record.

The stratal architecture of rift basins and passive margins is a function of base-level changes (including the effects of both eustasy and tectonics) and sediment supply. To predict stratal architecture and extract the eustasy component from the sediment "tape recorder," we need to understand tectonic and magmatic driving forces as a function of space and time, both during and after rifting. This complex forcing function must be evaluated to understand the evolution of rift and postrift basins, the relationship of basinal evolution to global sea-level changes, and the effects of tectonics and magmatism on sedimentary reservoirs through geologic time (e.g., see Fig. 15).

Achievements to Date

Planning by COSOD II (the Conference on Scientific Ocean Drilling in 1987), the 1990 JOI-USSAC (the U.S. Science Advisory Committee) Sea-Level Workshop, and the 1992 JOIDES Sea-Level Working Group—and subsequent drilling by ODP Legs 150, 150X, 166, 174A, 174AX, and 182—have accomplished the following:

- Proved that the age of sequence boundaries on passive margins can be determined to better than ±0.5 million years.
- Validated the "transect" approach of drilling passive continental margins (multiple arrays of boreholes—onshore, shelf, slope).
- Showed that siliciclastic and carbonate margins yield correlatable records of base-level change, as deduced from the chronostratigraphy of seismically observed stratal discontinuities.
- Evaluated the sedimentary response of a tropical carbonate platform to presumed eustatic changes.

- Provided preliminary amplitude estimates of 10–60 m for million-year–scale sea-level variations from the New Jersey margin; these agree with amplitudes derived from estimates based on oxygen isotope data (Fig. 22).

- Achieved stratigraphic resolution on the scale of orbital changes in strata of continental slopes and carbonate platforms.

Furthermore, coordinated study of the Antarctic Margin (ODP Legs 178, 188, and proposed future legs) should provide direct evidence of Antarctic Ice Sheet history.

The achievements to date lead to the formulation of another primary goal of an integrated program in ocean drilling: *to determine the rates, amplitudes, and mechanisms of eustatic change from the Cretaceous through the Cenozoic on scales of 106–103 years.*

Drilling by the ODP has provided a chronology of sea-level change during the past 42 million years, has linked observed lowerings of base level to glacio-eustasy, and has made progress toward estimating rates of eustatic change for the late Eocene–Miocene interval (from 42 to 5.3 million years ago). Continued develop-

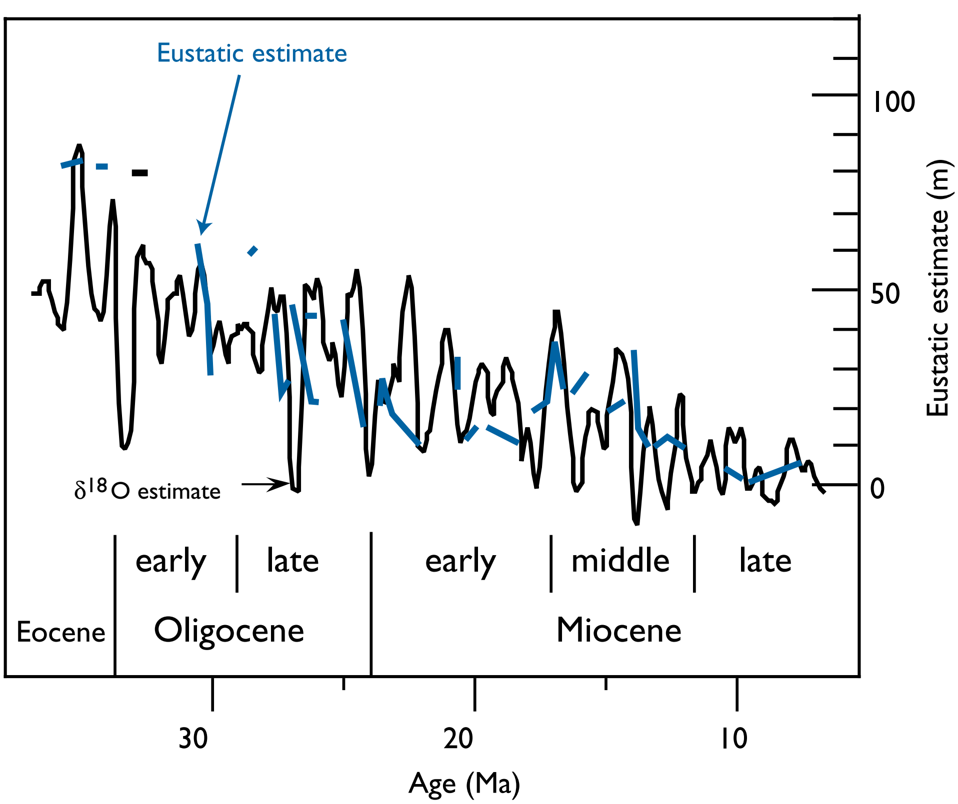


Figure 22. Comparison of eustatic estimates derived from elevation measurements along the New Jersey Coastal Plain with eustatic estimates derived from oxygen isotopes (K. G. Miller, J. D. Wright, and M. A. Kominz, personal communication, 1999). The plot shows that sea level changes by significant amounts on geologically short timescales.

ment of amplitude estimates is needed on different margins and across a broader spectrum of geologic time to test extant global models for eustatic changes of >100 m in the geologic past (e.g., for the late Oligocene). However, there are critical uncertainties about rates, amplitudes, and mechanisms of sea-level change that we have not begun to address. A major problem has been to identify cause and effect: Given a known change in eustasy, what is the effect on the preserved passive-margin stratigraphy?

Given a known change in eustasy, what is the effect on the preserved passive-margin stratigraphy?

How fast can global sea level rise? One possible experiment is to determine rates of sea-level rise during the late Pleistocene–Holocene. Coral records demonstrate that sea level has risen 120 m since approximately 20 thousand years ago and that there were two sharp inflections of >30 m that occurred in only 1,000 years. Passive-margin and coral-atoll records suggest rates that were even faster than this. Drilling suitable targets on passive margins should resolve the rates of these millennial-scale changes.

How fast can global sea level rise?

Is tectonism on the timescale of 10^6–10^4 years an important agent of global sea-level change? In-plane stress has been invoked as a possible mechanism to explain eustatic changes. However, given the immense importance of this mechanism, it has yet to be shown that it is, in fact, viable. Drilling arrays of boreholes (both across-dip and along-strike) on selected passive margins into strata deposited when large tectonic events influenced an otherwise well-defined glacio-eustatic sea-level change should allow us to determine how the margin has responded to changes of in-plane stress.

Is tectonism on the timescale of 10^6–10^4 years an important agent of global sea-level change?

What caused large, rapid sea-level changes during supposedly "ice-free" intervals? The only known mechanism for causing large (much greater than 10 m), rapid (happening in less than 1 million years) changes in sea level is the growth and decay of ice sheets. However, onshore studies of marine sediments have indicated that such changes also occurred during the Cretaceous–early Eocene, an interval of geologic time for which we have no evidence of significant ice sheets anywhere on Earth. Other mechanisms were clearly operating. Integrated borehole transects and arrays along selected passive margins should determine the amplitude and rates of Cretaceous–early Eocene sea-level variations that can be compared with estimates of near- and far-field tectonic events, global $d^{18}O$ records (ice-volume proxies), and other possible causal mechanisms (e.g., basin desiccation, formation of large igneous provinces).

What caused large, rapid sea-level changes during supposedly "ice-free" intervals?

Yet a third related goal is *to determine what processes control stratal architecture (i.e., geometry of stratal surfaces, including sequence boundaries and intrasequence stratal patterns) on margins, particularly passive margins*.

Acoustic images reveal surfaces and seismic facies on various scales that indicate past variations in eustasy, tectonics, and sediment supply. We can isolate these effects by drilling margin sequences in different tectonic and sedimentary settings, to answer the following questions:

What is the range of stratigraphic response to a known eustatic forcing?

What is the range of stratigraphic response to various tectonic influences?

How do differences in sedimentary setting and sediment input influence preserved stratigraphy?

What is the range of stratigraphic response to a known eustatic forcing? Answering this question can be accomplished by drilling to evaluate similarities and differences among stratal surfaces and facies on several margins, during an interval when the eustatic record is reasonably well known (e.g., the middle to late Pleistocene).

What is the range of stratigraphic response to various tectonic influences? The influence of tectonics can be evaluated by comparing stratal surfaces and sedimentary facies from along passive margins, translational margins, and foreland basins. Furthermore, stratal surfaces and seismic facies are apparently similar on passive and many active, convergent margins, although it is not yet clear that sedimentary-facies predictions can be extended to active margin sequences.

How do differences in sedimentary setting and sediment input influence preserved stratigraphy? Stratal surfaces and facies patterns must be compared in carbonate, mixed carbonate-siliciclastic, and siliciclastic margins across a wide spectrum of sediment inputs, to develop predictive facies models and to delimit fluid migration pathways.

All proven drilling, sampling, and logging technologies, including those optimized for shallow water, must be made available to the scientific ocean-drilling community. Many questions about eustatic change that deserve to be addressed will remain unanswered otherwise. Although the ODP has drilled the New Jersey, Bahamas, and Australian passive margins, a lack of shallow-water drilling capability has severely limited our understanding of global sea-level change and sedimentary architecture. The current status can be compared to what would be known about magma and seawater interactions if the ODP had been relegated to drilling only in abyssal plains, abyssal hills, and partially up ridge flanks!

FLUID FLOW IN PASSIVE CONTINENTAL MARGINS

We have long recognized that significant amounts of fluid migration (liquid and gas phases) occur within passive continental margins and isolated carbonate platforms. However, the magnitude of such flow and hence its geochemical significance remain largely unknown. For example, at the time of COSOD II (1987), it was estimated that approximately 100 km^3/yr of fluids were discharged through passive continental margins as a result of gravity flow. This estimate compares with an estimated total of 584 km^3/yr of fluids through ocean ridges and the flanks of ocean ridges and 1 km^3/yr through accretionary prisms (Fig. 23).

Although over a decade ago the estimate for passive-margin flow was recognized as being inadequate, it is now believed that discharge to the coastal zone and beyond in some areas may be significantly higher than previously assumed. In addition, several other mechanisms of fluid flow in continental margins have been

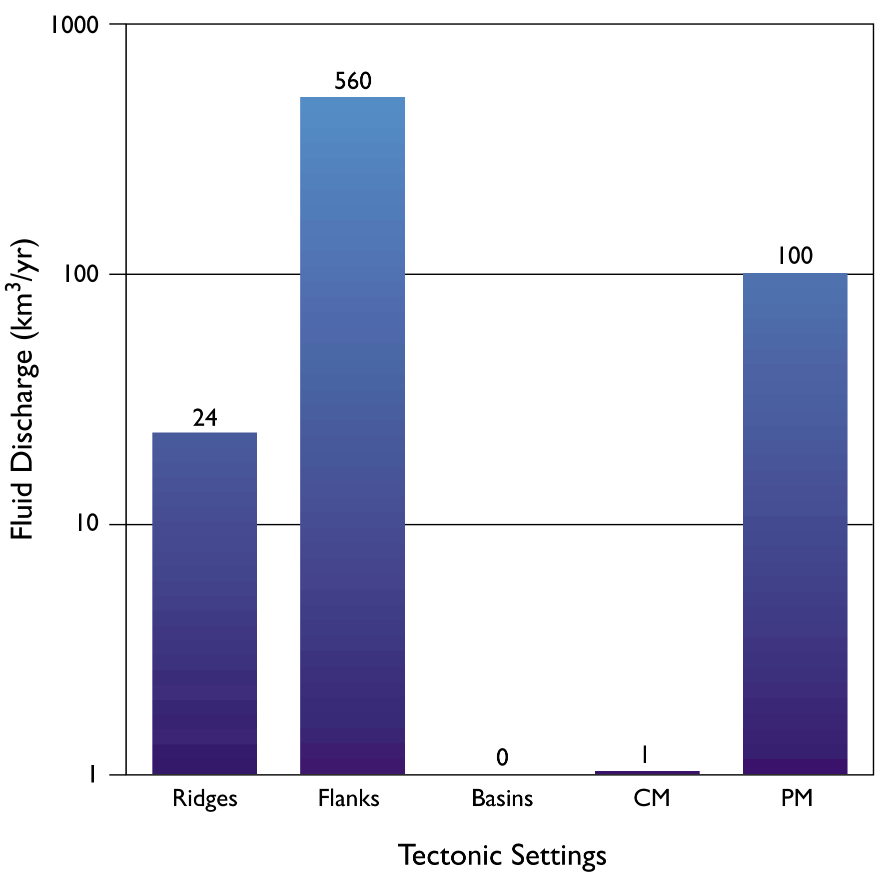


Figure 23. Estimated discharge of fluids (values above the bars are in km^3/yr) from the seafloor to the ocean in various tectonic settings. CM—convergent margins, PM—passive continental margins. (After *COSOD II [Second Conference on Scientific Ocean Drilling], Strasbourg, 6–8 JULY, 1987*. Strasbourg, France, [European Science Foundation], 142 p.)

recognized, leading to the realization that the COSOD II estimate of fluid discharge through passive margins may be in error by an order of magnitude or more! If true, such enormous fluxes would (1) exceed those estimated through all other types of systems combined, have (2) significant impact upon the geochemical cycling of critical elements in the lithosphere and biosphere, and (3) change our estimates regarding the residence time of important geochemical species.

An additional societally relevant aspect of fluid flow along and through continental margins is the encroachment of salt water into potable water sources, such as subsurface aquifers. Defining the location of the boundary between salt and fresh water is as yet poorly controlled because of the lack of drilling in shallow-shelf areas. However, this boundary is likely to migrate through time as a result of natural climatic variations that occur at different timescales (e.g., seasonal, glacial-interglacial cycles), as well as from anthropogenic causes. Understanding the mixing between continental and marine ground waters will require measuring the location and characteristics of the boundary, something that can only be accomplished by drilling and monitoring arrays of boreholes.

A great deal of research has confirmed that gravity-induced discharge of fluids occurs along passive continental margins. Again, unusual salinity is of interest; it can develop if fluids have been subject to evaporation en route or if they pass through preexisting evaporites. Such is the case in the example shown from Leg 182 (Fig. 24). In addition to continental margins, circulation of fluids occurs within carbonate platforms, both on the scale of smaller mid-plate atolls and guyots as well as larger carbonate bodies such as Great Bahama Bank (e.g., ODP Leg 166) and the Queensland Plateau, northeastern Australia (e.g., ODP Leg 133). Quantification of these fluxes and the mechanisms involved in them will lead to a greater understanding of the role that such flow plays in controlling important cycles, such as those involving carbon and nutrients. An understanding of fluid flow in passive continental margins and carbonate platforms can be integrated with other studies that target sedimentary architecture and geochemical fluxes. Our strategy will be to use a transect and array of boreholes across targeted passive and carbonate-platform margins to obtain samples by land drilling, shallow-water drilling, riserless drilling, and riser drilling. Initial targets will examine fluid flow in two-dimensional; the ultimate goal is three- and four-dimensional results.

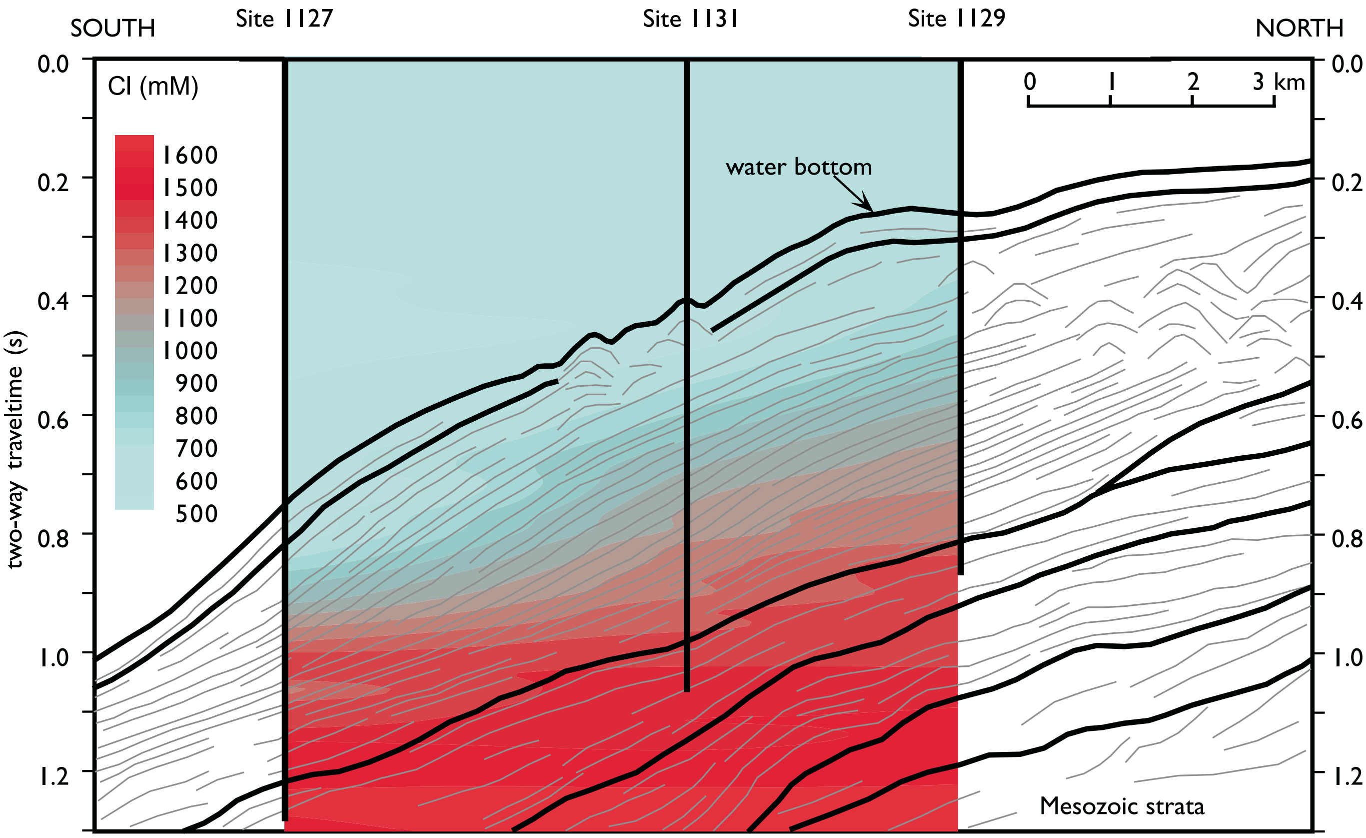


Figure 24. Concentration of chloride in the western transect from Leg 182 in the Great Australian Bight. High-salinity (i.e., chlorinity) fluids are believed to be derived from shallow evaporative lakes, which developed on the adjacent continental margin during a relative lowstand of sea level. (Courtesy D. Feary, Co-Chief Scientist, ODP Leg 182.)

At least some of the failure to understand flow in such environments in the past has been a result of technological problems, such as inadequate support for drilling in shallow water and the problems of retrieving pore fluids from cemented sections and under hydrostatic pressure. Solutions to these problems include the following:

- "Fit-to-mission" platforms for drilling in shallow water.
- Larger-diameter boreholes, using off-the-shelf borehole-fluid sampling technologies, including packers and geochemical tools.
- Legacy boreholes and in situ water monitoring and sampling.
- Pumping tests using geothermistor strings and flow meters.

Cooperation Between Industry and Academic Institutions

To realize the fullest potential of future integrated ocean-drilling research, a primary goal must be *to optimize and broaden cooperation between academia and industry in order to use multiple-platform scientific ocean drilling to solve problems of mutual interest.* As scientific ocean drilling moves to drill continental margins (slopes and shelves), industry can have an increasing role in providing drilling technology and scientific perspectives; in return, industry will benefit from higher-resolution data sets and more precise geologic models.

Industry shares with scientific ocean drilling the need to understand stratigraphic signatures in terms of the major forcing factors, such as climate, ocean circulation, paleogeography, and tectonism within continental-margin basins. Despite this common interest, language barriers have developed that need to be overcome. For example, the ocean-drilling community is involved in "basin analysis" whereas the petroleum industry carries out "exploration." "Margin architecture" is investigated by the former group, and "petroleum systems" are probed by the latter one.

Both the scientific ocean drilling and industrial communities share three primary concerns: (1) understanding tectonic and eustatic controls of sedimentologic processes that result in characteristic seismic geometries interpretable for facies variations of source rock, reservoir rock, and seal rock; (2) predicting of paleogeographic and temporal variations in facies distribution, across paleobathymetric and paleogeographic gradients, related to extreme climate events, oceanic upwelling systems, and ocean-anoxic events; and (3) recognizing and integrating patterns of continental-margin magmatism and tectonics as a predictive framework for basin history and fluid analysis. This research includes study of "geologic"-specific acoustic signals, heat-flow patterns, precise dating of magmatic events, stratigraphic architecture and deformational styles (e.g., extreme subsidence and structure inversions).

To build bridges between the two communities, industry should accept responsibility for two new initiatives, to be implemented in close cooperation with JOI, Inc.; these are liaison with the industrial geohazards community and identification and implementation of compatible database management systems, including, from the ODP, both site-survey and shipboard data. Such new initiatives follow on the heels of existing ODP Partnership Projects such as (1) technology projects including those of the Drilling Engineers Association, the JAMSTEC MOA (Japanese Marine Science and Technical Center Memorandum of Agreement), and HYACE (hydrate autoclave coring equipment, Germany) and (2) science projects including databases with the Energy and Geoscience Institute of the University of Utah and GIS (geographic information systems) and other joint, deep-water projects with industry. Finally, the industrial community should join with JOI, Inc., to formulate strategies for the following:

- Archiving surplus industry data, especially seismic field tapes.
- Facilitating permission to publish industry data.
- Obtaining industry and other organizational endorsement of the multiple-platform program, e.g., the American Association of Petroleum Geologists, the Society of Exploration Geologists, SEPM (Society for Sedimentary Geology), and the Society of Independent Professional Earth Scientists.
- Implementing industry representation on scientific ocean-drilling committees.
- Optimizing the ability of scientific ocean drilling to take advantage of unique opportunities, such as deepening existing wells, and recording deeper seismic data to meet academic scientific objectives. This goal will require procedural and funding policies to respond to very short term industry operational schedules.
- Integrating state-of-the-art industry technology into programs of scientific ocean drilling, including Arctic drilling, conventional coring, borehole stabilization, log analysis, seismic acquisition, and geotechnical engineering.
- Cooperatively developing new technologies for log calibration in hot rocks, ultra-deep-water riser drilling, deep drilling in ice-covered Arctic and Antarctic environments, and methods of high-resolution sampling.

- Promoting alternative sampling strategies, such as using the combination of drill cuttings and logs instead of continuous coring.

- Optimizing the scientific use of spatially robust continental-margin data sets existing within the geotechnical and petroleum industries.

- Sponsoring of workshops and seminars on how to use industry data sets for increasing the stratigraphic and spatial context of depositional systems, calibrated at scientific ocean-drilling sites.

Formulating a comprehensive plan to ensure continuity of communication and cooperation between members of the scientific ocean-drilling sector and industry, involving liaisons with both private- and state-owned companies.

Creation and Evolution of
Oceanic Lithosphere

Rigid and brittle lithospheric plates make up the outer shell of Earth, gliding across a layer of viscous asthenosphere at about the rate that fingernails grow, creating ocean basins, accumulating sediments, and transporting continental masses. Between the time that oceanic lithospheric plates are created at spreading centers and the time that they plunge back into the mantle at subduction zones, they interact with the hydrosphere, biosphere, and each other, resulting in a large range of dynamic processes influencing Earth's surface and interior. Volcanoes and mountain ranges are created and destroyed, earthquakes rumble along plate boundaries and within plate interiors, and energy and mass are exchanged between global reservoirs over a range of spatial and temporal scales, from the human to the geologic. Ocean drilling has played an essential role in our understanding of the products, fluxes, and processes resulting from plate-tectonic and magmatic cycles and will be required in the future to resolve fundamental questions that remain unanswered. Some of these questions have been challenging Earth scientists for decades, but other questions could not even be imagined just ten years ago. In this chapter, we review important accomplishments of past drilling and related experiments, describe outstanding questions that are now driving our science forward, and outline a strategy for resolving these questions, which includes ocean drilling as a primary part of an integrated scientific plan.

"Ocean drilling has played an essential role in our understanding of the products, fluxes, and processes resulting from plate-tectonic and magmatic cycles and will be required in the future to resolve fundamental questions that remain unanswered."

Examples of Recent Achievements

Recent achievements in ocean drilling of the lithosphere have changed fundamentally our view of the crust and upper mantle, and this new view has led to a need for new strategies and techniques that can be used to address unanswered questions. Significant advances have been made despite the limitation of drilling mainly into the uppermost crust and a few lower-crustal and upper-mantle sections fortuitously exposed at Earth's surface in "tectonic windows" (Fig. 25).

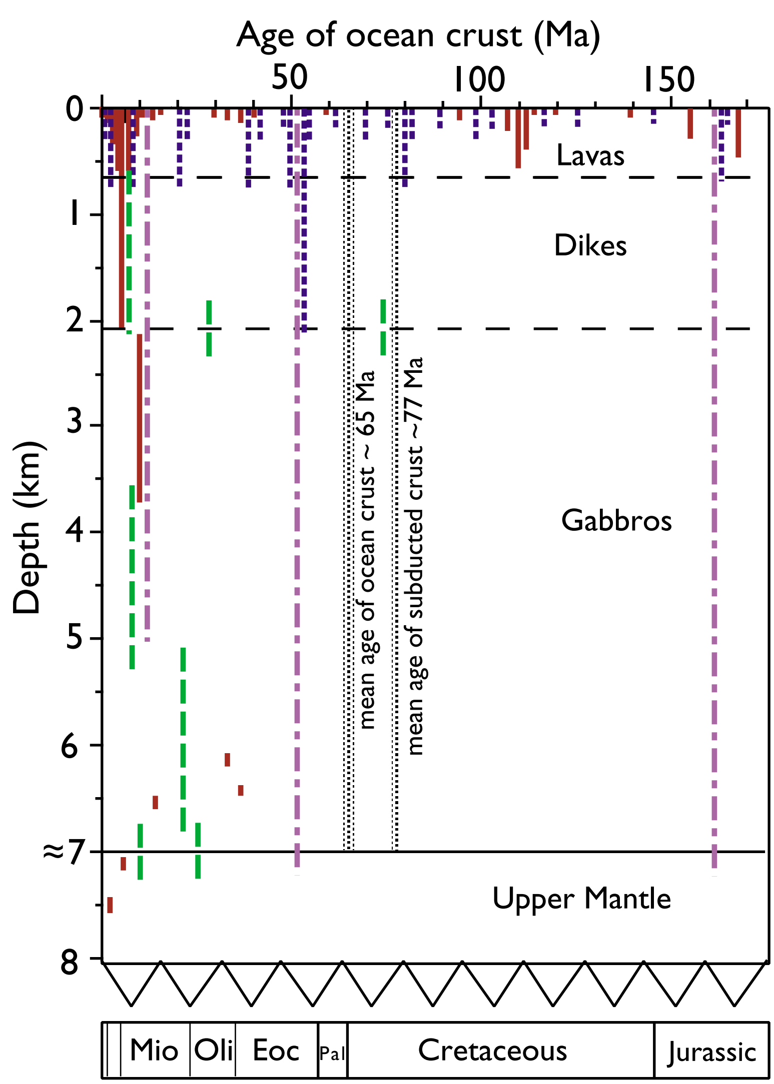


Figure 25. Schematic record of penetration into oceanic lithosphere based on crustal age and a possible scenario for proposed new drilling targets. Solid (red) lines indicate boreholes completed to date. All other lines indicate proposed new drilling targets. Although some progress has been made drilling upper-crustal sections in a few settings, relatively little of the lower crust and upper mantle has been drilled. There is also a major gap in drilling into all levels of crust of intermediate age (10–100 million years). Dashed (green) lines indicate proposed boreholes into shallow crust, dotted (blue) lines indicate proposed boreholes through intact crust and upper-mantle rocks, and dash-dot (purple) lines indicate proposed penetration of limited crustal sections at tectonic windows. (Mio—Miocene, Oli—Oligocene, Eoc—Eocene, Pal—Paleocene).

Melt Composition and Rate of Seafloor Spreading

By using the strategy of offset drilling in tectonic windows in the seafloor, ocean drilling has shown that segments of the lower oceanic crust formed at fast-spreading ridges differs dramatically in composition, structure, and degree and style of alteration from lower oceanic crust formed at slow-spreading ridges. Drilling in Hole 735B at the ultra-slow-spreading Southwest Indian Ridge has revealed numerous small gabbro intrusions, but little evidence of the well-developed layering—i.e., systematic vertical compositional variations—found in the large, on-land, fossil magma chambers once thought to be analogues for oceanic magma chambers. The rocks from the Southwest Indian Ridge show multiple phases of magmatism, alteration, and ongoing deformation in the zone of lithospheric necking and accretion. Hole 735B on the Southwest Indian Ridge is now 1.5 km deep, the longest section in the lower crust. Gabbros formed in a slow-spreading ridge were also drilled in a series of shallow-penetration boreholes near the Kane Fracture Zone in the North Atlantic Ocean, revealing significant lateral heterogeneity. The fact that it is difficult to find an on-land ophiolite consistent with these lower-crustal drilling results suggests that crust from this oceanic environment may not be well preserved on land.

In contrast, drilling at Hess Deep near the fast-spreading East Pacific Rise recovered gabbros that differ chemically and texturally from those drilled at slow-spreading ridges. Instead, the Hess Deep gabbros are similar to those found in the Oman ophiolite, which is believed to been have formed at a fast-spreading ridge. Contrary to the prevailing paradigm, the Hess Deep rocks suggest that the melt lens represents an accumulation of stagnated, evolved melt beneath the sheeted dikes and may not be the principal reservoir for eruption of MORB (mid-oceanic ridge basalt) along the East Pacific Rise.

Source of Seafloor Magnetic Lineations

Crustal magnetization measured in gabbroic rocks from Hole 735B is uniformly reversely polarized and appears to be of sufficient strength to account for the lineated "Vine-Matthews" magnetic anomaly that is measured on the seafloor at this location. The 1.5 km penetration at this site represents the first substantial penetration of deeper sources that may contribute to magnetic anomalies, and the significant magnetization of this deeper source raises questions as to the source of magnetic anomalies in general.

Hydrothermal Fluid Flow in the Lower Crust

Another major result of drilling is the demonstration that hydrothermal alteration is an important process in the lower crust. At slow-spreading ridges, it is integral to the initial accretion process and intimately related to deformation. In contrast, the Hess Deep gabbros, with no evidence of the high-temperature deformation, exhibit significant near-axis alteration under relatively static conditions.

ODP scientists drilled 200 m into serpentinized mantle peridotite at the intersection of the Kane Fracture Zone and the Mid-Atlantic Ridge (MARK area) in the North Atlantic Ocean. The peridotites are both highly altered and crosscut by evolved and primitive gabbros and basaltic dikes, indicating the incorporation of screens of mantle peridotite into the crust at a slow-spreading ridge. Several boreholes were drilled into a tectonic block of mantle peridotite at Hess Deep. The peridotite had been deformed at high temperature and intruded by dikes that had reacted with the surrounding peridotite. Boreholes drilled just a few hundred meters apart cored different proportions of residual and magmatic rocks, showing that magmas feeding the oceanic crust at fast-spreading ridges must be channeled along narrow pathways in the shallow mantle.

Deep drilling in intact upper crust at Hole 504B near the Costa Rica Rift complements offset drilling of lower crust and mantle in tectonic windows. Hole 504B penetrated most of the sheeted dike complex, validating ophiolite models for the shallow ocean crust, but it demonstrated that the boundary between seismic layer 2 and seismic layer 3 in this setting lies above the dike-gabbro transition and probably is an alteration front rather than a lithologic boundary. Complementary studies at two sites in the Atlantic and at two sites on Jurassic crust in the Pacific and Indian Oceans have provided remarkable views of the physical properties of older altered crust, helping to determine rates of crustal alteration.

A series of offset boreholes drilled into the active TAG (Trans-Atlantic Geotraverse) hydrothermal deposit on the Mid-Atlantic Ridge demonstrated that the evolution of this sulfide mound is intimately linked to entrainment of ambient seawater and the precipitation of massive anhydrite, a mineral that is not preserved in ophiolite-hosted massive sulfide deposits. This observation has changed our current models for the formation of these types of ore deposits and has provided new explanations for the lithologies of the massive sulfides. A complementary sediment-hosted massive sulfide deposit of extraordinary dimensions and character was also sampled in Middle Valley on the Juan de Fuca Ridge, providing new insights into ore accretion and modification processes. This deposit is underlain by a stockwork feeder zone and a silicified, diagenetic alteration front that acts as a hydrologic, thermal, and chemical barrier and, possibly, as an "aquifer" for the mineralizing solution.

Fluid flow is crucial to sustaining microbes and transports heat and chemicals between the lithosphere and hydrosphere. Recent hydrogeologic studies in the basement of the eastern Pacific Ocean have demonstrated that lateral flow of seawater through the uppermost oceanic crust can occur over distances of tens of kilometers, both parallel to and perpendicular to the ridge axis, at velocities of several meters per year. This flow contributes to enormous mass and energy fluxes. Ocean-drilling experiments have also revealed an apparent decrease in uppermost crustal permeability with age, suggesting that fluid flow in the upper crust may be highly channeled.

New Challenges and Opportunities to Answer Fundamental Questions on Lithospheric Creation and Evolution

These recent scientific ocean-drilling achievements raise important new questions and lay a solid foundation for future advances. Newly developed drilling, sampling, analytical, and in situ technologies now make possible numerous experimental approaches that Earth scientists could only wish for in the past. We find ourselves at the confluence of new scientific understanding, international cooperation, and rapidly changing technology. The future integrated program in ocean drilling will build on successes of the past and, through exploration of fresh ideas with state-of-the-art technology, will result in a dramatic new understanding of fundamental lithospheric products, fluxes, and processes.

How are the oceanic crust and upper mantle created and modified during their life cycle, from the ridge to the trench?

What are the time-integrated fluxes of heat, fluids, and other chemical processes associated with lithospheric creation and modification, and what are their impacts on global cycles?

What are the hydrologic, magmatic, tectonic, and biologic processes involved in lithospheric creation and modification?

Understanding oceanic lithospheric architecture and evolution requires that we address three primary questions:

- How are the oceanic crust and upper mantle created and modified during their life cycle, from the ridge to the trench?
- What are the time-integrated fluxes of heat, fluids, and other chemical processes associated with lithospheric creation and modification, and what are their impacts on global cycles?
- What are the hydrologic, magmatic, tectonic, and biologic processes involved in lithospheric creation and modification?

These questions cover *products, fluxes,* and *processes,* respectively, and will be addressed by exploring lithosphere in different locations and of different ages. We recognize that the divisions between these questions are arbitrary since they are interrelated, and many drilling, sampling, and experimental programs will address two or three of these questions simultaneously. One common thread that runs through many of the outstanding questions is the role of fluids as agents of change through the lithospheric life cycle, from initial creation through aging to subduction and entry into the upper mantle. In this section, we break the three main questions we have posed into a series of more specific questions and state why they are important to understanding lithospheric cycles.

From the Ridge to the Trench: How Are the Oceanic Crust and Upper Mantle Created and Modified During Their Life Cycle?

How are the oceanic crust and upper mantle created and modified during their life cycle?

What is the nature of the lower crust and upper mantle, and how should the ophiolite analogy be applied?

What Is the Nature of the Lower Crust and Upper Mantle, and How Should the Ophiolite Analogy Be Applied?

New oceanic lithosphere is the primary product of seafloor spreading. The nature of the uppermost crust is readily assessed by submersible observations, dredging of exposed outcrops, and drilling, but the nature of the lower crust remains unconstrained. Marine seismic data and land-based ophiolite studies led to the formulation of a layered model for the structure of the oceanic crust (Fig. 26), in which pillow lavas and sheeted dikes are underlain by gabbro and mantle peridotite. But gabbros and mantle peridotites are exposed on the seafloor at slow-spreading ridges, even in wide regions where the seismic structure appears to be "normally" layered. In addition, many ophiolite volcanic rocks have chemical affinities with modern arc rocks. The validity of the ophiolite model for fast-spreading ocean crust hinges on the composition of the lower crust. Typical ophiolite lower-crustal gabbros show abundant modal and compositional layering and a lack of

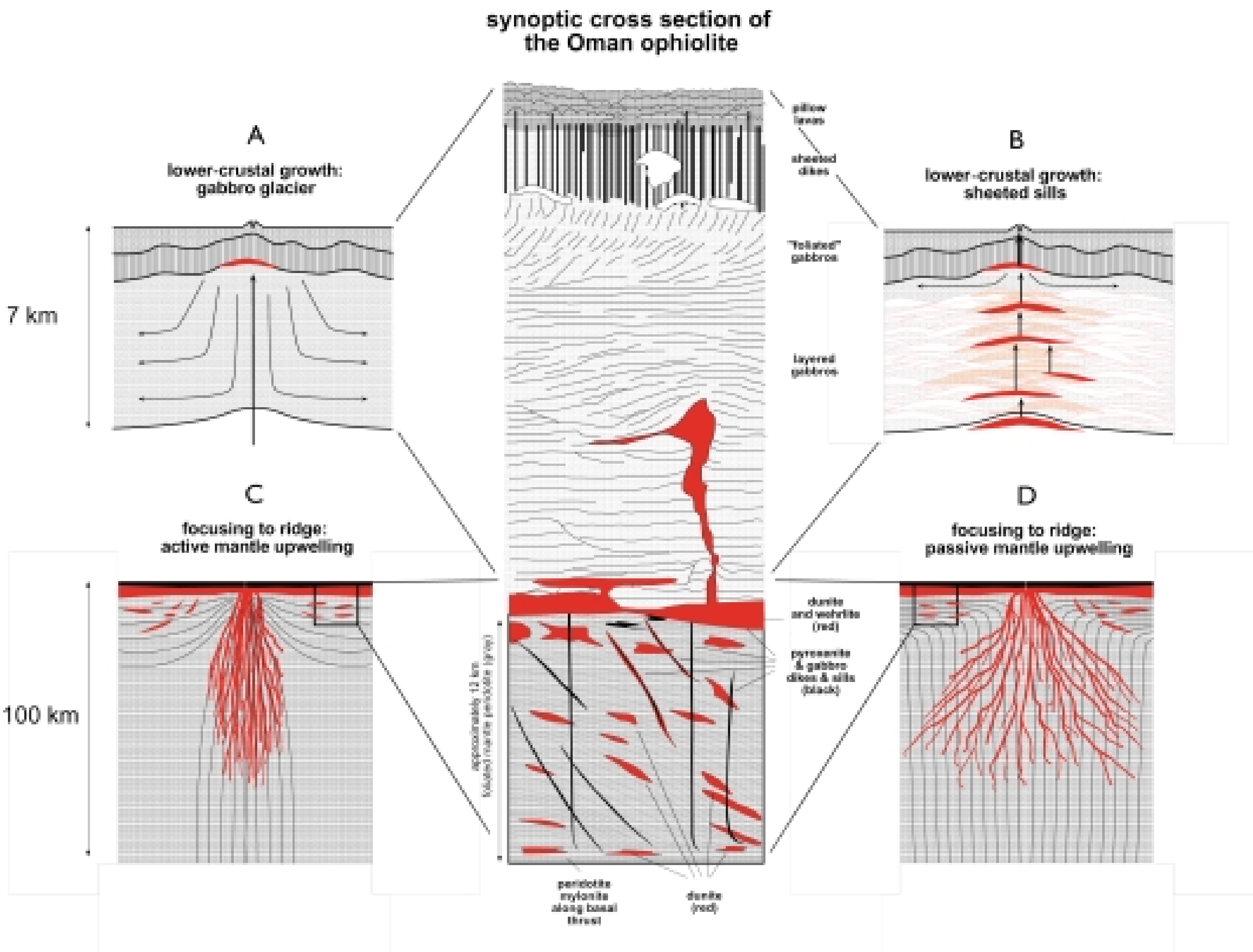


Figure 26. Schematic illustrations of recently proposed models for igneous accretion of the lower crust at fast-spreading mid-ocean ridges and for focusing of melt extraction from an approximately 100-km-wide melting region in the mantle to an approximately 5-km-wide crustal-accretion zone beneath the ridge axis. (A) "Gabbro glacier" model in its simplest form. Ductile flow downward and outward from a single, shallow axial magma chamber constructs the lower crust. (B) "Sheeted sill" model with melt transport by hydrofracture and in situ emplacement of the lower crust by on-axis sill intrusions. Most gabbros are crystallized at their current depth of emplacement. (C) Focused solid-mantle upwelling (fine lines), due to buoyancy-driven convection, with mainly vertical melt transport. (D) Passive solid-mantle upwelling (fine lines), due to plate spreading, with coalescing melt conduits. Central panel is a summary cross section of the Oman ophiolite, where upper-mantle and lower-crustal exposures allow testing of these hypotheses. It is essential to determine whether specific features of ophiolites are representative of similar features beneath mid-ocean ridges and, if so, at what spreading rate.

subsolidus plastic deformation. The lack of continuous sampling has made it impossible to determine whether these features are present in both fast-spreading–formed and slow-spreading–formed lower crust. It is crucial to obtain such samples via ocean drilling, both in tectonic exposures and via drilling of intact crustal sections.

What Is the Three-Dimensional Architecture of the Oceanic Crust?

What is the three-dimensional architecture of the oceanic crust?

How does the three-dimensional structure of the crust influence fluid flow and alteration, and how does this relationship change as the crust ages?

It is well established that the crust varies in composition and structure on the ridge-segment scale. Rock dredging around transform faults at very slow spreading ridges has recovered large quantities of peridotite and basalt, but little gabbro, suggesting that a gabbroic layer is attenuated or absent near the ends of many ridge segments. Moreover, gravity and seismic studies have confirmed that crust thins near transforms and small ridge offsets. There is also evidence that magmatic crustal production may vary with time at individual ridge segments. These variations in the architecture of the ocean crust are believed to depend on spreading rate, magma supply, and thermal structure. The higher rate of mantle upwelling at the East Pacific Rise may lead to a more uniform crustal structure with a nearly steady-state melt lens near the top of seismic layer 3. In contrast, the lower rate of mantle upwelling at slow-spreading ridges appears to lead to episodic formation of magma chambers and a variable thermal gradient. This variability implies that the internal structure and composition of the lower crust should be different at slow- and fast-spreading ridges, which the initial results of ODP drilling in tectonic windows support but have yet to confirm. Two related questions involve the hydrologic architecture of oceanic lithosphere: How does the three-dimensional structure of the crust influence fluid flow and alteration, and how does this relationship change as the crust ages?

What is the thermal structure and evolution of oceanic crust and upper mantle?

What Is the Thermal Structure and Evolution of Oceanic Crust and Upper Mantle?

The thermal history of axial intrusions is significantly affected by circulating fluids, and the exchange of energy between magmas and circulating fluids is the dominant control on the styles and mechanisms of crustal construction. There are currently two models for the mechanism of heat transfer between the heat source and the circulating seawater, but neither model has been tested by making direct measurements. The first concept envisages the conductive transfer of heat across a thin boundary layer immediately above the magma chamber or heat source, whereas the second predicts that heat is transferred convectively by fluid moving along cracking fronts that penetrate downward toward the heat source. Both models predict an exchange of heat that is sufficient to support vigorous hydrothermal systems that could create massive sulfide deposits and that are manifested on the seafloor as high-temperature black smoker chimneys. However, simple models of fluid penetration into the crust and heating to black smoker temperatures (350–400 °C) in the gabbro do not explain the steps in the temperature profile suggested by secondary minerals present in the dikes and lavas. Furthermore, the duration of vigorous fluid movement depends on the relationship between magmatic input to provide a continuing heat source and tectonic activity to maintain pathways of fluid flow.

As the magmatic heat source cools, or as the crust moves away from the dynamic environment of the ridge crest, thermal contraction of the rocks creates stresses and deformation that change the permeability and hence the paths of fluid flow. Complex water-rock reactions result in precipitation of secondary minerals in networks of fractures, while a sediment cover begins to develop on the seafloor. The sediment and precipitated minerals restrict fluid flow, producing a highly variable alteration pattern and a progressive change in the thermal structure. Determining the evolution of the thermal structure of oceanic crust and upper mantle as the seafloor moves away from the spreading axis is key to understanding the nature of fluid flow within the subsurface, the types of water-rock reactions that occur within different parts of the system, and the distribution of the subsurface biosphere.

Can We Correlate Between Lithostratigraphy, Seismic Stratigraphy, and Hydrostratigraphy?

Can we correlate between lithostratigraphy, seismic stratigraphy, and hydrostratigraphy?

The seismic velocity structure of oceanic crust and upper mantle has allowed us to make large-scale inferences about their composition and evolution, but since the acquisition of new geophysical data and geologic samples during the ODP, even the most fundamental correlations upon which many of our ideas have been based must now be questioned. Seismic properties result from a combination of bulk mineral contents, pore distribution, cracking, alteration, temperature, and pressure, none of which is well understood except in a few locations and over short depth intervals. Nonuniqueness in our interpretations of remote seismic data can be addressed only by direct correlation with rock properties, requiring good recovery, in situ measurements, and coupled experiments in several settings.

For example, seismic layer 2A in young crust hosts vigorous hydrothermal circulation, but layer 2A disappears when the crust is quite young. In contrast, global heat-flow compilations indicate that significant advective heat loss continues until the crust is at least 65 million years old, and regional surveys indicate that local convection may continue within some of the oldest remaining seafloor. What is the nature of layer 2A and why do the seismic properties of the shallowest ocean crust change over time? Does the base of layer 2A correspond to the top of the dike section, a porosity transition within the extrusive pile, or are there other causes in different locations?

What is the nature of layer 2A and why do the seismic properties of the shallowest ocean crust change over time?

Does the base of layer 2A correspond to the top of the dike section, a porosity transition within the extrusive pile, or are there other causes in different locations?

The transition between seismic layer 2 and seismic layer 3 is ubiquitous but poorly understood within crustal sections formed at both fast- and slow-spreading ridges; perhaps the transition correlates to the dike-gabbro boundary in some settings or to an alteration boundary within sheeted dikes in others. What is the geologic significance of the Moho, the seismic discontinuity that inspired Project Mohole more than 30 years ago? In some localities, particularly in fast-spreading–formed crust, the Moho almost certainly represents a transition from gabbros to ultramafic rocks. Elsewhere, there exist regions of widespread ultramafic outcrops on the seafloor, and the Moho may represent a transition from partially serpentinized peridotite to unaltered ultramafic rocks. Drilling through the seismically defined Moho and into mantle sequences at fast- and slow-spreading ridges is critical to resolving these questions.

What is the geologic significance of the Moho, the seismic discontinuity that inspired Project Mohole more than 30 years ago?

How Do Marine Magnetic Anomalies Relate to Crustal Architecture, Cooling, and Alteration?

How do marine magnetic anomalies relate to crustal architecture, cooling, and alteration?

The distribution of magnetization sources within the oceanic crust has allowed definition of a magnetic timescale and provides information about crustal accretion. Magnetism may be the only physical property that provides a temporal marker within the ocean crust. In the extrusive lavas, the shape of the polarity boundary is now thought to reflect the accretion of the upper crust through time. In the lower plutonic crust, the polarity boundary probably depends on the thermal history of the crust. Knowledge of both the shape of the lower-crustal polarity boundary and its relationship to polarity boundaries in the upper crust would provide vital information on the thermal and emplacement history of the crust. Understanding the magnetization of ocean crust remains a fundamental problem in plate tectonics today despite the fact that the magnetic reversal pattern is routinely used to date the seafloor. It is clear that the simple, layer-cake, block models based on constant magnetization intensity are no longer appropriate. Recent studies indicate that the extrusive lavas, sheeted dikes, and gabbros can all have magnetization that can give rise to magnetic anomalies. To fully understand the depth distribution of magnetization requires drilling of an intact crustal section, along with penetration of polarity boundaries within the lower crust, ideally at high magnetic latitudes and within a range of spreading environments.

What Are the Depth, Extent, and Consequences (Physical, Chemical, Biological) of Alteration in Crust and Upper Mantle?

What are the depth, extent, and consequences (physical, chemical, biological) of alteration in crust and upper mantle?

Water-rock reactions that end in black smoker fluids emanating from the seafloor are thought to occur in relatively shallow circulation systems driven by a magmatic heat source. On fast-spreading ridges, the vigorous circulation may be restricted by the depth of the axial magma chamber, but the incursion of fluids into the deeper crust remains poorly understood. However, on slow-spreading ridges, seismic evidence suggests that fluids penetrate to much greater depths—possibly into the mantle. How does the difference in spreading regime influence the distribution of permeability and thus the nature of fluid-rock interaction (Fig. 27)? A great deal has been learned about crustal alteration through sampling of vent fluids and upper crust as well as by experiments and modeling. On the basis of these studies, a generalized model has been developed that predicts the types of alteration reactions and resulting elemental exchanges between fluids and rocks from the time seawater enters the crustal section until it discharges at high-temperature hydrothermal vents. However, the true nature of the reaction zone—believed to be the region where fluids develop their chemical signatures through high-temperature reactions and where the metals that ultimately are concentrated at the seafloor in massive sulfide deposits are extracted—is unknown. The lack of samples from these depths has limited our ability to understand such processes as phase separation and the speciation of solutes and metals in fluids along the transport pathways. In addition, recent tantalizing evidence of microbial activity in rock samples suggests that bacteria may play an important role in crustal alteration; we have only just begun to determine the significance of this process.

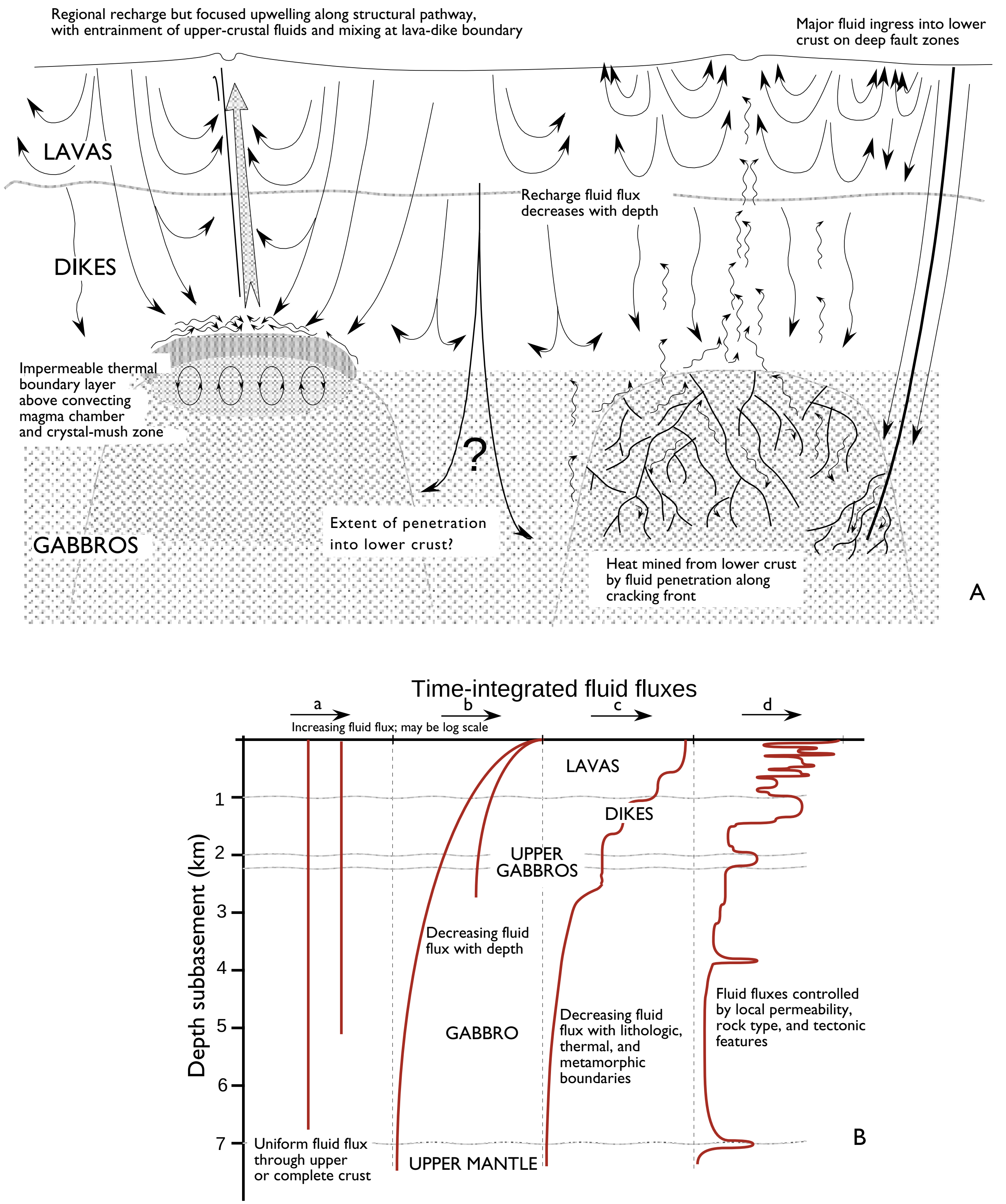


Figure 27. Cartoons of possible fluid-flow regimes within the lithosphere and their potential influence on water-rock interactions. (A) Competing models for ridge-crest hydrothermal circulation: (left) recharge through upper crust having a high bulk permeability and focused discharge or (right) recharge focused through faults or other conduits (not shown) and diffuse discharge. The drawing on the left includes an impermeable thermal-boundary layer, and the drawing on the right includes penetration of a cracking front into a magma body. (B) Possible time-integrated fluid fluxes through the crust, based on differences in permeability distribution, from more homogeneous to more heterogeneous (left to right). Heterogeneity could be caused by constructional structure, tectonism, or alteration.

Key questions remain concerning the extent and process of alteration of the lower crust and uppermost mantle. The paucity of samples has so far precluded investigation of thermal extraction and water-rock reactions that occur at depth in the oceanic crust. It has recently been discovered that mantle peridotites crop out more abundantly along slow-spreading ridges than previously thought and, in fact, constitute a significant fraction of the rocks exposed along those ridges. The rocks are invariably partially or totally serpentinized, and they also host active hydrothermal systems discharging fluids with distinct fluid chemistries. Are these altered mantle rocks also abundant in the lower crust? What are the pathways for such pervasive alteration of the lower crust?

Are these altered mantle rocks also abundant in the lower crust?

What are the pathways for such pervasive alteration of the lower crust?

As the crust ages, early high-temperature alteration can be overprinted by lower-temperature reactions. These processes likely lead to a crustal section that is extremely heterogeneous in its mineral content and chemical composition. In order to quantify the time-integrated effects of all the alteration processes that affect the lithosphere during its life cycle, it is critical that samples be obtained that represent various stages in the evolution and alteration of the lithosphere.

What Is the Origin and Influence of Non–LIP Intraplate Volcanism on Lithospheric Structure and Evolution?

What is the origin and influence of non–LIP intraplate volcanism on lithospheric structure and evolution?

Intraplate non-LIP (large igneous province) volcanism includes a broad grouping of magmatism that is not associated with normal crustal accretion along ocean ridges, nor with large-scale outpourings of lavas associated with the formation of large igneous provinces. It encompasses volcanism that forms structures such as (1) the off-axis isolated seamounts that are ubiquitous on the ocean floor, (2) en echelon and elongate ridges, and (3) large basaltic fields, such as the Hawaiian Arch volcanic field, which was discovered recently by drilling and through advances in seafloor remote-sensing capabilities. Although the volumes of magmas produced by this type of volcanism are small compared with those produced along ocean ridges and hotspots, non-LIP intraplate volcanism plays an important role in modifying the bulk composition of the oceanic crust through addition of new lava flows and associated intrusive rocks, and such volcanic activity may greatly influence off-axis lithospheric structure and heat flow.

These types of intraplate volcanism may serve as foci of later, off-axis, hydrothermal systems and associated alteration and mineralization. Non-LIP intraplate volcanism also provides clues about the thermal evolution of the oceanic upper mantle and lithosphere. Delineating the compositional spectrum of this intraplate volcanism may also better define the compositional range of the ambient upper mantle. The composition of non-LIP intraplate lavas is more heterogeneous than typical mid-ocean ridge basalts, perhaps because the LIP mantle sources are better sampled through lower degrees of melting and less mixing in magma chambers. Finally, magmas produced by this form of intraplate volcanism are rich in incompatible elements; therefore, basalts formed in this way may be an important component of the incompatible element budget recycled in the mantle through plate subduction. Quantifying these aspects of intraplate volcanism remains an important goal of future studies.

What are the time-integrated fluxes associated with creation and modification of the crust, and what are their impacts on global cycles?

What is the melt flux from the mantle to the oceanic crust?

What Are the Time-Integrated Fluxes Associated with Creation and Modification of the Crust, and What Are Their Impacts on Global Cycles?

What Is the Melt Flux from the Mantle to the Oceanic Crust?

The flux of basaltic melt out of the mantle creates a distinct chemical boundary layer, made of lava flows, dikes, and gabbros. Melting cools the upper mantle, and the melt flux carries with it sensible and latent heat. Many aspects of this melt flux remain uncertain. First, as was explained previously, it is not certain that we can directly equate the thickness of the oceanic crust as determined by seismic experiments with the thickness of the magmatic layer. Moreover, because seafloor basalts are fractionated relative to mantle-derived, parental liquids, the composition of parental liquids is uncertain. Only by sampling a complete crustal sequence can we determine the composition of the net magmatic flux from the mantle into the oceanic crust. The temperature structure of the crust is strongly affected by the depth of latent heat released by crystallization; thus the relative proportions of melt emplaced in the crust as lava, sheeted dikes, and plutonic gabbros are critical to the thermal state of the lithosphere. Analogy to ophiolites is useful but controversial because (1) we don't know which features of ophiolites are representative of features beneath mid-ocean ridges and (2) the differences between oceanic crust at fast- and slow-spreading ridges have never been determined.

What Are the Fluxes of Heat and Mass Between the Lithosphere and the Ocean?

What are the fluxes of heat and mass between the lithosphere and the ocean?

The patterns of heat flow from Earth's mantle through the ocean crust are fundamentally affected by two phenomena. One is the localization of magmatic processes primarily along constructional plate boundaries, resulting in the familiar theoretical conductive heat-flow curve that decays with the inverse square root of lithospheric age. The second phenomenon is the infiltration of seawater into fractured and porous crust and mantle, which redistributes heat by advection (Fig. 27). This process of advective fluid flow, coupled with chemical reactivity between seawater and oceanic rocks, leads ultimately to major fluxes of heat and mass within the lithosphere and between the lithosphere and the overlying ocean. The formation of giant ore deposits is one important result of mass transfer through oceanic lithosphere.

Alteration budgets for the crust and upper mantle need to be quantified at all stages of the life cycle of an oceanic plate, from its birth at a spreading center to beyond the time at which the plate is subducted, as well as for plates created at the full range of spreading rates and in various sedimentation regimes. Recent results indicate, for instance, that the hydrologic isolation of the crust occurs at various rates and efficiencies depending on the sedimentation rates and sediment types, as well as basement topography. Thus, ventilation of the upper crust may continue for variable periods of time. The cycling of seawater through the ocean crust and mantle must be understood in terms of global cycles of water, carbon, oxygen, metals, and other elements, but needs to be resolved in terms of specific lithospheric properties (Fig. 27). The rates of seawater cycling depend fundamentally on plate-tectonic rates, so that first-order differences in seafloor spreading rates have profound consequences for seawater chemistry, global ocean-atmosphere cycles, and, indeed, life on Earth.

What are the hydrologic, magmatic, tectonic, and biologic processes involved in lithospheric creation and modification?

What are the processes of melt transport?

After melt reaches the base of the crust, it is transported upward to magma chambers and to the seafloor.

How does this ascent of the melt take place?

What controls the size and frequency of delivery of melt to the crust in these settings, and how it is distributed through the crust?

What Are the Hydrologic, Magmatic, Tectonic, and Biologic Processes Involved in Lithospheric Creation and Modification?

What Are the Processes of Melt Transport?

Beneath spreading ridges, basaltic magma is produced by partial melting of peridotite in the upwelling mantle. Melt transport in the melt-production region may begin by porous flow along grain boundaries, but that cannot be the only mechanism. The composition of mid-ocean ridge basalts indicates that they have not been in equilibrium with the shallow mantle (i.e., shallower than 30 km beneath the seafloor surface). Lack of equilibrium requires that either melt is transported upward very rapidly in fractures and veins or rises in porous conduits that are chemically isolated from the surroundings. Seismic experiments have demonstrated that the entire crust is formed within a few kilometers of the ridge axis, yet there is evidence that the melt-production zone in the mantle may be hundreds of kilometers across. What is the nature of the network of fractures or sloping porous conduits that focuses melt back to the ridge axis?

After melt reaches the base of the crust, it is transported upward to magma chambers and to the seafloor. How does this ascent of the melt take place? At fast-spreading ridges, magma chambers about 1 km across and relatively thin (approximately 100 m thick) are found near the top of the crust at a depth of about 1.5 km. Melt may also pond at the base of the crust below fast-spreading ridges. Whether other melt pockets form at intermediate levels in the lower crust beneath these ridges is a matter of debate. In any case, despite the clear presence of magma chambers, delivery of melt to the surface is discontinuous or periodic, so that discrete dikes and lava flows are formed. At slow-spreading ridges, on the other hand, there are no steady-state magma chambers. What controls the size and frequency of delivery of melt to the crust in these settings, and how it is distributed through the crust?

There also is much debate about the importance of along-axis transport of melt within the crust at both slow- and fast-spreading ridges. What is the mechanism for the transition from relatively slow, relatively continuous porous flow in the distributed region of melt production to the rapid transport of melt? At slow-spreading ridges, the crust is thicker at the center of segments and thins toward fracture zones or nontransform offsets. Is melt delivered to the center of the ridge segment and then transported laterally in dikes? At fast-spreading ridges, do continuous magma chambers act as conduits for along-axis transport that redistributes the melt to form a crust of more uniform thickness? Testing models of melt transport and emplacement requires in situ samples because melt transport occurs on scales from individual grain boundaries to fractures to dikes and magma chambers. Fabrics, structures, and compositional variations preserved in the crustal section provide a record of the passage and storage of melt.

What is the mechanism for the transition from relatively slow, relatively continuous porous flow in the distributed region of melt production to the rapid transport of melt?

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At fast-spreading ridges, do continuous magma chambers act as conduits for along-axis transport that redistributes the melt to form a crust of more uniform thickness?

What Is the Pattern of Mantle Flow and How Is It Coupled to the Crust?

The pressure-release melting of upwelling mantle beneath spreading centers produces the magma that forms the new oceanic crust. We have made much progress in understanding the large-scale structure and pattern of flow in the upper mantle beneath ridges, but some of the fundamental controversies about the form of upwelling can only be resolved with detailed information that is beyond the resolution of geophysical techniques. One of the primary questions is the role of buoyant upwelling versus flow driven passively by the separation of the plates. On the basis of ophiolite studies, it has been suggested that buoyancy concentrates upwelling into narrow diapirs. At the top of diapirs, there must be lateral flow away from this upwelling center, including an along-axis component. This predicted flow could be discovered by examining the petrofabrics of an along-axis suite of samples drilled in a mantle section exposed off the axis of a spreading ridge.

What is the pattern of mantle flow and how is it coupled to the crust?

Depending on the temperature structure and rheology of the lower crust, dynamic flow in the upper mantle may couple to the crust, inducing additional deformation fabrics that may be recognized in the deep gabbro sections. In a cross section perpendicular to the axis, passively driven flow in the mantle will lag behind the rigid plate, but dynamically driven flow will overtake the plate motion, reversing the sense of shear, which can be determined by drilling through the crust-mantle boundary and recovering the affected rocks.

What Is the Role of Magma Chambers in Constructing the Crust?

What is the role of magma chambers in constructing the crust?

Early models, developed on the basis of observations in ophiolites, showed large crustal-level magma chambers several kilometers in diameter. These models have given way in recent years to the recognition that melt lenses may be small, scarcely more than 100 m in thickness, as imaged by seismic reflection experiments. This realization that the crust cannot have formed by crystallization of a crustal-scale magma chamber (i.e., a magma chamber having the thickness of ocean crust, 5 km) has led to conflicting models of the role of magma chambers in building the lower crust.

The simplest current model involves top-down growth of the plutonic section via a "gabbro glacier"; ductile flow of solid-state, cumulate crystals away from the base of the shallow magma chamber to form the lower crust (Fig. 26A). This model provides a simple mechanism for heat extraction during formation of ocean crust, but in its simplest form, it has difficulty explaining the presence of compositional layering—the presence of increasingly mafic cumulates with increasing depth in ophiolite sections. Another model attempts to address this problem by positing two magma chambers, one at the base of the crust in addition to the shallow-level magma chamber. The plutonic crust thus grows via ductile flow from both the top and the bottom. A third possibility is that the crust is constructed by a series of gabbroic sills injected at various levels into the crust, which is consistent with the observation in the Oman ophiolite of gabbroic sills in ultramafic rocks within the Moho transition zone and of ultramafic sills within the lower-crustal gabbros (Fig. 26B). Distinguishing among these competing models will require obtaining samples of the lower crust by drilling.

In addition to their role in building the lower crust, magma chambers play a crucial role in feeding the overlying sheeted dikes and lava flows. All or most melts forming the volcanic and dike layers are thought to reside in the melt lens prior to eruption; thus their chemical compositions are strongly influenced by the cooling, fractionation, and mixing processes that occur within the lens. Further, the lens probably plays an important role in controlling eruptive processes; supply of new magma batches to the lens may in fact trigger eruptions, as is thought to occur in many other types of volcanoes. Important evidence for the nature of these processes occurring in the magma lens can be obtained from study of the gabbros that are direct crystallization products from the lens. Complementary evidence is given by the dikes and flows, representing liquids removed from the magma lens. Reconstructing processes within the lens requires the study of both the solid (upper gabbros) and complementary liquid (dikes and flows) fractions, such as will be obtained by drilling intact sections of crust. The importance of lateral flow can be assessed by comparing the composition of cumulates and the overlying melt products.

What Is the Interplay Between Magmatic, Tectonic, Biological, and Hydrothermal Processes?

We can describe qualitative relationships between a range of processes involving evolution of the lithosphere, but the quantitative mechanisms are poorly understood. Heat and magmatic input at the ridge crest provide the driving force for high-temperature hydrothermal circulation, and off-axis magmatism may contribute to rejuvenated circulation after the crust has aged. We now have evidence that both magmatic and hydrothermal fluids interact with the lower crust during hydrothermal circulation. How much exchange of elements and volatiles takes place between hydrothermal and magmatic fluids? Magmatic injection likely provides conduits for fluid flow, by physically splitting the rock and allowing the penetration of cold seawater, creating additional fracture porosity by thermal contraction. How long does this dynamic porosity remain open, and how much of the surrounding lithosphere becomes geochemically altered by the channeled flow (Fig. 27)? What fraction of the fluid, solute, and heat fluxes occurs through channeled flow, and how much occurs through more ubiquitous flow? How do "blooms" of bacterial colonies in the deep bacterial biosphere influence the permeability of the rock? Do changes in bacterial populations help to control temperatures within the rock, optimizing conditions for growth? What role do bacteria play in mediating the deposition of clays and other alteration minerals over a range of thermal and chemical conditions?

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How Do the Nature and Thickness of Sediment Overburden Affect Hydrothermal Circulation and Alteration in Basement?

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How is it possible for heat to be efficiently mined from the lithosphere once the sediment layer is thickened beyond a few tens of meters?

Sediments typically begin to blanket the crust as soon as it is formed, but basement outcrops often are left exposed at the seafloor for several million years or more. Exposed basement allows relatively easy access for hydrothermal fluids to all levels of the crust, including deep sections exposed at tectonic windows. Global heat-flow compilations and comparisons to lithospheric cooling models suggest that considerable advective heat loss continues well after basement has accumulated a highly continuous sediment layer. This is a paradox: How is it possible for heat to be efficiently mined from the lithosphere once the sediment layer is thickened beyond a few tens of meters? One possibility is that heat-mining fluids flow laterally for tens of kilometers (or more) between fluid entry and exit points. Another possibility is that much of the fluid entering and exiting the lithosphere moves through the overlying sediments, altering them and the chemical and thermal state of the fluid. If this is true, then at times in the past when the distribution and composition of sediments were different, there may have been different forms of fluid-rock interaction within oceanic sediments and basement. Drilling, sampling, testing, and documenting the extent of fluid-rock interaction and how it has changed with time will allow quantification of the influence of sediments on hydrothermal circulation.

What Are the Characteristics of the High-Temperature Reaction Zone at Depth?

What are the characteristics of the high-temperature reaction zone at depth?

Despite the information derived from geochemical studies of recently sampled, active, hydrothermal systems, the characteristics of the high-temperature reaction zone at depth are unknown. Exposures of stockwork zones in mineralized ophiolites have provided the basis for modeling actively forming hydrothermal systems on the seafloor. However, the type of hydrothermal alteration seen in ophiolites that has been inferred to reflect reaction-zone conditions—i.e., pervasively altered rocks in which the primary igneous minerals have been completely replaced by epidote and quartz—to date have not been observed from the seafloor, calling into question the ophiolite analogue. Hole 504B, located in the Panama Basin of the Eastern Equatorial Pacific, is our deepest penetration so far into the ocean crust, and at >2 km depth, the section investigated there provides some intriguing insights into the role of hydrothermal alteration on the bulk oceanic crust, but does not allow us to determine either the fluid pathways or the fluid volumes necessary to generate substantial seafloor hydrothermal mineralization. Although we have clues from previous research that indicate the presence of magmatic fluids in the lower crust, we currently have no data on the relative impact of magmatic fluids on the hydrothermal system. Similarly, we have no data on the geometry, longevity, or episodic nature of activity in reaction zones underpinning giant ore bodies. Drilling provides the only mechanism for sampling the reaction zone of an active hydrothermal system.

What Are the Roles of Bacteria in Alteration and Mineralization?

Recognition that microbial populations exist deep within the oceanic crust has spurred interest in evaluating the impact of that activity on the alteration of the crust. Along fractures in otherwise fresh basaltic glass, channels that are associated with microbial activity radically increase the surface area of glass that is exposed to seawater. Hence, it has been postulated that microbial activity may influence the kinetics and extent of hydrothermal alteration. However, we have no constraints on the diversity or pervasiveness of organisms with depth, temperature, or age of the crust, nor on how the rates of microbially mediated alteration compare to those uninfluenced by microbes. Drilling provides the only way to identify and quantify the subsurface biosphere and to assess their role in crustal alteration. Accessing these microbial populations is of mutual interest to both the scientific and industrial communities, because the enzymes of the thermophilic and sulfophilic bacteria have many proven, as well as potential, industrial and biotechnological applications.

What are the roles of bacteria in alteration and mineralization?

Apart from the thermophilic bacteria associated with high-temperature hydrothermal systems, other types of bacteria that have been demonstrated to sequester various metals may influence mineralization at the seafloor or in the shallow subsurface. Similarly, microbial activity may also play a role in maturation of hydrocarbon deposits, particularly within young, hot lithosphere.

What are the nature and distribution of deformation in young lithosphere?

What Are the Nature and Distribution of Deformation in Young Lithosphere?

Deformation processes are intimately associated with the construction of oceanic crust and lithosphere, and they are fundamental in controlling crustal architecture and influencing pathways of fluid flow. Ductile flow and faulting are both important, but the specific styles and distribution of deformation, and their evolution with changing pressure and temperature conditions remain unclear. At slow-spreading ridges, deep-crustal and mantle rocks commonly are exposed at the surface, apparently because of the effects of normal faulting combined with limited magmatism. These large, surface-exposed, structures containing rocks from the base of the crust and upper mantle are referred to as megamullions. These features are a spectacular type of deformation feature that has recently been discovered. They provide tectonic windows that are thought to expose extensive cross sections of the crust and possibly upper mantle. The shear zones contained in the megamullion potentially contain a record of deformation beginning with plastic strain near the locus of the transition from plastic to brittle behavior at the base of the lithosphere and culminating in shallow, brittle deformation as the footwall was exhumed. They may also contain a record of effects of fluid flow and alteration (e.g., serpentinization) under specific pressure and temperature conditions. In addition, deformation and magnetization observed in the footwall well below the shear zone can be used to assess rotation of the footwall and thus the original dip of the fault in the lithosphere. Study of these and other tectonic exposures will contribute directly to understanding shear deformation in ocean crust and to the interpretation of comparable structural domes (metamorphic core complexes) in continental rift zones.

At fast-spreading ridges, an important question is the nature and extent of deformation within the lower crust. The absence of earthquakes at fast-spreading ridges indicates that most of the deformation is ductile, but the lateral extent and pattern of deformation are largely unknown. Specific predictions of strain mechanisms and deformation are made by models of lower-crustal formation that can be tested with a combination of boreholes in tectonic windows and deep-crustal penetrations through intact sections of the crust.

In addition, there are many important and still poorly understood along-axis variations in accretionary (i.e., melt-derived) modes and tectonic styles at both spreading centers and other tectonic features, such as transform faults, nontransform offsets, and microplates. The along-axis frequency and length scales of these unusual features suggest that they contribute to the architecture of approximately 10%–20% of the oceanic crust. Surficial studies of these features have been highly productive, but key questions regarding the material, strain mechanisms, and stress geometries at depth can only be obtained by drilling.

What Are the Mechanisms Deforming the Lithosphere Within Plates and at Transforms?

What are the mechanisms deforming the lithosphere within plates and at transforms?

How strong or weak are oceanic transforms?

What role does this alteration play in the mechanics of transforms?

Deformation at transform faults obviously includes large-scale horizontal shear, but the compositional, physical, and mechanical properties of the material within the shear zone and the geometry of lithospheric stress and strain within and surrounding the shear zone remain largely unknown. How strong or weak are oceanic transforms? Understanding the details of stress, strain, and rheology within oceanic transforms is especially important because the assumption that they are weak is key to the prevailing wisdom explaining the basic orthogonality of ridges and transforms. Furthermore, interpretations of surficial tectonic and magmatic patterns near ridge-transform intersections and along transform faults—as well as portrayal of the access of hydrothermal fluids to deep-crustal exposures—require an understanding of whether and how stress is transferred across the plate boundary. Within major transform-fault zones, the crust is often thicker than beneath the walls of the transforms or beneath nontransform offsets, suggesting that hydrothermal alteration is enhanced. What role does this alteration play in the mechanics of transforms?

Significant parts of oceanic crust are affected by deformation processes associated with other offsets of ridges such as microplates, propagating rifts, and overlapping spreading centers. Surficial mapping, sampling, and geophysical observations of these features have led to hypotheses about their formation and specific predictions about rock types and the stress geometries and strain mechanisms involved that need to be tested.

What is the interplay among stress, fluid flow, and alteration?

But how are these stresses expressed in terms of hydrologic properties and alteration?

What are the largest possible pressure gradients hosted within the lithosphere, and how far from the source can they be maintained?

Are any of these stresses transmitted through fluid pressure and thus responsible for generating hydraulic gradients within the lithosphere?

Does alteration of the lithosphere increase or decrease crustal "stiffness"?

How does crustal compressibility (and thus hydrologic storage capacity) vary with the extent of alteration?

How does alteration of the lithosphere influence the transmission of stresses over large lateral distances?

Several distinct styles of intraplate deformation affect the evolution of oceanic crust, all of which are poorly understood. Intraplate compressional regimes appear to impose contractional structures such as buckling in the old lithosphere south of India and apparent thrusting of young ocean crust associated with microplates. Large-scale en echelon intraplate volcanic ridges in the South Pacific have been observed and may be associated with megaboudinage caused by ridge-parallel tension or with small-scale convection within the off-axis asthenosphere. Important questions exist regarding the tectonic response to the thermal contraction associated with aging of oceanic lithosphere. Whether fracture zones have renewed tectonic activity beyond the transform-fault domain (e.g., because of differential subsidence, thermal contraction, or intraplate stress) remains an open question as well. The basic geometry of stress and variations in rock rheology within the crust in these and other intraplate settings must be delineated to advance understanding of the tectonic evolution of oceanic crust and lithosphere.

What Is the Interplay Among Stress, Fluid Flow, and Alteration?

Oceanic lithosphere is affected by stresses generated by ridge crests, transform faults, subduction, hot-spot loading, and other sources. The tectonic fabric of the lithosphere is influenced by regional and local stresses. But how are these stresses expressed in terms of hydrologic properties and alteration? Within both ridge crests and ridge flanks, the causes of lateral gradients in fluid pressure—the driving forces for fluid flow—are poorly understood. What are the largest possible pressure gradients hosted within the lithosphere, and how far from the source can they be maintained? Are any of these stresses transmitted through fluid pressure and thus responsible for generating hydraulic gradients within the lithosphere? Does alteration of the lithosphere increase or decrease crustal "stiffness"? How does crustal compressibility (and thus hydrologic storage capacity) vary with the extent of alteration? How does alteration of the lithosphere influence the transmission of stresses over large lateral distances? These questions can be addressed only through drilling, coring, and in situ experiments.

Approaches to Lithospheric Drilling

We envision a multidisciplinary, phased approach to lithospheric drilling to address the questions discussed above. The approach we propose is rooted firmly in existing technology and known challenges, but we also identify (in the next section) additional technical developments that will be required to achieve all of our goals.

We propose to drill a combination of intact crustal sections and crustal exposures at tectonic windows (Fig. 28). Intact crustal sections allow evaluation of geologic relationships in locations that may be characteristic of much of the seafloor, while tectonic windows allow access to deep-crustal and upper-mantle intervals that would require months or years of drilling if drilled into through complete, intact sections. Selection of the ideal locations for drilling of complete crustal sections, including penetration of the Moho and recovery of upper-mantle rocks, will require completion of many shallower-penetration boreholes. We envision that the number of boreholes to be drilled through intact crust to particular depths will be inversely proportional to final borehole depth: there will be many shallow boreholes (approximately 700 m deep into extrusive rocks and uppermost intrusive rocks), a moderate number of deeper crustal boreholes (approximately 2 km deep, perhaps to the base of the dikes), and a small number of complete crustal penetrations (5–7 km deep, through the Moho) (Figs. 25 and 28). Some of these boreholes should be drilled into moderate-aged lithosphere where we have little or no information on crustal structure and alteration at present.

Drilling tectonic windows is extremely important by itself, but is also an important prerequisite for drilling intact sections. Drilling tectonic windows will allow penetration and recovery of material from deep-crustal layers and layer interfaces, indicating the nature of heterogeneity, alteration, and potential drilling challenges. By targeting these environments, we can begin work immediately to address fundamental issues associated with the lower crust and upper mantle, while at the same time laying the groundwork for future, technically challenging efforts of whole-crustal penetration.

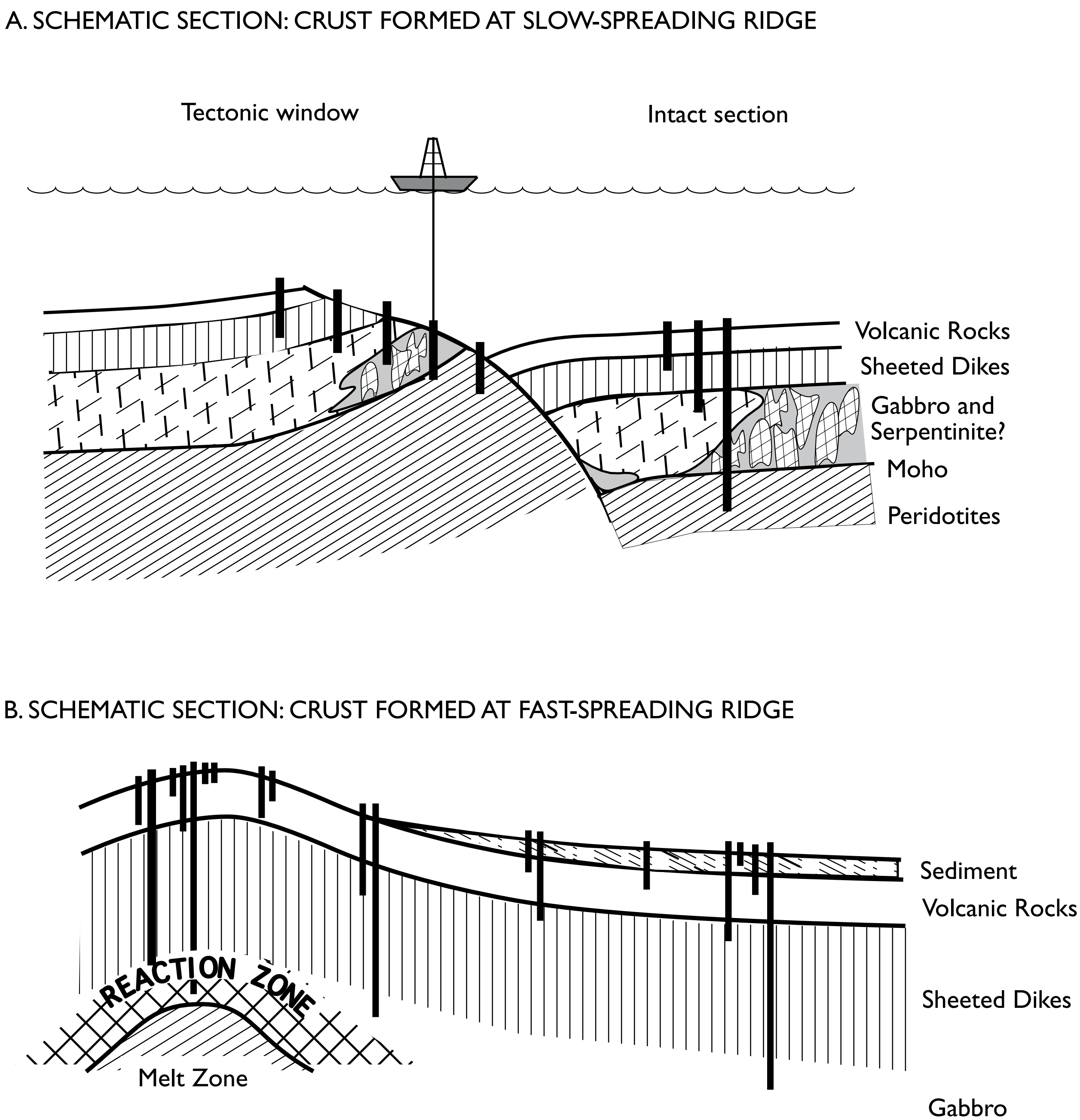
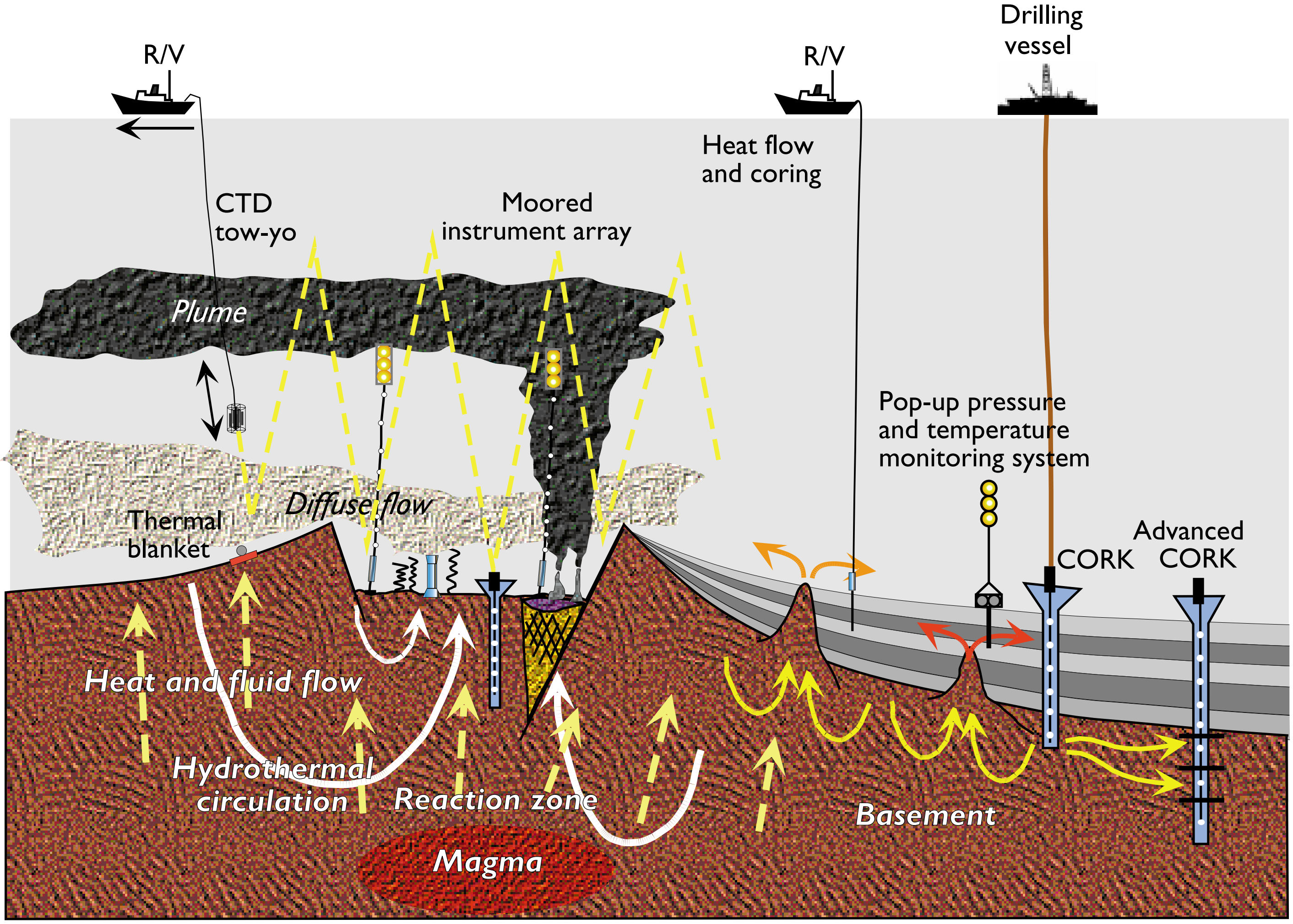


Figure 28. Cartoon of primary strategies for drilling intact and tectonically exposed crustal sections. These drawings are not to scale, nor are they intended to indicate proposed lateral spacing between boreholes or the number of boreholes to be drilled at a particular site. (A) Within continuous crustal sections, particularly those in slow-spreading–formed crust, it will be desirable to drill a series of shallow boreholes well into the volcanic and shallowest intrusive rocks. Ultimately, we need to complete arrays of such boreholes from the ridge crest, out along aging ridge flanks, and in some of the oldest remaining seafloor, depending on the nature and scale of hydrothermal systems found to be active. According to the results of drilling and experiments in these shallow arrays, locations will be proposed for deeper penetration, including complete crustal sections. (B) The drilling of tectonic windows is particularly appropriate for fast-spreading–formed crust (as shown) but could also be applied to drilling of crust formed at faster-spreading ridges. Results of drilling in tectonic windows will help prepare for deeper drilling of intact sections.



Integrated Lithosphere Experiments

Figure 29. Cartoon showing how a wide array of borehole, seafloor, and sea-surface experiments could be integrated within one or more lithospheric settings. Multidisciplinary experiments will help to obtain the maximum possible scientific return from lithospheric drilling. R/V—research vessel. CTD tow-yo—conductivity-temperature-depth (ctd) instrument that is towed behind a ship so that it moves up and down like a yo-yo to get a detailed map of temperature and salinity (conductivity) in the water column.

Maximum return for our efforts will be achieved by coupling drilling and sampling with in situ measurements and long-term observations. For example, deep-crustal boreholes should be instrumented for seismic monitoring, as part of a global, deep Earth network and to understand coupling between seismic activity and crustal emplacement and evolution. Deep boreholes can be instrumented and used as observation points for crustal-scale hydrologic and seismic experiments and for collecting time-series samples of crustal fluids and microbiology. Paired boreholes will also provide opportunities for cross-hole experiments to investigate lateral heterogeneity in the physical properties and chemical composition of the crust. Boreholes should be surrounded by additional seafloor observatories and should be sited within areas that have been extensively surveyed both locally and regionally to place drilling results in geologic context (Fig. 29). Data and samples collected at different vertical and horizontal scales will be used to focus earlier results and to draw conclusions regarding the temporal and spatial processes, fluxes, and products of lithospheric creation and evolution.

Although our highest long-term priority includes the completion of one or more boreholes through the entire crust and into the upper mantle, our immediate priority is to drill a series of boreholes extending significantly into the volcanic and upper intrusive layers within intact crustal sections and to drill into the lower crust and upper mantle at tectonically exposed windows. Boreholes should be cored and logged, and arrays of boreholes should be configured as observatories and used for long-term, active experiments. This work can begin immediately with existing and observational equipment, but expected incremental improvements in coring, sampling, and observatory techniques will improve the scientific return of these initial efforts.

Subduction Factory

Oceanic lithosphere, generated at the ridge crest and extensively modified off-axis, enters the subduction trench, at which point the oceanic lithosphere is termed the "slab." The downgoing slab, with the sediments, volatiles, and altered basalt, drives the subduction factory as sketched in Figure 30. Physical processes and chemical reactions in the downgoing slab release fluids to the overlying lithospheric plate and change the composition of the residual slab. These progressive changes in the slab with depth mediate virtually all processes operating in the factory and are intimately related to the hazards and resources of convergent margins. Subduction of the cold slab causes coupled convection of the mantle in the lithosphere above the slab; this convection brings a continuous supply of fresh mantle to feed the subduction factory. Once through the factory, the subduction process often carries the residual slab to the core-mantle boundary. Such slabs carry to the deep mantle a memory of their residence at Earth's surface, driving mantle circulation and introducing volatile and heat-producing elements.

"These processes drive massive interactions between Earth's surface and its interior."

The processes from the beginning of subduction of oceanic lithosphere to the slab's interaction with the deep mantle are known collectively as "subduction recycling." These processes drive massive interactions between Earth's surface and its interior. More specifically, subduction recycling supervises the net growth of continental and arc crust, constructs the rock and structural fabric of oceanic plate margins, steers the geochemical evolution of the oceans and mantle, generates volcanic and seismic hazards, produces hydrocarbon and precious metal resources, and provides nutrients for benthic biochemosynthesis.

This chapter builds on planning for studies of the subduction factory in a number of ODP partner countries. The chapter focuses on three essential aspects of the factory:

- Earth's deep hydrosphere and the impact of subduction-zone volatile cycles,
- mass transport through the factory and the major tectonic events that initiate and end subduction, and
- the role of subduction in changing the composition and rheology of both the shallow and deep mantle.

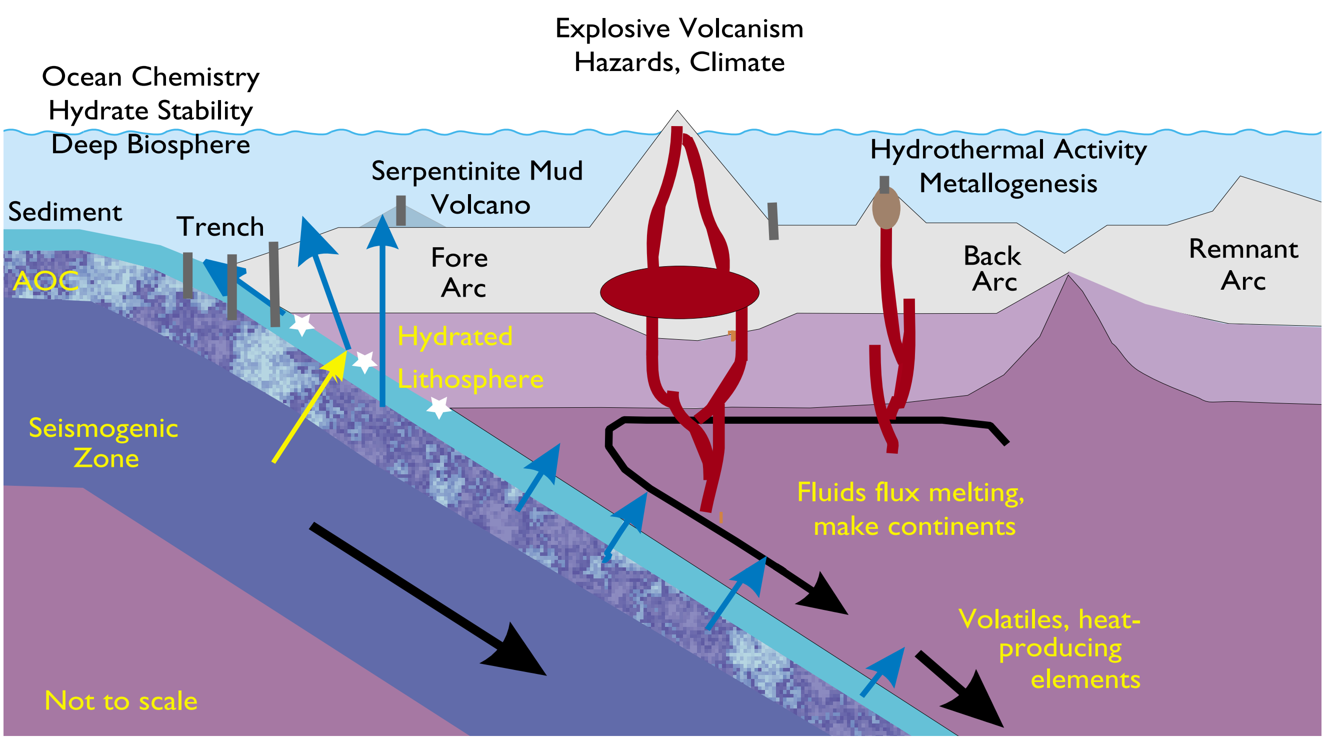


Figure 30. Snapshot of the subduction factory in continuous operation. The factory extends from the trench to the remnant arc and includes crust, mantle wedge, and the slab passing below to approximately 200 km depth (below the lower edge of the cross section). The incoming ocean lithosphere, with its alteration products (AOC is altered oceanic crust), volatiles, and overlying sediments, is an input to the factory. The slab passing beneath the back arc on its way to the deep mantle is one of the outputs from the factory, along with the fluids and melts that move through the upper plate. Blue arrows indicate fluid pathways within and often through the subduction factory; stars indicate earthquake hypocenters. Labels emphasize the impacts of fluid-driven or fluid-mediated processes in global cycles or crucial processes governing the factory. Vertical black bars pinpoint drilling targets; observatories should be placed near the trench and the serpentinite mud volcano for long-term monitoring.

Recent Advances

A number of recent advances provide critical new angles of attack that make study of these three aspects both tractable and timely. Some recent developments of broad impact in the understanding of the subduction factory include the following, where the red bullets indicate a significant contribution from the ODP:

- Discovery of extensive off-ridge-axis and near-trench hydrological circulation in the incoming oceanic plate (see previous chapter). This active circulation plays a major role in establishing the input of volatiles to the subduction factory and profoundly affects the thermal properties of the slab surface.

- High-resolution geodesy, largely via GPS (the Global Positioning System), that allows precise measurements of contemporary convergence rates and discloses intra-arc strain, deformation, and crustal shortening in response to collision or to subduction of rough seafloor topography.

- The ability to trap and analyze microquantities of fluids—e.g., fluid samples collected via instrumented corks placed in boreholes, pore fluids squeezed from sediments, fluids in melt inclusions in deeply crystallized magmatic minerals, and fluid inclusions in hydrothermal minerals—that preserve a signature of processes operating deep within the factory.

- Breakthroughs in crust and mantle imaging, including three-dimensional seismic reflection and refraction as well as seismic tomography. These techniques enable high-resolution imaging of structural architecture of accretionary prisms, reveal high-porosity channels (fluid conduits), identify mid- and lower-arc crustal layers with seismic velocities appropriate for silicic intrusive rocks, and identify pathways of fluids and melts in the mantle.

- Logging while drilling (LWD). This technique provides high-quality logging data often not otherwise available in the unstable borehole conditions typical of convergent margins; LWD data for in situ physical properties are essential in extrapolating beyond the borehole to a regional scale comparable to that of three-dimensional seismic surveys.

- Improving geochemical methods. These utilize new (e.g., B, Li, Cl isotopes) and more common tracers (O, Be, and Sr isotopes, high field strength elements, U-series isotopes) in fluids, incoming sediments, altered oceanic crust, and arc magmas. Together, these geochemical methods fingerprint specific reactions (e.g., the smectite-to-illite transition) or identify distinct fluid sources from the downgoing slab.

- Analysis of volcanic tephras, recovered by drilling into the seafloor. Tephras provide a history of the temporal evolution of their source arc.

- Corks and advanced corks. Use of instrumented corks in boreholes provides essential hydrological information and fluid samples that are otherwise not recoverable; both the corks and the planned advanced corks enable the proposed focus on the volatile cycle of the subduction factory.

Earth's Deep Hydrosphere

A major new goal of subduction factory research is to determine the budget of important volatiles such as water, methane, and carbon dioxide as they enter, traverse, and exit subduction zones. The subduction process carries water and other volatiles, stored in the oceanic crust and sediments, to progressively higher pressures and temperatures. At each step, fluid fluxes distilled out of the downgoing slab influence and often control fundamental processes in the subduction factory (Fig. 30). At the shallowest depths, water and carbon fluxes influence the formation and destruction of gas hydrates and may support a deep subsurface biosphere as well as the chemosynthetic vent communities often observed in forearc regions. At greater depths, the presence of excess pore-fluid pressures moderates the strength of faults and influences the hazards associated with the great earthquakes of the seismogenic zone. Deeper still, the water flux out of arc volcanoes powers explosive eruptions. The cycling of CO_2 through the subduction factory and out the volcanoes is a little-known aspect of Earth's natural carbon cycle, operating on a subduction timescale of approximately 1.5–3 million years (i.e., relevant to Pleistocene icehouse and late Pliocene greenhouse climates). Beneath the arc and back arc, slab-derived volatiles flux the mantle melting that builds continents. Devolatilization of the slab also contributes fluids and metals to gold- and silver-rich supra-subduction-zone (SSZ) hydrothermal deposits hosted in felsic volcanic rocks, deposits thought to be analogous to many Archean gold deposits. Finally, at the end of the subduction cycle, those volatiles retained in the slab are carried down into the mantle, there to modify mantle rheology, oxygen fugacity, and convection. At the very least, the following key questions on the deep hydrosphere can be addressed by drilling.

What Is the Contribution of Multistage Alteration of the Oceanic Crust, and Perhaps Active Near-Trench Hydrological Circulation, to the Volatile Budget and Thermal Structure of the Incoming Plate?

What is the contribution of multistage alteration of the oceanic crust, and perhaps active near-trench hydrological circulation, to the volatile budget and thermal structure of the incoming plate?

Heat-flow data from the equatorial east Pacific and recent drilling off Costa Rica provided compelling evidence for circulation of modern seawater into the seafloor basement. Such circulation carries major implications for the thermal structure of the upper slab, its volatile content, and the distribution of slab-borne hydrous minerals. Leg 185 drilling on the old Pacific plate entering the Mariana Trench has revealed pronounced oxidative alteration deeper than 300 m into oceanic basement and the presence of abundant sediment interlayers in the basaltic section, both at depths far greater than expected. Long-term monitoring of any hydrologically active regimes in shallow basement and deep penetration of the oceanic basement (approximately 500 m) itself are critical for quantifying the volatile input to the subduction zone. Also required to calculate a meaningful estimate of volatile input to the factory are modeling and seismic techniques that estimate heterogeneity of fluid circulation and alteration of the incoming crust. And heat-flow measurements and thermal modeling are necessary to establish the effects of circulation on the thermal structure of the slab entering the seismogenic zone.

What Are the Hydrologic Pathways for Fluid Flow in the Prism, How Do They Vary over the Course of the Earthquake Cycle, and What Information Do Venting Fluids Carry from Depth?

What are the hydrologic pathways for fluid flow in the prism, how do they vary over the course of the earthquake cycle, and what information do venting fluids carry from depth?

Recent drilling, logging while drilling, and fluid studies on squeezed pore fluids and cork-collected samples from fore-arc regions suggest the existence of several discrete fluid-circulation systems that are partially or completely isolated from one another. They include flow along the decollement, within the underlying sediments, and within the igneous basement itself in some cases. Venting of fluids through the upper plate in out-of-sequence thrust faults and rear-prism normal faults is an important and little-known part of the shallow hydrology of the subduction factory. We know virtually nothing about the absolute fluid fluxes through any of these separate systems or the proportion of the total return flow accommodated by each, essential for calculating the shallow volatile flux out of the factory. To determine whether there are clear variations through an earthquake cycle, we need additional *JOIDES Resolution*–style drilling, LWD, four-dimensional seismic data collection (i.e., repetitive three-dimensional seismic surveys to determine changes over time), and long-term observatories to monitor the temporal variability in fluid temperature, flux, pressure, and composition in high-permeability conduits. Techniques for establishing the magnitude of background fluid flow in diffuse-flow rather than focused-flow regimes must be further developed. Continuing development of methods that use the chemistry of fluids from deep in the slab to determine its temperature, pressure, and mineral constituents are essential to both seismogenic-zone and subduction factory goals. Rigorous hydrological modeling is critical to extrapolate physical values from the borehole to a regional scale and to translate geochemical data to distance and timescales of fluid flow.

What are the fluid fluxes out of the deeper slab (through the sediment-starved fore arc, the magmatic arc, and the back arc) and the impacts of deep fluid cycles on the subduction factory?

What Are the Fluid Fluxes out of the Deeper Slab (through the Sediment-Starved Fore Arc, the Magmatic Arc, and the Back Arc) and the Impacts of Deep Fluid Cycles on the Subduction Factory?

Although recent surveys have documented the extensive distribution of serpentinite mud volcanoes along the strike and across as much as 100 km width of the Izu-Bonin–Mariana fore arc, Leg 125 drilled only one actively venting mud volcano, in the Mariana fore arc, approximately 29 km above the slab. Deep drilling across the width of a carefully selected fore arc and long-term monitoring of active flow through serpentinite mud volcanoes are essential for determining fluid compositions, flux rates, microbial geology, and mantle serpentinization of this otherwise inaccessible part of the subduction factory. Often actively venting from depths of approximately 16 to 30 km, serpentinite mud volcanoes and their fluids provide a unique window into the pressure, temperature, and mineral constituents of the slab and the fluids distilled therefrom. The mud volcanoes also yield otherwise inaccessible data for studying the massive serpentinization of the mantle in the overlying lithospheric wedge. Serpentinization profoundly affects the stable sliding behavior of the slab through the seismogenic zone, and the chemical processes associated with serpentinization may support a deep subsurface biosphere.

Arc magmas, whether intruded at depth or erupted on the seafloor, trap magmatic volatiles that better preserve their original isotopic and chemical signatures than do subaerial lavas. With recently developed microanalytical techniques, melt inclusions in early-formed crystals can be used to quantify fluxes and determine compositions of deep magmatic fluids. Both riser-style and *JOIDES Resolution*–style drilling (with good recovery of volcanic tephras) techniques are essential to collecting the samples necessary to quantify the fluxes of water and CO_2 out of the subduction factory. Slab-derived fluids, although a small part of the total volatile budget, may contribute to the high gold and silver contents of subduction-related sulfide deposits. Scheduled drilling in the Manus Basin will be the first exploration of sulfide formation in the subduction factory. Shallow drilling in ore-grade gold deposits in submarine arc calderas (e.g., Miyojin Knolls in the Izu arc) and a region of active Kuroko-type iron formation (e.g., Panarea in the Aeolian arc) are examples of next steps for the drilling program in understanding ore-forming processes and the resources they produce.

Mass Cycling Through the Subduction Factory

Current drilling focuses on inputs to, and outputs from, the convergent margin. The prospect of drilling in deeper water with deeper penetration and better borehole stability in the next phase of scientific ocean drilling, together with judicious use of geologic (tectonic) windows, will allow us to sample inside the subduction factory. Once inside, it is imperative to seek data to allow us to look not only at the continuous operation of the factory, but also at the major events that start, perturb, and terminate the operations of the factory and that permanently add its products to the continents.

Determining the diagenetic and prograde metamorphic changes of the downgoing slab over drillable intervals and developing predictive models for changes in the deeper slab are critical for understanding the dynamics of material and fluid flow through subduction systems. As the slab passes downward, it is metamorphosed, a process of mineral change that controls the composition and volumes of fluids moving into the upper plate. Devolatilization, diagenesis, and metamorphism control the physical properties of the subduction interface and its seismogenic potential and determine the composition of the slab delivered to the depth at which the arc magmas form. Exhumation of rocks in the little-studied region of the accretionary prism near the downdip limit of the seismogenic part of the subduction zone—the rear of the accretionary prism—can provide an important window into material and fluid flux from deep within the prism. Understanding processes operating in the rear of the prism can help evaluate seismic hazards, including earthquake nucleation and distribution deep within the prism (e.g., in the Aegean region).

Arc rocks provide another view of operations within the factory. Determining the composition of intrusive rocks formed in intraoceanic arcs is essential for understanding the currently problematic role of the subduction factory in generating proto–continental crust. Because the arc samples the downgoing plate, the chemistry of arc lavas can reveal the volume and lithology of sediments carried down through the seismogenic zone and beyond.

How do mineral assemblages vary with depth along the decollement?

How Do Mineral Assemblages Vary with Depth along the Decollement?

Both the sedimentology of the seafloor and the limited amount of drilling on incoming plates show that different margins are subducting very different proportions of clay-, diatom-, and carbonate-rich sediment. Thus, slabs may start with different physical properties and will undergo diagenetic, devolatilizing, and metamorphic reactions determined by their starting compositions; ultimately, examples of the different sedimentary end members should be drilled. In addition, fore-arc sediment dynamics (frontal accretion, underplating, and erosion) will change the mass flux to depth and must be investigated by drilling, seismic imaging, and mass-balance approaches. Objectives involving both the subduction factory and seismogenic zone will be met by any drilling into the incoming plate and by shallow fore-arc drilling or deep (*JOIDES Resolution*–style or riser-style) penetration into the decollement at depth. For the subduction factory, such drilling will provide constraints on the shallow recycling of water and CO_2 and on the composition of the residual slab transported into the upper seismogenic zone (approximately 10–50 km depth). Penetration into the igneous basement is essential to begin quantifying volatile losses and phase changes with subduction. Drilling in margins with an active and well-studied volcanic arc allows the full volatile cycle to be quantified and makes use of the arc as a flow monitor to determine the lithology of sediments transported below the downdip limit of the seismogenic zone.

Drilling can also be used to determine whether spatial and temporal variations in the subducted input are linked to changing modes of operation in the subduction factory—e.g., onset of particularly voluminous and explosive volcanism or along-strike changes in seismicity.

How Do Processes Operating in the Rear of the Accretionary Prism Affect Its Overall Fluid and Mass Budget, and What Processes Control Exhumation of Accreted Materials Such As Blueschist from Deep within the Prism?

How do processes operating in the rear of the accretionary prism affect Its overall fluid and mass budget, and what processes control exhumation of accreted materials such as blueschist from deep within the prism?

Two markedly different models, with different implications for mass cycling, have been proposed for the geometry and kinematics of the rear of accretionary prisms. When the rear boundary of the prism dips trenchward, a doubly vergent prism is constructed. Accreted rocks exhumed by the resulting backthrust system have therefore been cycled only to relatively shallow depths beneath the crest of the accretionary prism (Fig. 31A). When the rear boundary of the prism dips arcward (Fig. 31B), however, a narrow subduction channel results along which sediments may potentially be transported to the mantle or underplated to the overlying crust. Accreted rocks within the rear of the exhuming "orogenic wedge" are thereby brought up from much greater depth, potentially near the downdip limit of the seismogenic zone, providing the only geologic window to the region believed to be key to the initiation of great earthquakes. The two models and their predictions for mass cycling need to be tested by observations of state of stress, strain histories, metamorphic histories, thermal structure, and fluid chemistry across the rear part of the prism. Exhumation can be accomplished through either erosion or normal faulting, where both are of critical importance in controlling uplift, thermal structure, and dewatering of accretionary prisms. Erosion removes material from subaerial mountain belts (and from submarine fore arcs), exposes rocks from deep-crustal levels, and can operate with strong feedback between topography and climate. Normal faulting can be either distributed across the accretionary prism, reflecting gravitational collapse, along the fore arc as a result of oblique convergence, or localized along the rear part of the prism, reflecting tectonic exhumation. Drilling across the rear of actively eroding or faulting accretionary prisms can provide much-needed, and otherwise inaccessible, data on the thermal and strain histories of exhumed rocks that can directly document exhumation processes. The objectives of this section are all achievable through deep *JOIDES Resolution*–type drilling, strain monitoring, and fluid sampling.

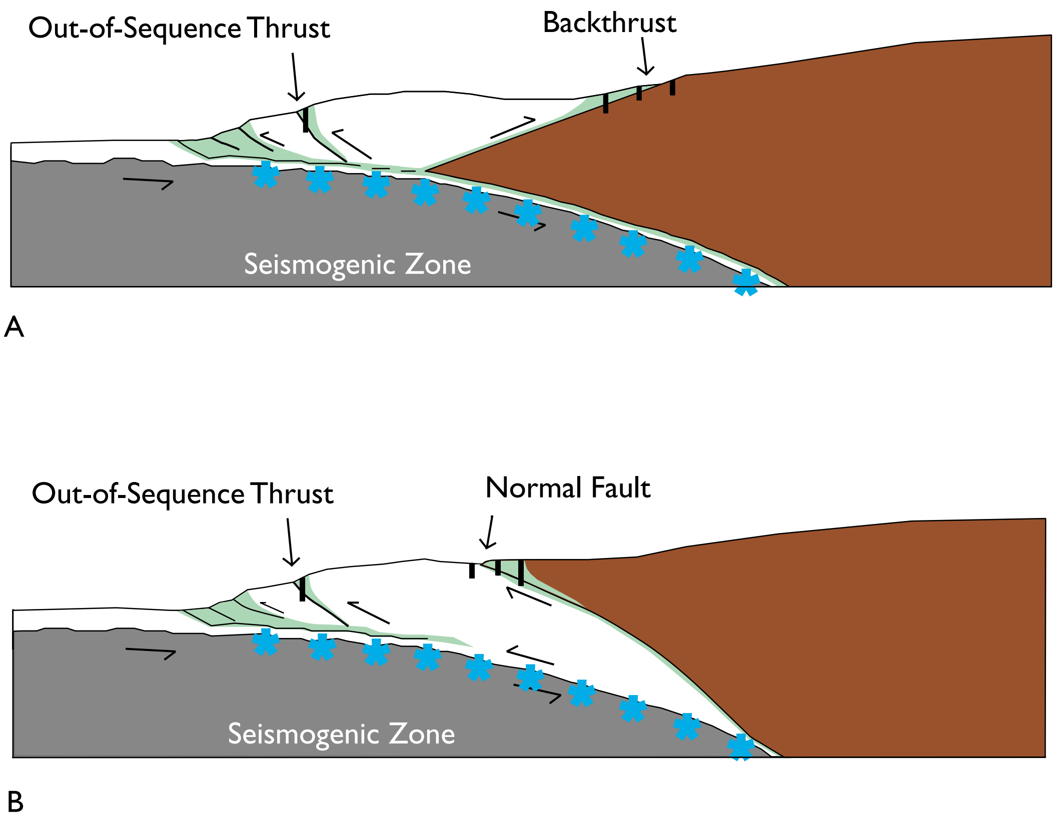


Figure 31. Cross section of accretionary prisms (white), showing end-member geometries for the structural relationships at the rear of the prism. (A) The fault bounding the rear of the prism dips trenchward, and material is exhumed from relatively shallow levels. (B) The fault bounding the rear of the prism dips arcward, and material may be exhumed from much greater depths along a subduction channel. Blue stars indicate the seismogenic zone. Both exhumation and fluid flow along out-of-sequence thrusts provide windows into the intermediate and deeper seismogenic zone, otherwise inaccessible to drilling. Vertical black bars show drillable targets; fluid monitoring on out-of-sequence thrust sites is necessary.

How is Proto–Continental Crust Generated in the Subduction Factory?

How is Proto–Continental Crust Generated in the Subduction Factory?

Convergent margins are the sites where most of the materials that become continents are assembled. However, the bulk "andesitic" composition of the continents is apparently paradoxical, given that the primary melt extracted from the upper mantle and erupted above subduction zones is basaltic. We lack an understanding of a fundamental Earth process that causes a compositional change from basalt to andesite in subduction-zone–generated crust. Juvenile oceanic-island arcs, mostly submarine, are an ideal site for addressing this fundamental question. Extensive dredging and seismic surveys suggest that a major part of the middle crust of the arc is made of rocks with andesitic compositions (tonalite), even where the primary erupted rocks are basaltic. A more mafic lower crust is inferred to be present beneath the andesitic middle crust. Direct sampling of new "continental" materials in the middle and lower crust of juvenile oceanic arcs thus provides the only chance for understanding the origin of the andesitic continental crust. Deep-water and deep-penetration *JOIDES Resolution*–style and riser-style drilling into tectonic exposures of middle and lower arc crust will be necessary. Such exposures are accessible in the inner trench wall of eroding fore arcs, along major tectonic lineaments such as the S_fu Gan tectonic line (southeast of Japan in the Bonin Islands), and in some remnant arcs.

Causes and Consequences of Birth, Death, and Major Tectonic Events in the History of Convergent Margins

The causes and consequences of subduction initiation remain among the most fundamental and least understood problems in Earth science. The startup of new subduction zones controls rates of plate motion and the location of spreading ridges and consequently has a profound effect on long-term changes in sea level. Earliest arc activity is characterized by extremely high magma-production rates and magmatic compositions that indicate high volatile fluxes through the subduction factory. An important product of subduction initiation, drillable in many intraoceanic systems, is an extensive fore-arc crustal terrane that is petrologically, structurally, and geochemically similar to large, intact ophiolites. This early arc setting has been proposed as a more likely site for the formation of many ophiolites (including those of Troodos, the California Coast Range, and Oman) than is a spreading ridge. If this controversial idea is true, it would fundamentally alter how ophiolites are used in the interpretation of geologic histories and how they are used as analogues for processes in the ocean basins.

Collisions perturb the subduction factory and can ultimately terminate their operation. Collisions significant enough to rearrange plate boundaries are largely responsible for growth of the continents through amalgamation, including the addition of hydrocarbon- and metal-rich terranes to accessible continental margins. Major collisions exaggerate the fundamental processes of accretion at trenches by changing the inputs to the subduction zone from oceanic lithosphere to lithosphere with thicker and more buoyant arc or continental crust. Collisions (on all scales) are important Earth processes that culminate in the growth of mountains.

By closing entire ocean basins (e.g., Tethys) or major gateways (e.g., the Isthmus of Panama), collisions control oceanic circulation and thereby drive climatic change. The growth of major mountain chains during continental collision can directly affect global climate and ocean chemistry (e.g., onset of monsoons and Sr isotope changes with the rise of the Himalayas). The feedback between orographic climate and orogenic uplift patterns is a two-way street, providing insight into a more complex link between climate and convergent-margin tectonics than the more widely appreciated atmospheric effects of explosive arc volcanism.

What tectonic conditions lead to subduction initiation, what are the compositions and production rates of the earliest subduction products (magmas and fluids), and is initial arc crust the progenitor of many ophiolites?

What Tectonic Conditions Lead to Subduction Initiation, What Are the Compositions and Production Rates of the Earliest Subduction Products (Magmas and Fluids), and Is Initial Arc Crust the Progenitor of Many Ophiolites?

Drilling in the Marianas region suggested that subduction was initiated along an extended transform fault. Drilling in incipient subduction zones, such as the Hunter Fracture Zone in the southwestern Pacific or the Wetar region of the Indonesian arc can test the model, its global applicability, and its tectonic implications. It can also be tested where the oldest parts of young arcs are preserved and accessible. The oldest volcanic rocks record thermal, mass, and volatile fluxes during the initial phases of subduction and provide information about the initial thermal state of the plates involved. The distribution of earliest arc products, their ages, and their magnetic signatures guide the creation of models for the tectonic conditions leading to subduction. The oldest sedimentary deposits record the early structural and subsidence and/or uplift histories of the upper plate. Evaluating a supra-subduction-zone (SSZ) origin of ophiolites requires careful documentation of the sedimentary and magmatic basement history of one of these early arcs, which can be achieved with arrays of 200–600-m-deep drilled boreholes. Ultimately, a deep-crustal section of one of these "fore-arc" ophiolites will be essential. Such a section would have to be drilled in the context of a complete and detailed seismic refraction study, but could be accomplished either by on-land drilling or drilling from a riser-equipped ship.

How Does the Evolution of Subduction Zones into Collisional Mountain Belts Change Fluid and Mass Transport within the Evolving Orogenic Prism?

With the approach of a colliding massif (e.g., ridge, arc, continental fragment) to the subduction zone, important parameters in the downgoing slab begin to change, including crustal density, thickness, and rheology. Especially in collisions that force the migration of plate boundaries, such changes in input lead to (1) changes in the partitioning of incoming crust via offscraping and underplating processes and (2) changes in mass and fluid pathways within the accretionary prism. As a rifted continental margin enters a subduction zone, we know that upper-crustal levels are scraped off into a thin-skinned fold-and-thrust belt, and we know that there is significant, earthquake-inducing deformation of the underlying crust. How these deeper layers deform, however, and how processes within the accretionary prism accommodate to the deforming transitional and continental crust are unknown, as are the consequences for fluid flux through the prism. Drilling active collisions can elucidate processes that cannot be addressed in mature suture belts, by combining riser-style and *JOIDES Resolution*–style penetration with selection of targets containing uplifted, deeply deformed rocks (e.g., those involved in out-of-sequence thrusts, backthrust terranes, and zones of tectonic exhumation), across transects that represent different stages of collision. Measurements and observations of in situ stress, strain, and metamorphic histories, heat flow, and fluid pressure and chemistry can be compared across transects and with precollisional subduction zones in order to track mass and fluid pathways through a growing orogenic prism. In a region undergoing diachronous collision, such observations could be compared along parallel transects to construct a three-dimensional model that depicts temporal evolution along strike (providing direct observation of time as well, by exploiting the space-time equivalency of oblique collision). In several cases, the resulting picture of the transition from subduction to collision can also be compared with that of mature stages of collision exposed above sea level and exhumed to deep-crustal levels. The potential even exists for quantifying mass and fluid flux over time and space.

How does the evolution of subduction zones into collisional mountain belts change fluid and mass transport within the evolving orogenic prism?

Quantifying the Consequences of Subduction on the Composition and Structure of Earth's Interior

To understand the pathways for transport of fluids, mass, and energy from Earth's surface through the subduction system into the shallow-mantle wedge above the subduction zone as well as into the deep mantle and back to the surface, we need to quantify supra-subduction zone (SSZ) wedge processes. Attaining this goal is necessary for us to fully comprehend the composition and structure of Earth's interior.

The subducted plate carries oceanic crust and upper mantle, terrigenous and biogenic sediments, and extraterrestrial dust into the mantle. All of these materials have interacted with the hydrosphere. A very large fraction of the subducted mass is not recycled into the arc crust, but rather serves to hydrate and modify the wedge of mantle above the shallow slab (approximately 15–200 km depth) and to feed deep-mantle circulation and the source region for mantle plumes. Understanding the effects of subduction on the volatile budget, rare-gas composition, internal heating capacity, rheology, and temperature of the mantle has been an important and long-standing goal for defining mantle geodynamics.

Geophysical and geochemical models of the SSZ mantle wedge indicate that it has an extraordinarily complex history. The initial mantle wedge, with its previous history of intramantle processes, is progressively overprinted by thermal and material exchange with the downgoing slab (Fig. 32). This process, dominated by recycling of fluids and dissolved materials, results in the creation of a cooled, hydrated, metasomatized wedge at shallow levels and promotes melting at depth. Over time, the SSZ mantle wedge—with its components from ancient upper mantle, subducted crust and hydrosphere, and in situ melting—develops into a chemically heterogeneous reservoir that will be eventually disrupted and remobilized by tectonic processes like exhumation, collision, and delamination. This mantle is available to be tapped by volcanism, as at the southeast end of the Chile Rise or in clearly rift-related volcanic rocks that carry an arc chemical signature. The residual slab, depleted of much (but retaining some) of its budget of aqueous fluids, dissolved species, and melt, enters the deep mantle and becomes one source for plume magmatism.

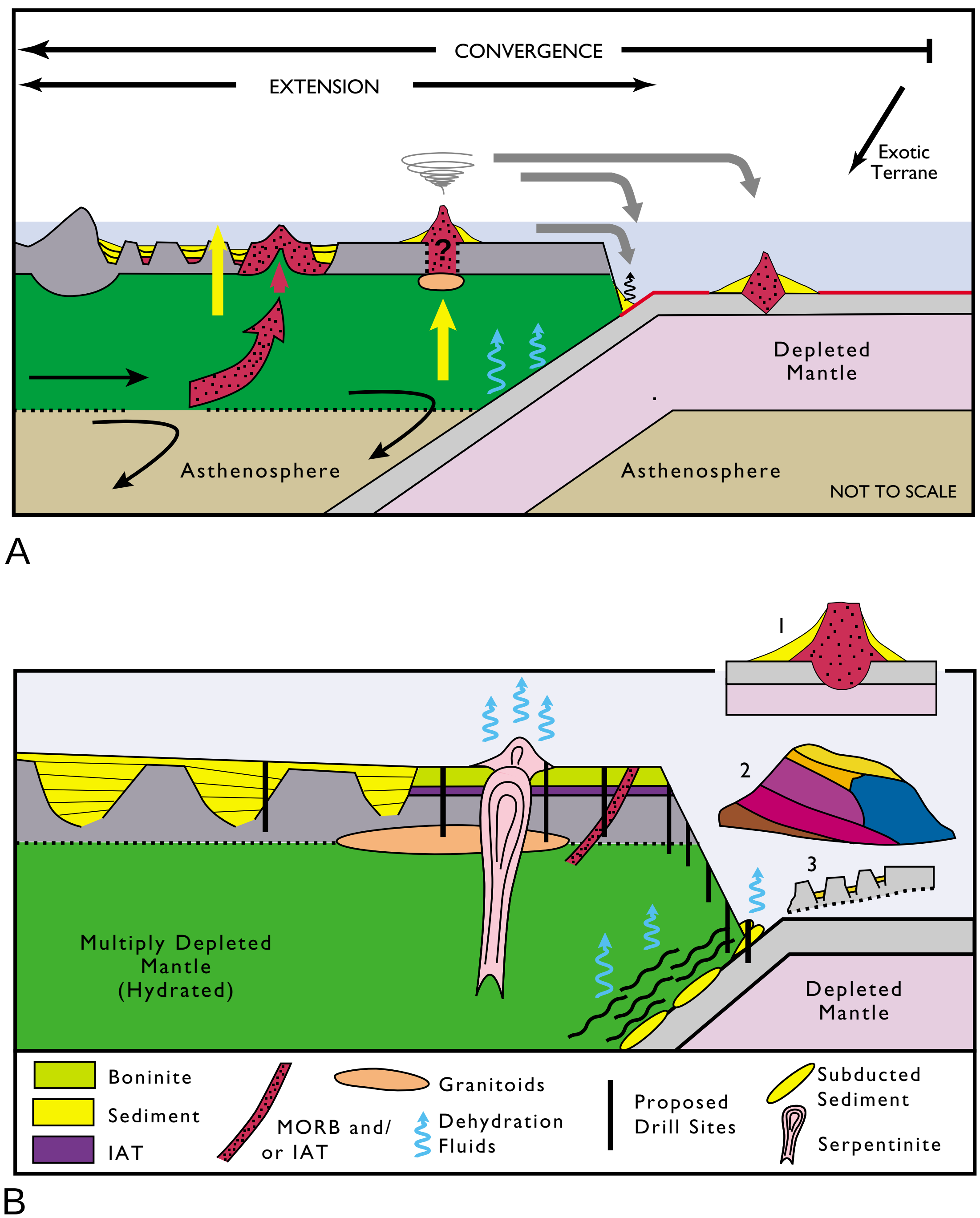
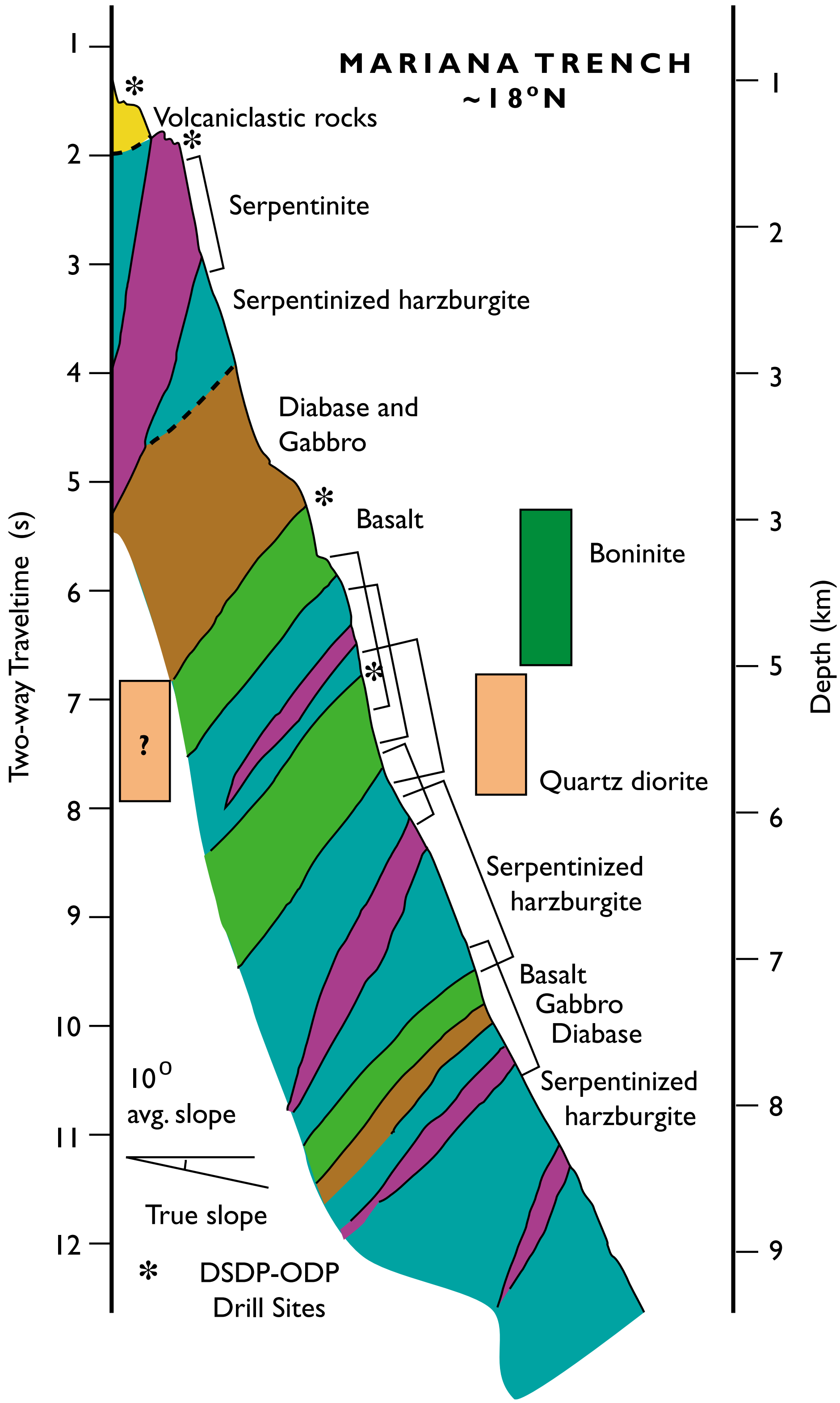


Figure 32. (A) Cross-section view of the supra-subduction zone (SSZ) system; the SSZ consists of the overriding upper plate that is under extension. For the igneous rocks that are produced in the back arc (left side, above the subduction zone), the chemically most significant constituent of the SSZ oceanic lithosphere is hydrated upper-mantle peridotite (green), which has been depleted of certain elements by previous episodes of melt extraction. Above the mantle is oceanic crust (gray), material that is filling rift basins (yellow layers showing sedimentary rocks over a thin red layer, which indicates the initial basaltic rocks of the rifting event), and younger igneous rocks (red with black "crystals"). The mantle of the SSZ has been further altered by re-enrichment in mobile, water-soluble elements (indicated by blue wavy arrows) derived from the subducted lithosphere (on the right), which consists of oceanic crust (mainly gray; thin red layer at the top is MORB—mid-oceanic-ridge basalt) and mantle (lavender). An additional potential source of enrichment includes any previously enriched mantle rocks that are brought into the SSZ region by subduction-driven mantle counterflow (black arrows on the left side) as well as any oceanic feature that happens to be subducted, for example, a volcanic edifice (red on right side) and its apron of sedimentary deposits (yellow). (B) Schematic view of the geology of fore arcs in intraoceanic settings. The extended and rifted fore-arc crust (gray) has small grabens and half grabens that act as traps for arc-derived clastic sediments (yellow). The fore arc may have been intruded by mafic magmas (red shows MORB and purple shows IAT—island-arc tholeiite) derived from the volcanic arc or intruded beneath the fore arc; boninite lavas (yellow green) may have erupted on the seafloor within a few tens of kilometers of the trench slope break. Serpentinite diapirs (pink) may have entrained deep-crustal materials—including MORB-like and IAT-like mafic rocks, boninite, serpentinized peridotite, granitoids (orange), and moderate- to high-pressure metamorphic rocks (shown by wavy lines in the mantle)—and brought them to the seafloor. Exotic terranes that may be carried on the incoming oceanic plate (on the right) and subducted or partly subducted include (1) volcanic edifices of MORB and OIB (oceanic-island basalt; shown in red), (2) lithologically and structurally complex seamounts or plateaus perhaps with carbonate rocks, and (3) sediment-filled grabens between crustal horst blocks. Each subducted feature adds its peculiar signature to the subduction factory. Sites for proposed boreholes to sample and understand this heterogeneity are shown schematically by black vertical bars.

Figure 33. Interpretive sketch showing the heterogeneity of the inner slope of the Mariana Trench near 18∞N latitude as determined from dredged rocks and borehole data from the Deep Sea Drilling Project (DSDP) and the Ocean Drilling Program (ODP). Brackets show the depth range of individual dredge collections. Note that serpentinized peridotite occurs over a wide range of depths from near the top of the slope to deepest levels; the peridotite is probably interlayered with other rock types. Basalt compositions include mid-oceanic ridge basalt (MORB), oceanic-island basalt (OIB), and island-arc tholeiite (IAT); they too occur over a wide depth range and appear to be interlayered with the peridotites. Tectonic imbrication is a likely explanation. Boninite has been recovered at mid depths; from drill data, it is known to be interlayered with island-arc tholeiite. Of particular interest is the occurrence of minor amounts of quartz diorite. The lithostratigraphy seen here is duplicated at other areas of the Mariana island arc and is typical of the Tonga and Philippine Trenches. The sketch shows extreme vertical exaggeration; the actual slope is about 10∞.



What Are the Petrology, Geochemistry, and Structure of the Fore-Arc (Shallow) Mantle Wedge?

Recent exploration of this region by dredging of trench walls in nonaccretionary settings has uncovered an unexpected diversity of lithologies, from quartz diorite to boninite to serpentinite (Fig. 33). These discoveries make it clear that the fore-arc mantle wedge is involved in the initiation of subduction and generation of felsic arc crust and may be an analogue for the crust and upper mantle preserved in ophiolites. Nevertheless, the origin, structural relationships, and lithostratigraphy of fore-arc materials remain an enigma that can only be understood by deep drilling. The ideal drilling strategy for exploration of the fore-arc mantle wedge is a series of boreholes extending from the active arc to the deeper part of the inner trench wall (Figs. 32 and 33). Chemical techniques used to identify recycled-slab signatures in the arc may also be used to pinpoint subduction-zone chemical signatures stored in the fore-arc lithospheric mantle, which may contribute to later magmatism in other tectonic settings.

What are the petrology, geochemistry, and structure of the fore-arc (shallow) mantle wedge?

How Does the Fore-Arc Mantle Wedge Change with Distance from the Trench and over Time?

Drilling tectonically exposed parts of the fore-arc mantle wedge reveals the cumulative effect of subduction up to that point in time and space. For the deeper zone where melt generation occurs, we can use magma chemistry to examine the progressive changes that occur both with depth and over time within the mantle wedge. Contemporaneous changes in the quantity and composition of slab fluids with depth have been demonstrated by transect studies of arc magmas in active subduction systems like the Izu arc and Kuriles. This information is critical for understanding the sequence of processes affecting the slab and wedge as well as the limit at which slab components, including mineralizing fluids, cease to influence the upper plate. It is especially important for understanding the ultimate composition of the slab as it enters the deep mantle. Although the shape and configuration of subducting lithosphere can be determined by seismic tomographic studies, detail of its composition can only be determined by solving "the subduction equation"—that is, the initial slab entering the trench minus all materials extracted and added through the upper 200 km of the subduction factory equals the residual slab delivered to the deep mantle.

How does the fore-arc mantle wedge change with distance from the trench and over time?

What can we learn by looking at the chemistry of magmatic products of arcs and basins that have developed at a given convergent margin over time?

What Can We Learn by Looking at the Chemistry of Magmatic Products of Arcs and Basins That Have Developed at a Given Convergent Margin over Time?

Changes in the bulk composition of the wedge's magmatic products from boninite to tholeiitic basalt to felsic differentiates are a first-order record of the thermal history of the convergent margin. Furthermore, since the chemical imprint of slab-derived components in arc and back-arc magmas is decipherable by using trace elements and isotope tracers, changes in magma composition yield information about temporal changes in the nature of subducted materials and in their transport to the zone of magma generation. Examination of temporal changes in arcs is necessary to construct a four-dimensional view of the thermal and material exchanges between the mantle wedge and subducted slab.

Several drilling strategies are needed to resolve these questions (Fig. 32):

- Drilling of volcaniclastic sequences in the arc and back arc that reveal fine-scale spatial and temporal variations in wedge processes. Study of such rocks has been recently revolutionized by the development of laser-ablation ICP-MS (inductively-coupled-plasma mass spectrometry), which permits chemical analysis of glass shards and minerals in heavily altered rocks.
- Drilling of selected deep sections of extrusive and intrusive rocks from remnant arcs, chosen to parallel observed along-strike changes in the active convergent margin.
- Drilling in exceptionally juvenile oceanic arcs, without back-arc basins (like Sangihe, near Indonesia), where slab-derived fluids have just begun to interact with unmodified mantle of the type from which MORBs (mid-oceanic-ridge basalts) are derived.

Technological Needs

Most of the technology required to achieve our objectives exists at present in some form, but much of it needs to be modified before it can be applied to future scientific ocean drilling. Meeting some of our technological needs will require major engineering developments; rapidly changing technology will play an important role in any integrated program of ocean drilling. The following list is not prioritized; all of the following are essential for successfully addressing the stated scientific research goals.

- Continuous coring with good recovery. The disciplines of paleoclimatology and paleoceanography have made enormous progress since the beginning of the ODP that would not have been possible without the recovery of complete sedimentary sections. In contrast, scientists working below the sedimentary part of the lithosphere have had to make do with relatively low recovery since the beginning of the DSDP, often less than 10% within fractured rocks, massive sulfides, interbedded cherts, or friable carbonates. In proximal ridge and hydrothermal vent localities as well as arc settings, sand and volcanic tephra interbeds record an essential part of the available geologic record, yet often they have been poorly recovered.

- Drilling in all water depths. Critical scientific targets lie in water depths from as shallow as a few tens of meters to as deep as 8,000 m. The restriction of the *JOIDES Resolution* to water deeper than 75 m has limited scientific achievements in studies of sedimentary processes and sea-level and rifting histories. Our future approach must involve a multiple-platform capability and probably a mix of long-term and short-term leases of both commercial and "project-invented" drilling technologies.

- Greater sample volume. Demands for additional scientific studies of varying types on a single available core require larger volumes of cored sample.

- Drilling bare, fractured rock. Sampling very young crust, massive sulfide deposits in settings without sediment cover, and sediment-starved volcanic fore arcs or back arcs requires the ability to initiate boreholes on bare rock. The hammer-in casing method currently under development within the ODP promises to play an important role.

- In situ fluid and gas sampling. Recovery of pristine samples, unperturbed by the drilling process, is essential. Multiple-packer advanced corks—equipped with gas and osmotic fluid samplers and engineered for stable deployment in both oceanic lithosphere and sediments—are necessary.

- Pressure cell sampling. Preserving in situ conditions of ever more deeply recovered materials is critical for studies of fluids evolved during diagenesis and metamorphism, the deep biosphere, and gas hydrates in rifting and convergent margins.

- Experiments at in situ conditions. Laboratory facilities that allow experiments on—and extractions of—fluids, gas, and biota at the pressures, temperatures, gas pressures, and compositions comparable to those of the sampled intervals must be available both at sea and ashore.

- Oriented cores. Paleomagnetic and structural investigations require continuous core orientation.

- Directional coring. Directional drilling could provide critical information on subhorizontal heterogeneity and in situ properties; such technology is now readily available in industry.

- Stress orientation. Tools that can measure and monitor stress orientation over both short- and long-term experiments are required in order to relate stress state to lithospheric construction and evolution.

- High-temperature drilling and logging. Experiments in high-temperature hydrothermal areas and in the deep crust require development of specialized tools for downhole experiments, using both wireline and stand-alone instruments. Drilling tools impervious to these high-temperature environments are also required.

- Long-term monitoring and crustal-scale active experiments. To maximize the return from drilling, many of these boreholes (particularly deeper ones) should be instrumented to monitor pressure, temperature, chemistry, seismic activity, and other parameters. Observatories that isolate limited depth intervals within long boreholes will be particularly valuable, as will networks of borehole observatories that can be used for crustal-scale experiments (e.g., cross-hole hydrologic tests, seismic monitoring, strain).

- Deep penetration. Using the riserless vessel to its greatest depth capacity, along with riser drilling for deeper penetration, will enable important scientific achievements not currently possible.

Seismogenic Zone

Uncounted numbers of lives have been lost from earthquakes and associated tsunamis, and more than 90% of seismic energy worldwide is released in subduction-zone earthquakes. The largest events rupture along the entire downdip extent of the seismogenic zone; the along-strike rupture width determines the final magnitude of the event. Large earthquakes are more important than all the smaller events, both from a scientific and societal perspective. About 20 great (magnitude [Mw] 8.2) events due to underthrust motion have occurred in the twentieth century; the number increases to 42 by counting underthrust events with Mw 8.0 (Fig. 34). In addition to earthquake magnitude, factors that influence the destructiveness of a subduction-zone earthquake are its position with respect to population and whether the fault displacement propagates to the seafloor, causing sudden changes in the seabed and the generation of tsunamis. The uneven distribution of the largest events due to underthrusting is one manifestation of the diversity of subduction zones. Subduction zones that pose a major threat to cities having populations greater than 1 million include those of Peru-Chile, Middle America, Cascadia (i.e., Oregon and Washington and southern British Columbia), Northeast Japan, the Nankai Trough (in the Pacific Ocean offshore southeastern Japan), and Java-Sumatra.

"Uncounted numbers of lives have been lost from earthquakes and associated tsunamis, and more than 90% of seismic energy worldwide is released in subduction-zone earthquakes."

The theory of plate tectonics provides the underlying kinematic explanation for these destructive earthquakes. Studies of earthquake foci show that only a small part of the plate contact generates earthquakes: this is the seismogenic zone (Fig. 35). The seismogenic zone is the region of the subduction zone where the subducting and overriding plates are coupled to some degree so that elastic strain accumulates. The locked or coupled region is bounded at the top and base by what we term here the "updip" and "downdip" limits of the seismogenic zone (Fig. 35). In this coupled zone, elastic strain builds up and is eventually released as an

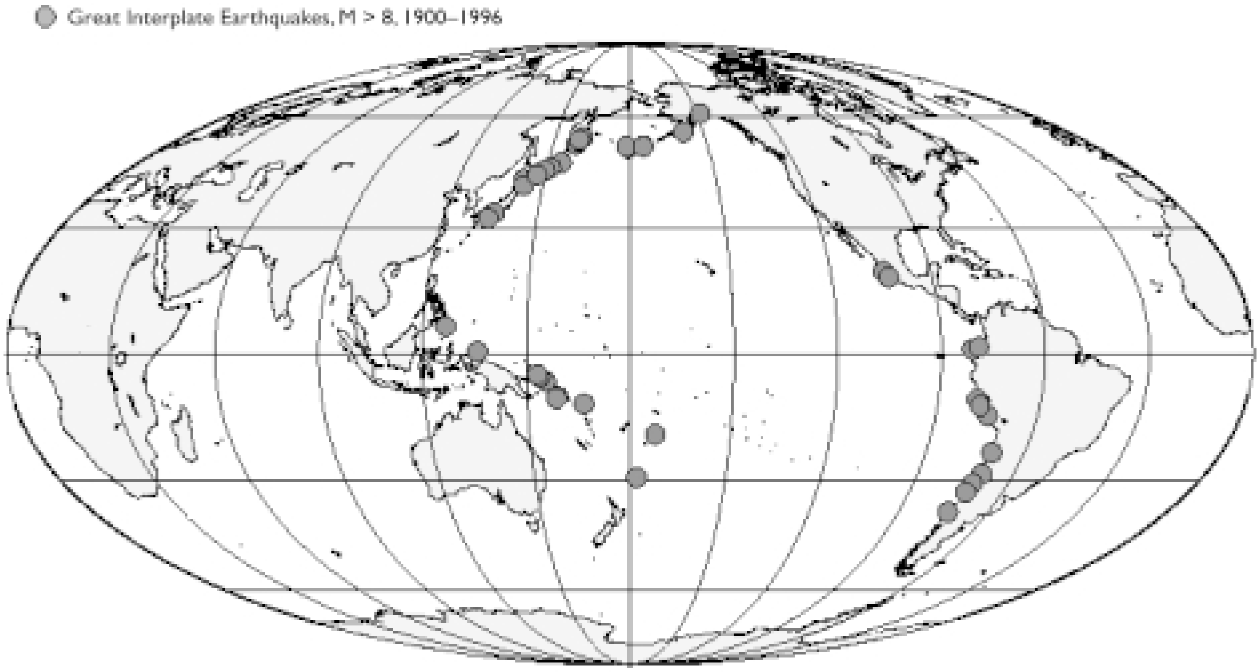


Figure 34. Global distribution of great interplate earthquakes with magnitudes greater than 8 (shaded circles).

earthquake. The amount of destructive energy released by an earthquake is controlled by the rupture area, the amount of slip, and the drop in shear stress. Seismology and geodetic strain measurements reveal considerable complexity in the manner in which energy is stored and released within the seismogenic zone. Rupture characteristics of large subduction earthquakes vary among different subduction zones and sometimes within the same subduction zone. Rupture most often seems to be initiated from the downdip end although there are many exceptions in which rupture starts within the zone or at the updip limit. Seismographic studies of earthquakes have revealed the following:

- Many seismogenic zones, although capable of generating earthquakes, do not generate large earthquakes.
- As the level of modeling detail increases, an increasingly complex picture of stress and of slip motion has emerged.
- Because the same fault does not necessarily slip in the same way over successive earthquake cycles, dynamic controlling factors must be considered.

- Some earthquakes involving relatively slow slip (slow earthquakes, tsunami earthquakes) generate large destructive tsunamis without a correlative large seismic energy release.

These findings from remotely measured seismographic data are yet to be related to the actual spatial distribution of physical properties at or near the seismogenic zone. To understand why the seismogenic zone behaves in the way it does requires a variety of information to be input from a very broad interdisciplinary base so that realistic models can be constructed that are based on actual material and physical properties obtained through direct sampling of the fault zone itself. Subduction environments have a unique property—the main thrusts are part of the subduction conveyor belt. Only near the trench can we sample the incoming sediments that become part the subduction zone and determine how their evolution affects seismogenic behavior.

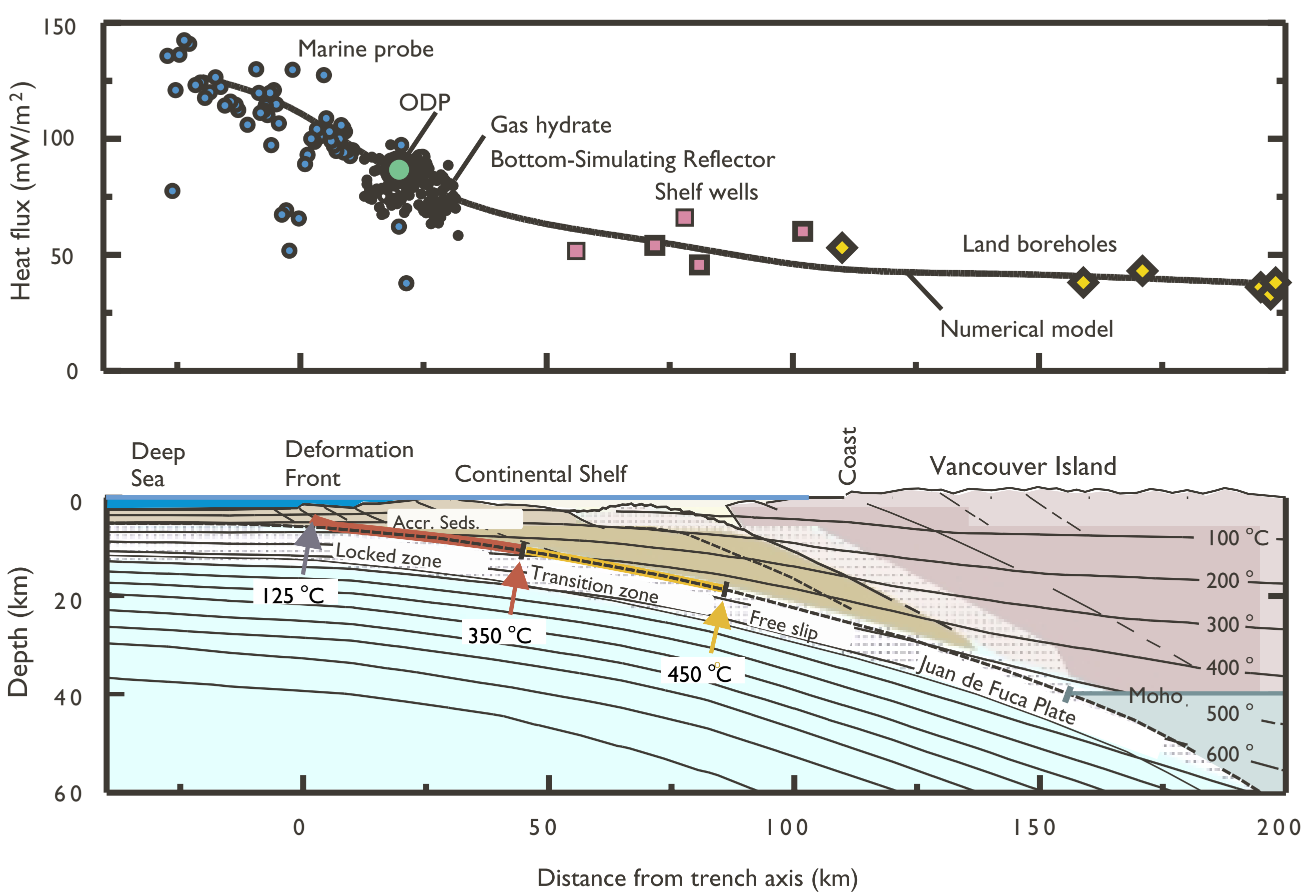


Figure 35. (Top) Heat-flow data used to model the thermal structure of the wedge above the Cascadia subduction system. (Bottom) Line drawing of a seismic reflection section across the Cascadia subduction system showing the expected temperature and depth of the seismogenic zone and the relative positions of the updip and downdip limits of the locked region of the fault.

Key Scientific Questions to Be Addressed Through an Integrated Multiple-Platform Drilling Program and Related Studies

What controls the updip and downdip limits of the seismogenic zone? Why does the coupling on the seismogenic fault change laterally, and what is the nature of seismic asperities?

What fundamental mechanisms control the earthquake cycle of elastic strain buildup and its sudden release through fault rupture?

The seismogenic-zone experiment in a subduction-zone environment has been conceived over a number of years as a multidisciplinary program that will allow both direct sampling and monitoring of the upper and intermediate levels of the seismogenic zone through drilling a transect of boreholes by riser-equipped and riserless ships (see Fig. 36). The goal of the seismogenic-zone experiment is to understand the relationship between earthquakes, deformation, and fluid flow in this environment. The experiment will address, among others, the following questions:

- What controls the updip and downdip limits of the seismogenic zone? Why does the coupling on the seismogenic fault change laterally, and what is the nature of seismic asperities?
- What fundamental mechanisms control the earthquake cycle of elastic strain buildup and its sudden release through fault rupture?

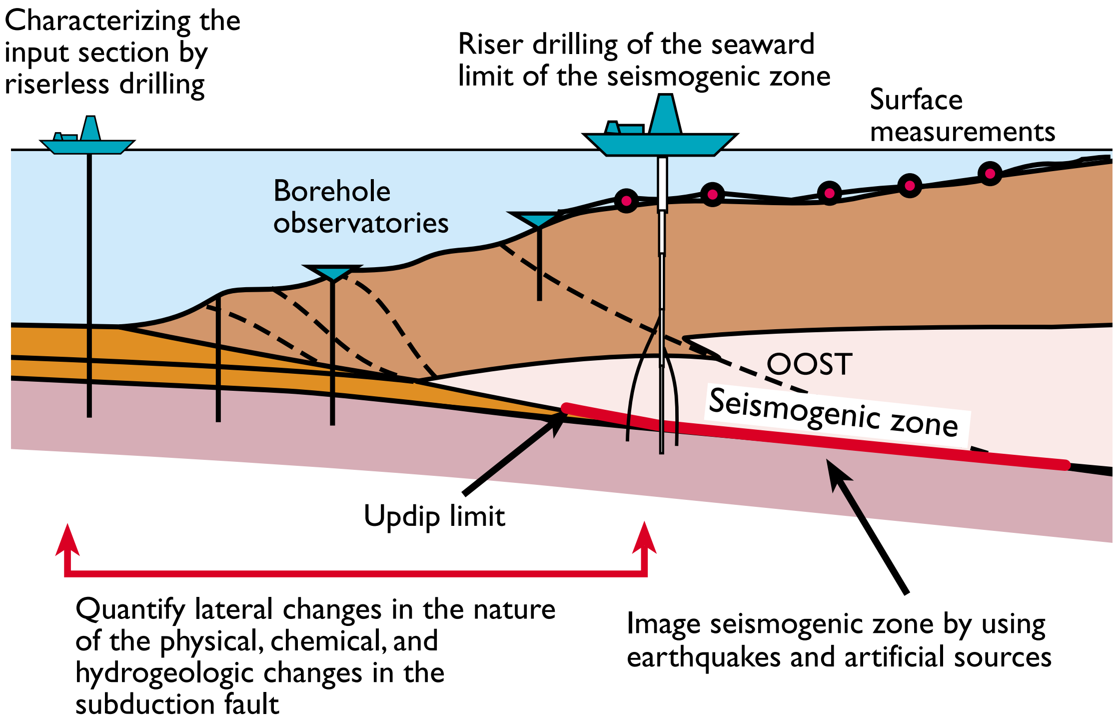


Figure 36. Integrated strategy of multiple borehole drilling with riser-equipped and riserless ships and related surface measurements to study subduction-zone earthquakes. OOST—out-of-sequence thrust.

- Are there temporal changes of stress, pore pressure, chemistry, and other parameters that define the times of increasing probability of great earthquakes?
- What is the nature of the tsunamigenic earthquake zone?

What Is the Nature of the Updip Limit of Seismogenic Activity?

Central to an understanding of the mechanics of seismogenic faulting in general is the related question, Why does the fault change from stable to unstable sliding as materials are thrust down into the seismogenic zone during progressive subduction (Figs. 35 and 37)? This question can be directly answered through the future ocean drilling of subduction-zone seismogenic thrusts. The following competing hypotheses exist to explain this transition from aseismic to seismic fault slip:

- The updip limit may be a temperature-controlled boundary because in many subduction zones, its position typically conforms to the 100–150 °C isotherm. The onset of unstable sliding may occur because of temperature-induced diagenetic or metamorphic changes within the fault, such as clay-mineral dehydration.
- Increase in coupling across the subduction zone occurs because the pore-pressure regime changes downdip from shallow highly overpressured systems to a lower-pressure regime in the region of reduced fluid production that is coincident with the seismogenic zone. The factors affecting fluid production in this case include both the effects of mechanical porosity reduction and diagenetic release of water from hydrous mineral phases.
- Changes in the active deformation mechanism alter the effective frictional properties and lead to healing of the fault. For example, the onset of seismogenic behavior may correspond to the increasing dominance of pressure-solution reactions in the materials of the seismogenic zone.

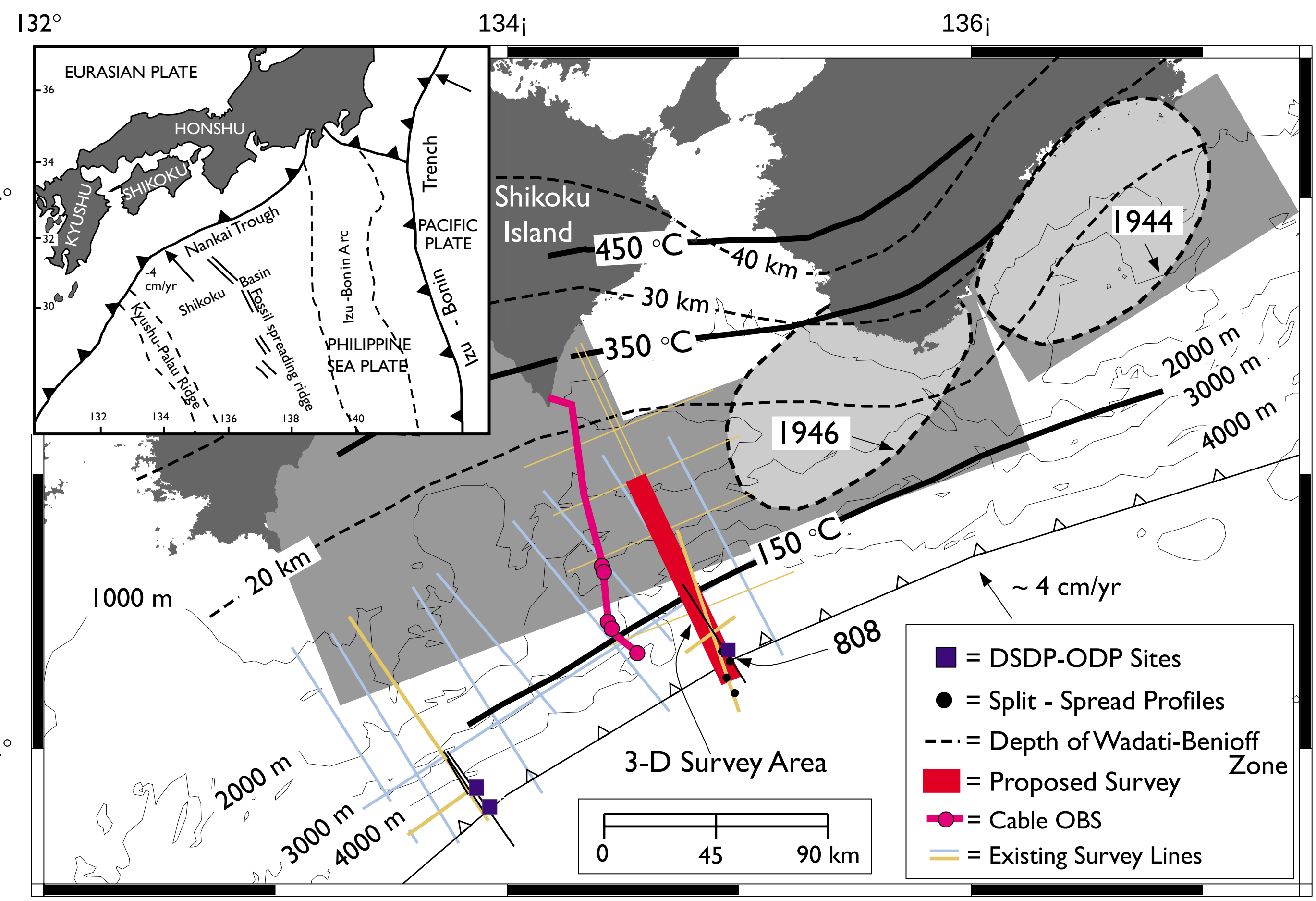
Are there temporal changes of stress, pore pressure, chemistry, and other parameters that define the times of increasing probability of great earthquakes?

What is the nature of the tsunamigenic earthquake zone?

What is the nnature of the updip limit of seismogenic activity?

Why does the fault change from stable to unstable sliding as materials are thrust down into the seismogenic zone during progressive subduction?

A



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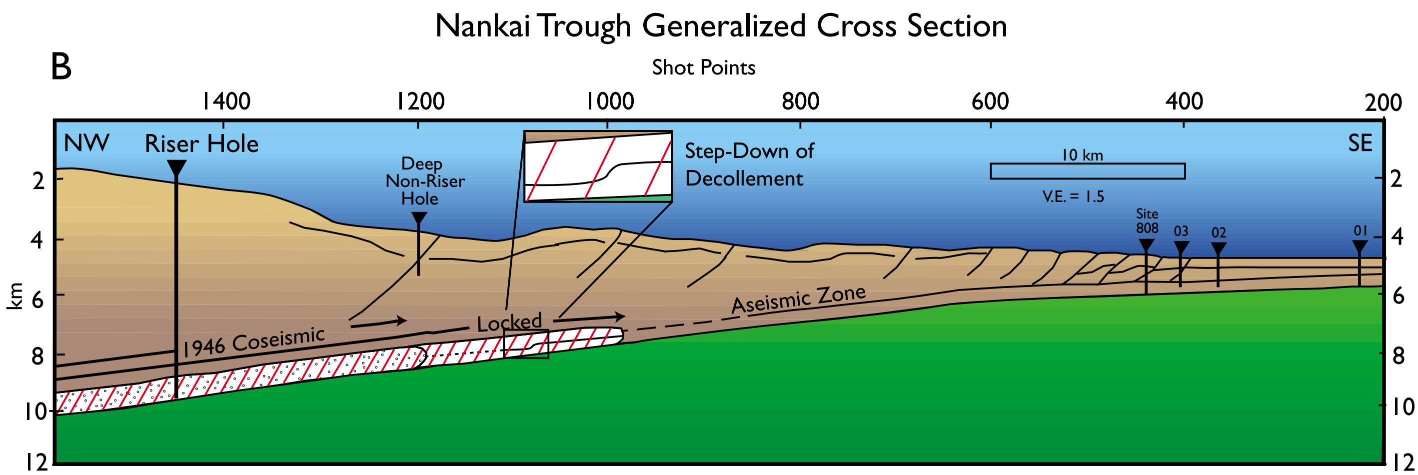


Figure 37. (A) Map of the temperatures at different depths on the subduction zone southeast of Japan (islands are shaded dark gray), the estimated position of the locked region of the subduction zone (medium gray shaded region), and the positions of some of the earthquake rupture zones (light gray shaded rounded regions) of historical earthquake activity where the Nankai Trough intersects Japan. The historical slip patterns have varied in position and areal extent but suggest that a segmented and heterogeneous distribution in properties exists on the subduction zone. (B) Line drawing of a seismic reflection section running through the three-dimensional seismic survey area in A, showing the locked region and a possible location for the deep borehole to be drilled by a riser-equipped ship.

Why Are Seismogenic Faults Weak?

Why are seismogenic faults qeak?

It has been observed that plate-boundary faults in general are anomalously weak with respect to the crust. Despite years of study, there is no tested model for the fundamental mechanics of major faults. Several hypotheses have been proposed to explain the weak-fault observation; they broadly fall into two categories: (1) The fault zone is intrinsically weak over long timescales, either because of the presence of mineral components of low frictional strength (e.g., clay-rich fault gouge) and/or because of very high pore pressure that reduces the fault-normal stress. (2) The fault zone becomes dynamically weak only during earthquakes because of specific physical phenomena associated with seismic energy release, such as propagating dislocation slip or acoustic fluidization.

Why Is the Seismogenic Zone Heterogeneous?

Why is the seismogenic zone heterogeneous?

To take a large-scale global view, perhaps the most important single characterization of seismicity is the size of the largest earthquake that occurs within a particular subduction zone. Even this most basic characteristic shows great variation among subduction zones, from the giant earthquakes that occur in Chile and Alaska to the near absence of significant interplate events in zones such as the Marianas (Fig. 34). All other aspects of seismicity follow the great earthquakes in their diverse behavior. Why these differences occur is another fundamental mystery that can be addressed by both drilling and other types of geophysical and geologic study.

The distribution of slip during earthquakes is also often uneven, and it is also clear, based on geodetic measurements, that the degree to which the seismogenic zone is coupled can vary between, and within, subduction systems. Some seismogenic zones currently appear to be almost entirely locked along their full length (such as the Nankai and Cascadia systems), indicating the possibility of future giant earthquakes should more that one segment break (Fig. 37). Others (e.g., the Costa Rica system) show lateral variations in the degree of coupling, with some strain being released aseismically or in smaller earthquakes. There also appear to be regions within the seismogenic zone that release larger amounts of seismic energy (termed "seismic asperities") and that have been inferred to be stronger. Why these differences in behavior occur is not currently known, but they probably relate in some way to one or both of the following factors:

- The material properties or environmental conditions of the fault vary laterally. Asperities could be regions of the fault that are stronger because of fault geometry, different material frictional properties, and/or fluid pressure. Weakly coupled regions may be composed of weaker materials or have highly elevated fluid pressure.

What controls the earthquake cycle?

- The dynamics of earthquake propagation are naturally complex, and strain buildup and release patterns vary between earthquake cycles even when fault properties are relatively uniform laterally. Some asperities could products of the earthquake-propagation dynamics and may not always be permanent through subsequent seismic cycles.

What Controls the Earthquake Cycle?

There are fundamental uncertainties concerning how the interactions between temporal changes in stress, strain, and fluid flow and/or fluid pressure influence the nature of the earthquake cycle. Many of these uncertainties are applicable to seismogenic zones in all tectonic environments. Several hypotheses have been put forward as to how the earthquake cycle may be moderated by fluids in the system. For example, in the favored fault-valving hypothesis, the episodic stress buildup and release during earthquakes dynamically interacts with a hydrologic-valving action on the fault. The valving action is in turn driven by the buildup and release of fluid pressure generated by mineral-dehydration reactions. Observed pore-fluid anomalies at the toe of some accretionary wedges are proposed to be episodic pulses generated by such a fault-valving mechanism. The actual applicability of these episodic fault-valving models has yet to be tested and verified.

Why do anomalous tsunami earthquakes occur?

What is their mechanism?

Is their source distinctly different from typical seismic events?

Do they occur on the decollement similar to a typical subduction-zone earthquake or do they occur on out-of-sequence faults?

During and after these earthquakes, do large submarine landslides contribute to the tsunami response?

Why Do Anomalous Tsunami Earthquakes Occur?

Large subduction-zone earthquakes generate hazardous tsunamis with devastatingly catastrophic consequences. Large earthquakes are expected to generate tsunamis. However, in some cases, large tsunamis are generated by relatively modest magnitude earthquakes (e.g., the 1992 Nicaragua earthquake) known as "tsunami earthquakes." Many vital questions remain about tsunami earthquakes: What is their mechanism? Is their source distinctly different from typical seismic events? Do they occur on the decollement similar to a typical subduction-zone earthquake or do they occur on out-of-sequence faults? During and after these earthquakes, do large submarine landslides contribute to the tsunami response? These events pose a particular hazard for coastal areas because their relatively modest magnitude fails to provide warning of the potentially devastating tsunami that follows.

Recent modeling studies indicate that tsunami generation associated with these events results from fault slip located near the trench axis, which is seaward of the expected seismogenic decollement zone. Coincidentally, tsunami earthquakes apparently occur preferentially where the surface of the subducting ocean crust is rough. A physical model suggested by this observation is that strong contact may occur between subducted horsts and the overlying plate near the trench and thus provide a mechanism for generating tsunami earthquakes. The part of the decollement critical for tsunami earthquakes is reached by current riserless drilling. A primary test is to monitor surface and borehole displacement and strain to see whether the strain is actually accumulating in this zone at the base of the trench slope. The second test is to study rock samples from the contact zone to estimate its strength characteristics (pore-fluid pressure and frictional properties).

Strategies to Address These Key Questions That Bear on the Seismogenic Zone

For the first time, these various competing hypotheses can be tested by using the new technologies planned for the proposed scientific drilling program (Fig. 36). An integrated analysis of the seismogenic zone requires at least a ten-year program. Many of the basic strategies outlined in this section will help answer one or more of the questions we have asked. The ordering of certain elements of an integrated drilling program should be undeniable, for example, extensive surveys are required prior to deep drilling. Other aspects of the program would be completely interwoven, and results from one area would often trigger further studies in another.

Geophysical Surveys

The early stages of the seismogenic-zone experiment will require (1) seismic reflection imaging and characterization of the subduction zone in two dimensions to depths within the seismogenic region, (2) determination of the position of the updip limit by geodetic methods and microseismicity patterns, and (3) resolution of the thermal structure of the wedge. By extending seismic and geodetic recording arrays offshore, we can monitor the buildup of stress and strain in the oceanic crust as the earthquake cycle progresses to determine the position of the updip limit of the locked region. Any asperity on the fault would also cause variation in the strain and stress buildup and should cause intraplate focal mechanisms to take on an increasingly stronger compressional component. The possibility that the acoustic properties of the fault zones may also vary with the nature of its physical properties and environment (i.e., fluid pressure) may also allow sophisticated three-dimensional seismic reflection images to be made of the laterally changing character of the fault zone (Fig. 38). Current two-dimensional seismic reflection images of the seismogenic zone display a coherent band of high-amplitude, low-frequency reflections about 1 km thick. Although the low seismic resolution can be explained with Earth filtering and constructive interference or tuning, wide-angle seismic observations commonly require a 1-km-thick low-velocity zone along the plate boundary. Thus if seismic records are interpreted literally, the plate boundary is a broad zone of distributed shear. Field evidence suggests, however, the active region of fault zones often localize into narrow regions within the zone of damaged rock and that the structure and properties vary considerably in three dimensions. Indeed, it has been demonstrated that three-dimensional seismic reflection methods can reveal considerable information on the laterally changing acoustic properties and/or density distribution within subduction zones, at least at shallow levels of the system (see Fig. 38). There are current programs that will extend such three-dimensional data to cover the deep seismogenic regions of the Nankai Trough subduction system. It is tempting to indirectly associate these three-dimensional changes in acoustic properties with variations in coupling on the fault through the required changes in physical properties. Ultimately, however, the questions surrounding heterogeneous fault-zone behavior have to be addressed by drilling into regions of fault zones with different acoustic properties, degrees of strain accumulation, and coupling; only then will we be able to determine what it is that makes them different. Once geophysical imaging methodologies are calibrated, it should then be possible to use them to extend the drilling observations to characterize the properties of the large regions of the subduction zone.

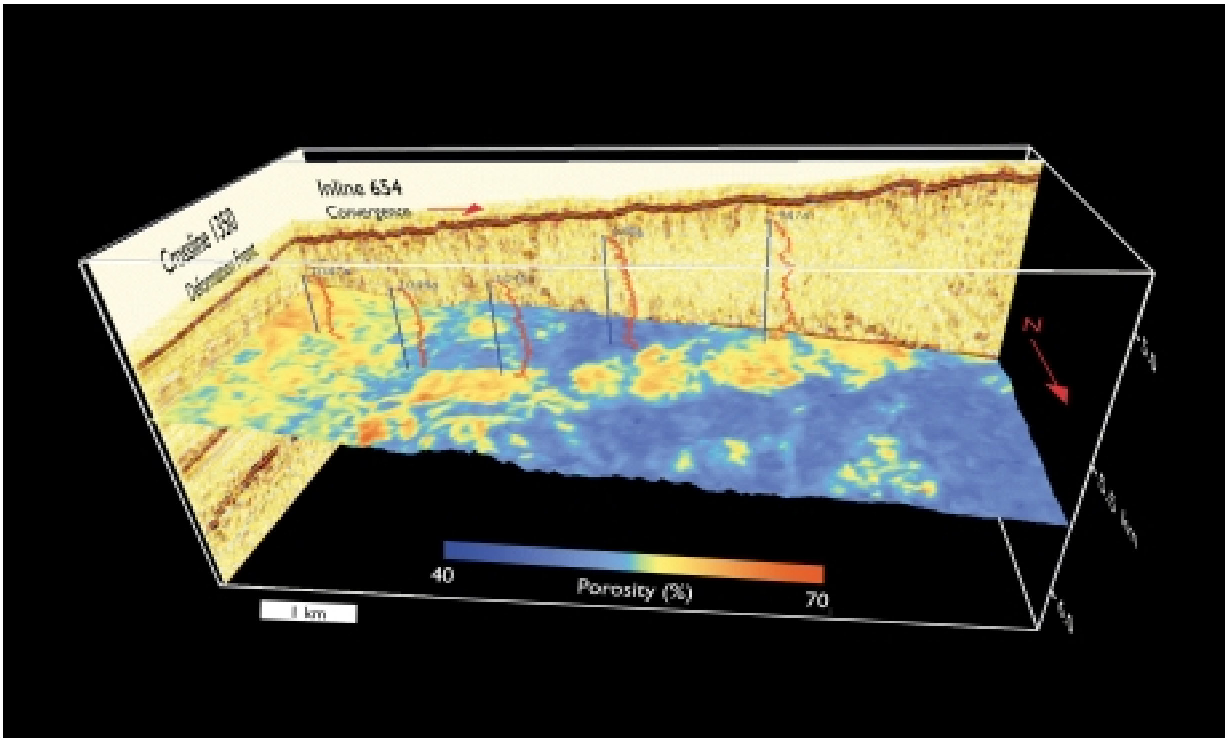


Figure 38. Three-dimensional seismic reflection image showing the calculated porosity variation in the decollement of the North Barbados wedge. The bright regions correspond to high-porosity, lower-density regions in the decollement zone. The reflective properties of the decollement zone were found to be highly heterogeneous, suggesting that lateral variations in fluid pressure and frictional coupling may exist on the subduction zone.

Two-Ship Drilling Strategy

A two-ship drilling strategy will utilize a transect of boreholes and monitoring stations (Fig. 36) to define the lateral and depth-related changes in physical and chemical environment and properties of the materials entering the seismogenic zone—i.e., their temperature, stress, mechanical properties, deformation mechanisms, constituent minerals, fluid pressure, fluid flow, and fluid chemistry. Determination of the lateral changes has direct relevance to both seismogenic and subduction-flux objectives (see the chapter on the subduction factory). The basic experimental methodology will be to use the riserless ship to determine the nature of the input materials and to measure and monitor the initial depth-related changes that occur within the shallow region of the system above the updip limit (subbottom depths, 1 km to maximum riserless-drilling penetration; water depths, more than 2.5 to 4 km). Shallow riserless drilling will also provide vital information on the lateral changes in the nature of the input materials and how they relate to changes in seismogenic response. Our knowledge of the hydrologic regime and the physical conditions that exist deeper within the subduction zone could also be extended with a series of shallow to intermediate-depth boreholes drilled into faults (e.g., out-of-sequence thrusts) that splay off the decollement (Fig. 36). The Tokai thrust in the Nankai wedge that forms southeastern Japan is one such hydrologically active structure that intersects the seismogenic zone. The primary objective of drilling out-of-sequence thrusts is in situ monitoring of pressure, temperature, and geochemistry of the fault-zone fluids by utilizing long-term observatories. By monitoring changes in the hydrology and fluid chemistry along subsidiary faults that are connected to the subduction zone at various depths, it should be possible to remotely monitor changes in the seismogenic environment during the earthquake cycle. Furthermore, displacements along these deeply rooted out-of-sequence thrusts may be intimately tied to tsunami generation and could hold critical clues to conditions conducive to tsunami as well as earthquake generation. Some tsunami earthquakes (i.e., Nicaragua) have been located in the shallow regions of the main subduction zone, and the depths to the zones responsible appear to be within the depth capability of the riserless ship.

Ultimately, the deep drilling capability of the riser-equipped ship would be used to directly sample the seismogenic zone (probably between 4 and 7 km below seafloor). The deep drilling environment is expected to be difficult, particularly as the seismogenic zone is approached, so the main borehole drilled by the riser-equipped ship will be cased throughout. Perforations in the casing will allow hydrogeologic monitoring. The main borehole would also be preceded by a pilot hole to evaluate the shallow structure, the geotechnical conditions, and the thermal gradient—requirements for planning the main hole. During the phase of main borehole drilling, the fault zone would be extensively imaged and characterized by downhole geophysical methods including logging-while-drilling during the initial phase of drilling. Hydrogeologic well tests, spot cores, and fluids samples could also be taken at casing set points, and changes in mineral constituents with depth would be assessed by examining cutting samples. Once the main hole is stabilized by casing, any actively deforming region within the main fault zone would be located (1) by the placement of arrays of seismometers within the seismogenic zone to define local patterns of microseismicity and (2) by monitoring deformation of the cased borehole for a few years. It would then be possible to drill a series of lateral wells off the main cased borehole to conduct a wide range of physical, hydrogeologic, and chemical measurements within the previously defined active region of the seismogenic fault (Fig. 36). The use of lateral wells would allow a cost-effective utilization of the investment made at the deep sites by enabling the fault to be sampled and measurements to be made at multiple locations within a few hundred meters around the main hole. Perforation and sidewall coring in the main central well would also allow the relevant active sections to be sampled and hydrogeologically monitored for changes in fluid pressure and chemistry at multiple levels by using multiple-packer systems (see the next section, Long-Term Monitoring). There is even the possibility that some lateral wells can be used to conduct cross-hole experiments within the main fault zone. One conceivable way is to place autonomous measuring devices in the lateral wells and conduct cross-hole tomographic studies by pumping or placing active electrical or seismic sources in the main well (Fig. 36).

The drilling, sampling, and measurements to be conducted at different locations and depths in the subduction zone will provide the fundamental information to allow us to differentiate between the various hypotheses concerning why the fault properties change across the updip limit. We will also be able to determine the causes of weakness and heterogeneity of the seismogenic zone. In addition, drilling would permit the placement of long-term observatories and associated instrumentation directly within in the seismogenic fault to monitor its response. Only by directly comparing and contrasting the various properties of the seismogenic zone in regions that exhibit different degrees of coupling will we be able to ascertain which properties primarily control the strength of subduction faults. Drilling is also required to define the nature of the plate-boundary faults that give rise to the anomalous tsunami earthquakes.

Long-Term Monitoring

The time-varying properties of the system can be addressed (1) by long-term monitoring of surface strain and seismicity patterns and (2) by utilizing an instrumented transect of boreholes drilled across the subduction system (Fig. 35) as long-term monitoring stations that measure fluid pressure, strain, seismicity, and fluid flow and chemistry above and within the subduction zone (Figs. 35 and 36). Instrumented corks that hydraulically seal boreholes would provide a real-time record of subsurface transient events manifested by temperature, pressure, and pore-water chemistry anomalies. At the very least, these records will establish the "steady-state" hydrologic conditions in various parts of the formations that host seismogenic zones and even the faults themselves. The monitoring devices may also define precursor, co-seismic, or postseismic signals, since it is almost certain that hydrologic signals are sensitive to changes in stress, ground motion, and fault-zone slip. It is also possible that by monitoring changes in seismic anisotropy by downhole seismometers, it would be possible to detect fluid movement in oil reservoirs. Anisotropy in the seismogenic zone is expected to be due to (1) fabric alignment by shear strain along faults or (2) crack alignment in the regional stress field (extensive dilatancy anisotropy). The degree of anisotropy in the seismogenic zone may be correlated with friction during creep and rupture, while temporal changes in extensive-dilatancy anisotropy might be earthquake precursors. Fluctuations in any or all of the measured parameters at the deeper sites can be compared with those at sites near the toe of the wedge (Fig. 36). We will be able to investigate the time delay between events in the seismogenic zone and those occurring at the toe of the margin and between strain, seismic events, fluid flow, and pressure fluctuations at and between sites. Fluid-pressure monitoring additionally offers the possibility of determining fault-zone permeability, both absolute and relative to the surrounding country rock. Fault-zone permeability, which may be time-dependent, is also a discriminator between competing models for the earthquake process, some of which require low permeability to maintain high fluid pressures.

Laboratory and Theoretical Studies

An integrated scientific drilling program will also require detailed geologic, in situ, laboratory, and modeling studies of the hydrology and evolution of the physical and chemical properties of the system and the rate and state-dependent frictional properties. Laboratory experiments should address the following fundamental processes:

- Steady-state fluid-rock reactions and their kinetics, partition coefficients, and isotopic fractionation factors.
- Thermally and physically activated mineral-dehydration reactions and their impact on rheological boundaries.

- The changes in relationships among seismic velocity (Vp and Vs), seismic attenuation, density, fluid content and composition, and stress during sedimentary compaction, diagenesis, metamorphism, and deformation—all necessary to infer the physical meaning of seismic images and wave propagation.

- The linkage of chemical and physical processes to changes in porosity, permeability, stress, and rheology, crucial to understanding the temporal and spatial changes in seismogenic behavior and interplate coupling (e.g., velocity strengthening and weakening relationships, seismic and aseismic stress release).

Numerical models will also be essential for integrating the field observations and laboratory results and for guiding data-collection needs at a variety of scales. New observations and parameter values can be used to refine the existing models and guide further sampling and experiments. As our level of knowledge about the important processes grows, new models will be required that account for multiple coupled processes such as coupled pore pressure, stress, and temperature or coupled fluid flow, chemical reactions, and transport. Moreover, some existing models will need to be extended from two to three dimensions to account for variations along strike of important controlling processes. Simulations will be required on a range of scales from the borehole to the entire subduction zone.

Looking with New Eyes Through On-Land Windows to the Deep Seismogenic Zone

Once the thermal and metamorphic regimes and the fabric in the seismogenic zone are directly determined, it would be possible to conduct more focused on-land field studies in analogous ancient exposed subduction terranes to fill out a larger, three-dimensional picture of the overall nature of the seismogenic environment and fluid-expulsion patterns as shown in veins. Paleo–seismogenic zones will be studied with the disciplines of structural geology, metamorphic petrology, geochemistry, and geochronology. Particular attention should be focused on (1) structural packages that may represent the paleodecollement and (2) out-of-sequence faults that display large amounts of vertical displacement of the paleotemperature structure. Analyses should focus on contrasts among hanging-wall, footwall, and associated shear zones. These contrasts may be defined by differences in deformation fabrics, mineral assemblages in veins, stable-isotope values in vein minerals, fluid-inclusion microthermometry, vein density and orientation, alteration of organic matter, and phyllosilicate diagenesis. Fluid-inclusion studies would also provide information on the changes in paleotemperature, fluid pressure, and composition during repeated crack-seal events in the fault zones. Determination of the thickness of paleo–seismogenic zones will provide a basis for waveform models from seismic reflection data. Timing of faulting can be established by using fission-track geochronology, for example.

In addition to the field studies, seismology and geodesy will place significant bounds on the position of the downdip limit of seismogenic rupture (Fig. 35) through investigation of main shock and aftershocks of great earthquakes and strain buildup in the coastal environment. The base of many subduction seismogenic zones lies between 20 and 40 km depth and, thus, is beyond the depth capability of even the riser-equipped ship. Drilling at shallower depths and the associated downhole and surface instrumentation will, however, indirectly add considerably to our information on the nature this region. At present, the downdip limit is thought either to be thermally controlled, perhaps governed by a temperature of 350 °C (Fig. 35), or to be a rheological boundary associated with the position where the weak altered mantle (serpentinized mantle) comes into contact with the subduction zone. Knowledge of fore-arc architecture, thermal state, and rheology are consequently critical to understanding and modeling possible controls on the downdip limit. Temperature measurements in boreholes will certainly improve the constraints that can be placed on the thermal structure of the wedge. The placement of borehole seismometers at different depths seaward of the deeper parts of the seismogenic zone will also greatly improve the tomographic studies, and it may also be possible to conduct guided-wave studies in the seismogenic fault itself.

Linkage to Other Seismogenic Fault Drilling and Earthquake Studies

Subduction-related investigations form an integral part of a developing comprehensive study of the seismogenic process. Seismogenic zones occur in compressional, extensional, and strike-slip environments. Drilling proposals exist for investigations in the San Andreas system and extensional structures in the Gulf of Corinth. Certain questions apply globally to all seismogenic zones; others, like the anomalous tsunamis, are unique to the subduction environment. Studies of the nature of the seismogenic zone in the subduction environment have a unique contribution to make because (1) these zones produce the largest earthquakes and (2) the low angle of the seismogenic zone should allow it to be well imaged three dimensionally so that specific regions of interest are targeted. It should also be possible to repeatedly resurvey the properties of the seismogenic zone to ascertain whether they change during the earthquake cycle. A shallowly dipping subduction zone also provides a large fault surface that is accessible to study by a combination of drilling and ongoing monitoring. Therefore, the processes that control the partitioning of strain, the flow of fluids, the formation and behavior of faults, and the onset of seismic slip are relatively accessible. Information on fluids obtained by deep drilling into the seismogenic region of a subduction zone would complement similar information from a proposed San Andreas borehole. In addition, a narrower range of conceptual models may be more suitable for the fluid-flow regime of a subduction system than for the regime of a strike-slip fault. First, the expulsion of volatiles by volcanism places a constraint on fluid composition beneath the seismogenic zone that is not available for strike-slip faults. Second, compared to the situation of strike-slip faults, the composition of fluids and sediments entering the seismogenic zone can be better constrained and their progressive evolution better studied. Third, the maintenance of high pore pressure by compartments of low hydraulic gradient seems unlikely in a subduction zone because there the fluid supply is continually replenished and additional fluids are generated by dehydration reactions. Subduction zones are therefore optimum places in which to determine what makes a fault zone capable of failing seismically to produce great earthquake events.

Considerable benefits will be gained during the integration of subduction-zone drilling with related drilling projects in extensional and transform environments (e.g., San Andreas drilling) and with other national and international programs that focus on earthquakes. Foremost among the programs in the United States is the National Earthquake Hazard Reduction Program (NEHRP), which includes four government agencies: the Federal Emergency Management Agency (FEMA) as the lead organization, the U.S. Geological Survey (USGS), the National Science Foundation (NSF), and the National Institute of Standards and Technology (NIST). The NEHRP mission is directed toward regions of the United States where large populations and human-made structures are at greatest risk, especially California and the Cascadia subduction zone, and to a lesser extent, the Gulf of Alaska and Puerto Rico–Virgin Islands. Another program that could be involved with future scientific ocean drilling is the Incorporated Research Institutions for Seismology (IRIS), which manages a broad-band, high-dynamic-range global seismic network, a set of portable receivers, and a data management center. IRIS is funded in part for nuclear test-ban verification, but a major component of its funding goes toward understanding earthquake sources and the degree of seismic coupling at plate boundaries.

Internationally, the organization most involved in earthquakes is the Inter-Union Commission on the Lithosphere (ICL), which has a subprogram on earthquake hazards of megacities, many of which are at risk because they are near subduction zones. ICL has limited funds, and its goal is mainly to bring people, particularly from developing countries, together to discuss ways to reduce hazards from earthquakes. ICL is a good channel for contacts in countries adjacent to subduction zones that are possible drilling targets, such as Central and South America.

Key Needed Technologies

The proposed transects across subduction-zone margins will include both deep boreholes drilled by a riser-equipped ship and shallower boreholes drilled by a riserless ship. The drilling and measurement technologies used in the seismogenic-zone experiment must be able to cope with the expected elevated temperatures, large fluid overpressures in certain parts of a formation, and faulting and associated geologic problems, as well as gas hydrates and gas and/or water flow. These problems should be less significant for a riser-equipped ship, compared to the current riserless *JOIDES Resolution*, because the riser-equipped ship's ability to circulate drilling mud and control well pressure will allow the following: increased borehole stability and thus much higher-quality and continuous core; balancing of fluid pressure with heavy mud, especially where the drilled section is overpressured; a blowout preventer for drilling areas that may contain hydrocarbons; continuous return of cutting samples; much higher quality downhole geophysical logs because of the constant-diameter (gauge) borehole that is possible through stabilization by drilling mud; and access to the borehole through large-diameter casing pipe.

High downhole temperatures will be a feature of most deep sites where the subduction zone is at a depth within the drilling limit, typically because young crust is being subducted. For such a region, e.g., the Nankai Trough, the temperature at a decollement 5 km below the seafloor is expected to be 150 ± 50 °C. The borehole may be cooled by drilling circulation, which reduces the temperature problem for drill bits and downhole assemblies. A much more serious temperature limitation exists for long-term downhole recording. It may be necessary to limit electronic recording equipment to the top of the borehole and to connect the equipment to sensors with high-temperature limits located at greater depth. Detailed heat-flow probe measurements and thermal proxy data such as BSR depth (i.e., the seismically imaged bottom-simulating reflector), detailed thermal modeling, and pilot-hole temperatures are essential to accurately predict the temperature of the formation to be drilled.

In the following list, red bullets denote measurements for which significant instrument technology development is required for use at very high temperatures (greater than 175–250 °C). If high-temperature tools are known to exist, the temperature limitations of these tools and the known sources for these tools are given in parentheses. Downhole geophysical tools are being developed rapidly, and it is recommended that a review of the current status of high-temperature and other tool development in industry, government, and university laboratories be carried out, to ensure that this list is current and to identify which new high-temperature tool development is warranted. It is noted that development of high-temperature tools is expensive. If possible, high-temperature target sections should be logged by using rapid circulation cooling followed by short measurement durations so that conventional logging and other measurement tools can be used.

Required Measurements

Wireline Logs

- Formation micro-imager (FMI or FMS)
- Borehole televiewer
- Density (in high-temperature environments)
- Natural gamma
- Porosity

- Dipole sonic (directional Vp, Vs, and full waveform)
- Resistivity, short- and long-normal
- Geochemical logging (essential, especially if coring is not continuous)
- Vertical seismic profiling (VSP), zero-offset, three-component
- Cement bond log
- Temperature, continuous logging tools (to 260 °C)
- Temperature, bottom-hole penetrating probes (limited to 100 °C, for shallow, less consolidated sediments)

Logging-While-Drilling

Logging-while-drilling (LWD) is especially important for SEIZE (seismogenic-zone experiment) drilling because it will be necessary to case much of the borehole. Conventional logging may be limited to short segments prior to installation of each casing string. LWD is being rapidly developed, and the tools available are rapidly increasing and improving. The state of tool development and availability should be reviewed just prior to the SEIZE drilling. The tools and capabilities should include the following:

- Resistivity imaging at bit (to 150 °C)
- Azimuthal density neutron instrument (to 150 °C)
- Sonic and/or natural gamma instrument (to 150 °C)
- Monitoring drilling parameters in real time (to 175 °C)

Some of these tools may be used in boreholes as hot as 175 °C in MWD (monitoring-while-drilling; pulse telemetry) mode. Also, the borehole may be cooled by as much as 30–50 °C during drilling. However, depending on circulation cooling may result in tools overheating if they become stuck in the borehole.

Fluid Sampling, Permeability, Pore Pressure, and Stress

- Cased-hole packers, set over perforations in cemented casing and above pilot holes at casing set points; permeability, fluid pressure, and stress (to 250 °C)
- Borehole fluid samplers (to approximately 250 °C); used for fluid sampling in conjunction with cased-hole packers only if rock permeability is high
- Modular dynamics tester (limited to 150 °C with packers, 175 °C with rubber pads); used for fluid sampling and permeability through perforations if rock permeability is low
- Temperature–pressure–spinner flow meter–natural gamma instrument, open-hole, static and during fluid injection (to 250 °C); gives vertical distribution of permeability if borehole flow rates are high

Downhole Monitoring and Recording

Borehole measurements using instrumented corks and remote observatory systems are a critical part of the scientific program providing insights into time-varying deformation, geochemical, and hydrologic processes within the subduction zone. The parameters that should be monitored in the borehole include the following:

- Strain and tilt
- Seismometry for earthquakes and controlled sources (to 250 °C; 15 and 2 Hz; may need development for clamping, array deployment, and broad-band sensors)
- Temperature vs. depth
- Fluid pressure (requires development for multiple horizons)
- In situ fluid chemistry

Seafloor Recording and Monitoring

Borehole downhole monitoring should be augmented by ocean-bottom seismometers or a seafloor observatory (i.e., similar to the Italian GEOSTAR system). Important parameters to be recorded include seismic radiation (with geophones and hydrophones) and seafloor deformation (geodetics).

Core and Mantle Dynamics

It is probably no coincidence that the most dynamically active planet in our solar system is the only one with an environment conducive to life. Convection in Earth's mantle is responsible for renewing the atmosphere, hydrosphere, and solid surface. Convection in the core produces the magnetic field that shields us from cosmic radiation. Despite some spectacular progress in the last decade in modeling the dynamics of Earth materials at high temperatures and pressures, we are just beginning to understand the interior state of the planet and how it behaved in the past and will evolve in the future. The greatest challenge is the inaccessibility of this region. Geoscientists have only a few ways to investigate the deep inner workings of the planet and must depend on remote sensing with geophysical data and geochemical sampling of magmas thought to have originated from source rocks deep within the mantle. To date, activities of the drilling program have not contributed much to progress in the area of core and mantle dynamics. However, new drilling strategies, particularly plans to install seafloor observatories in boreholes, will likely provide much needed new observations on Earth's deep interior.

"However, new drilling strategies, particularly plans to install seafloor observatories in boreholes, will likely provide much needed new observations on Earth's deep interior."

Seismology

Global Earth Structure

One of the most fruitful developments in solid Earth geophysics in the post–plate-tectonic era has been the creation of seismic images of Earth's interior with ever increasing resolution by using the methods of seismic tomography. With the simple assumption that the seismic wave-speed variations reflect differences in temperature in the deep interior, it has been possible to use these images to directly model mantle convection. The remarkable progress in understanding the patterns of convection and the rheological properties of the deeper layers was made possible by the installation of the Global Seismographic Network (GSN) and by advances in computing power. There are now 106 stations on the global network operated by IRIS (Incorporated Research Institutions for Seismology). In addition, there are networks operated by other countries, in particular the French GEOSCOPE that also has a global coverage. Many of the national and regional networks have sensors of requisite quality and participate in data exchange. Yet, some 80% of the instrumentation lies in the Northern Hemisphere, and there are areas of several thousand kilometers in dimension without a single seismographic station on account of the absence of a landmass (island or continent).

During the past ten years, although much progress has been made in studies of Earth's interior; the limitations imposed by the uneven distributions are also clear. Figure 39 shows the current sampling of the D≤ region (the lowest 300-km-thick layer at the bottom of the mantle) that can be achieved by using digital broadband data for the development of three-dimensional models of the propagation speed of horizontally polarized shear waves (SH waves) in the deep mantle. Dots are bounce points of ScS*n* waves (*n* is the number of times the reflected waves have bounced off the core-mantle boundary with $n = 1, 2, 3$), and lines are parts of the paths of S_{diff}/S (shear waves diffracted around the core) within the D≤ region (courtesy of C. Megnin and B. Romanowicz). Clearly, the Northern Hemisphere is much better sampled than the Southern Hemisphere, limiting the resolution of three-dimensional structure in the latter.

Figure 40 is from a recent paper on the radial anisotropy (transverse isotropy) beneath the Pacific plate. The bottom map is similar to maps of shear-velocity anomalies obtained with the assumption that the lateral variations in the shear

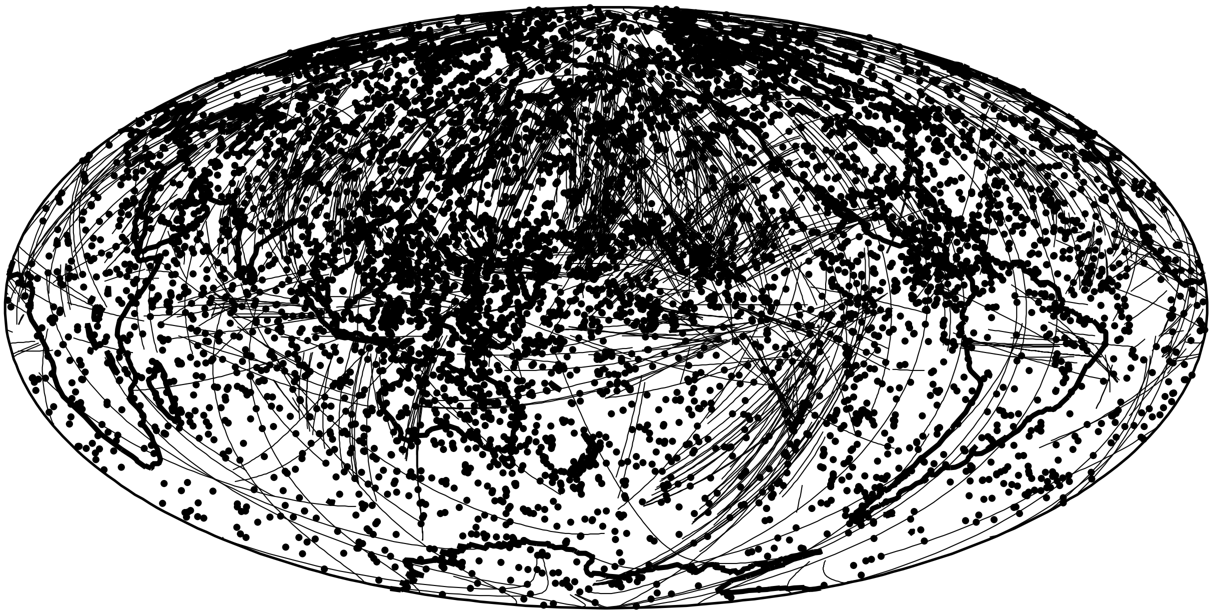


Figure 39. The sampling of the bottom 300-km-thick layer of the mantle (the D≤ region) for ScS*n* (points) and $S_{diff}S$ (lines). (From Megnin, C., and Romanowicz, B., in press. The 3D shear velocity structure of the mantle from the inversion of body, surface and higher mode waveforms. *Geophysical Journal International.*) Note the very poor sampling of the Southern Hemisphere and much of the Pacific Ocean largely because of the lack of global coverage.

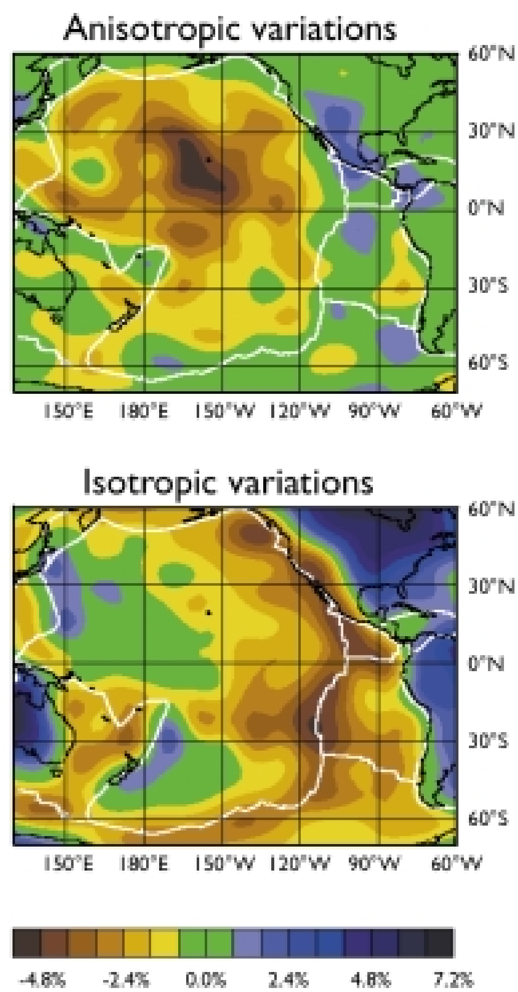


Figure 40. Map showing the behavior of shear-wave velocity anomalies in the Pacific. (From Ekstrom, G., and Dziewonski, A., 1998. The unique anisotropy of the Pacific upper mantle. *Nature,* 394:168–172.) The bottom frame is the shear-wave velocity anomaly at a depth of 150 km. The top frame shows the difference between the radial and horizontal anisotropic shear velocities. It is important to note that the data in the top frame show no correlation with plate age.

velocities are isotropic. The anomalies under the East Pacific Rise and the overall change of the velocities correlate well with the age of the plate, despite the fact that the image is at 150 km depth. Most thermal models of the plate assume isothermal conditions at close to 100 km, whereas seismic results require lateral variations in seismic velocity correlated with the age of the plate down to at least 200 km. The top map shows the variations in the difference between the radial and horizontal velocities. The pattern and the amplitude are totally unexpected. The distribution of the anomaly clearly has nothing to do with the plate's age, and its maximum amplitude is comparable to that beneath the ridge in the isotropic map (about 5%). At this time, there is no explanation for the observed anisotropic anomaly. As the quality of the network and the amount of data it has recorded increase, it will be possible to begin inverting for the parameters that determine the texture of the material, not only its isotropic properties. Yet our experience shows that to obtain a more uniform distribution and clearly resolve the properties of the Indian, southern Pacific, and Atlantic Ocean, ocean-bottom stations will be required.

High-resolution tomographic images showing subducted slabs supposedly penetrating into the lower mantle have caused much excitement among the geophysical community. Two maps at 1,300 km depth (Fig. 41) come from independent studies by Steve Grand, who inverted S waves, and by Rob van der Hilst, who inverted P waves. The meridional anomaly beneath eastern North America has a very similar shape in the two solutions. Overall similarity can be also discerned in the anomaly extending from Indonesia to the Mediterranean along the site of subduction of the former Tethyan seafloor, even though it is somewhat broader in the S-wave map. What is characteristic of both maps is the difference in the overall amplitude of the anomalies between the Northern and Southern Hemispheres. There are indications that this difference is not real, but rather caused by the uneven sampling by seismic rays of the two hemispheres. Inversions using different schemes show more evenly distributed patterns of anomalies, not all of which can be related to subduction. Again, the lack of adequate data coverage in the Southern Hemisphere introduces the uncertainty.

One of the most intensively studied regions of Earth is the core-mantle boundary. It is compositionally and perhaps dynamically the most dramatic boundary in Earth. It is perceived to be the origin of hotspots and the graveyard of subducted slabs.

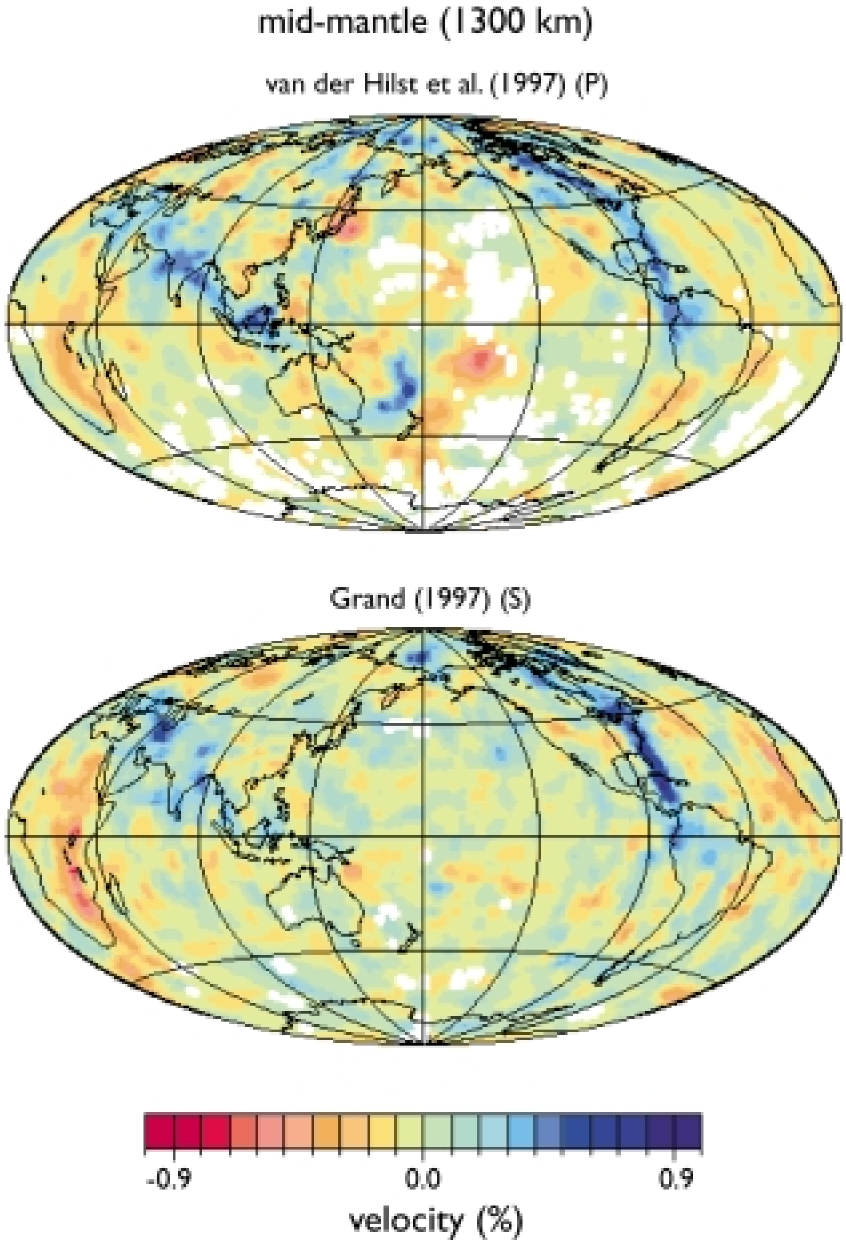


Figure 41. Two tomographic maps of velocities of compression waves (P waves) and shear waves (S waves) in the mantle at 1,300 km depth show a major difference in the anomalies in the Northern and Southern Hemispheres. The amplitudes are large in the Northern Hemisphere whereas those in the Southern Hemisphere are subdued, and there are few Southern Hemisphere anomalies that are coincidental in both maps. These characteristics almost certainly result from the lack of seismic station coverage in the Southern Hemisphere. (P-wave inversion by van der Hilst , R.D., Widiyantoro, S., and Engdahl, E.R., 1997. Evidence for deep mantle circulation from global tomography. *Nature,* 386:578–584; S-wave inversion by Grand, S., van der Hilst, R., and Widiyantoro, S., 1997. Global seismic tomography: a snapshot of convection in the Earth. *GSA Today,* 7[4]1–7.)

It may contain ultra-low-velocity zones and strong anisotropy. As tomographic models show, there is much energy in the heterogeneity of the very low degrees of the spherical harmonics (degrees 2 and 3). Yet the spherical harmonics are interpolated over fairly large areas in the Southern Hemisphere where there are no observations. There is also mounting evidence for strong heterogeneity in the D≤ region occurring over much shorter length scales. Figure 42 shows a vertical cross section across the central Pacific Ocean illustrating lateral variations of 8%–10% over distances of less than 500 km near the bottom of the mantle; these lateral variations were obtained by modeling differential traveltimes of S waves that bounce off the core as compared with the direct S-wave arrival. Such detailed studies are currently possible only along a very few particularly well sampled paths and do not allow a comprehensive understanding of the relationship of this heterogeneity to global mantle processes.

The inner core of Earth is the final frontier for solid Earth geophysics. It has been the object of intensive studies in recent years, with some unexpected results. The anisotropy of the inner core and the measurement of its differential rotation with

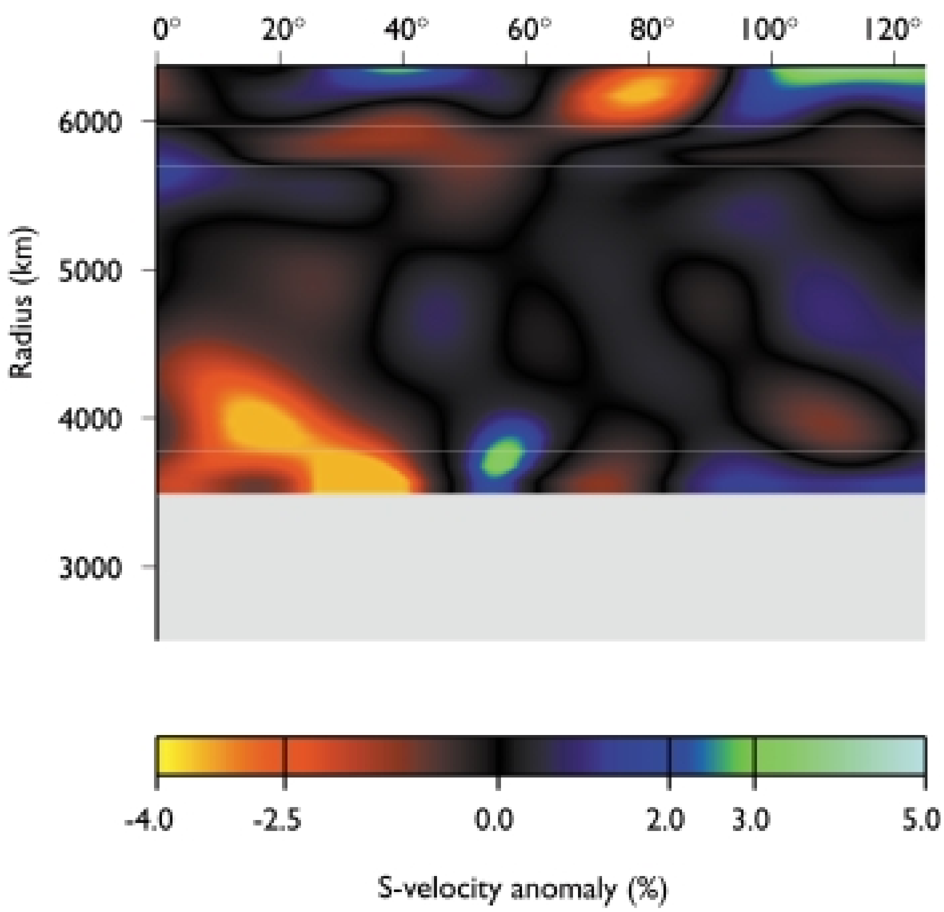


Figure 42. Shear-wave velocity anomalies for a vertical slice through the mantle in the central Pacific. Coverage in the Pacific and Southern Hemisphere limits such studies to specific profiles rather than a broad study of velocity heterogeneity associated with core and mantle processes. In this profile, the radius is the distance above the center of the Earth (in kilometers), and the horizontal direction plots the distance along a slice of the mantle that spans 120° of the circumference of the Earth at the various depths. The S-velocity anomaly is the difference (in percent) between the shear waves that bounce off the core and those that arrive directly. At any given depth, the lack of uniform differences in these shear-wave arrival times indicates heterogeneity in this region of the Earth. (After Bréger, L., and Romanowicz, B., 1998. Three-dimensional structure at the base of the mantle beneath the central Pacific. *Science,* 282:718–720.)

respect to the mantle have been among the more widely known results from seismology in the past decade or so. But there is a great deal of uncertainty that has to be attached to the results for this region. Its volume is less than 1% of Earth's volume, yet the waves that sample it must travel through the remaining 99%. Therefore, all the errors that we make in introducing corrections for the three-dimensional structure in the mantle, or the inaccuracies introduced by assuming that the differential traveltimes are not sensitive to the mantle structure, project themselves onto the inner core. There are indications that the properties of this region may be more complex than previously thought and will remain difficult to assess, particularly given that the coverage for the polar paths is very uneven.

Earthquake Sources

Seismic networks are also indispensable in studying earthquakes. An example of an unusual earthquake whose analysis suffered from the poor azimuthal coverage in the Southern Ocean is the Balleny Islands earthquake of March 25, 1998, the largest-ever recorded intraplate oceanic event. Seismic observatories in the Northwestern Pacific or Nazca plate, for example, would provide important data for studying earthquakes in some of the most active subduction zones at angles not obtainable from observations on land. Better coverage in the oceans could also help to solve the recent puzzle of what processes are continuously exciting the free oscillations of Earth. Are these processes aseismic mantle creep and/or atmospheric movements?

Are these processes aseismic mantle creep and/or atmospheric movements?

NOAA (the U.S. National Oceanic and Atmospheric Administration) has maintained several, continuously recording hydrophones sensitive to acoustic waves from earthquakes on the TAO (Tropical Atmosphere-Ocean array; Fig. 43) used for climate monitoring since May 1996. The data are recorded on hard disk drives within the instruments and recovered once per year during maintenance visits. The network demonstrates clearly the value of long-term recording for seismology. Although many events are located on the East Pacific Rise and the Middle America Trench by solely using land and island stations, the TAO data indicate that the actual level of seismicity is much higher. Furthermore, a substantial number of intraplate earthquakes were also located. A more complete network of ocean stations will lead to a much greater understanding of present-day seismicity and tectonic behavior.

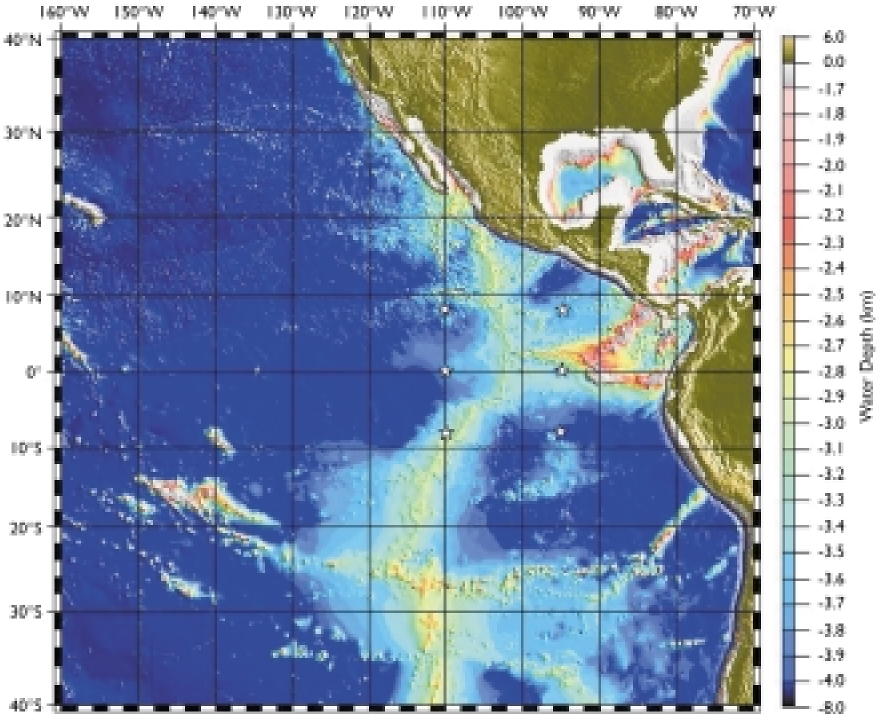


Figure 43. Locations of moored autonomous hydrophones (yellow stars) placed by NOAA in the equatorial Pacific. The instruments are co-located with several of the TAO ATLAS buoys used for climate monitoring.

Drilling to Install Seismic Observatories

On the basis of these arguments, it should be clear that further progress in seismic imaging of Earth's interior and in monitoring seismicity requires the addition of ocean stations to complete a global network. Although it is possible to place seismometers directly on the seafloor, borehole installations are greatly preferred because they provide significant improvement in signal-to-noise ratio in the frequency bandpass relevant to teleseismic body-wave studies (periods shorter than a few seconds). Borehole installations are necessary for the collection of critical data for body waves sampling the deep mantle (P waves) and the core (PKP, PKIKP). High-quality permanent seismic stations also improve the station coverage and the quality of the data recovered when used in conjunction with temporary seismometer deployments for regional studies of upper-mantle seismic anomalies.

It is likely that seismometers installed in boreholes will become the focal points for interdisciplinary process studies. Today, many fundamental scientific questions in the ocean sciences require the measurement of variations in physical, chemical, biological, and geologic processes on timescales ranging from seconds to decades, as well as a synoptic characterization of these processes on a global scale. Attempts to answer the questions have highlighted the need for what might be termed "ocean observatories" with sensors in the water column and on or beneath the seafloor. Given the range of time and space scales involved, it is convenient to consider current and planned efforts on seafloor observatories in two classes:

1. "Global network" observatories are required to complete the geometrically uniform global coverage necessary to fully image the interior of Earth, understand whole-Earth processes occurring at very long timescales, and provide a synoptic view of oceanographic variables on a global spatial scale. With 70% of Earth's surface under the oceans, global networks will never be complete without seafloor observatories.

2. "Active process" observatories should be located where particular dynamic systems are currently most active near Earth's surface. The best examples are at plate boundaries: mid-ocean ridges, transform faults, and subduction zones. Given that these plate-tectonic boundaries occur almost exclusively beneath the seas, a seafloor observatory capability is imperative on both scientific and societal grounds.

Observatory-type studies on a planetary scale offer a number of important scientific opportunities. In the global network of seismic stations, large gaps exist that cannot be filled with island stations, particularly in the eastern Pacific and Southern Ocean. Improved spatial sampling provided by long-term, broadband seismic stations at approximately 20 ocean sites would provide much improved tomographic imaging of the structure of the lower mantle (especially in the Southern Hemisphere) and of the core-mantle boundary as well as clarify the role of subducting slabs and plumes in deep-mantle circulation.

To understand planetary-scale processes such as the formation of ocean crust at mid-ocean ridges and seismogenesis at oceanic subduction zones and oceanic transforms, or to quantify global hydrothermal fluxes, observations on a more regional or even local spatial scale will be required. There is a clear need to be able to make time-series observations for periods of up to a few years, but not necessarily indefinitely, anywhere in the world's ocean. A mobile observatory would make it feasible to carry out comparative time-series studies in several remote areas of the world's ocean without a huge infrastructure investment. These portable arrays, which might operate continuously for as long as 2–5 years at a given site, need to be tied together through a reference network of permanent observatories.

Geomagnetism and Paleomagnetism

Close examination of Earth's magnetic field reveals a dynamic quantity that varies in a complex manner over space and time. At the longest periods, these variations are known to originate in Earth's core, providing us with a glimpse of the physical state and dynamics of this inaccessible region. At periods of a decade and less, interactions of the geomagnetic field with the Sun generate electric currents in the magnetosphere and ionosphere, resulting in a highly variable external component of the field. These external variations in turn induce currents in the electrically conducting crust and mantle of Earth. Ocean drilling can provide the time history of this dynamic field through a combination of installing seafloor magnetic observatories and drilling seafloor sections that recorded the variability of the field in the geologic past.

The Core Field

Four centuries after the demonstration by W. Gilbert that Earth's magnetic field is largely of internal origin, our understanding of the dynamo process that is responsible for generating the field remains incomplete. Although our desire to understand the dynamo continues to motivate most studies of Earth's main magnetic field, there is a growing recognition that changes in Earth's main field have important implications for a broad range of other problems in the Earth sciences. Examples include long-term variations in the rate of production of beryllium and carbon isotopes (specifically ^{10}Be and ^{14}C) in the upper atmosphere by cosmic rays, whose atmospheric penetration is to some extent controlled by the strength of Earth's magnetic field, and short-term monitoring of the exchange of angular momentum among the atmosphere, the oceans, the solid Earth, the fluid outer core, and the solid inner core.

There is growing recognition that it is the behavior of the field on very short timescales—from a few decades right down to annual periods—that now lies at the heart of some of the most important issues in geomagnetism. Direct, detailed, and global observations of very high frequency magnetic jerks and of torsional oscillations of the core will improve numerical modeling of the geodynamo. Better determinations of the angular momentum budget of the core are required in order to isolate global-change–induced variations in the angular momentum of the hydrosphere.

Electromagnetic Induction Imaging of the Mantle

Seismology and electromagnetic induction provide the only means of propagating energy into Earth's deep interior, allowing remote sensing of the internal structure and physical properties of the mantle from surface observations. Seismic methods are sensitive to the density and elastic properties of Earth materials. Electromagnetic induction methods are sensitive to the electrical conductivity of those materials. The electrical conductivity of mantle minerals depends on a number of factors: temperature, oxidation state, composition (e.g., iron content), and presence of partial melt or volatiles. Recent high-pressure laboratory studies of electrical conductivity have substantially clarified the nature of these dependencies.

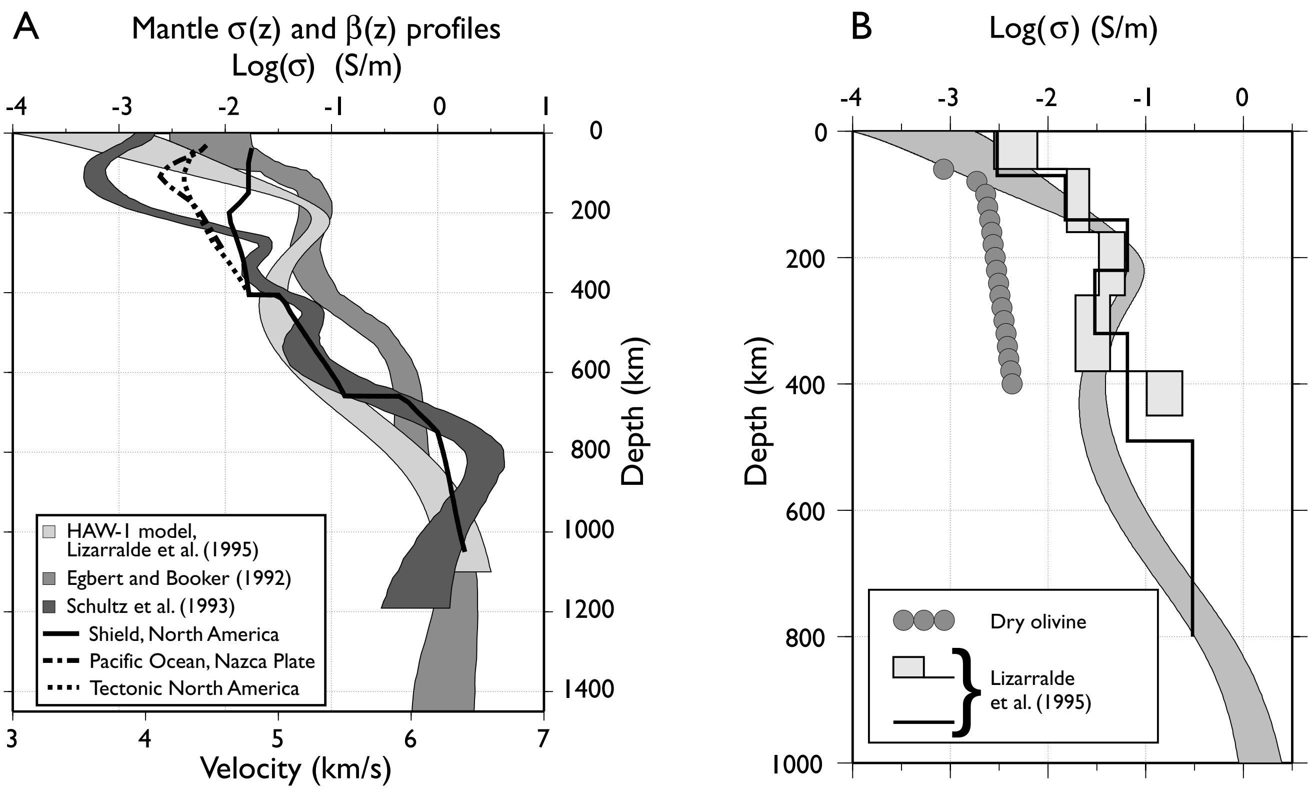


Figure 44. (A) Mantle s(*z*) (electrical conductivity in siemens per meter, S/m) and b(*z*) (seismic shear wave velocity in km/s) vs. depth (*z* in km) for regional one-dimensional models obtained from very long period magnetotelluric experiments at the central Canadian Shield (solid curve), northeastern Pacific Ocean (dot-dash curve), and southwestern United States (dotted curve). Ranges of values from other models are shown by shading that is identified in the key. (B) The northeastern Pacific profile plotted on the same scale as predicted conductivities from a dry olivine model and appropriate geotherm. Such a discrepancy is seen in mantle electromagnetic studies in a variety of tectonic settings. (References: Egbert, G.D., and Booker, J., 1992. Very long period magnetotellurics at Tucson Observatory: implications for mantle conductivity. *Journal of Geophysical Research,* 97:15,099–15,112. Lizarralde, D., Chave, A., Hirth, G., and Schultz, A., 1995. Long period magnetotelluric study using Hawaii-to-California submarine cable data: implications for mantle conductivity. *Journal of Geophysical Research,* 100:17,873–17,854. Schultz, A., Kurtz, R.D., Chave, A.D., and Jones, A.G., 1993. Conductivity discontinuities in the upper mantle beneath a stable craton. *Geophysical Research Letters,* 20:2941–2944.)

Coupled with ongoing advances in three-dimensional electromagnetic modeling and new data-analysis strategies, the real possibility to image—and interpret—three-dimensional variations in mantle conductivity has emerged over the past decade. Because of the diffusive nature of electromagnetic fields in a conductor, these deep three-dimensional images will be capable of resolving conductivity variations with a length scale of hundreds of kilometers or more. This resolution scale is similar to that of normal seismic reflection and refraction rather than that of body-wave tomography. However, the definition of the physical state of the mantle provided by electromagnetic methods is complementary to the information provided by seismic methods. The sensitivity of electromagnetic induction and seismology to different material properties gives electromagnetic induction methods the potential to play a major role in disentangling the compositional and thermal heterogeneity of the mantle. Achieving this goal will lead to fundamental advances in our understanding of mantle convection and chemical recycling into the mantle.

Historically, studies of mantle conductivity have depended on two strong simplifying assumptions: that the conductivity of Earth varied only with depth and that external inducing fields were of a simple known form (e.g., a zonal dipole). However, more recent studies have revealed strong, and generally tectonically sensible, lateral variations in mantle conductivity. Strong lateral variations in upper-mantle conductivity have been observed between three tectonic regimes (Archean craton, a region of upwelling asthenosphere between the Rio Grande Rift and East Pacific Rise, and stable ocean basin; see Fig. 44). Note the strong inflections in conductivity for the subcratonic profile that show gross correspondence to the major mineralogical transitions.

The strong heterogeneity detected in mantle electrical conductivity, as well as the correspondence between patterns of heterogeneity and tectonic regime, has stimulated the development of new analytical and numerical tools for modeling the mantle. By using the new three-dimensional electromagnetic modeling codes, simulations have been carried out to determine the sensitivity of electromagnetic-induction methods to image lateral changes in mantle properties. These studies clearly show that magnetic observatory data are sufficiently sensitive to the range of conductivity variations expected in the mantle to provide useful data on dynamically important processes within Earth.

The first three-dimensional mantle conductivity models (Fig. 45) show remarkable similarity to shear-wave velocity distributions imaged by seismic tomography. The model shown here was generated by a regularized inversion procedure that was damped to inhibit introducing fine structure where there were few measurements. Regions far from observatories used in the inversion show little structural detail. It is encouraging that disparate approaches to sensing different material properties (seismic and electromagnetic) should provide a mutually coherent picture, especially given the grossly inadequate spatial distribution of observations used in the derivation of the present model.

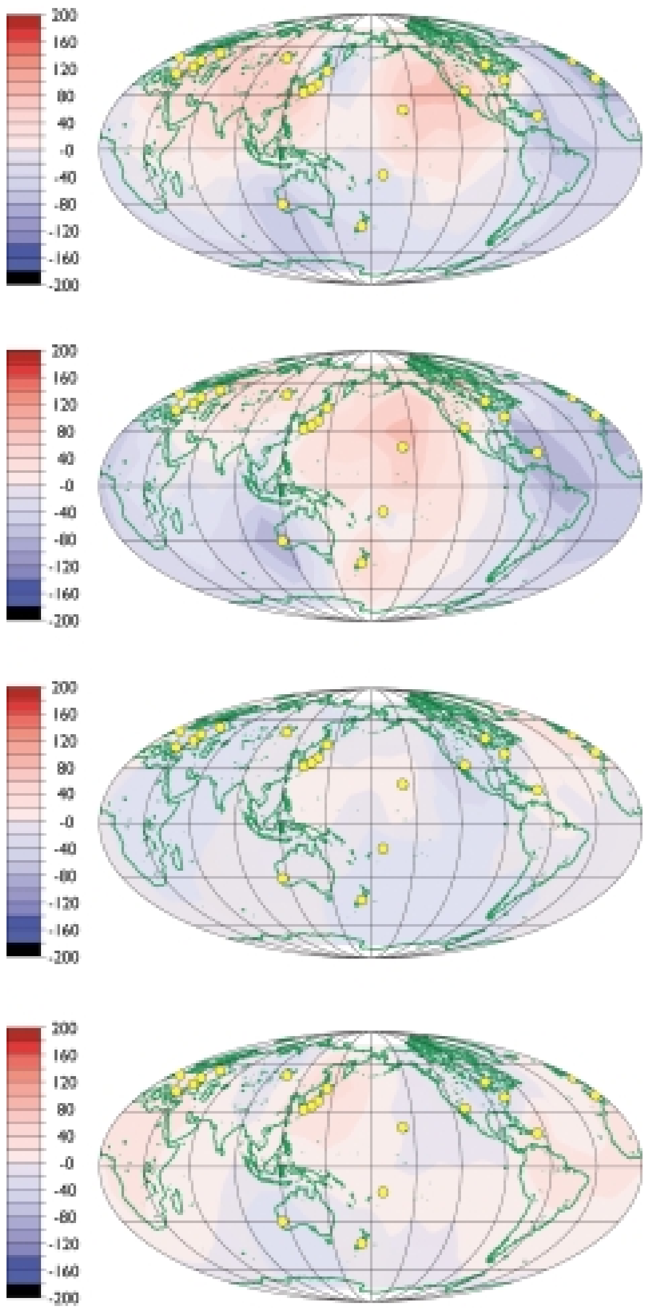


Figure 45. Mantle electrical conductivity model. Four heterogeneous shells (i.e., depth-defined layers) are shown. For the plots from top to bottom, the depths and model reference conductivities (s) are (A) 0–436 km and 0.001 S/m (siemens per meter), (B) 436–774 km and 0.311 S/m, (C) 774–1630 km 1.397 S/m, and (D) 1630–2828 km and 2.136 S/m. The variations in conductivity with respect to an underlying one-dimensional reference model are shown. Deep red represents a +200% perturbation on the underlying conductivity (anomalously conductive). Deep purple represents a –200% perturbation (anomalously resistive). The yellow circles represent locations of magnetic observatories whose responses were used in the inversion. The inversion was regularized to inhibit introducing structural variations in areas where there was no observatory coverage and hence little information. The gross spatial inadequacy of the observatory distribution is evident, particularly in the Southern Hemisphere and the oceans. (From Schultz, A., and Pritchard, G., 1998. A three-dimensional inversion for large-scale structure in a spherical domain. *In* Spies, B., and Oristigliano, M. (Eds.), *Three-Dimensional Electromagnetics:* Tulsa, Society of Exploration Geophysicists, Geophysical Developments Series, 7:451–476.)

Work is currently underway to refine such conductivity models by employing (1) new methods of forward and inverse modeling of electromagnetic induction in a three-dimensional globe and (2) much improved continental- and island-based data distributions. The techniques available to deep-mantle electromagnetic induction studies have progressed to the point that rather than being limited by theory, the application of these methods to imaging the mantle is restricted by the sparse distribution of data available from the irregularly scattered nodes in the magnetic observatory network.

Paleomagnetism

The ocean crust preserves a record of the direction and intensity of Earth's magnetic field in the past. This record has been useful for learning about magnetic field behavior during eras long before we had instrumental recordings and at timescales longer than can be observed with geomagnetic observatories. In addition, the magnetic field preserved in rocks and sediments provided the most compelling data in support of plate tectonics and has been used to date geologic events. There has been a recent resurgence of interest in the paleomagnetic field because of several key developments:

- Modern computing has allowed the first realistic simulations of the geomagnetic field and statistically robust geomagnetic reference models for the time-averaged field (Fig. 46A). Numerical simulations of the geomagnetic field have explored the possible consequences of changing thermal-boundary conditions at the core-mantle boundary and have provoked intriguing predictions about the possible connections between the geodynamo and mantle dynamics. Analyses of the historical field (Fig. 46B) show long-standing features that persist for at least hundreds of years. Comparisons of model results with the time-averaged field over the past 5 million years show similarities that imply a long-term structure of the field that is poorly understood (Fig. 46C).

- The latest generation of paleomagnetic instrumentation allows us to collect data with greater reliability, resolution, and global distribution than before. These higher-resolution measurements of paleomagnetic direction and intensity will yield more detailed correlation on shorter timescales.

These two advances make it possible to explore several long-standing questions about the fundamental nature of the geomagnetic field. They are discussed next.

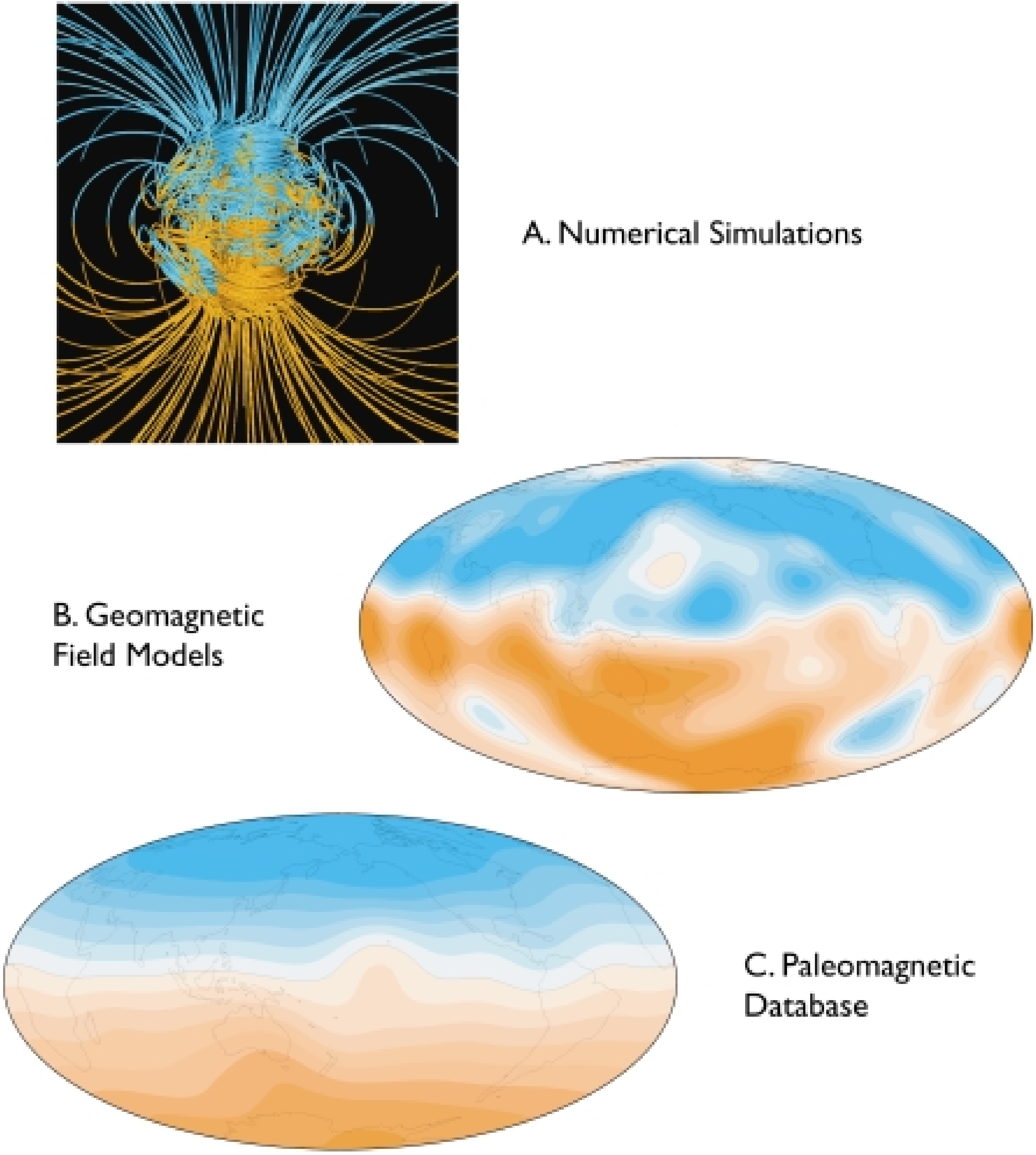


Figure 46. (A) Results of numerical simulations of the geomagnetic field. (From Glatzmaier, G.A., and Roberts, P.H., 1995. A three-dimensional self-consistent computer simulation of a geomagnetic field reversal. *Nature,* 377:203–209.) Blue lines indicate flux directed toward the core, and yellow is outward-directed flux. External to the core, the field is approximately that of a dipole. Numerical simulations make predictions about field behavior (average intensity, secular variation, behavior during reversals) for different assumed boundary conditions. Figure courtesy of G. Glatzmaier. (B) Averages of geomagnetic field observations over the past 300 years are plotted as radial flux on the core-mantle boundary. Blue lines indicate flux directed toward the core, and orange is outward-directed flux. Although the field is dominantly dipolar, there are significant departures (shown as flux patches with the "wrong" color) from a dipole model that persist for hundreds of years. (Field model UFM1 from Bloxham, J., and Jackson, A., 1992. Time-dependent mapping of the magnetic field at the core-mantle boundary. *Journal of Geophysical Research,* 13:19537–19563.) (C) Averages of paleomagnetic data spanning the past 5 million years. (From Johnson, C.L., and Constable, C.G., 1997. The time-averaged geomagnetic field: global and regional biases for 0–5 Ma. *Geophysical Journal International,* 131:643.) Blue lines indicate flux directed toward the core, and orange is outward-directed flux. There is loss of resolution relative to the geomagnetic field average shown in B owing to the difficulty in getting global coverage with high-quality data.

What Is the Structure of the Geomagnetic Field on Long and Short Timescales?

What is the structure of the geomagnetic field on long and short timescales?

Just how dipolar is Earth's magnetic field when averaged over long timescales (more than 5 million years), and how long has the field been predominantly dipolar?

- Short-term variations in both direction and intensity—i.e., paleo–secular variation—not only provide a means for high-resolution correlation, but also provide important constraints on the processes that generate the geomagnetic field.
- What produces polarity reversals and excursions remains one of the outstanding problems in geoscience, in large part because of the lack of globally distributed, high-resolution records. Cores of strata deposited at the highest sedimentation rates have the greatest potential of showing unprecedented details of the reversal process (see Fig. 47).
- The present field is well approximated by a geocentric axial dipole. However, there also exist important deviations from this state. Just how dipolar is Earth's magnetic field when averaged over long timescales (more than 5 million years), and how long has the field been predominantly dipolar?

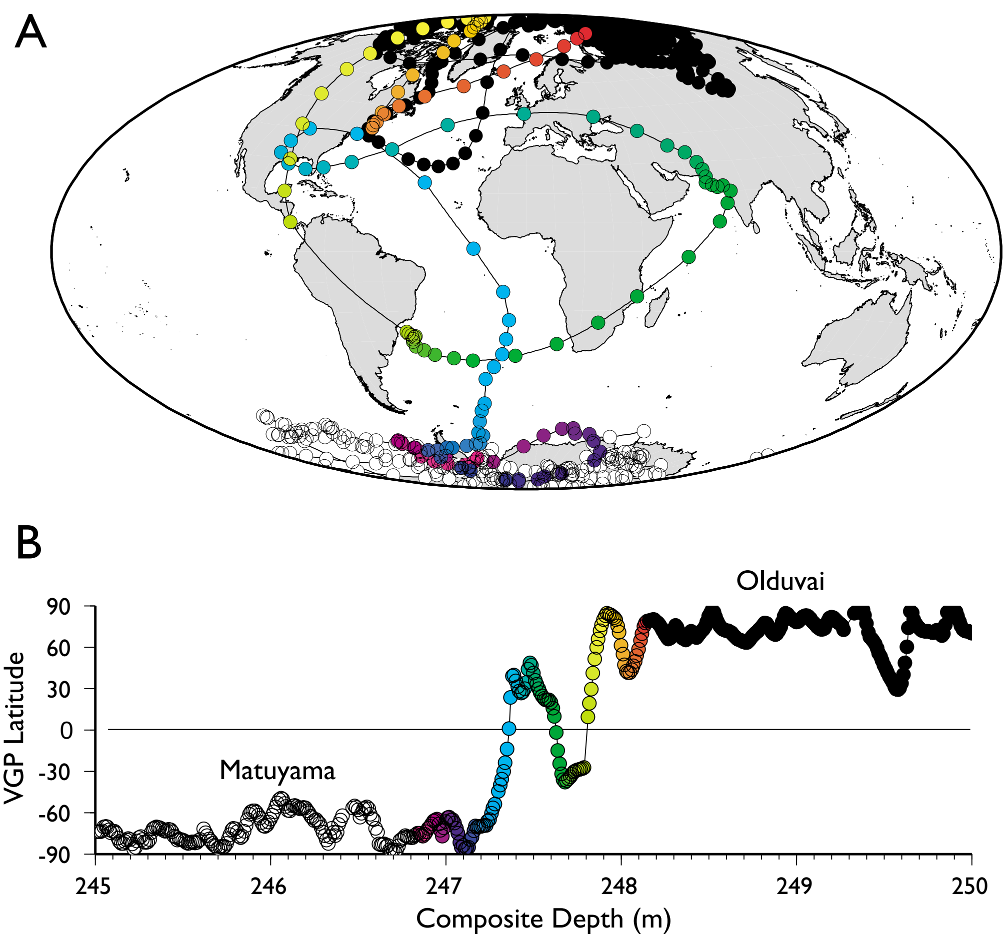


Figure 47. (A) Track of virtual poles obtained from measurements of high-sedimentation-rate cores that penetrated the upper Olduvai transition. (From Mazaud, A., and Channell, J.E.T., 1999. The top Olduvai polarity transition at ODP Site 983 (Iceland Basin). *Earth and Planetary Science Letters,* 166:1–13.) (B) Latitude of virtual poles plotted against depth.

What Is the Average Strength of the Field and What Controls Its Variations over Time?

Tools for systematically studying geomagnetic intensity variations have improved dramatically. These new tools will provide reasonable limits for geodynamo models and help to determine what underlies the process of reversal. For example, there are suggestions from sedimentary records that the average field strength may be related to average reversal frequency, yet few data are available for testing this hypothesis. Furthermore, numerical models make specific predictions concerning the average field intensity as a function of boundary conditions, and in addition, intensity information must be incorporated into models of the time-averaged field.

What Is the Link Between the Geodynamo and Mantle Dynamics?

Numerical simulations of the geodynamo indicate that variations in heat flow through the core-mantle boundary may strongly affect the geomagnetic field. This concept implies that spatial variations in heat flow out of the core as a result of mantle dynamics will affect the geomagnetic field as well. Such a linkage raises an important question of whether changes in reversal frequency (and possible changes in average intensity) are related to changes in mantle convection.

What Is the Long-Term Relationship Among the Earth's Spin Axis, the Geomagnetic Dipole Axis, and the Hot-Spot Reference Frame?

Initial results from seamount drilling (see Fig. 48) indicate that the paleolatitudes for the seamounts in the Emperor seamount chain are significantly different from the expected latitude of the Hawaiian hotspot. These observations imply that the Hawaiian-Emperor seamount chain may not be the result of a fixed hot spot. Another explanation is that the entire mantle, with the hotspots, has moved with respect to the magnetic dipole.

What Is the Source of Marine Magnetic Anomalies?

Marine magnetic anomalies have long provided a rich source of information about polarity history that allows us to calculate seafloor spreading rates and date the oceanic crust. Information from the intensity of magnetization of the upper crust suggests that deeper layers contribute to the observed intensity of magnetic anomalies. A problem occurs, however, if rocks from layer 3 of the lithosphere contribute significantly to the anomaly amplitude, because thermal-cooling models of the

What is the average strength of the field and what controls its variations over time?

What is the link between the geodynamo and mantle dynamics?

What is the long-term relationship among the Earth's spin axis, the geomagnetic dipole axis, and the hot-spot reference frame?

What is the source of marine magnetic anomalies?

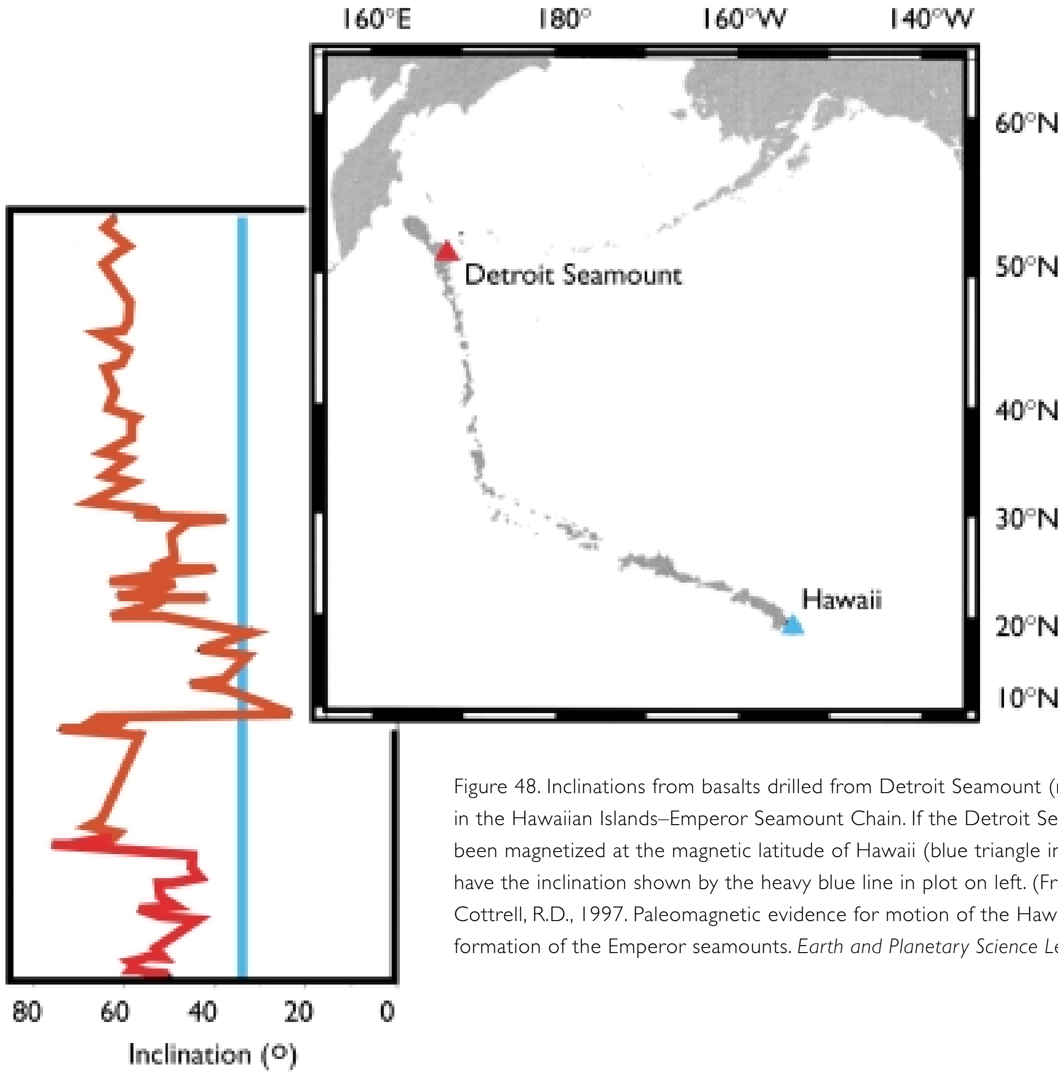


Figure 48. Inclinations from basalts drilled from Detroit Seamount (red triangle in map) in the Hawaiian Islands–Emperor Seamount Chain. If the Detroit Seamount basalts had been magnetized at the magnetic latitude of Hawaii (blue triangle in map), they would have the inclination shown by the heavy blue line in plot on left. (From Tarduno, J.A., and Cottrell, R.D., 1997. Paleomagnetic evidence for motion of the Hawaiian hotspot during formation of the Emperor seamounts. *Earth and Planetary Science Letters,* 153:171–180.)

timing of acquisition of magnetization predict different anomaly shapes than are commonly observed. Improved knowledge of the source layer for marine magnetic anomalies through direct sampling of the ocean crust will be of great value in understanding how we can use magnetic anomalies to infer more subtle changes in the geomagnetic field, such as intensity variations and excursions.

Is there a relationship between magnetic field and climate?

Is There a Relationship Between Magnetic Field and Climate?

There are intriguing new results suggesting a possible connection between the geomagnetic field and climate over a large range of timescales. This possibility emphasizes the importance of knowing the geomagnetic field intensity through time so that its possible influence on long-term climate change can be studied.

DRILLING STRATEGIES

Our current understanding of geomagnetism owes much to the geomagnetic observatories that have been maintained (in varying numbers) over the past century. Data from these observatories have been used to explore a wide range of physical phenomena, from flow in Earth's liquid core, to the electrical conductivity of the solid mantle, to resonant hydromagnetic oscillations in the plasma environment of the ionosphere. From these studies, much has been learned, not only about the geomagnetic field per se, but also about the physical state and dynamics of the solid Earth and near-Earth space environment. Advances in theory and computational capability, together with modern satellite data, provide exciting new possibilities to extend our knowledge—and use—of geomagnetism on a number of fronts. However, to fulfill this promise it will be necessary to extend the existing, uneven, land-based geomagnetic observatory array to achieve truly global coverage. This expansion will require long-term, stable deployment of approximately 10 magnetic observatories on the seafloor. Provision must also be made for long-term but temporary installation of regional instrument arrays. The studies of three-dimensional variation in the mantle's electrical properties (e.g., those related to temperature, composition, volatiles, and melt) are not possible with the incomplete sampling from existing continental and island stations. Geomagnetic instrumentation will have to be placed at some distance from seismic boreholes, despite the fact that logistically, its operation would benefit from collocation with the seismic instruments.

Extending the geographical coverage of high-resolution paleomagnetic records from sediments and igneous rocks is critical for testing predictions made by geodynamo theory. Ocean drilling provides the only means of attaining these goals. Such records will provide vital details on paleo–secular variation and time-averaged field models. Geomagnetic field variations may be assessed by three fundamentally different but complementary types of records: marine magnetic anomalies and remanent magnetization in both sediments and igneous rocks.

There are four types of drilling strategies required to address these paleomagnetic objectives:

1. Sequences of sediments deposited at a high sedimentation rate (more than 5–10 cm per thousand years) exist in the form of sedimentary drifts, and these sequences contain high-resolution records of climate, ocean biogeochemistry,

and paleomagnetism. Paleomagnetic records from such drifts could extend the database for global magnetic field inversions for times prior to human observation and would allow us to image the evolution of such features as the "flux patches" visible in the geomagnetic field inversions (see Fig. 46B). Records of magnetic intensity and climatic variability over time are required to test hypotheses suggesting possible links. Moreover, the details of what happens during a polarity transition could be documented, as shown in Figure 48.

2. Sampling of the igneous basement (particularly fine-grained basalt and glass) allows absolute estimates of paleo–magnetic field intensity. These samples are only obtained by deep (more than 500 m) penetration of igneous basement. Such sites are extremely rare in Paleogene and Mesozoic crust, yet material from these times is vital for testing possible links between magnetic intensity and reversal frequency.

3. Questions about the differences between the paleomagnetic and the hotspot reference frames, and about true polar wander, require drilling of hotspot chains.

4. To understand the magnetic source layer of marine magnetic anomalies, we must drill through the source layer over a magnetic reversal boundary.

Technological advances made by the DSDP and the ODP revolutionized paleomagnetic study of seafloor materials. The new phase of drilling provides an opportunity to improve the quality and quantity of the material needed to answer these questions. We advocate the following technical goals:

- Core orientation is required for both sediments and hard-rock cores. To extract the information needed to address geomagnetic problems, it is necessary to recover cores that are accurately and dependably oriented.
- A large volume of undisturbed material of a given age is necessary for high-resolution studies. The rind effects associated with mechanical deformation along the core edge need to be minimized.
- Coring disturbance, both magnetic and mechanical, must be eliminated and core recovery maximized. Remagnetization effects caused by the drilling process are just now being understood. It is imperative that future coring solve this problem.
- Cores of APC-quality (advanced piston core) are required from mixed-lithology intervals and from deeper sections to extend high-resolution studies back before the Pliocene.

Large Igneous Provinces

Their Implications for Earth and Planetary Evolution

Plate-tectonic theory has provided a breakthrough in our understanding of how the continuous opening and closing of ocean basins reflects convection in Earth's upper mantle. Among the terrestrial planets and moons of our solar system, however, global plate tectonics may well be unique to Earth. Even on Earth, current plate-tectonic theory does not predict the major crustal-growth events termed "large igneous provinces" or LIPs (Fig. 49). LIPs are a continuum of voluminous magmatic constructions that include continental flood basalts and associated intrusive rocks, volcanic passive margins, oceanic plateaus, submarine ridges, seamount groups, and ocean-basin flood basalts. They form in massive volcanic events that result from a mode of mantle convection different from that driving plate tectonics on Earth. Furthermore, unlike the magmatism associated with plate tectonics that creates new crust exclusively in the ocean basins or at ocean margins,

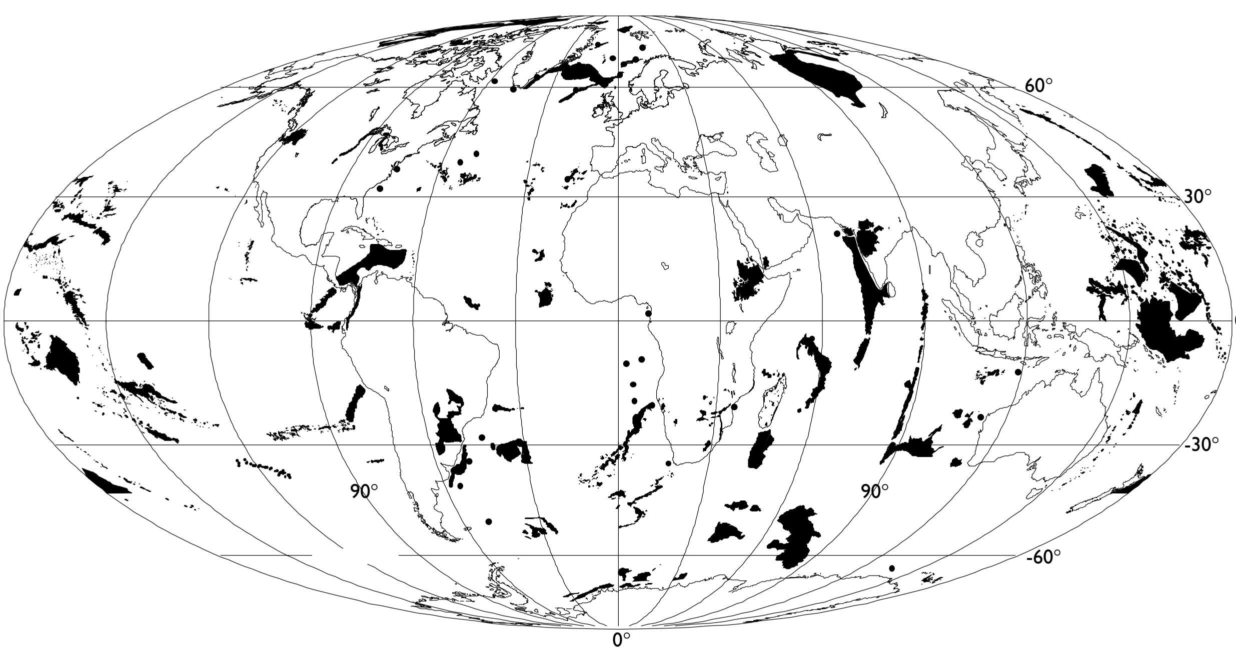


Figure 49. Global LIPs, including oceanic plateaus, volcanic passive margins, continental flood basalts, submarine ridges, seamount groups, and ocean-basin flood basalts. (After Coffin, M.F., and Eldholm, O., 1994. Large igneous provinces: crustal structure, dimensions, and external consequences. *Reviews of Geophysics,* 32:1–36.)

LIPs form independently of plate setting: they form on the continents, in the oceans, and along margins between the two; and they form either wholly within plates or at plate boundaries. The alternative, non-plate-tectonics, mode of convection manifested by LIPs is probably how other terrestrial planets and moons lose most, if not all, of their interior heat.

LIPs represent enormous outpourings of predominantly basaltic magma that commonly cover areas of 10^5 km^2 or more. The largest LIPs occur in ocean basins, where giant plateaus such as the Ontong Java Plateau in the western Pacific and the Kerguelen Plateau in the Indian Ocean have formed. Similarly, flood basalts were erupted along many "volcanic passive margins" (e.g., Greenland, Norway, Brazil, Namibia, northwestern Australia) during continental breakup, as well as in continental settings (e.g., the Columbia Plateau basalts in the U.S. Pacific Northwest, the Deccan traps in India, the Karoo and Ferrar basalts in South Africa and Antarctica, respectively, the Paraná in Brazil, and the Siberian traps in Asia). Primarily because of ease of access, continental flood basalts are the best sampled and documented type of LIP. Studies of continental flood basalts illustrate the evolution in thinking regarding the importance of such events for Earth evolution. Twenty years ago, when systematic studies of continental flood basalts began, flood volcanism was largely viewed as produced by continental rifting—a "standard" plate-tectonic interpretation. Improvements in geochronology, however, have demonstrated that all well-dated continental flood-basalt provinces initially thought to have formed over many tens of millions of years instead formed, for the most part, in 1 million years or less. The rapid melt production rates documented by the eruption of huge volumes of magma in such short time intervals implies a generation mechanism other than rifting, since available data indicate that passive rifting cannot produce such high melting rates. This realization has led to other models involving either the melting of a plume of hot mantle that rises to the surface from a deep thermal boundary layer, such as that between the core and mantle, or upward flow of deep upper mantle in areas where the plate thickness varies greatly. Neither the initial phase of activity that produces the LIPs ("plume head") nor the subsequent volcanic activity that commonly produces trailing volcanic ridges and island chains ("plume tail") in the ocean basins (Fig. 50) are directly related to, or predicted by, the standard cycle of plate formation, aging, and destruction described by plate-tectonic theory.

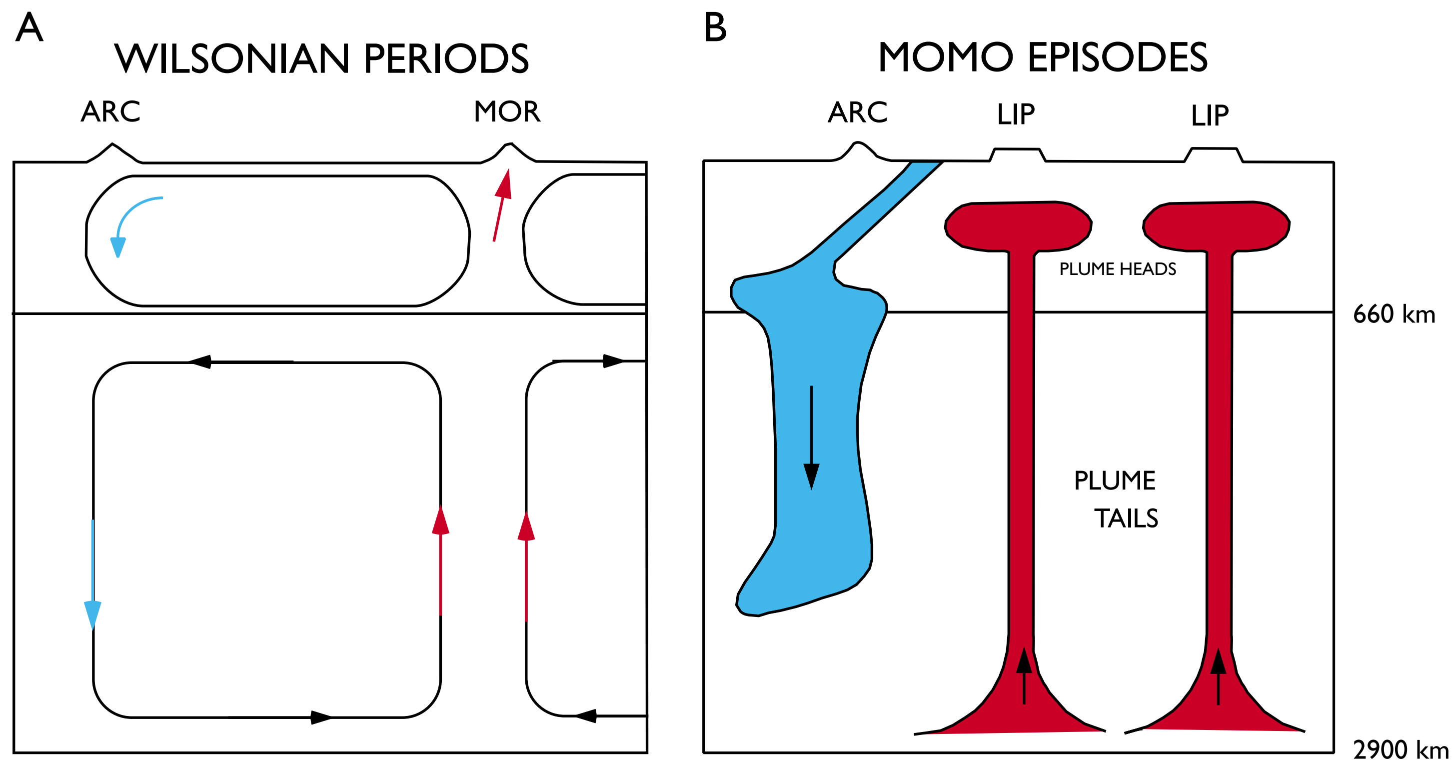


Figure 50. Model of Wilson Cycle periods and MOMO (mantle overturn and major orogeny) episodes. (A) During Wilson Cycles, the normal mode of plate tectonics prevails, with opening and closing of oceans and mantle convection with isolated upper and lower mantle. Plumes originate predominantly from the base of the upper-mantle layer, and continental growth is dominated by arc accretion. (B) During MOMO episodes, accumulated cold material descends from the 660-km-deep 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. (After Stein, M., and Hofmann, A.W., 1994. Mantle plumes and episodic crustal growth. *Nature,* 372:63–68.)

The magnitude of such igneous events is best illustrated by oceanic plateaus. The Ontong Java Plateau in the western Pacific, for example, consists of more than 50 ¥ 10^6 km^3 of mafic volcanic and plutonic rocks that form an approximately 30-km-thick plateau encompassing an area equal to one third of Australia. Events of this magnitude are unknown to human experience, but the consequences are dramatic. For example, 1 ¥ 10^6 km^3 of basalt, the size of an average continental flood-basalt province, would bury the area east of the Appalachians from Maine to Florida under more than 1 km of basalt. The release of gases (CO_2, SO_2, Cl, F, H_2O, etc.) accompanying such great eruptions must have had tremendous consequences for the composition of the ocean and atmosphere, with dramatic impacts on climate and environment. Indeed, formation of LIPs correlates temporally with ecological changes and extinctions of life forms. For instance, the eruption of the Siberian continental flood-basalt province 250 million years ago at the Permian-

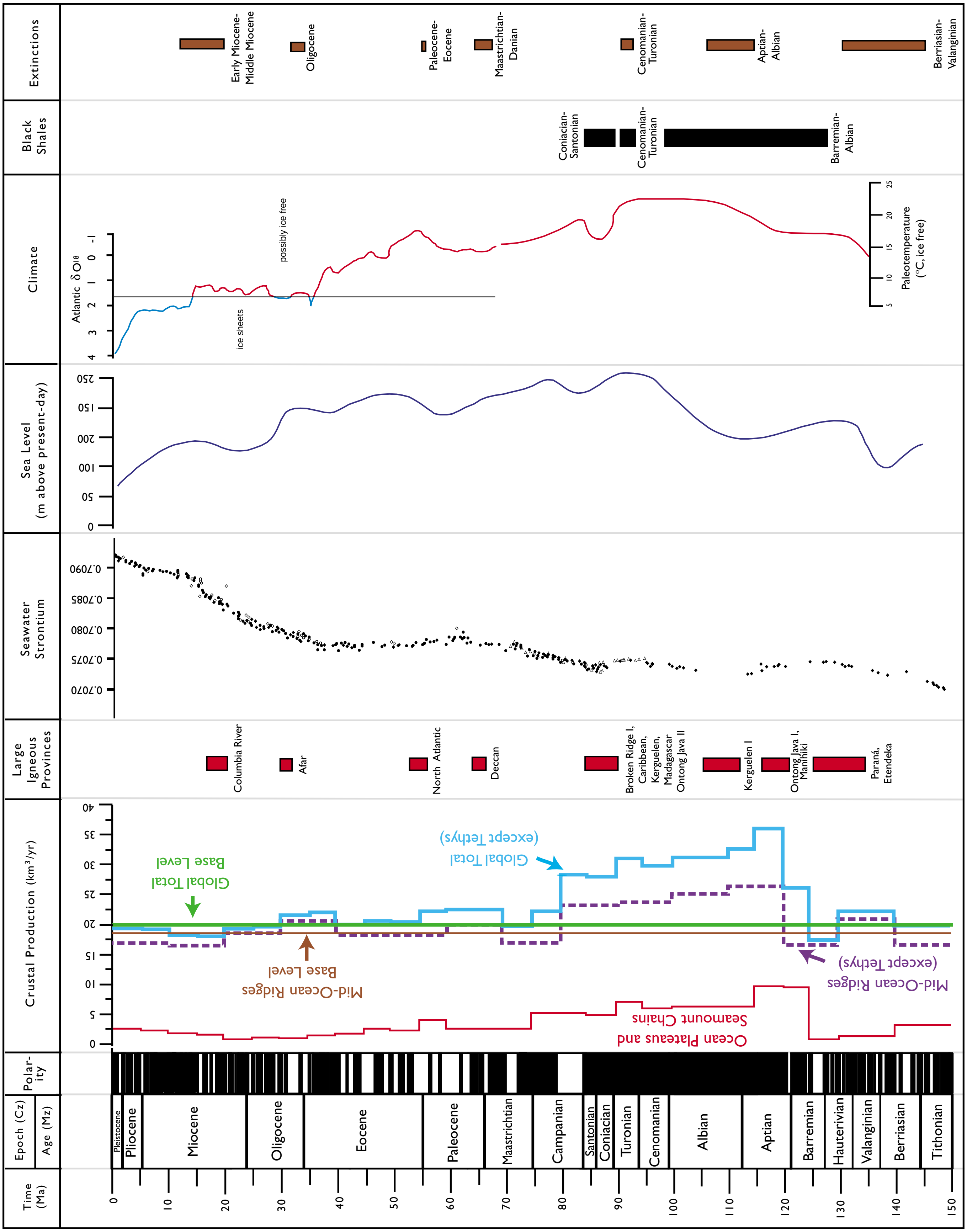


Figure 51. Temporal correlations among geomagnetic polarity, crustal-production rates, LIPs, seawater strontium, sea level, climate as interpreted from oxygen isotope values, black shales, and mass extinctions. (After Coffin, M.F., and Eldholm, O., 1994. Large igneous provinces: crustal structure, dimensions, and external consequences: *Reviews of Geophysics,* 32:1–36.)

Triassic boundary coincided with the largest extinction of plants and animals in the geologic record. Ninety percent of all species became extinct at the boundary. On Iceland, the 1783–84 eruption of Laki provides the only human record of experience with the type of volcanism that constructs large igneous provinces. Although Laki produced a basaltic lava flow that represents only 1% of the volume of a typical LIP flow, the eruption's environmental impact resulted in the deaths of 75% of Iceland's livestock and 25% of its population from starvation. If such a relatively small eruption happened today, all air traffic over the North Atlantic would likely be halted for three to six months.

Observational and modeling efforts to understand LIP formation and development are at an early stage and are comparable to investigations of the mid-ocean ridge system prior to development of the plate-tectonics paradigm, in that no one theory adequately explains large-volume basaltic magmatism on Earth and the other terrestrial planets and satellites. Understanding the processes in Earth's mantle and crust, and the effects of LIPs on the oceans, atmosphere, and biosphere (Fig. 51), is of particular importance. Because the scientific problems associated with LIPs range widely, scientists from many disciplines are involved in their study. These fields include geochronology, marine geophysics, petrology, geochemistry, mineral physics, rock deformation, oceanic and atmospheric chemistry, physical volcanology, paleomagnetism, tectonics, seismology, geodynamics, micropaleontology, paleoclimatology, paleoceanography, sedimentology, remote sensing, and planetary geology.

Scientific Rationale

LIPs provide the strongest evidence that at specific times in the past, most recently during the Cretaceous Period, mass and energy transfer from Earth's interior to its surface have occurred in a mode substantially different from that of present-day processes (Fig. 50). In fact, large igneous pulses may have occurred repeatedly from Archean to Cretaceous time, but much of the evidence for pre-Cretaceous LIPs is either obscured by collisional tectonics or has been removed by erosion. Nevertheless, we have observed probable analogues to LIPs on Venus, Mars, the Moon, Io, and possibly Mercury. The paucity of evidence for plate tectonics on these planetary bodies implies that the mode of abrupt mantle overturn and internal energy loss that may have operated on Earth in Cretaceous time is more fundamental to the solar system than the steady-state plate-tectonic mode that we observe on Earth's surface today. On Earth, LIPs form the largest expressions of transient basaltic volcanism, and emplacement rates of the largest provinces may have exceeded the global mid-ocean ridge production rate over time periods of approximately 1 million years. Despite the global occurrence and importance of LIPs to Earth's dynamics, heat budget, chemical differentiation, and environment (Fig. 51), our knowledge of LIPs is rudimentary because of a profound lack of geologic and geophysical data. For example, reliable estimates of such basic LIP parameters as ages, volumes, fluxes, compositions, and tectonic settings are scarce for most provinces.

Today, we investigate upper-mantle circulation by studying the mid-ocean ridge system, which currently accounts for approximately 95% of the mass and energy transfer from mantle to crust. During certain intervals of the Cretaceous Period, however, 50% or more of the mantle mass and heat flux may have occurred via emplacement of the approximately 20 Cretaceous oceanic plateaus, volcanic passive margins, and continental flood basalts (Fig. 49). Therefore, to investigate the contrast between Wilson Cycle and mantle overturn and major orogenesis (MOMO) modes of mantle dynamics (Fig. 50), including the state of the mantle before and after individual LIP events, we need to examine globally significant Cretaceous and Cenozoic LIPs.

First-Order Scientific Themes

Three first-order scientific themes are associated with understanding mantle dynamics, as recorded by LIPs, and the associated environmental effects that occurred during Cretaceous and Cenozoic time:

- Mass and energy transfer among the core, mantle, and crust related to LIP genesis
- Emplacement and postemplacement mechanisms
- Consequences of emplacement and evolution for the hydrosphere, atmosphere, and biosphere

Each of these themes includes several outstanding scientific questions that can be addressed in whole or in part by scientific ocean drilling.

Mass and Energy Transfer Among the Core, Mantle, and Crust Related to Lip Genesis

The mechanisms by which mass and energy (primarily heat) are transported among the core, mantle, and crust shape Earth's surface, drive the motion of tectonic plates, and control the physical and chemical evolution of the planet. Aside from plate-tectonic processes and features, LIPs are the only surface expression of the dynamics of Earth's interior. The geologic products of these systems record answers to the following questions.

What Are the Depths of Origin and Scales of the Mantle Sources?

The biggest mantle plumes may originate at the core-mantle boundary. Smaller ones may originate shallower in the mantle. Do some plumes correspond to hot mantle that incubates beneath continental lithosphere or to convective instabilities in the upper mantle? Sampling by ocean drilling of continuous and deep sections of basement rocks will allow us to measure the isotopic and trace element compositions of the basalts. These geochemical determinations will enable characterization of the mantle sources and thus quantification of the relative contributions of mantle reservoirs. In addition, an oceanic network of seismic observatories is needed to provide sufficient resolution to tomographically image mantle thermal anomalies and active LIPs. Of particular interest is the core-mantle interface and the D≤ layer, where many plumes may originate.

Are these processes aseismic mantle creep and/or atmospheric movements?

What Is the Time-Dependent Behavior of the Mantle Source?

Are the sources giant, single, mushroom-shaped heads of starting mantle plumes, multiple plume heads, or long-lived mantle upwellings? How does the chemistry of the source evolve with time, locally and globally? Answers to these questions are vital to understanding the fluxes among mantle reservoirs and the entrainment mechanisms as well as the vigor and style of convection within Earth, both today and in the geologic past. Determinations of ages and geochemistry will provide valuable constraints on these processes.

How Hot and How Large Are the Mantle Sources?

Understanding these physical properties is important in understanding the thermal state of the Earth at the present time and through geologic history. The petrology and geochemistry of volcanic rocks reflect the depths and extents of mantle melting, both of which are controlled by the source temperature. Geophysical data on magma volume will allow us to determine the volume of source mantle melted. In addition, the volatile content of erupted magmas as well as sediments overlying the volcanic rocks reveal the depth of eruption; this information is useful in quantifying the degassing history and amount of thermal uplift. Higher-resolution seismic structure of the mantle from seafloor observatories will indicate the size and temperature of active systems.

How Do LIPs and Plate Tectonics Interact?

Controversy exists as to how continental breakup, the location of seafloor spreading, and changes in plate motion are influenced by LIP formation or vice versa. A variety of geologic data suggests that a large global flux of LIP events in the Cretaceous may be connected to a large influx of lithosphere into the lower mantle by plate subduction. Several changes in Pacific plate motion, perhaps related to changes in subduction dynamics, appear to have occurred near the time of eruption of some Pacific LIPs; however, age data on the eruptions are few. Comprehensive dating and careful detailed geochemical studies provide critical information to address these questions.

How Do LIP Events Influence the Geomagnetic Field?

The influence of LIPs on the geodynamo is suggested by the coincidence of the long Cretaceous Normal Superchron with the formation of many LIPs. A core-mantle boundary origin of the LIP source would strongly influence convection in the core and thus Earth's magnetic field. Age data are needed to better establish the chronology of LIP events and magnetic reversals, and geochemical and seismic measurements will address the influence of LIP sources at the core-mantle boundary.

Crustal Emplacement and Postemplacement Mechanisms

What Are the Rates and Timing of Crustal Emplacement, Both at Individual LIPs as Well as Globally?

Which and how many oceanic LIPs formed by catastrophic flood-basalt volcanism that erupted in episodic and less voluminous events, and which formed by steady, long-lived eruptions? What was the global flux of LIP magmatism during Cretaceous and Cenozoic time, and how did it vary? Quantitative answers to these questions can only be determined by drilling and dating these features, in combination with geophysical observations. These data are important in addressing many of the questions regarding the mantle sources and in assessing the impact of LIP formation on the environment.

How Is Magma Transported from the Mantle Source and How Does It Interact with the Lithosphere During Transport?

To what extent is magma transported through lithospheric dikes versus a permeable network of melt veins? How extensive is the change in magma and lithosphere geochemistry due to interaction between them? How does this interaction change with time? Unraveling these topics—primarily through comparative studies of oceanic LIPs with obducted and continental flood basalts—addresses basic problems of deep magma transport and is also important in characterizing the source composition before magma-lithosphere interaction occurs.

What Is the Three-Dimensional Structure of LIP Crust and How Is Magma Emplaced?

What is the compositional and petrologic stratigraphy of LIP crust? How is the crust partitioned among extrusive rocks, intrusive rocks, and crystallized cumulates? Did magma reside and evolve in large magma chambers before erupting? How is magma transported at the surface and how did this shape surface morphology; was magma transported in extensive sheetlike flows, tube-fed pillow flows, or elongate subsurface dikes? Were fissures or discrete volcanic centers the main loci of eruption? How explosive are volcanic eruptions related to LIPs emplacement? A combination of ocean-drilling and geophysical observations can resolve these issues, which in addition to addressing basic scientific questions have relevance to assessing the volcanic hazards of modern-day vestiges of LIPs (Iceland, Hawaii, Yellowstone).

How Extensive Is the Nature of Hydrothermal Circulation at LIPs and What Is Its Nature?

It is now well understood that hydrothermal circulation associated with volcanism at mid-ocean ridges is the primary mechanism of heat loss from the crust and mantle. Hydrothermal flux through mid-ocean ridge crust induces mineralization in the crust and supports extensive biological communities. Are hydrothermal effects of heat transport, mineralization, and biological productivity as extensive at sites of LIP volcanism? These questions can only be addressed by ocean drilling.

What Role Do LIPs Have in the Growth of Continental Crust?

Are LIPs preferentially accreted to continents instead of subducted and thus contribute to continental growth? Do LIPs act as nuclei for continental growth? Careful examination of obducted parts of LIPs, e.g., Ontong Java, the Caribbean, and Wrangellia, as well as the older geologic record of basaltic volcanism on the continents, will address these problems.

Consequences of Emplacement and Evolution for the Hydrosphere, Atmosphere, and Biosphere

Cretaceous oceans were characterized by global variations in ocean chemistry, relatively high temperatures, high relative sea level, episodic deposition of black shales, high production of hydrocarbons, mass extinctions of marine organisms, and radiations of marine flora and fauna. Intense pulses of igneous activity associated with LIP formation affect the physical and chemical character of the hydrosphere and atmosphere to an undetermined extent and may have significant effects on the biosphere. Tentative temporal correlations of Cretaceous pulses and rates of LIP formation with major environmental changes (Fig. 51) require further analysis to define linkages, threshold levels, and causes. To assess the range of environmental responses to LIP formation, we require sampling of the paleo–hydrothermal fields and metamorphic zones to determine fluid compositions from alteration effects and the timing and scale of discrete events. Effects can also be observed in high-resolution sedimentary sections drilled in near- and far-field settings, e.g., on topographic highs such as older plateaus or seamounts.

How Do LIPs Affect the Hydrosphere and Atmosphere?

Submarine and subaerial volcanism have substantially different effects on Earth's environment, yet the emplacement environments for many oceanic LIPs are unknown. Once drilling and geophysical results establish submarine/subaerial ratios for the volcanic products of individual LIPs and the volatile contents of the lavas are determined, fluxes of volatiles, particulates, and heat from LIPs into the atmosphere-hydrosphere-biosphere system can be estimated and their environmental impact can be assessed. What are the precise temporal relationships between LIP emplacements and changes in environmental parameters, and what are possible threshold levels for LIP "impacts" such as climate change, oceanic and atmospheric chemistry, anoxia (black shales), oceanic and atmospheric circulation, sea level, and evolution—including both mass extinctions and radiations?

What Are the Effects of Hydrothermal Activity on the Oceans, Atmosphere, and Biosphere?

What are the chemical fluxes, depths, spatial distribution, geometry, and alteration processes of hydrothermal circulation and metamorphism at LIPs? The thermal and permeability structure of old oceanic and transitional crust invaded by LIP heat sources likely differs from those of mid-ocean ridges. Therefore, the products and consequences of hydrothermal activity and metamorphism in this setting may differ significantly from the spreading-ridge environment. Abundance patterns and gradients in trace metals in pelagic sediments resulting from hydrothermal activity may "fingerprint" each LIP and enable precise correlation with global oceanic anoxic events.

Drilling Strategy for Oceanic LIPs

Drilling is the only means of sampling most submarine LIPs and contemporaneous sedimentary sequences. Drilling provides critical information on age, composition, and eruptive setting needed to address the issues of mantle dynamics, emplacement, and environmental consequences. Because of their large size, oceanic LIPs pose considerable challenges for adequate sampling to address our first-order questions. Extensive shallow basement drilling (approximately 200 m below the seafloor) combined with significant geophysical surveying is needed. Furthermore, at some point in the future, deep drilling on LIPs (more than 2,000 m below the seafloor) will be needed to reveal the age and composition of middle to lower crust and to relate these physical and chemical properties to geophysical data on seismic velocity and density structure. Study of continuous, thick stratigraphic sections of lava is required to reliably document the processes controlling the formation of LIPs.

Understanding the complete temporal and compositional range of features of this scale will require a variety of approaches in appropriate locations (Fig. 52). Lavas forming the upper crust of LIPs are predominantly tholeiitic basalts, but also include alkalic varieties. More silicic lavas are known from oceanic plateaus, volcanic passive margins, and continental flood basalts, but are estimated to constitute a relatively small percentage (approximately 10%) of LIP rocks. Seismic imaging of oceanic LIPs has revealed several characteristics: crustal thickness varies from one to more than five times that of normal oceanic crust. Volcanic sections, commonly lying beneath sediments several hundreds to thousands of meters thick, range from a few kilometers to possibly 10 km thick. Lava flows commonly appear as dipping reflections in seismic profiles and represent a temporal sequence related to eruption location and magma supply. Internal reflections and velocity structure indicate thick sections of higher-density material at depth, probably mafic sill complexes, cumulate layers, and ultramafic bodies.

A significant sampling of the total igneous stratigraphy using the capabilities of current *JOIDES Resolution*–type and advanced riser-equipped ships can be obtained through a combination of several strategies (Fig. 52):

- Transects of shallow (approximately 150 m) basement holes across the surface of the LIP over crust of varying thickness, i.e., from feather-edge to center, guided by temporal relationships indicated in dipping reflection sequences.

- Offset drilling in tectonic windows that expose deep levels of otherwise inaccessible parts of the LIP. These sites occur at tectonized margins or interiors of many LIPs and must be well characterized by geophysical and submersible surveying and surface sampling.

- Deep boreholes will sample a significantly greater percentage (20%–30%) of LIP total crustal thickness (20–35 km) compared to the less than 1% cored by transects of shallow basement boreholes. At carefully surveyed and (reconnaissance) drilled locations, deep boreholes will document the chronology and geochemical development of magmatism.

- On-land sections of obducted parts of LIPs (e.g., Haiti, Solomon Islands) or of autochthonous LIPs along volcanic passive margins (e.g., Voring Plateau) provide opportunities for detailed sampling of parts of the stratigraphy. In most instances, however, it is difficult to relate these tectonized sections to the intact (submarine) parts of the province by geophysical methods; careful geochemical studies of tectonized and intact LIPs are necessary.

- Reference boreholes address three important components of our sampling strategy: (a) Samples are needed to establish the age and composition of the older plate on which some or all of the LIP is built, to properly assess the

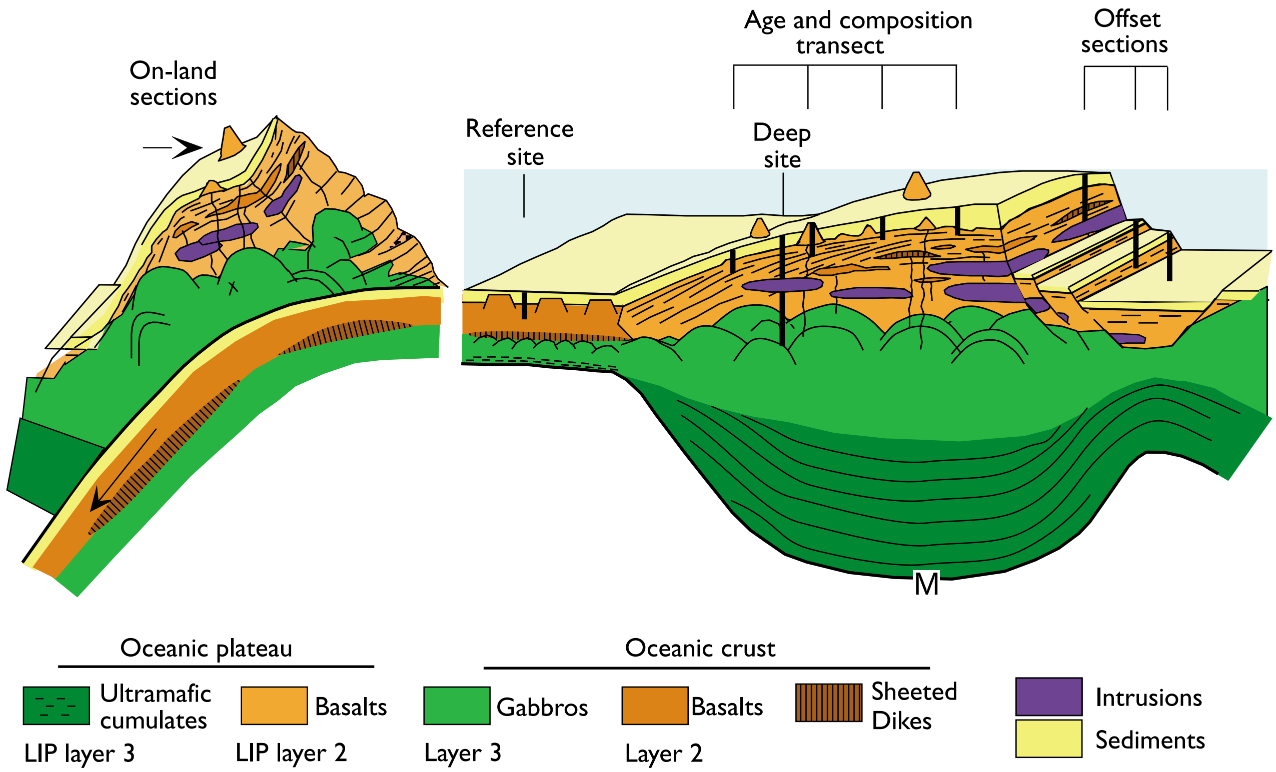


Figure 52. Proposed LIP drilling strategy. Boreholes along a transect penetrate approximately 150 m to determine the age and composition of the shallow volcanic basement. Intermediate-depth and deep sites are then chosen following the exploratory drilling. Offset sections provide windows into middle- and deep-crustal levels. On-land sections permit detailed sampling, albeit of tectonized rocks. Reference sites on older oceanic crust record the volcanic and deformational history of LIP emplacement.

effects of lithospheric contamination on compositions, to evaluate pre-emplacement mantle compositions, and to model uplift and subsidence. (b) The sedimentary section on older adjacent crust records the near-field environmental impact of emplacement. (c) Debris shed from the LIP during its construction accumulates in sedimentary aprons on the old plate, providing a means of establishing the volcanic history.

- Boreholes of opportunity involve penetrating basement to bit destruction whenever any scientific ocean-drilling borehole is within reach of basement on any LIP. Basement samples from such boreholes will provide age and compositional data for the LIP, data that do not exist for the overwhelming majority of submarine provinces.

- Logging should be undertaken in all basement boreholes so that the physical and chemical properties of the rocks penetrated by the borehole can be studied. Furthermore, logging provides important information on the state of stress, as well as on dynamic parameters such as permeability, temperature, and pressure.

Paleobiology and Evolution

The Marine Biosphere

Among the most pressing challenges facing modern-day research in the Earth, ocean, and atmospheric sciences is the need to understand the causes and effects of rapid major perturbations of the carbon cycle, global climate, and biodiversity. Evolutionary studies of the oceanic biosphere have three broad goals:

- To understand evolutionary processes and the origins of marine biodiversity. Our twofold purpose in striving toward this goal is to better appreciate the way evolution has given rise to the great variety of life and to gain fundamental knowledge of our own origins.
- To evaluate the sensitivity of marine ecosystems to large perturbations such as abrupt climate change, massive release of greenhouse gases, and removal of key parts of the oceanic food chain. All are issues we face as a result of human-induced climate change and exploitation of ocean resources.
- To decipher the evolution and ecologies of marine organisms and their critical, but poorly understood, roles in the cycling and uptake of greenhouse gases, major nutrients, and carbon (Fig. 53). We are only just beginning to appreciate the feedback processes between life and the regulation of Earth's climate and inventories of many nutrients, gases, and chemical species.

Ocean drilling is particularly important because of its proven potential to yield truly global records of life in the oceans with excellent age control. Furthermore, the best examples from the geologic record of rapid changes—on the timescale of 1 thousand to 1 million years—in Earth's biosphere do not come from recent Earth history, i.e., the Quaternary (the past 1.8 million years), but instead from tens of millions to more than 100 million years ago. Within this time interval, there are six prominent biotic crises that could be better understood by scientific ocean drilling:

1. The beginning of the glaciation of Antarctica at the Eocene/Oligocene transition (36 million years ago)
2. The significant decrease of surface-water biodiversity in the middle Eocene (about 38 million years ago)
3. The extreme warm climates of the Paleocene/Eocene boundary (about 55 million years ago) and the biologic response
4. The mass extinction and bolide impact at the Cretaceous/Paleogene boundary (65 million years ago)
5. The turnover of plankton and benthos in the late Campanian and early Maastrichtian (about 71 million years ago)
6. The oceanic anoxic event at the Cenomanian/Turonian boundary 91 million years ago

However, beyond the most rudimentary models that are based on what are essentially only preliminary records, very little is known about the underlying biological causes and effects of most of these crises in Earth history. Nonetheless, high-quality records of these critical events in the biosphere do exist in the oceans and are readily available for drilling.

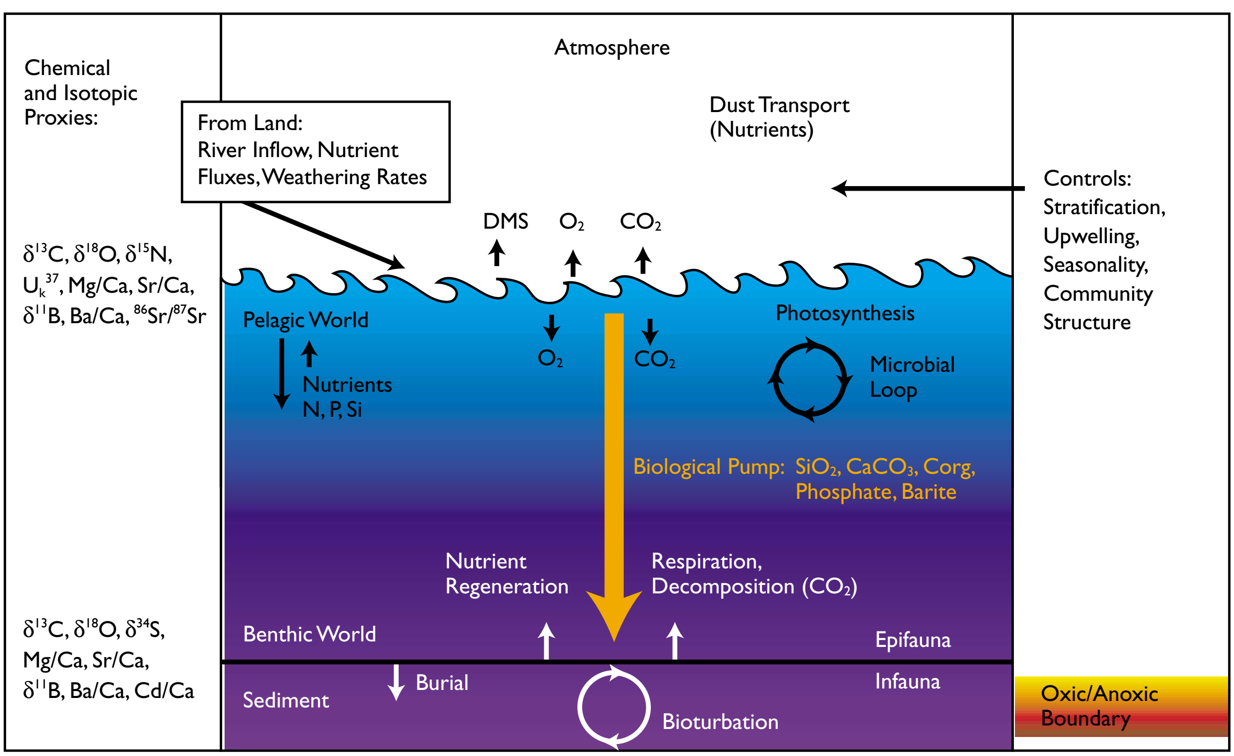


Figure 53. Linkages between the marine biosphere and global biogeochemical cycles in the oceans, as well as to various proxies used in study of ancient climates. The proxies include particular isotope measurements (indicated by lowercase deltas followed by the heavy isotope), organic chemical "fingerprints" (e.g., U_k^{37}, which is an alkenone ratio; the 37 refers to the carbon number of the alkenones of interest), and elemental ratios. DMS is dimethylsulfide.

Evolutionary Processes and Biodiversity

Investigation of the marine biosphere addresses fundamental processes of the formation, distribution, and maintenance of organisms and ecosystems on Earth. The deep biosphere, existing within subseafloor sedimentary and volcanic rocks, offers us the chance to study the structure and origin of biodiversity that has evolved under completely different conditions than are found in the surface world. Analysis of evolutionary dynamics in the fossil record of the surface and seafloor marine environments provides similar opportunities; we can compare and contrast patterns and mechanisms of evolution under the wide array of boundary conditions that have existed in Earth's geologic past. As a bonus, we hope to better understand our own origins.

Ocean drilling is a key to exploration of the whole oceanic biosphere. Through study of the cores retrieved, we will acquire our first glimpse into the diversity and origins of life in the extreme environments below the seafloor. The samples will provide an unparalleled opportunity to examine fundamental evolutionary processes and their interplay with Earth's climate in the past.

Key Scientific Questions

What is the structure of the geomagnetic field on long and short timescales?

Just how dipolar is Earth's magnetic field when averaged over long timescales (more than 5 million years), and how long has the field been predominantly dipolar?

How do the fundamental mechanisms of speciation and extinction work in the open-ocean realm and how do they differ from evolutionary processes on land? How do evolutionary processes operate over time to create and regulate the larger-scale patterns of marine biodiversity?

All large-scale evolutionary changes in biodiversity are driven by the speciation and extinction of individual taxa. Testing theories of how speciation and extinction actually work remains one of the major challenges of evolutionary biology. The uniquely continuous, high-resolution, deep-sea microfossil record offers an unparalleled chance to observe how these mechanisms operate in the oceanic realm. Most models for speciation in terrestrial environments, for example, emphasize the role of geographic isolation in allowing populations to become genetically differentiated from their relatives elsewhere. However, there is increasing evidence from ocean drilling and genetic studies of living species that many pelagic organ-

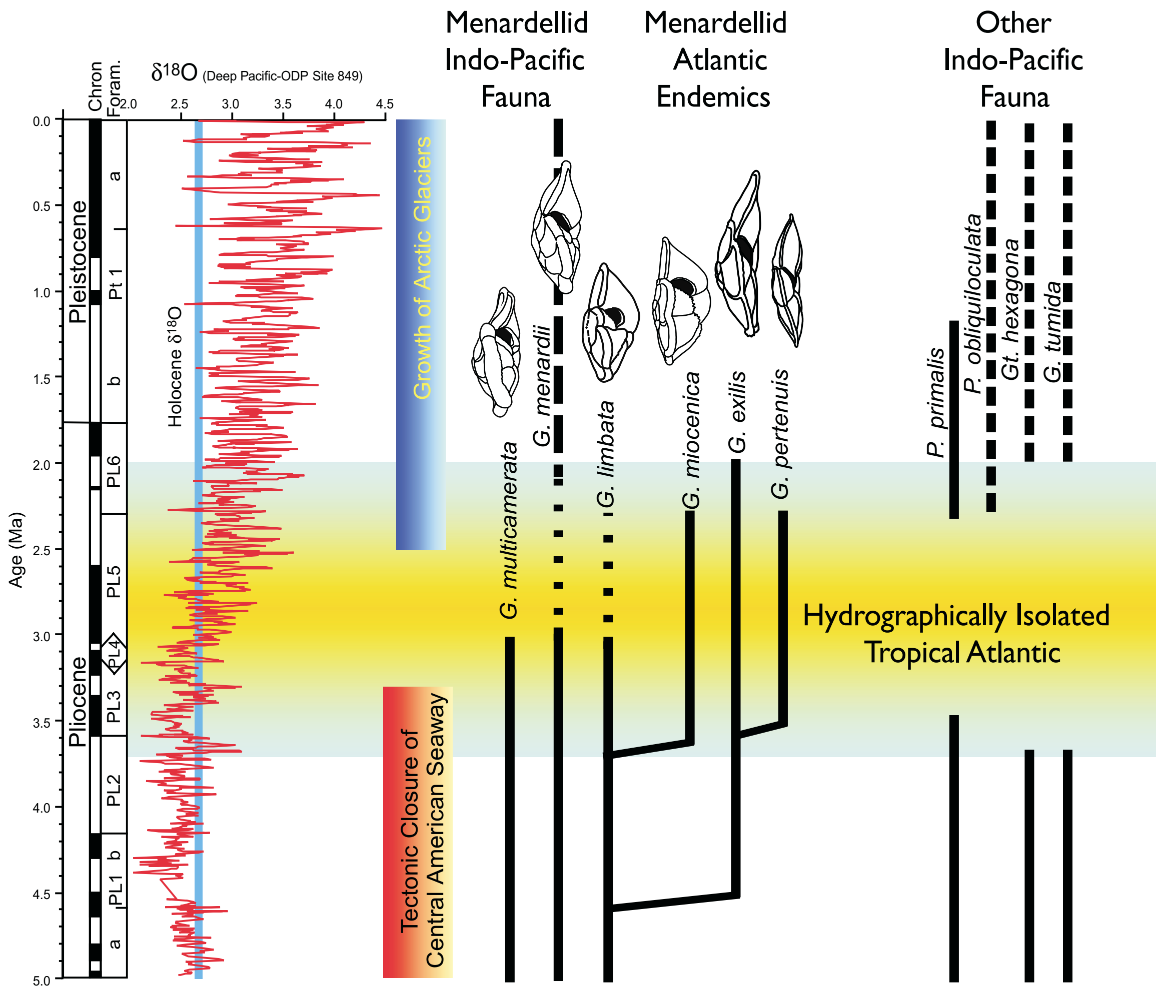


Figure 54. Formation of the Isthmus of Panama (in the Pliocene, about 3–5 million years ago) led to the evolution of new species of planktic foraminifera and local extinction of others in the Atlantic. The new Atlantic species evolved before complete closure of the gateway into the Pacific, showing that oceanographic differences rather than an inability to get from one ocean to the other caused the biotic changes. Evolutionary studies bearing on the Pliocene oceans will be significantly advanced by an integrated scientific drilling program that will core sediments on both sides of major gateways and by the use of orbitally tuned chronologies.

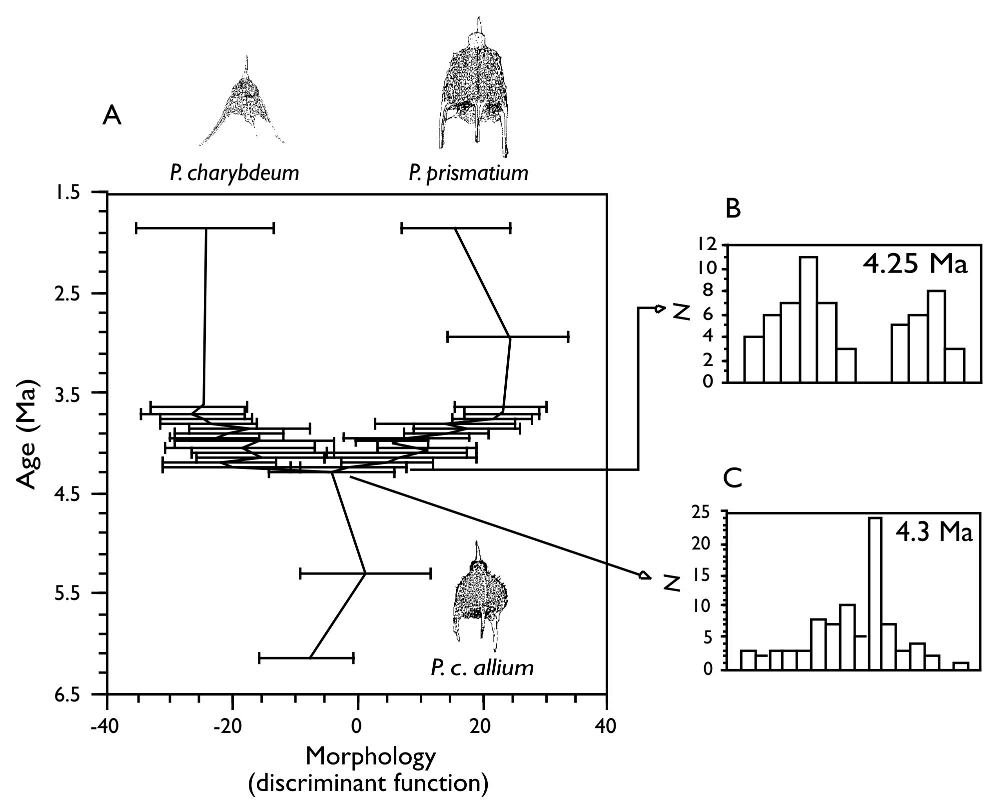


Figure 55. Example of speciation of the radiolarian *Pterocanium prismatium* from *P. charybdeum* (*P. c. allium*) at about 4.3 million years ago. (A) Change in population morphology (connected by vertical lines) in equatorial Pacific DSDP Site 573. Morphologic changes are enumerated by using discriminant function analysis. (B and C) Histograms of morphologic variation for two samples from the base of the speciation event show initial origination of the two species within an estimated 50,000-year interval (B = 4.3 million years ago [Ma]; C = 4.25 million years ago). An even larger amount of morphological change accumulated in the next 500,000 years by phyletic evolution in both descendant lineages before coming to a stop.

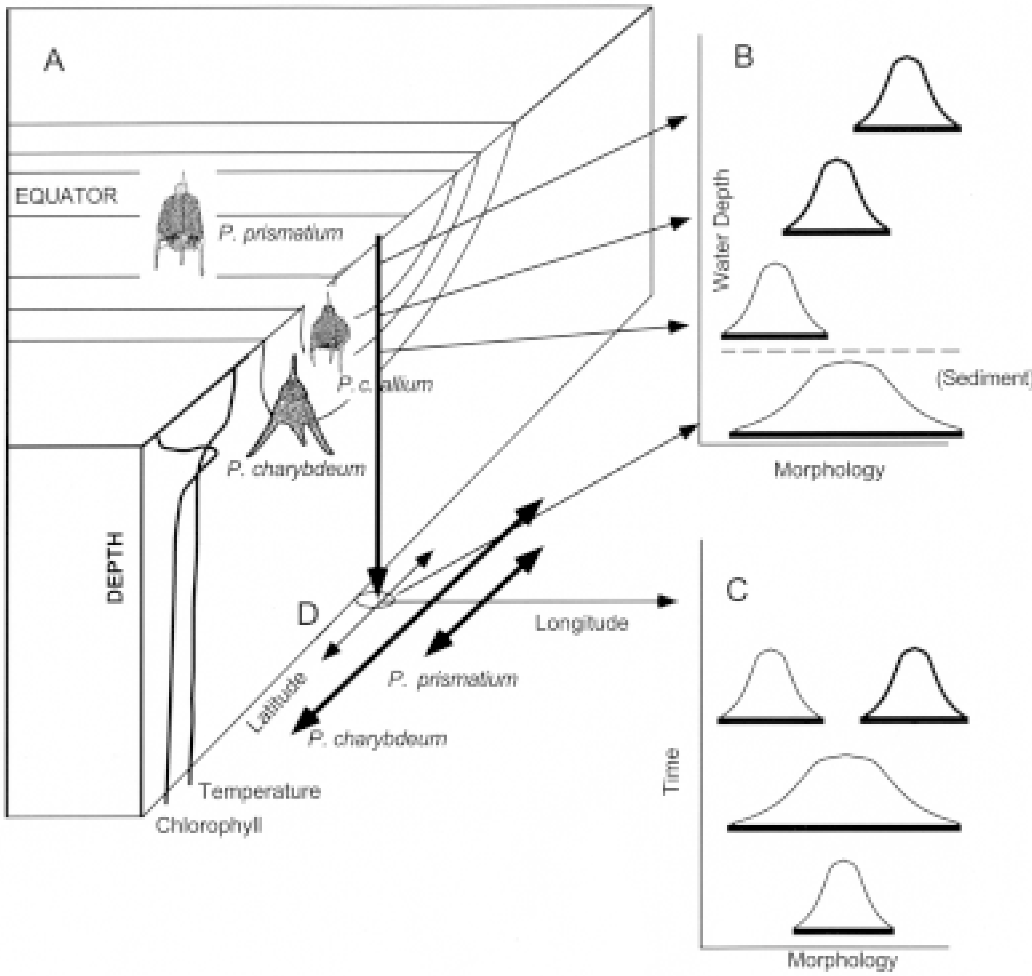


Figure 56. Speciation theories compared to model predictions. The data in Figure 55 suggest a change in depth habitat during speciation in which (A) a new, surface-water tropical species *P. prismatium* evolved from a tropical, intermediate-depth ancestral species *P. charybdeum allium*. (B) Ancestor living in intermediate-depth environments. Water depth in planktonic environments correlates strongly to gradients in biologically important parameters, e.g., temperature and chlorophyll (curves in lower left of A). In B, three living populations of cline are shown relative to depth in the water column, whereas lower curve shows combined distribution as recorded in the sediment record below (cumulative rain of shells to sediment shown by vertical black arrow in A). The temporal record in the sediments of speciation (C) is marked by the loss of intermediate-water-depth populations in the cline (central part of medium-dotted distribution) and phyletic evolution in both descendant lineages.

isms encounter few effective barriers to interchange between distant populations (Fig. 54) and that new species may arise within a single geographic region (Figs. 55, 56). Speciation may work differently in the oceans than on land, or long-standing theories explaining evolution in terrestrial populations may need revision.

Scientific ocean drilling affords us a unique opportunity to compare the patterns of evolution in fossilized marine organisms with predictions from studies of living species. Further ocean drilling is needed to determine the history of well-known and newly recognized species. Genetic data for pelagic and deep-sea organisms are just now becoming available. Combining preliminary studies of fossilized organisms that lived in the deep sea with the genetic analysis of their living relatives has recently yielded the fascinating suggestions that marine biodiversity may be considerably higher than previously believed (Fig. 57) and that our view of what a "species" is may require fundamental revision. To date, there are relatively few deep-sea borehole sites with continuous recovery and orbitally tuned chronologies in sediments older than the late Pliocene (i.e., older than 3 million years). Even for upper Pliocene sediments, geographic coverage is not nearly extensive enough to compare evolutionary patterns in the subtropical gyres with those in the tropics for more than a handful of species.

For benthic organisms, scientific ocean drilling will yield information on the development of deep-sea diversity over Earth history. Knowledge of the origins of deep-sea diversity is critical to evaluating general ecological models for diversity gradients on Earth, because the deep-sea environment is the only one of the three regions of highest biodiversity on Earth—rain forests, coral reefs, and deep-sea floor—where it is possible to track diversity changes back in time in the detailed, long-term geologic record of the oceans.

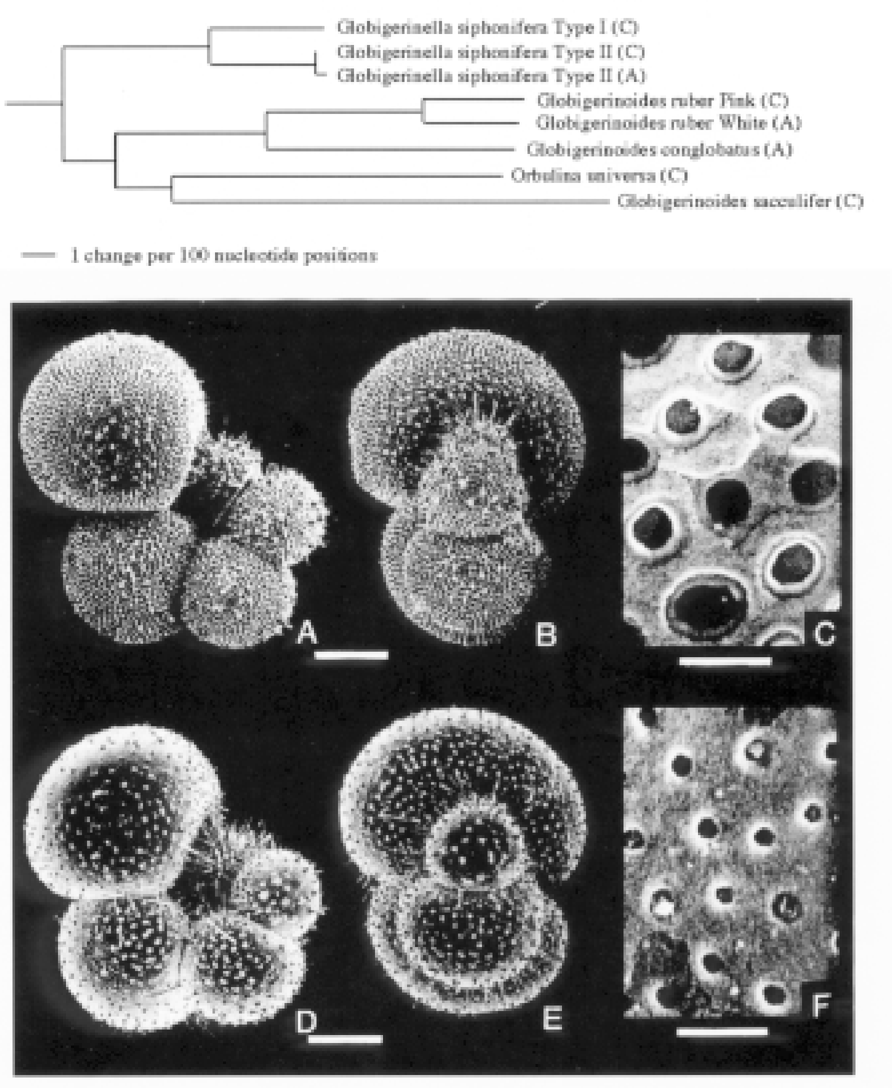


Figure 57. Genetic data now available for planktic foraminifera show that relatively minor morphological differences may represent differences between biological species, as shown by this example of "cryptic" speciation in which two genetically distinctive species have similar, but not identical morphologies. (Top) A molecular tree for the globigerinid planktic foraminifera that shows the deep division between *G. siphonifera*, Type I and Type II, similar to the degree of genetic distinctiveness between widely recognized species. (Bottom) Photomicrographs of *G. siphonifera* Type I (A–C) and Type II (D–F). Note the difference in porosity of the shells of these closely related foraminifera (close-ups C and F) and the looser coiling of Type I (A and B) compared to Type II (D and E). Scale bars for A, B, D, and E represent 100 _m, and those for C and F represent 10 _m.

The Sensitivity of the Biosphere to Climate Extremes and Its Role as a Forcing Mechanism in Climate Dynamics

The evolution of biological systems has fundamentally structured the biogeochemical and climatological systems on Earth. Major originations and extinctions of species have played a central role in altering the cycles of nutrients through the biosphere with potentially important, but poorly understood, consequences for Earth's climate (Fig. 58). In turn, rapid changes in climate have led to equally dramatic changes in the structure and diversity of marine ecosystems. The structure of pelagic ecosystems strongly affects the budgets of carbon, nitrate, and phosphate in the global oceans and, thus, the working of the "biotic pump" and global biogeochemical cycles (Fig. 53). Because the oceans are so large, their nutrient budgets influence the whole world. The next phase of ocean drilling should place strong emphasis on understanding how these geochemical systems and climate are organized relative to major events in biological evolution. Therefore, some critical questions that can be addressed with an of integrated program of deep ocean drilling include the following: What are the effects of various species' origin, diversification, and extinction on the cycling of greenhouse gases and nutrients through the oceans? Has the structure of oceanic biodiversity during times of extreme climate been very different from that of today? How flexible are ecosystems to climate change? On what timescales does biodiversity respond to rapid climate change?

Mass extinctions and large-scale reorganizations of pelagic ecosystems have occurred periodically throughout geologic time and are clearly accompanied by large changes in carbon cycling, atmospheric CO_2, and nutrient utilization that may last millions of years (Fig. 59). An integrated program of deep-ocean drilling should concentrate on discovering the following:

- The pattern and process of recovery from major extinction events to determine how sensitive the combined geochemical and climate system is to the extinction or decimation of groups with different roles in the biogeochemical system

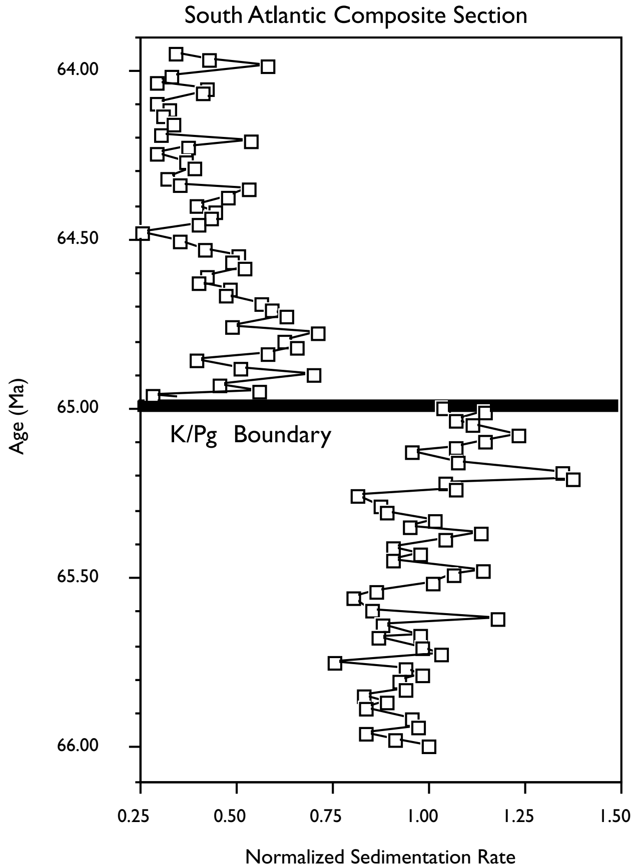
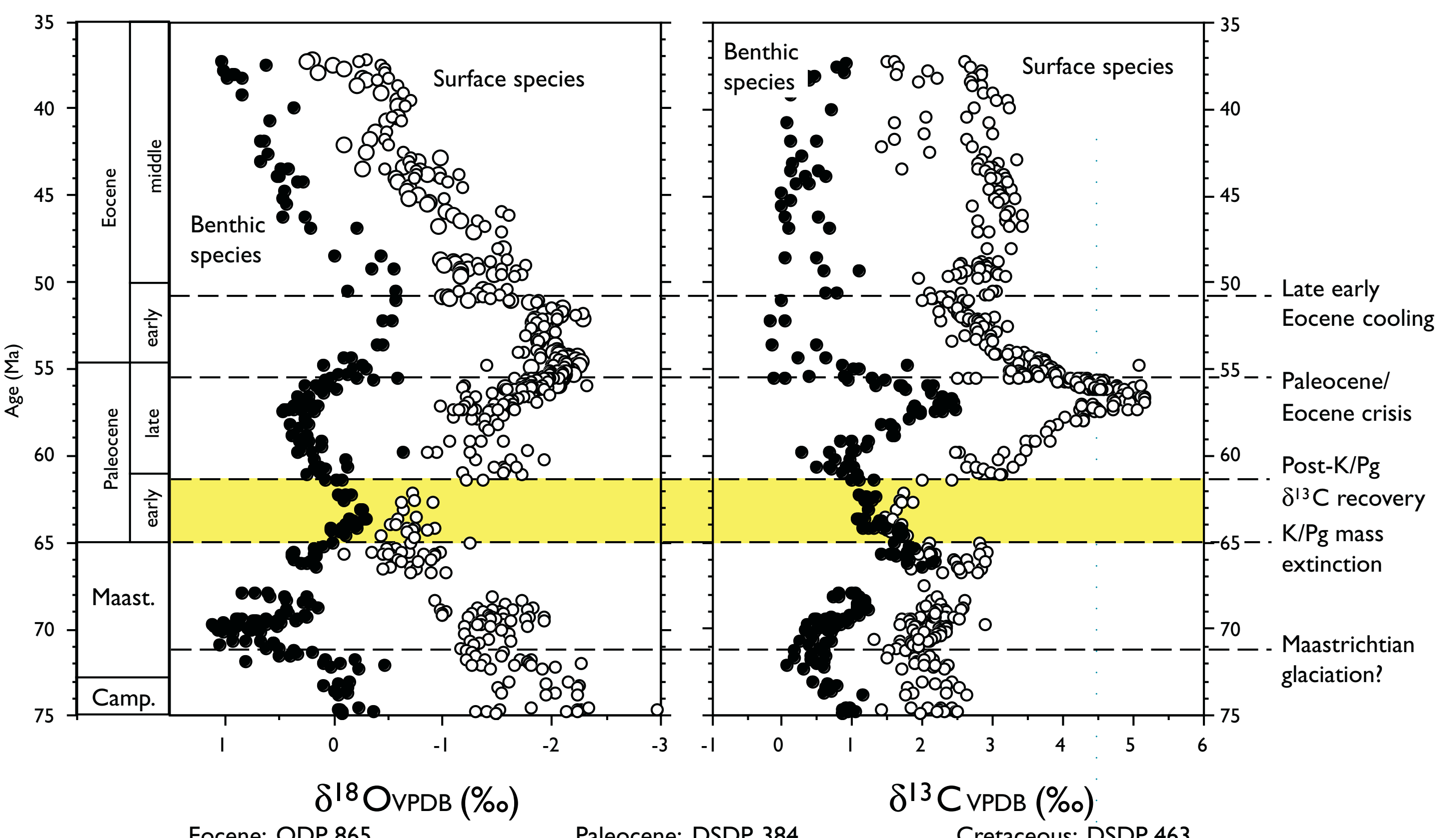


Figure 58. Collapse in production of sediment consisting of the tests of calcium carbonate–secreting organisms in the deep sea at the Cretaceous/Paleogene (K/Pg) boundary mass extinction (65 million years ago). The prolonged reduction in calcium carbonate production is a measure of how marine ecosystems were restructured in the aftermath of the extraterrestrial impact that triggered the extinction. Examination of the details of these biotic and geochemical events should be a focus of the next phase of ocean drilling through targeted drilling of high-deposition-rate sediments that span critical boundaries.

Figure 59. The Cretaceous/Paleogene (K/P) mass extinction fundamentally altered the cycling of carbon in the oceans for 3.5 million years (yellow band). The collapse of the carbon isotope gradient between surface and deep water reflects a wholesale reorganization of the way carbon was cycled through oceanic ecosystems, probably because of massive changes in the structure of the marine communities. The Paleocene/Eocene biotic crisis (55 million years ago) represents a much shorter transitory shift in carbon isotopes than the K/P event. Most studies of these events have been conducted at low resolution (a sample every ten thousand years or more). A future integrated program of ocean drilling should focus on specific scientific questions surrounding these transitory events.



- The recovery time of different biological systems
- How perturbations of nutrient utilization contribute to restructuring of ecosystems

With the unprecedented advances in chronological resolution that are occurring, we are now well prepared for high-resolution analysis of sedimentary and fossil records spanning a few million years around large extinction or speciation events. There are four crucial needs:

- The recovery of well-preserved records of siliceous biota to study their role in the major chemical cycles
- The recovery of middle Cretaceous strata to support the study of major swings in carbon cycling and biotic reorganization during that time interval (Fig. 60)
- The recovery of cores through sections having high deposition rates and containing critical boundaries such as the Cretaceous/Paleogene extinction, late Paleocene thermal maximum (LPTM), and the Eocene/Oligocene boundary
- Development of new proxies (such as biomarkers) to reconstruct the record of organisms and ecologies not represented by the skeletal fossil record.

Considering present-day conditions that indicate that climatic and biotic change can occur at an extremely rapid pace, it is vital to understand how the biosphere behaves at times of rapid changes in the ocean-climate system. Modern marine ecosystems show considerable variation in the relative importance of bacteria, phytoplankton, and zooplankton in creating and recycling resources within the food chain. The relative proportions of these different groups of organisms have probably changed over time in response to differences in the nutrient inventories and rates of supply within the ocean. For example, the mass extinction that defines the Cretaceous/Paleogene boundary was triggered or at least strongly assisted by an extraterrestrial impact 65 million years ago; the mass extinction seems to have fundamentally restructured the way carbon and other nutrients were cycled in the upper ocean for at least 3 to 4 million years (Figs. 58 and 59). Ancient times of biological crisis should be used as natural experiments to study the role of physical perturbations in the evolution of biogeochemical cycles and their feedbacks into Earth's climate.

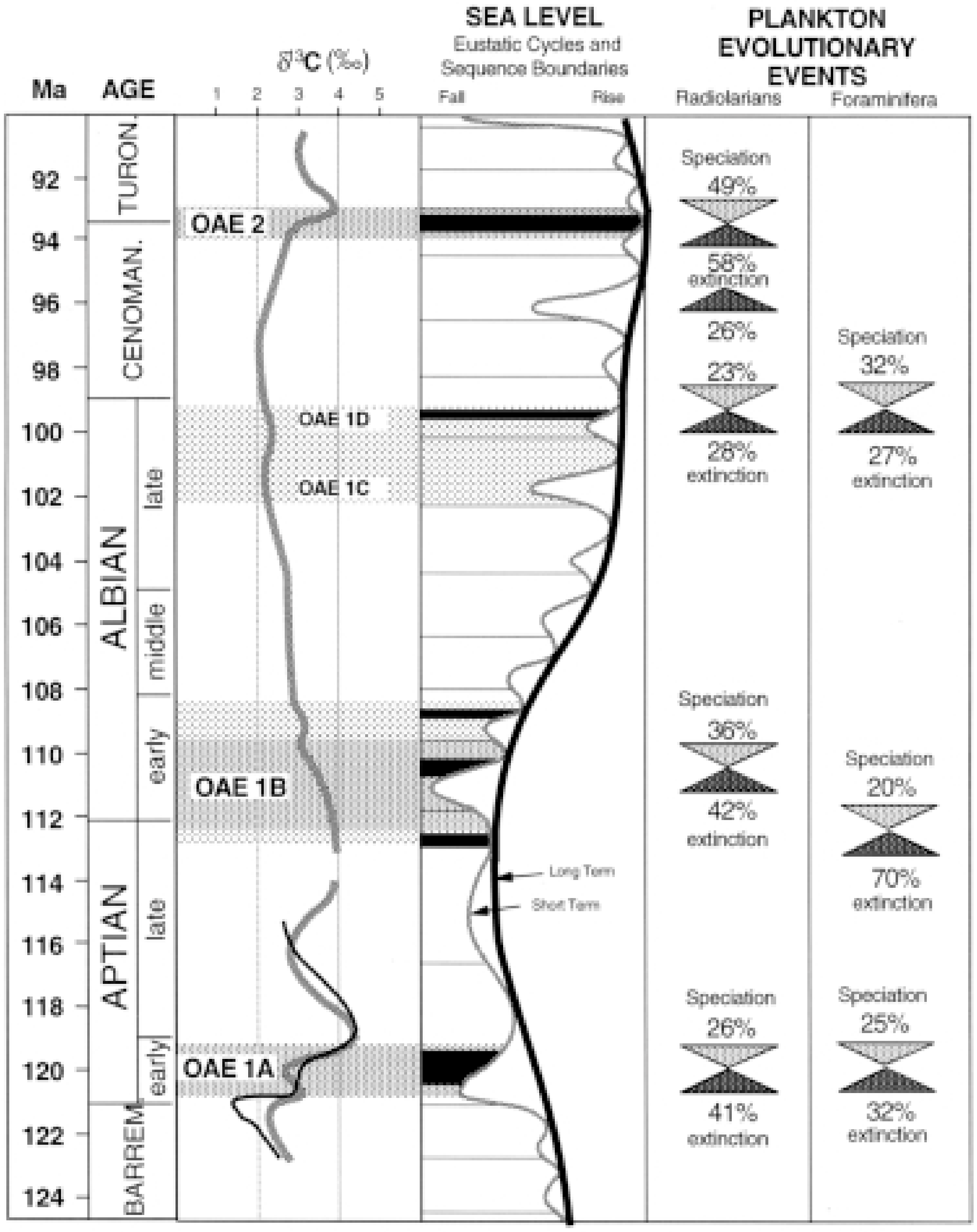


Figure 60. Relationship between times of severe oxygen depletion in the oceans (known as oceanic anoxic events or OAEs) and events in biotic evolution during the middle Cretaceous. The OAEs represent transitory shifts in carbon burial and nutrient cycling within the oceans that had significant effects on the evolution and extinction of marine organisms. We know little about the causes of these large changes in the biosphere's carbon budget or the details of how these events started or ended, yet they may provide important insights into the interaction of biota, climate, and nutrient budgets of the oceans in more "normal" times.

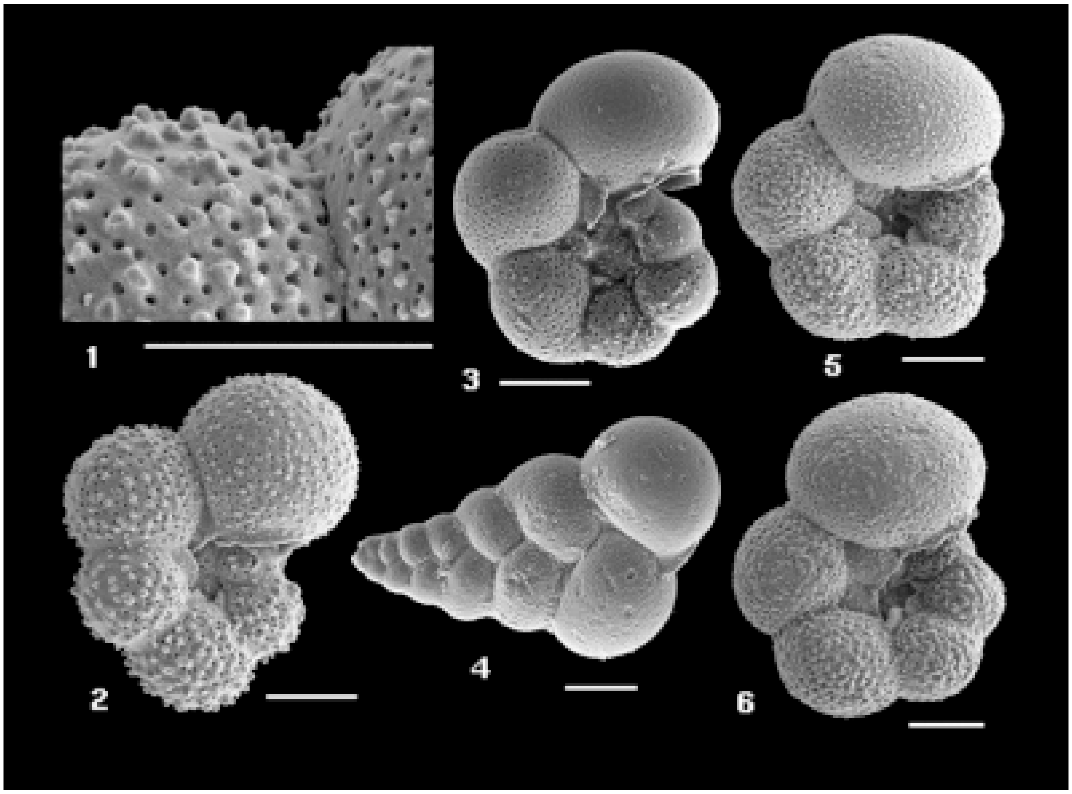


Figure 61. Exceptionally well preserved foraminifera from the upper Cenomanian (91 million years old) sedimentary rocks of the Demerara Rise, off the coast of northeastern South America (DSDP Site 144). Geochemically well preserved microfossils such as these present opportunities to reconstruct the climate during the unusually warm period of the middle Cretaceous: (1–2) *Hedbergella delrioensis* (1 is detail of 2), (3) *Globigerinelloides bentonensis*, (4) *Heterohelix moremani*, (5–6) *Whiteinella* sp. All scale bars represent 50 _m. In the next phase of ocean drilling, recovery of texturally and geochemically well-preserved microfossils such as these is critical to studies of extreme climate and biotic events.

DRILLING STRATEGY

Previous ocean drilling did not, until recently, target continuous recovery of rapidly accumulated sediments that preserve the archive of past life in the oceans. Numerous partial records exist that have used in exploratory studies of evolution and biodiversity, but records of pre-Miocene strata dated with the resolution of an orbitally tuned timescale are very rare. It is critical both for understanding evolutionary mechanisms and for documenting diversity history to have reasonably complete records through time that document each fossil group in each oceanic biogeographic province. Records from Arctic seas, from lower-latitude upwelling zones, and of older—particularly siliceous—biotas sorely need augmentation.

It is also increasingly obvious that very expanded records of seafloor Cretaceous and lower Cenozoic sediments can often be found without the thick cover of younger sediments that frequently made the older record inaccessible in previous phases of ocean drilling. Further, with careful site selection, these ancient sediments can yield exquisitely preserved fossils that record with high fidelity the chemistry and conditions in the ancient oceans (Fig. 61).

Finally, a critical advance in the study of evolution in the deep sea is the development of timescales tuned to Earth's orbital cycles (Fig. 62). Orbitally tuned timescales are just now being extended into the Paleogene and Cretaceous, making it possible to determine the rate and pattern of evolution with unprecedented precision. We are seeing a revolution in our ability to understand the linkages between climate and biotic changes in far-flung parts of the oceans.

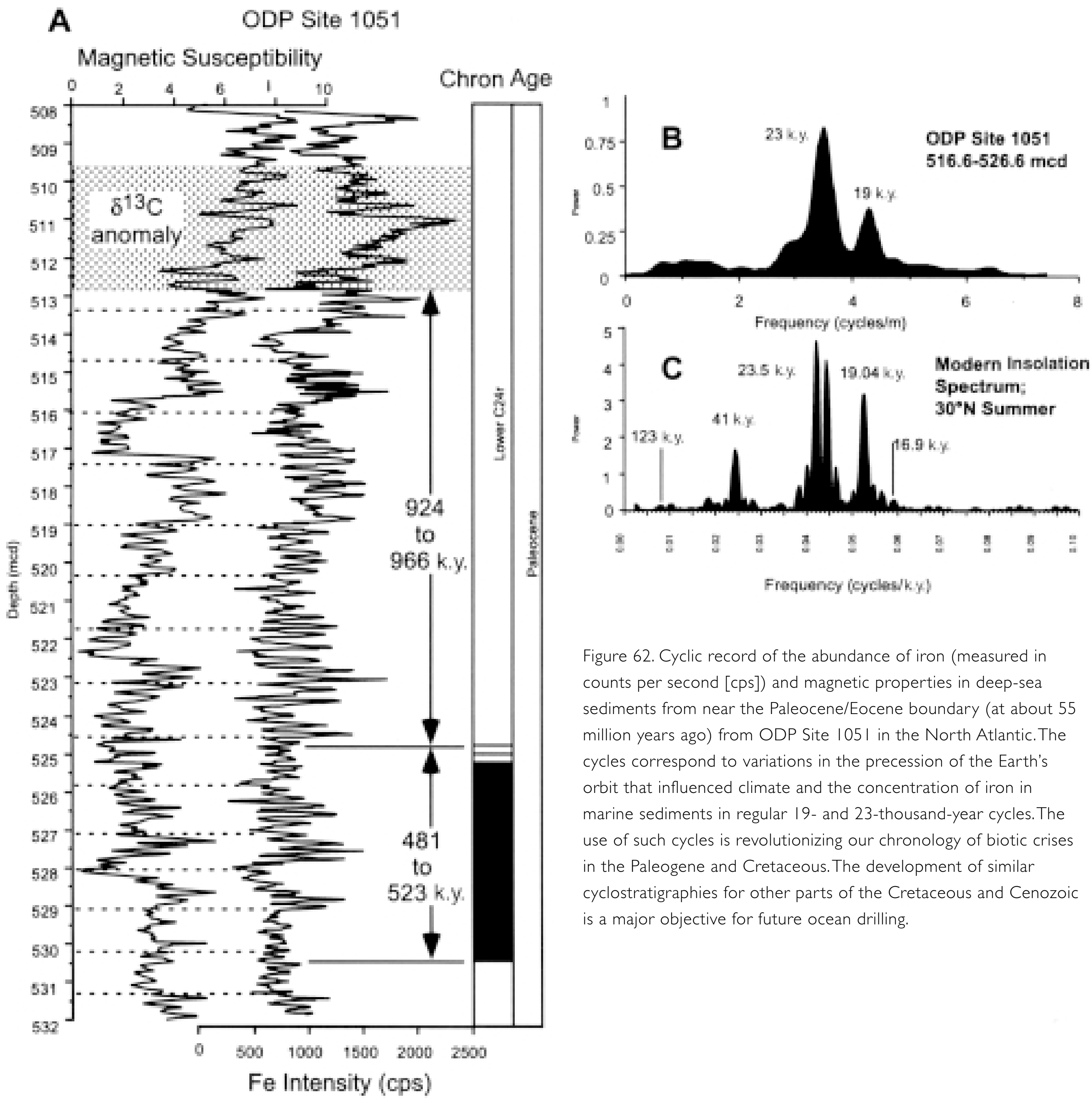


Figure 62. Cyclic record of the abundance of iron (measured in counts per second [cps]) and magnetic properties in deep-sea sediments from near the Paleocene/Eocene boundary (at about 55 million years ago) from ODP Site 1051 in the North Atlantic. The cycles correspond to variations in the precession of the Earth's orbit that influenced climate and the concentration of iron in marine sediments in regular 19- and 23-thousand-year cycles. The use of such cycles is revolutionizing our chronology of biotic crises in the Paleogene and Cretaceous. The development of similar cyclostratigraphies for other parts of the Cretaceous and Cenozoic is a major objective for future ocean drilling.

Catastrophic Events

Catastrophic geologic events such as earthquakes, volcanic eruptions, tsunamis, mass-wasting events, and ice-sheet collapse are of immediate societal concern. All of these processes are instrumental in shaping the Earth system today and have operated throughout its history. Other catastrophic events like impacts have played a major role in the evolution of the planet and particularly its biosphere. Understanding catastrophic geologic processes, their controls, and their societal effects involves a diverse array of observational and surveying techniques. Ocean drilling can be a key element in investigating the past and present influences of these processes and thus potentially in their prediction.

Earthquakes and tsunamis are discussed in the chapter on the Seismogenic Zone, effusive volcanism is discussed in the chapter on Large Igneous Provinces, and gas hydrate venting is discussed in the New Foci chapter in the section on quantifying the gas hydrate cycle. The other types of catastrophic events that our Earth is subject to are described briefly here.

Impact Events

There are more than 150 impact craters identified on Earth. These range from small in size up to the 180-km-diameter Chicxulub crater beneath Yucatán. The larger impacts have had major effects on the course of evolution and on climate. Even though the impact at the Cretaceous/Tertiary boundary has received a great deal of investigation (Fig. 63), there is still a great deal of uncertainty as to the environmental and biological perturbations caused by this event. We have even less understanding of the environmental effects of smaller events such as the late Eocene Chesapeake Bay impact. Understanding the environmental and biotic effects of impacts must involve investigation of events at a variety of scales. Critical

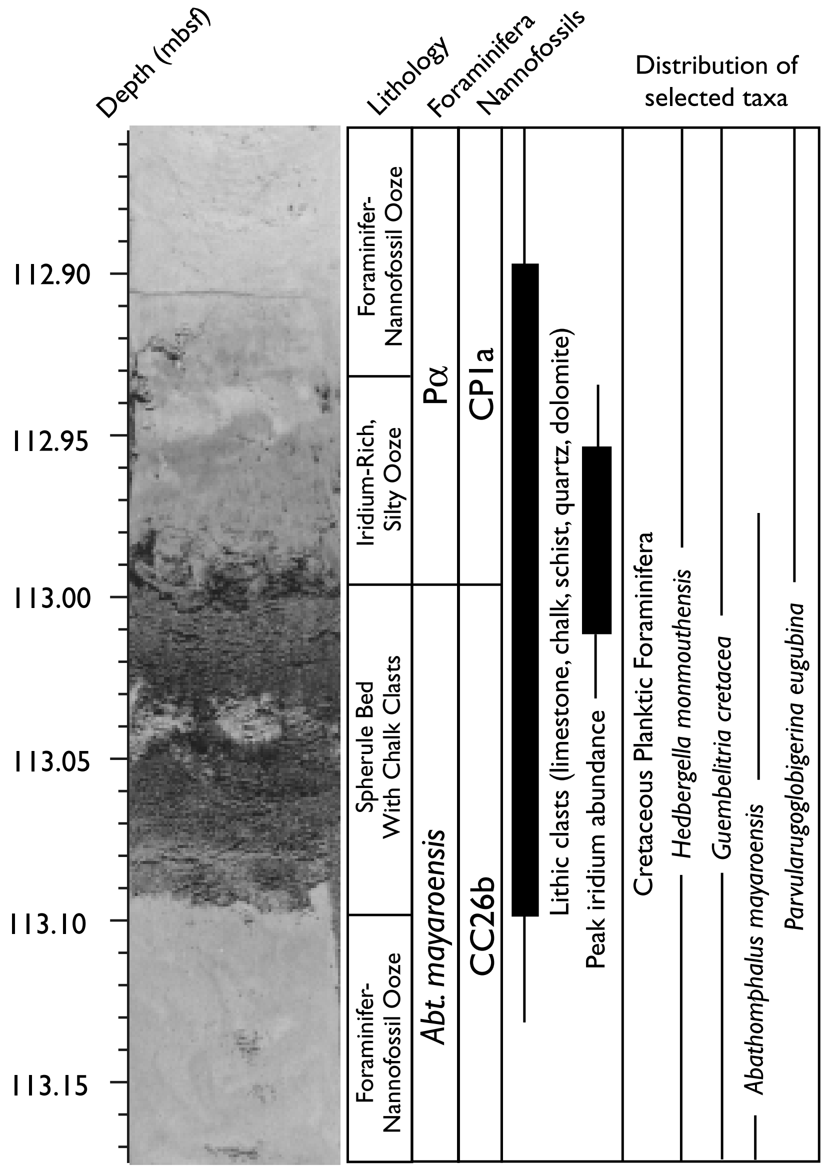


Figure 63. Cretaceous/Tertiary boundary at Site 1049 on Blake Nose (on the Blake Plateau, western North Atlantic; off the southeast coast of the United States), ODP Leg 171B. Illustration shows lithology (core photograph marked in meters below seafloor [mbsf]), planktic foraminiferal and nannofossil zones, distribution of impact-derived materials, and ranges of critical planktic foraminiferal taxa.

unanswered questions bear on the extinction and recovery mechanisms, the effect on global climate and local submarine morphology, and the recognition of impact deposits in the geologic record.

Extinction Mechanism

We do not understand the exact killing mechanism for any impact event. In particular, we need to determine why some species are more sensitive to extinction than others. Is extinction of a given species a direct result of a particular environmental perturbation, or is the susceptibility of that species to extinction at the time of the impact more important?

Recovery Mechanism

Large impacts clearly cause a major change in oceanic and terrestrial biogeochemical cycling that can last for millions of years. We need to determine the exact effects of impacts on oceanic nutrients and how these effects influence the recovery of faunal and floral groups. For example, we need to answer first-order questions. For example, how long does it take for different groups to recover and why do some groups appear to recover faster than others? Understanding these major questions is clearly associated with defining how biogeochemical cycling changes during the recovery period.

Short- and Long-Term Climate Effect

Large impacts cause major changes in long-term as well as short-term climate. We need to develop a better understanding of the exact climate perturbations, both their magnitude and duration. This knowledge is of fundamental importance in understanding extinction mechanisms. We need also to determine the size threshold at which an impact has a long-term climate effect and the exact relationship of impact angle and the nature of the target terrain to the climate perturbation. Our best estimates indicate that the trajectory of the Cretaceous/Tertiary boundary asteroid was from southeast to northwest at a low angle. At such a low impact angle, target vaporization would have been enhanced. We know that the severity of the Cretaceous/Tertiary boundary extinctions was amplified by the evaporites that existed on the Yucatán at the time impact; sulfur and sulfate aerosols derived from these evaporites may have increased short-term cooling and may have also resulted in acidic conditions in marine environments. Further investigation and modeling of ejecta dispersal at the Cretaceous/Tertiary boundary are required to fully determine the exact environmental effects of this unique impact event. Such investigation will require a denser array of sites than that so far drilled.

Effect on Submarine Morphology

The impact at Chicxulub is thought to have triggered massive collapse of the Campeche margin in the Gulf of Mexico and continental margins around the Caribbean and proximal Atlantic. More observation is required to map out the exact

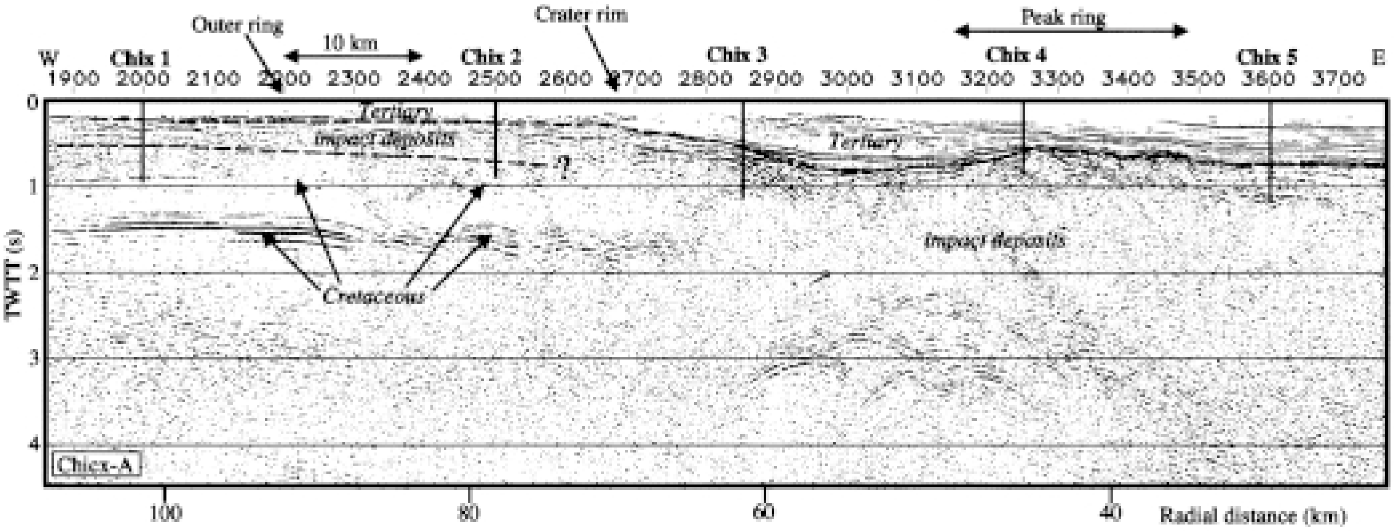


Figure 64. West-east multifold seismic line Chicx-A across the northern offshore part of the buried Chicxulub Cretaceous/Tertiary impact crater, northern Yucatán margin, Mexico. The line is located approximately 25 km north of the Yucatán coast. It shows the major crater features and the following stratigraphy: (1) undisturbed, disturbed, and collapsed Cretaceous target rocks, (2) various impact deposits in the crater and on its flanks, and (3) the overlying Tertiary fill (deep-water deposits in the crater and shallow-water deposits on the flanks). Also shown is a transect of proposed drilling sites for the integrated program of scientific ocean drilling. Chix 1 and 2 are designed to sample the thin, shallow-water Tertiary section, the impact deposits just outside the crater, and the top of the Cretaceous target rocks. Chix 3 to Chix 5 are designed to sample the thicker, deep-water Tertiary section and the upper part of the various impact deposits.

effects of the impact on submarine morphology. Further study of the ancillary submarine effects of the late Eocene Chesapeake Bay impact structure would also be instructive.

Identification of Impact Deposits in the Geologic Record

There are approximately 150 known cratering events in the history of Earth. Distally deposited impact debris has been found from fewer than 10 of these events. Recognition of impact ejecta deposited in sediment is often problematic and sometimes controversial. In locations close to the crater, high-energy processes related to the impact event have complicated the stratigraphic record so that the origin of the deposits is often questioned and their age is disputed. Only by studying the sedimentology of known impact deposits can we develop a clearer set of guidelines for identification of proximal and distal impact deposits in the stratigraphic record. A more complete inventory of impact events in the geologic record will ultimately allow an assessment of recurrence intervals.

Drilling Strategy

Ocean drilling of the deposits that resulted from the Chicxulub impact must be coordinated with the planned continental drilling of the crater itself. We need a transect of sites from the crater (Fig. 64) to the proximal and distal landslides related to margin collapse. This experiment will require platforms ranging from jack-up rigs designed for drilling in shallow water to the successor to the *JOIDES Resolution*.

Distal sites away from the Chicxulub structure are critical to understanding extinction and recovery of marine biotas, as well as ejecta dispersal and thus the environmental effects of the Cretaceous/Tertiary impact. Of particular interest to testing the postulated low-angle, southeast-to-northwest trajectory are sites in the northern Pacific. These targets are important scientific objectives that should be integrated with other drilling goals in the area.

Explosive Volcanic Events

Explosive volcanic events have a major effect on short-term (1–5 year) climate change. The influence of large, repeated volcanic episodes on longer-term climate is undemonstrated. Documentation of eruption frequency of major volcanic provinces over geologic time is required to understand the role of volcanism in forcing climate and biotic evolution over longer-term timescales.

Of more direct societal relevance, one way to help characterize the eruptive behavior of active, potentially hazardous volcanic systems is to determine the episodic frequency of eruptions in the recent record. Ocean-drilling transects near active systems such as Iceland and New Zealand will extend land-based records, help document the volume (i.e., the magnitude) and the age distribution of recent eruptions and help pin down recurrence intervals.

Drilling Strategy

For studying an active volcanic system, a drilling leg should entail a proximal to distal transect. This approach may require drilling in shallow water. Coring systems capable of good recovery in this type of section are required.

Mass-Wasting Events

Mass-wasting events occur at all scales and on all margins—active, passive, and volcanic. Rapid large-scale events involve collapse of margins that can generate destructive tsunamis. Smaller-scale events have displaced oil rigs, broken deep-sea communication cables, and, in a few cases, liquefied segments of coastline, such as near Seward, Alaska, and Nice, France. Large and small events along coastal zones can damage coastal facilities and property and cause loss of life. We need a stronger understanding of the processes of mass wasting, especially the triggering mechanisms such as earthquakes, diffusion of gas, disassociation of gas hydrate, sediment loading, rapid sea-level change, and oversteepening of slopes by biological, chemical, and physical mechanisms. Ultimately the goal is to develop the ability to predict mass-wasting events by using established physical parameters of slope stability and predictive downhole instrumentation and possibly by determining recurrence interval.

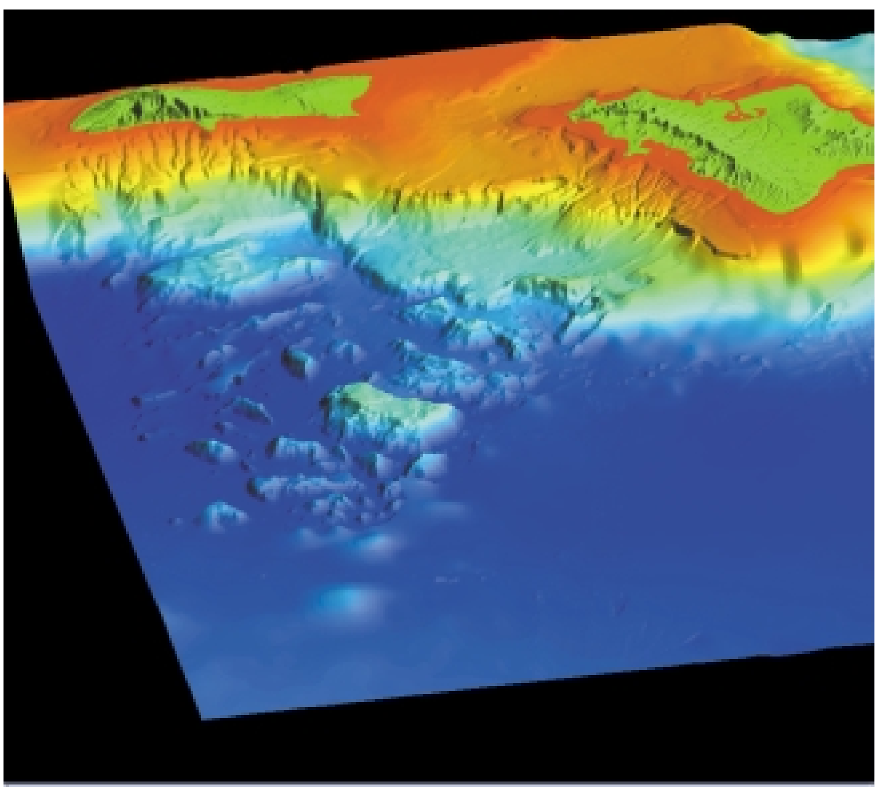


Figure 65. Perspective view of the Nu'uanu and Wailau debris avalanches, north of the islands of Oahu and Moloka'i, respectively. Many of the large blocks were derived from the collapse of Ko'olau volcano on Oahu about 1–1.5 million years ago. The largest block is about 30 km across and stands about 1.5 km above the surrounding 5-km-deep seafloor. Offshore benches adjacent to the islands may represent rotational slump blocks still attached to the volcano flanks. View is from the north-northeast. (Bathymetry compiled by G. Moore and J. Morgan.)

Drilling Strategy

An understanding of large mass-wasting events will require a transect from proximal to distal parts of the deposits and sampling of in situ as well as allochthonous deposits. The scientific objectives outlined here will require the full range of drilling technology including (1) the ability to drill in shallow water, (2) riser drilling through unstable zones, and (3) casing of instrumentation to monitor fluids and stress regimes through time.

Active Mass Wasting in Hawaii: An Example

Giant landslides have been recognized in and around the Hawaiian Islands and are thought to accompany late shield-building stages of volcano growth. Coherent slumps are interpreted along the flanks of the volcanoes; debris avalanche deposits with blocks as much as 30 km across are observed within the Hawaiian Deep and are thought to have traveled as far as 230 km away to the Hawaiian Arch (e.g., north of Oahu, Fig. 65). The southeast flank of Kilauea volcano, on the island of Hawaii, is the site of an active landslide, the Hilina Slump; this slump has been the site of major ground motions associated with earthquakes, shoreline subsidence, and generation of a local tsunami resulting in deaths. If this slump, or an analogous feature, were to fail catastrophically, the scale of geologic hazards that might accompany failure is almost unimaginable.

Drilling Strategy

To predict the potential for future flank collapses, and to understand past failures, we need to know the compositions, extents, and volumes of both active and ancient landslides and the geometry of structures controlling their movement. Drilling into flanks of active volcanoes, and into deposits in the Hawaiian Deep, would provide information on lithology and ages of the landslides, from which we might infer material strength, landslide frequency, source area, and so forth. Drilling would allow us to identify bounding structures. In situ measurement of stresses, pore pressures, and fluid compositions would instruct us about slope stability and potential for failure.

ICE-SHEET COLLAPSE

Heinrich events dramatically illustrate that ice sheets behave in a dynamic way, and not always in phase with Milankovitch forcing. Ice-sheet buildup is progressive, but decay is usually rapid and often catastrophic. These facts are apparent in the saw-tooth pattern seen in the oxygen isotope record, which represents a global average ice volume. But ice sheets do not operate all in lockstep.

Collapse of the Laurentide and Fennoscandian ice sheets left a variety of imprints on the deep-sea record. Documenting past collapse of existing ice sheets is more difficult, but must be a high priority for future drilling, in order to evaluate the threat of future collapse and concomitant sea-level rise. In terms of natural hazards, future collapse of the West Antarctic Ice Sheet poses the highest threat of future rapid sea-level rise of several meters (Fig. 66). Evidence exists, from beneath the existing ice sheet, of past collapse during the Quaternary, in agreement with sea-level proxies. Unfortunately, identifying such events in the deep-sea record is difficult, especially those relating to the Antarctic Ice Sheet.

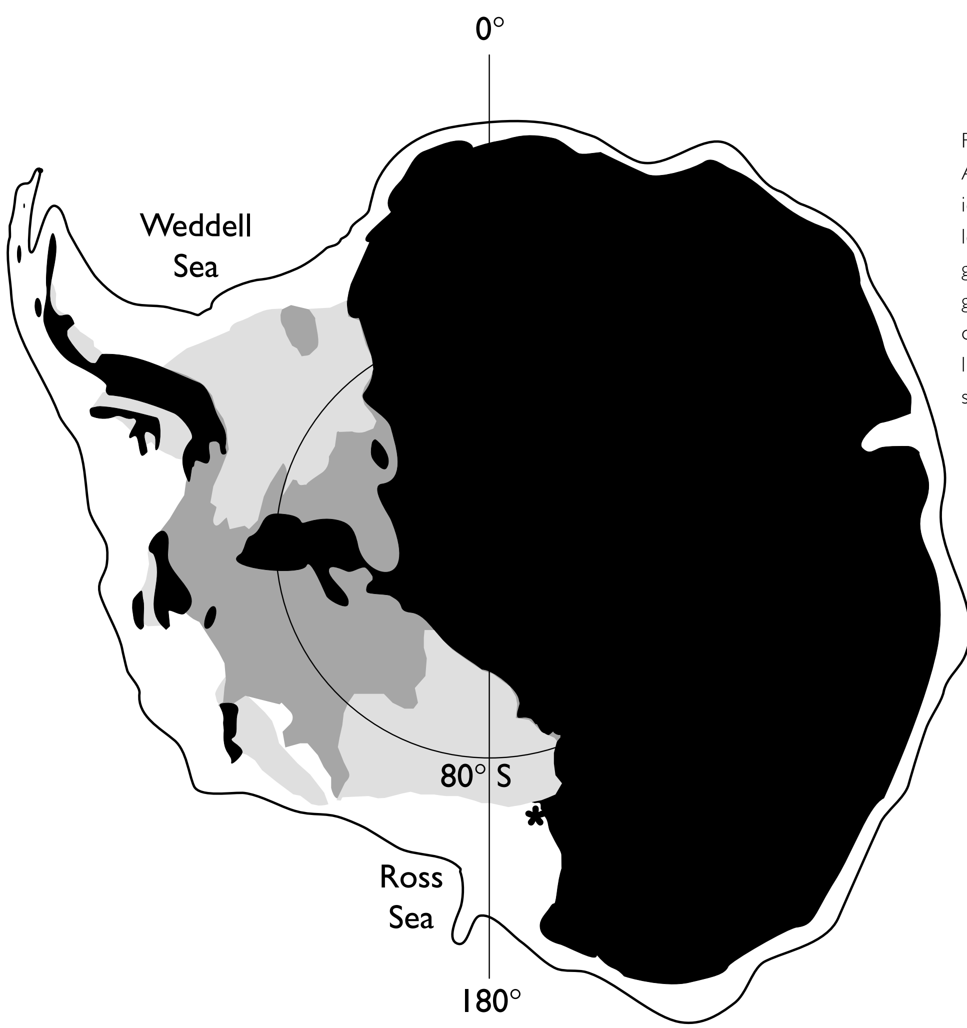


Figure 66. Grounding of the West Antarctic Ice Sheet. Black is glacial ice grounded near or above sea level; dark gray is glacial ice grounded well below sea level; light gray is ice shelf. With a marked rise of sea level, both gray areas will likely calve, leading to a further substantial sea-level rise.

Drilling Strategy

A variety of platforms will be needed to address the potential of ice-sheet collapse. The *JOIDES Resolution* has had very poor success recovering sediments from polar continental shelves. The sedimentary record includes rapid lithostratigraphic changes from unconsolidated sands and muds into overcompacted diamictons and large dropstones. Riser drilling from sea-ice platforms (e.g., the Cape Roberts Project) has been successful in recovering these lithologies, but to date the thematic concentration of research has been toward seeking the early development of ice sheets, rather than subsequent ice-sheet dynamics. A variety of ship-based platforms can be used to drill in ice-jammed waters to recover sediments from perched basins on the polar shelves. Thick sedimentary sequences exist in the West Antarctic interior basins. These can be recovered via drilling through hot-water–drilled access boreholes on the ice sheet to provide in situ records of marine sedimentation in the West Antarctic interior.

Part 3

Technical Requirements for a Multiple-Platform Integrated Ocean Drilling Program

Drilling, Sampling, Logging and Laboratory Requirements

> **The ambitious scientific goals laid out in the various sections of this report, and discussed at the COMPLEX meeting itself, require multiple platforms to achieve.**

The ambitious scientific goals laid out in the various sections of this report, and discussed at the COMPLEX meeting itself, require multiple platforms to achieve. The individual chapters of this report in Part 2 describe specific technical needs for those scientific objectives, often emphasizing areas in which scientific progress has been limited to date by difficulties in drilling and obtaining appropriate samples. The technical needs for riser drilling, along with the scientific opportunities involved, have been discussed more fully in the report from the Conference on Cooperative Ocean Riser Drilling (CONCORD). We emphasize here the requirements for riserless platforms in scientific ocean drilling; these include the successor vessel to the *JOIDES Resolution*, with significantly enhanced capabilities, as well as mission-specific platforms for needs that cannot be addressed effectively with either of the two new ocean drilling vessels. The capabilities of the vessels and mission-specific platforms for accomplishing the envisioned integrated program will overlap in some areas, and we suggest a possible partitioning of science needs among the several platforms here (Table 1). We emphasize the requirement of an integrated science advisory structure that effectively and flexibly assigns scientific ocean drilling to the most appropriate platform(s) without requiring the individual scientist to be expert in platform capabilities, costs, and availability.

In the following summary, we organize a discussion of the technical requirements for riserless ocean drilling around drilling, sampling, downhole-logging, and in situ measurement needs as well as necessary laboratory facility improvements. We focus on common threads tying together the technical requirements of different scientific emphases in this report. The needs here identify the capabilities of the *JOIDES Resolution* as the minimum required, but to realize the desired scientific success calls for improvements. Our vision for future scientific success is built on the substantial achievements of scientific ocean drilling to date and incorporates fully the limitations that have hampered scientific progress. We need to be able to recover high-quality samples in a wider range of water depths, in a wider range of lithologies, and in challenging and hostile situations, including ice-covered regions and gas-pressured and/or potentially unstable sediments. Core recovery and quality are of utmost importance, and increased sample volume is needed for many efforts. Enhanced in situ measurement, testing, and logging capabilities are critical components for success, as are expanded and enhanced shipboard laboratory capabilities.

DRILLING NEEDS

Key climate and ocean biogeochemistry objectives require globally distributed borehole arrays at high spatial resolution and with 50–150 m of sediment penetration. The new program must be able to drill continuous sedimentary sequences of all ages and lithologies in a wide range of locations and in site water depths from a few meters to 8000 m. The environmental range includes tropics to high latitudes. In the tropics, carbonate reefs, atolls, and banks, including seasonally and annually banded corals, are scientifically valuable but difficult to sample. Polar continental shelves contain critical records, but require special technical considerations; significant to complete ice cover hinders operations of many types of drilling platforms. Settings with high sediment-accumulation rates include sediment drifts, shallow continental-margin sites, and marginal basins. Some of the sediments in these settings have scientifically valuable laminated sediments with millimeter-scale features important to recover in as undisturbed a fashion as possible. Some settings have the potential for drilling into gas-pressured sediments.

Ocean-crust drilling is identified in a number of scientific themes. Such drilling necessitates the ability to set the bit directly on bare and fractured rock without going through an overlying, supportive sedimentary section. High downhole temperatures are expected. The scientific objectives require arrays of relatively shallow penetration boreholes (200–700 m subbottom depths), including in older crust, and require deep-crustal boreholes as well. The deeper desired penetrations probably require riser drilling.

In addition to drilling to enable recovery of sediments and ocean crust, drilling will also allow the emplacement of remotely operated observatories for seismic activity, strain effects, and fluid composition, temperature, and flow.

Sampling Needs

The investigations of the history of climate and ocean biogeochemistry have made enormous strides, especially those studies based on time intervals, lithologies, and locations for which continuous sequences of high-recovery and high-quality samples can be constructed from drilled material. High core recovery and sample quality are important to all of the scientific objectives identified in this report, particularly in older sedimentary sequences, in variable lithologies (e.g., in interbedded sediments with hard and soft layers like alternating cherts and chalks or in alternating sequences of basalt flows and softer sediments), in oceanic crust of all characteristics, and in gas-pressured sediments. Sample disturbance and contamination by the drilling and sampling processes must be minimized, particularly for studies of magnetic properties, fluid composition, microbiology, and sediment structure and fabric. Continuous core orientation is required to effectively study and utilize paleomagnetic information in all settings. Some crustal objectives call for directional drilling, and stress orientation is requested in some settings. Gas hydrate research requires the recovery and handling of cores at in situ conditions.

Increased sample volume is a consistent request across many objectives, often expressed as a desire for a larger core diameter. The need for increased sample volume reflects the increasingly multidisciplinary nature of studies carried out at high spatial and temporal resolution on sedimentary and ocean-crust samples. High core quality, with minimum contamination of core interiors and minimum disturbance, must be considered when defining core diameter.

Downhole Logging and In situ Measurement Needs

Downhole logging has been increasingly and successfully integrated into drilling and sampling programs for scientific ocean drilling, and the vision of the future defined here builds on that success. Scientific objectives require the widest range of logging tool availability as well as improvements in logging capabilities, such as working in more challenging environments (e.g., higher temperatures) and making higher-resolution logging measurements. Logging while drilling (LWD) is especially important for some objectives.

In situ measurements of pore-fluid composition, of gas, and of temperature and pressure are required in a number of scientific objectives, and downhole microbial measurements would benefit deep biosphere science. Downhole experiments are identified in some thematic areas, and some objectives call for long-term monitoring of holes and long-term experiments in legacy holes.

Laboratory Improvements Required

A useful matrix for defining shipboard laboratory requirements focuses on measurement of properties related to safety decisions, properties for aiding in real-time drilling decisions, and ephemeral properties and others best determined on shipboard immediately after recovery. The extensive laboratory facilities of the *JOIDES Resolution* have spurred the productivity and creativity of the scientific parties, and these facilities are generally viewed as the minimum required to achieve the scientific objectives in this report. Beyond that minimum, additional needs and improvements have been identified, in particular, enhanced laboratory facilities and shipboard support for microbiology studies and for carrying out experiments at in situ temperatures and pressures. The support for microbiology must include clean-lab capabilities and the ability to work with radioisotope tracers. Finally, key hallmarks of laboratory improvement are enhanced laboratory flexibility overall and appropriate laboratory support for mission-specific platforms.

Appendix 1
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