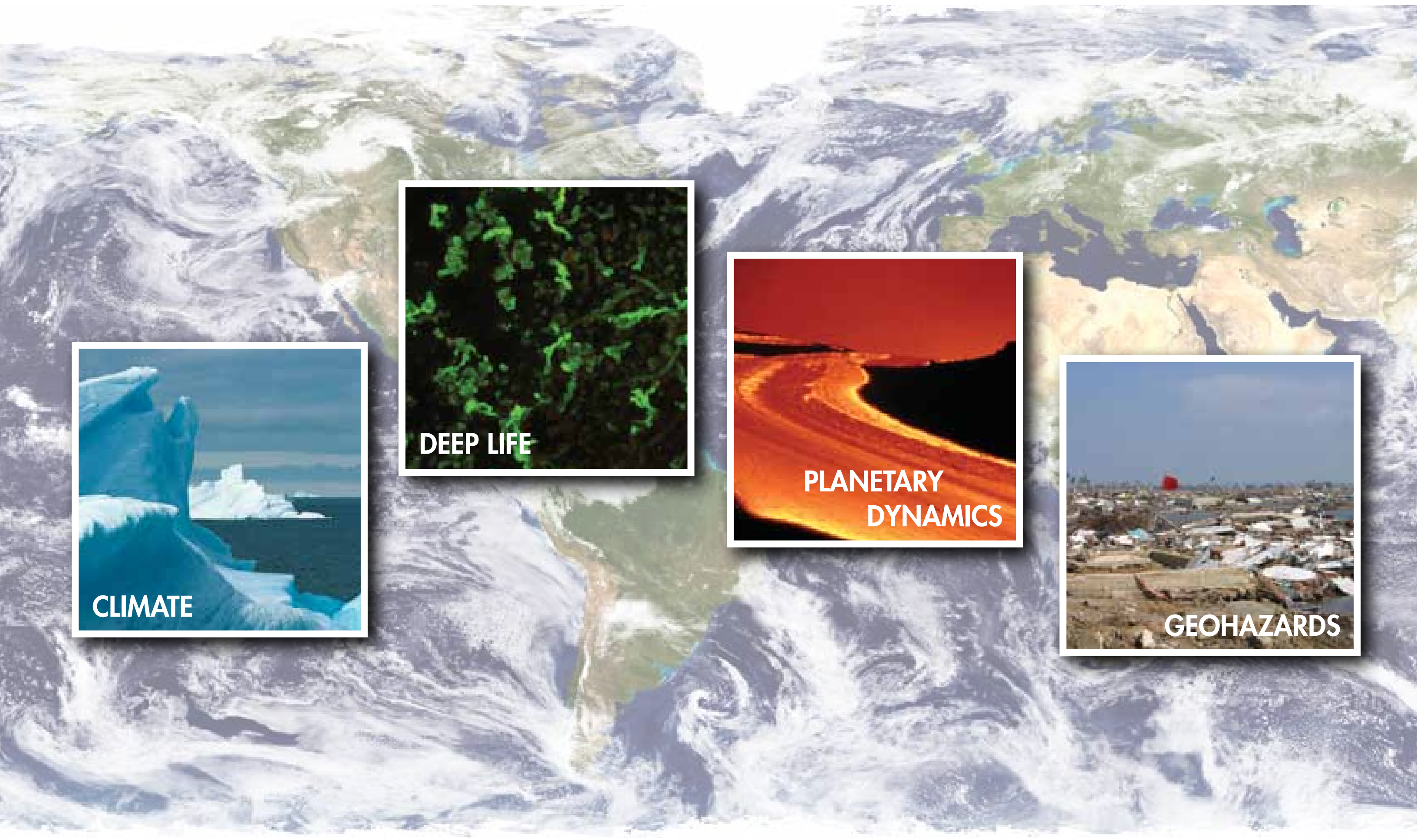
Illuminating Earth's
Past, Present, and Future



THE INTERNATIONAL OCEAN DISCOVERY PROGRAM

EXPLORING THE EARTH UNDER THE SEA

SCIENCE PLAN FOR 2013–2023

Science Plan Writing Committee

Mike Bickle, University of Cambridge, Chair
Richard Arculus, Australian National University
Peter Barrett, Victoria University of Wellington
Rob DeConto, University of Massachusetts–Amherst
Gilbert Camoin, Centre Européen de Recherche et d'Enseignement des Géosciences de l'Environnement
Katrina Edwards, University of Southern California
Andrew Fisher, University of California, Santa Cruz
Fumio Inagaki, Japan Agency for Marine-Earth Science and Technology
Shuichi Kodaira, Japan Agency for Marine-Earth Science and Technology
Naohiko Ohkouchi, Japan Agency for Marine-Earth Science and Technology
Heiko Pälike, University of Southampton
Christina Ravelo, University of California, Santa Cruz
Demian Saffer, Pennsylvania State University
Damon Teagle, University of Southampton

Liaisons

Susan Humphris, Woods Hole Oceanographic Institution, IODP-MI BoG
Hans Christian Larsen, IODP-MI
Maureen Raymo, Lamont-Doherty Earth Observatory of Columbia University, SASEC
Yoshi Tatsumi, JAMSTEC, IODP-MI BoG

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Robert Duncan, Oregon State University
Katrina Edwards, University of Southern California
Sean Gulick, The University of Texas at Austin
Fumio Inagaki, Japan Agency for Marine-Earth Science and Technology
Heiko Pälike, University of Southampton
Ryuji Tada, University of Tokyo

Additional Contributors

Mark Chandler, NASA GISS/Columbia University
Jim Channell, University of Florida
Brad Clement, IODP, Texas A&M University
Jan de Leeuw, Utrecht University
Peter deMenocal, Lamont-Doherty Earth Observatory of Columbia University
Steven D'Hondt, University of Rhode Island
Henry Dick, Woods Hole Oceanographic Institution

Additional Contributors, continued

Kathy Ellins, The University of Texas at Austin
Elisabetta Erba, Università degli studi di Milano
Gretchen Früh-Green, ETH Zurich
Marguerite Godard, Université Montpellier
Mark Leckie, University of Massachusetts–Amherst
Kristin Ludwig, Consortium for Ocean Leadership
Catherine Mevel, Institut de Physique du Globe de Paris
Alan Mix, Oregon State University
Casey Moore, University of California, Santa Cruz
Richard Norris, Scripps Institution of Oceanography
Terry Plank, Lamont-Doherty Earth Observatory of Columbia University
Terry Quinn, The University of Texas at Austin
Michael Schulz, University of Bremen
Alan Stevenson, British Geological Survey
Lisa Tauxe, Scripps Institution of Oceanography
Ellen Thomas, Yale University
Alicia Wilson, University of South Carolina
Chris Yeats, Commonwealth Scientific and Industrial Research Organisation

And the numerous people who sent in comments.

External Reviewers

Bo Barker Jørgensen, Aarhus University
Jan Bermann, IFM-GEOMAR
John Hayes, University of California, Berkeley
Steve Ingebritsen, US Geological Survey
Ikuo Kushiro, Tokyo University
Syukuro Manabe, Princeton University
Andrew Roberts, Australian National University
Pinxian Wang, Tongji University

Editing and Design

Ellen Kappel and Johanna Adams,
Geosciences Professional Services, Inc.

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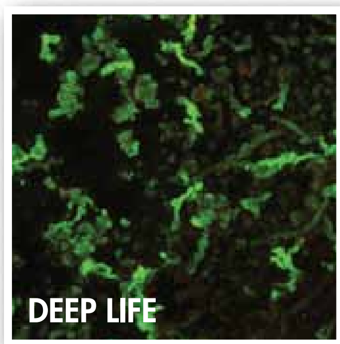

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SCIENCE PLAN FOR 2013–2023

Development of this Science Plan

Planning for the International Ocean Discovery Program began in early 2009 with the solicitation of input from the international community on scientific topics that could be addressed by a new ocean drilling program. In September 2009, approximately 600 scientists from 21 nations gathered at the INVEST conference in Bremen, Germany, to discuss and refine a set of scientific questions that require drilling and associated capabilities deep below the ocean floor (go to http://www.marum.de/Page7894.html to download a full copy of the INVEST report). Subsequent to this meeting, a science plan writing team was assembled, consisting of scientific leaders from Integrated Ocean Drilling Program member countries or consortia having expertise in geology, geophysics, geobiology, paleoclimatology, climate modeling, and geochemistry. This writing committee circulated an early draft of the science plan for community review and comment in late 2010. In early 2011, an external panel reviewed a revised draft, and additional comments and discussions contributed to substantive revision as the final document was prepared. This process demonstrates the foundational strength of scientific ocean drilling: the community's ability to think big, challenge itself, and incorporate diverse ideas through a rigorous process of peer review and prioritization.

Contents

(background) Iceberg, IODP Expedition 318, Wilkes Land Glacial History. Courtesy of IODP/USIO.

(left inset) Labeling the ever-increasing number of cores in the Underway Geophysics Lab, IODP Expedition 334, Costa Rica Seismogenesis. Courtesy of IODP/USIO.

(right inset) Choosing samples to be taken during the "sampling party" on IODP Expedition 334, Costa Rica Seismogenesis. Courtesy of IODP/USIO.

Executive Summary

All parts of the Earth system—the solid Earth, hydrosphere, atmosphere, cryosphere, and biosphere—are linked through flows of mass, energy, and life. Interactions between these realms have affected the development and evolution of our planet, and ultimately determined its habitability through time. Buried beneath the ocean floor are records of millions of years of Earth's climatic, biological, chemical, and geological history. Scientific ocean drilling permits researchers to access these records and explore, analyze, theorize, and test models that describe how Earth works. Scientific ocean drilling also enables collection of subseafloor fluids, microbes, and geophysical and geochemical data by instrumenting boreholes, and using networks of boreholes for active experiments to resolve important properties and processes. As a growing global population demands more resources and a better understanding of geological hazards and ongoing and future climate change, access to data and samples acquired through scientific ocean drilling is essential.

This science plan for the International Ocean Discovery Program is intended to guide multidisciplinary, international collaboration in scientific ocean drilling during the period 2013 to 2023. The new program will allow the scientific community to address fundamental questions, such as: What are the limits of life on our planet? How do ecosystems respond to rapid environmental change? How do deep Earth processes affect Earth's surface environment? What are the underlying mechanisms of geologic hazards and how can we improve risk assessment and prediction of catastrophic events? How do fluids flowing through most of the seafloor impact linked geological and biological systems? Scientific ocean drilling will play a central role in testing, calibrating, and improving predictive Earth system models at local to global spatial scales, and on decadal to millennial time scales. The International Ocean Discovery Program will build on past successes and address global challenges facing current and future generations with new research approaches, expanded scientific communities, and continued development of its unique collaborative model.

This ocean drilling science plan for 2013 to 2023 was crafted on behalf of Earth, ocean, atmospheric, and life scientists at the request of science funding agencies from 24 nations representing approximately 75% of the world's economy. The commitment to conduct subseafloor research extends beyond addressing the plan's scientific questions and the goals of individual drilling expeditions and experiments. The International Ocean Discovery Program will also build intellectual capacity through the promotion of multidisciplinary, international collaboration and education. In addition, the program will advance understanding of Earth's past to be able to better understand and predict its future. Enhanced understanding of topics addressed by the International Ocean Discovery Program will inform decision making about some of the most important environmental issues facing society today.

RESEARCH THEMES

This International Ocean Discovery Program science plan covers a 10-year period of operation and highlights four main themes, each encompassing a short list of high-priority scientific challenges. These themes are:

- Climate and Ocean Change: Reading the Past, Informing the Future
- Biosphere Frontiers: Deep Life, Biodiversity, and Environmental Forcing of Ecosystems
- Earth Connections: Deep Processes and Their Impact on Earth's Surface Environment
- Earth in Motion: Processes and Hazards on Human Time Scales

These themes incorporate shared interests with other national and international research programs, some marine-based (e.g., various ocean-observing initiatives, Past Global Changes, InterRidge, InterMARGINS) and others focused on land (e.g., the International Continental Scientific Drilling Program). Collaborations and mutually beneficial experiments will make the International Ocean Discovery Program essential for addressing fundamental problems, as summarized below.

Climate and Ocean Change targets one of society's most pressing questions—how will climate, the ocean, and ice sheets respond to ongoing increases in greenhouse gases? Even at the decadal scale, climate trends are difficult to predict. If, as some say, humanity is conducting an "experiment" on Earth's climate system, it is not widely appreciated that parts of this experiment have been run in the past. The geologic record includes numerous periods during which Earth's climate changed significantly, and often rapidly, in response to both internal and external forcing. Only scientific drilling can recover samples and data having sufficient distribution and resolution to understand the causes and impacts of global climate change in Earth's past. Reconstructions of dramatically different past climates challenge the modeling community to improve the physics and chemistry represented in numerical climate simulations. Ocean drilling is generating increasingly detailed temporal and spatial arrays of paleoenvironmental data, revealing our planet's dynamic climate system over a range of climate states and time periods.

Biosphere Frontiers includes exploration of deep life within the subseafloor, where microbes isolated from the photosynthetic world live at the limits of habitability. Subseafloor biosphere studies have evolved from early exploratory work to systematic broad-based research on genomics, habitats, ecological niches, and metabolic pathways. These studies are being facilitated by rapid developments in DNA technology, complex lipid analysis, and other techniques. Scientific ocean drilling will also investigate ecosystem response to environmental forcing. Samples and data will be recovered

(left) Core retrieved during the Great Barrier Reef sea level and climate history IODP Expedition 325 aboard a mission-specific platform. Courtesy of IODP/ECORD.

(right) Working the natural gamma ray core logger, Physical Properties Lab, IODP Expedition 317, Canterbury Basin Sea Level. Courtesy of IODP/USIO.

from periods when climate and ocean chemistry changed dramatically on relatively short time scales. Drilling will address the impacts of such events on individual micro-organisms to whole ecosystems, including hominid evolution.

Earth Connections examines the links between surface, lithospheric, and deep Earth processes. Enhanced drilling capabilities are essential for extending the vertical dimension of subseafloor studies, permitting recovery of pristine samples of Earth's upper mantle. Reactions between seawater and the ocean floor depend on crustal structure that, in turn, depends on geodynamic processes that are poorly understood. For instance, the oceanic crust takes up CO_2 during reaction with seawater, but at rates and in locations that are weakly constrained by observations. These processes determine how much CO_2 and water are fed into subduction zones, where their return to the surface influences volcanic and hydrothermal processes. Volcanic outputs, in turn, can be used to test models of subduction initiation and the transformation of ocean island arcs into continental crust. Drilling is an essential tool for unraveling and understanding the geologic, geochemical, magmatic, and hydrological processes responsible for development and evolution of these solid Earth systems.

Earth in Motion addresses dynamic processes that occur on human time scales, including those leading to and resulting from earthquakes, landslides, and tsunami. Scientific ocean drilling will resolve the frequency, magnitude, mechanisms, and impacts of these events, including changes of in situ properties during the earthquake cycle related to fault rupture. This theme also explores fluid flow in seafloor sediments and volcanic crust, formation and stability of gas hydrates, and the potential for sequestering large quantities of CO_2 in deep-sea reservoirs. Earth in Motion studies will use real-time observations from individual and linked networks of long-term, subseafloor observatories installed in boreholes. These systems provide the only means to collect pristine fluid and microbial samples from the volcanic oceanic crust. They can also yield critical information on the accumulation of stress and resulting strain, large-scale crustal movements, and links between these processes and fluid transport at scales of seconds to decades. Observatory networks will be linked to land using cables for real-time monitoring and experimental response to active Earth processes.

The research conducted by International Ocean Discovery Program scientists and addressed by this plan's four research themes will play a valuable role in establishing the research framework and geological understanding that is necessary for the development of resource opportunities, and will provide a platform for collaborative efforts between governments, academia, and industry.

(left) Microbiology samples being taken, IODP Expedition 329, South Pacific Gyre Microbiology. Courtesy of IODP/USIO.

(right) Scientists examine a core recovered from the riser hole, IODP Expedition 319, Nankai Trough Seismogenic Zone Experiment. Courtesy of IODP/JAMSTEC.

(left) ECORD summer schools for graduate students and early-career scientists take advantage of the unique facilities offered by the Integrated Ocean Drilling Program Bremen Core Repository. Courtesy of IODP/ECORD.

(middle) Engaging fifth graders in the delights of studying ocean fossils recovered through scientific ocean drilling. Courtesy of M. Leckie, University of Massachusetts Amherst.

(right) The Deep Earth Academy's School of Rock is a one-to-two week-long immersive program for teachers on board *JOIDES Resolution* or at the Gulf Coast core repository. Courtesy of IODP/USIO.

EDUCATION AND OUTREACH

Education and outreach will be crucial components of the International Ocean Discovery Program. The program's wealth of tangible assets—research vessels with state-of-the-art laboratories, core repositories on three continents, openly accessible data, and thousands of scientists, marine technicians, and other professionals who actively participate in the program—will contribute to a wide variety of activities with special emphasis on three outreach initiatives.

Training the Next Generation of Scientists

By providing opportunities for shipboard and shorebased participation alongside international teams of scientists and engineers, the International Ocean Discovery Program will serve as a technical and scientific training ground for early-career scientists, graduate students, and undergraduates. As environmental challenges increasingly require global solutions, the multidisciplinary, international training acquired through participation in the drilling program will be invaluable to the future scientific leaders in the private sector, academia, and governments around the world.

Fostering Stewards of the Planet

The International Ocean Discovery Program will provide access to resources and help educators develop materials for teaching geoscience, bioscience, and related disciplines to children of all ages. It will also offer opportunities for educators to participate in hands-on activities at sea and at core repositories, where they can work with scientists on real samples and data, and develop educational activities for the classroom.

Informing and Inspiring the Public

The International Ocean Discovery Program will build and maintain a vibrant public communication program, using print, audio, and video media, public institutions, and social networking to inform, influence, and inspire citizens about Earth system and life science.

IMPLEMENTATION

No single platform can meet the drilling requirements of the four science themes. To maximize drilling capability, the International Ocean Discovery Program will use three primary platforms: the multipurpose drillship *JOIDES Resolution*, the riser-drilling-capable *Chikyu* for ultra-deep drilling, and mission-specific platforms chartered on an ad hoc basis for drilling in challenging environments. The US-supplied *JOIDES Resolution* is the workhorse of the international scientific drilling community, a flexible and multifunctional platform capable of addressing many of the major challenges laid out in this science plan. *JOIDES Resolution* will operate with as close to a full annual schedule as possible. *Chikyu*, a state-of-the-art, deepwater riser drilling platform supplied by Japan, is expected to be made available for scientific drilling for about five months per year. *Chikyu* will provide access to the deep oceanic crust, the underlying mantle, and subduction zone environments and their associated seismogenic zones, and to geological and biological systems in hydrocarbon-prone regions. Mission-specific platforms, expected to involve one major operation per year, will continue to operate at the frontier of challenging drilling environments, including the high Arctic and shallow-water reefs. Long-term borehole observatories comprise an additional platform through which generations of researchers can build on the legacy of scientific ocean drilling, collecting new samples and deploying new instruments as technology and ideas change. Such research will leverage the expertise and experience of International Ocean Discovery Program scientists and engineers, and enhance the permanent presence of instrumented laboratories in the seafloor.

Specific drilling expeditions will be scheduled based on proposals from the scientific community in response to this science plan. A competitive, peer-review selection process administered by an international science advisory structure will identify the highest-priority science. Three experienced implementing organizations located in the United States, Japan, and Europe will be responsible for drilling operations. About 200 shipboard scientists from the program member countries will participate every year. Cores will be stored and curated in three global core repositories together with legacy cores of previous drilling programs. Data collected on each expedition will be added to the program's publicly available databases.

(left) The riser-drilling platform D/V *Chikyu*. Courtesy of IODP/JAMSTEC.

(middle) Example of mission-specific platforms. Courtesy of IODP/ECORD.

(right) The riserless drilling platform D/V *JOIDES Resolution*. Courtesy of IODP/USIO.

1. A Legacy of Discovery, a Vision for the Future

From 2003 to 2010, a total of 2,638 sample requests were made for IODP materials with 617,535 samples provided to the scientific community.

Scientific drillships allow scientists to access some of Earth's most challenging environments, collecting data and samples of sediment, rock, fluids, and living organisms from below the seafloor. Drilling expeditions and experiments have transformed understanding of our planet by addressing some of the most fundamental questions about Earth's dynamic history, processes, and structure. Drilling scientists and engineers have developed tools and methodologies that are now used across the terrestrial and marine geosciences, and in the private sector. Equally important, scientific ocean drilling has fostered enduring international collaborations, trained new generations of multidisciplinary students and scientists, and engaged the public worldwide in scientific discovery. Through these achievements, scientific ocean drilling has had a significant impact on numerous research fields, and has opened up new lines of inquiry (**Table 1.1**). Examples of major contributions by scientific ocean drilling to resolving important questions include:

- Scientific ocean drilling tested and confirmed the theory of plate tectonics, which revolutionized geological sciences in the late 20th century.
- Drilling provided the first samples of intact volcanic crust below thick layers of marine sediment, revealing the complexity of crustal construction processes.
- Drilling recovered extensive layers of salt deposits deep below the bottom of the Mediterranean Sea, proving that it had dried out repeatedly in the past.
- Drilling helped to define and refine the geologic time scale, as determined through the study of paleomagnetic records, radiometric dating, and the layering of marine microfossils.
- Drilling extended the marine sedimentary record from the present day back to nearly 200 million years ago, allowing reconstruction of planetary history and life at high resolution during periods of tremendous change and adaptation.
- Samples collected from ocean drilling cores have linked Earth's orbital variability to long-term climate changes.
- Sediment and coral samples recovered by drilling allowed construction of a 100-million-year history of global sea level change, showing how quickly ice sheets have melted and how sea level rise was globally distributed.

Table 1.1. List of publications

Publication Dates	• *Nature* • *Science* • *Nature Geoscience**	• *Earth and Planetary Science Letters* • *Geology* • *Geophysical Research Letters* • *Journal of Geophysical Research* • *Micropaleontology* • *Palaeoclimatology* • *Palaeoecology* • *Palaeogeography* • *Paleoceanography*	All Peer-Reviewed Publications
1968–1974	18	14	1582
1975–1981	69	124	3616
1982–1988	95	163	4474
1989–1995	63	415	5835
1996–2002	75	568	5840
2003–2010	117	840	5464
Totals			
1968–2010	437	2124	26,811

*Began publication in 2008

- Ocean drilling has permitted shallow sampling of large igneous provinces, vast outpourings of lava that may have had a catastrophic influence on Earth's climate, and that serve as windows into deep Earth processes.
- Drilling has revolutionized understanding of continental breakup, faulting, rifting, and associated magmatism.
- Scientific ocean drilling researchers and engineers have developed the first subseafloor borehole observatory systems, generating long-term samples and data records used to explore remote environments and processes.
- Drilling allowed an initial assessment of what materials are recycled by subducting plates at convergent margins.
- Drilling has begun to illuminate fault zone behavior and related tectonic processes at active plate boundaries where Earth's largest earthquakes and tsunami are generated.
- Scientific ocean drilling revealed large flows of fluids through virtually all parts of the seafloor, from mid-ocean ridges to deep-sea trenches.
- Drilling demonstrated that a previously unknown biosphere exists within sediments as deep as 1.6 km below the seafloor, and within the volcanic carapace of the oceanic crust.

With its array of platforms, proven drilling, sampling, and long-term observational techniques, as well as the diverse range of science that can be addressed by studying Earth beneath the sea, the International Ocean Discovery Program will build on this legacy and accelerate the pace of discovery and understanding. The following four chapters of this plan describe 14 scientific challenges that the scientific ocean drilling community has identified as the most important to pursue during 2013 to 2023. Topics range broadly from how a changing climate impacts ocean ecosystems, sea level, and monsoons; to understanding the role that deep microbial ecosystems play in the global carbon cycle; to how mineral resources form and fluids move between the mantle, crust, and Earth's surface; to resolving active processes at continental margins where earthquakes and other geohazards threaten the safety and livelihood of coastal communities. The chapters discussing these scientific challenges are followed by chapters describing education, outreach, and communications efforts, as well as the implementation strategy that will be used to make progress on the scientific goals, including required infrastructure and partnerships.

(left) Working on a core at the sampling table during IODP Expedition 324 to study the formation of Shatsky Rise, a large igneous province. Courtesy of IODP/USIO.

(right) Sampling a core on the catwalk. IODP Expedition 317, Canterbury Basin Sea Level. Courtesy of IODP/USIO.

BOX 1.1 | RESOURCES FOR THE 21ST CENTURY

Population growth and the rising standard of living in our global society has led to vast increases in the need for food, water, energy, metals, novel biochemical compounds, and waste storage (e.g., CO_2, nuclear waste), among other resources. Energy security and strategic mineral supplies are major concerns of governments and industry worldwide. Covering over 70% of our planet, the seafloor is a potentially significant source of resources as well as a location for waste storage, if development is carried out responsibly.

Scientific ocean drilling will continue to play a valuable role in establishing the research framework and geological understanding needed for the development of resource opportunities, especially in frontier and nontraditional resource environments. Active processes operating today within ocean rocks and sediments are similar to those that formed some of the major resources we presently use. Continuing to advance understanding of these analogs through ocean drilling is a powerful approach for successful discovery of new mineral resources on land and on the seafloor.

Despite current initiatives to develop alternative, cost-effective, reliable energy sources, hydrocarbons will continue to be a major component of the energy mix for much of the 21st century. Both the petroleum and tectonic communities are interested in the mechanisms of continental breakup and the initial stages of ocean basin formation when hydrocarbon reservoirs develop. Scientific ocean drilling has shown how some rifted margins are associated with formation of large igneous provinces, while others form with a remarkable absence of volcanism. These findings, and the collaborative efforts between the scientific drilling community and industry, continue to guide exploration strategies adopted by energy companies.

Gas hydrates are one of the largest hydrocarbon reservoirs but their potential as an energy resource, or geohazard, requires improved understanding of their formation mechanisms, extent, and stability (Figure 5.4). Similarly, subseafloor environments of shale-hosted gas or coal-bed methane provide opportunities to understand the nature and role of microbial communities in generating and biodegrading hydrocarbons, as well as potentially providing environments for CO_2 storage. Ongoing and ancient reactions between the ocean and subseafloor basalt and peridotite may lead to alternative approaches for storing CO_2. Ocean drilling can undertake "proof of concept" experimentation that will be an essential precursor to industrial-scale testing.

Seafloor spreading centers host, albeit challenging-to-harness, geothermal reserves. Seawater reacts with mantle rocks, leading to the formation of H_2, and these abiotic hydrocarbons are targets for alternative energy research. Seawater-rock interactions can lead to the formation of major base (Cu, Zn, Pb) and precious metal (Au, Ag) and metalloid deposits, some of which have already been studied by ocean drilling. The extreme conditions (e.g., high temperatures, high/low pH, high salinity) in these and many other seafloor environments (e.g., deep sedimentary basins, mud volcanoes) have led to the evolution of highly adapted microbial communities with the potential to reveal novel chemical compounds of medical and industrial value. Photo courtesy of C. Yeats, Commonwealth Scientific and Industrial Research Organisation.

2. Climate and Ocean Change

Reading the Past, Informing the Future

CHALLENGES

1. How does Earth's climate system respond to elevated levels of atmospheric CO_2?
2. How do ice sheets and sea level respond to a warming climate?
3. What controls regional patterns of precipitation, such as those associated with monsoons or El Niño?
4. How resilient is the ocean to chemical perturbations?

Ocean floor sediment cores provide records of past environmental and climatic conditions that are essential for understanding Earth system processes.

INTRODUCTION

Deep ocean cores are the most important, widespread, and continuous archive of Earth's climate history. Sediments recovered through scientific ocean drilling allow reconstruction of key biogeochemical cycles, fluxes, and interactions among the biosphere, hydrosphere, atmosphere, cryosphere, and solid Earth. Past scientific ocean drilling studies have shown how dramatically Earth's climate has varied over the last ~100 million years, from the presence of a permanent El Niño-like state during the slightly warmer world of the mid Pliocene 3 million years ago, to evidence that the Arctic Ocean was capped by warm, fresh surface waters and covered by the free-floating fern *Azolla* 48 million years ago. These archives of past environmental conditions provide a record of natural climate variability that is crucial for understanding the instrumental records of recent climate change. Marine sediment cores allow us to resolve spatial patterns of climate change on annual to millennial time scales and provide the fundamental observations against which terrestrial records from ice cores, lake cores, and land sequences are compared. Most importantly, only the much longer records recoverable through ocean drilling can provide critical environmental information from millions to tens of millions of years ago when atmospheric carbon dioxide levels and global temperatures were much higher than today (e.g., **Figures 2.1 and 2.2**).

Scientists are working to predict the response of the climate system to human-induced perturbations against this backdrop of natural climate variability. By integrating and assimilating data from ocean drilling cores with numerical models used to predict future climates, scientists are able to conduct "back-casting" experiments, allowing them to evaluate and improve model performance. Drilling data are particularly useful for understanding climate sensitivity and the nature and strength of climate feedbacks, helping to identify potential thresholds that could trigger rapid climate change. Development of ever more sophisticated analytical techniques is revolutionizing our ability to reconstruct past environmental conditions and allowing us to reduce uncertainties associated with these reconstructions (**Box 2.1**). Drilling strategies that include latitudinal,

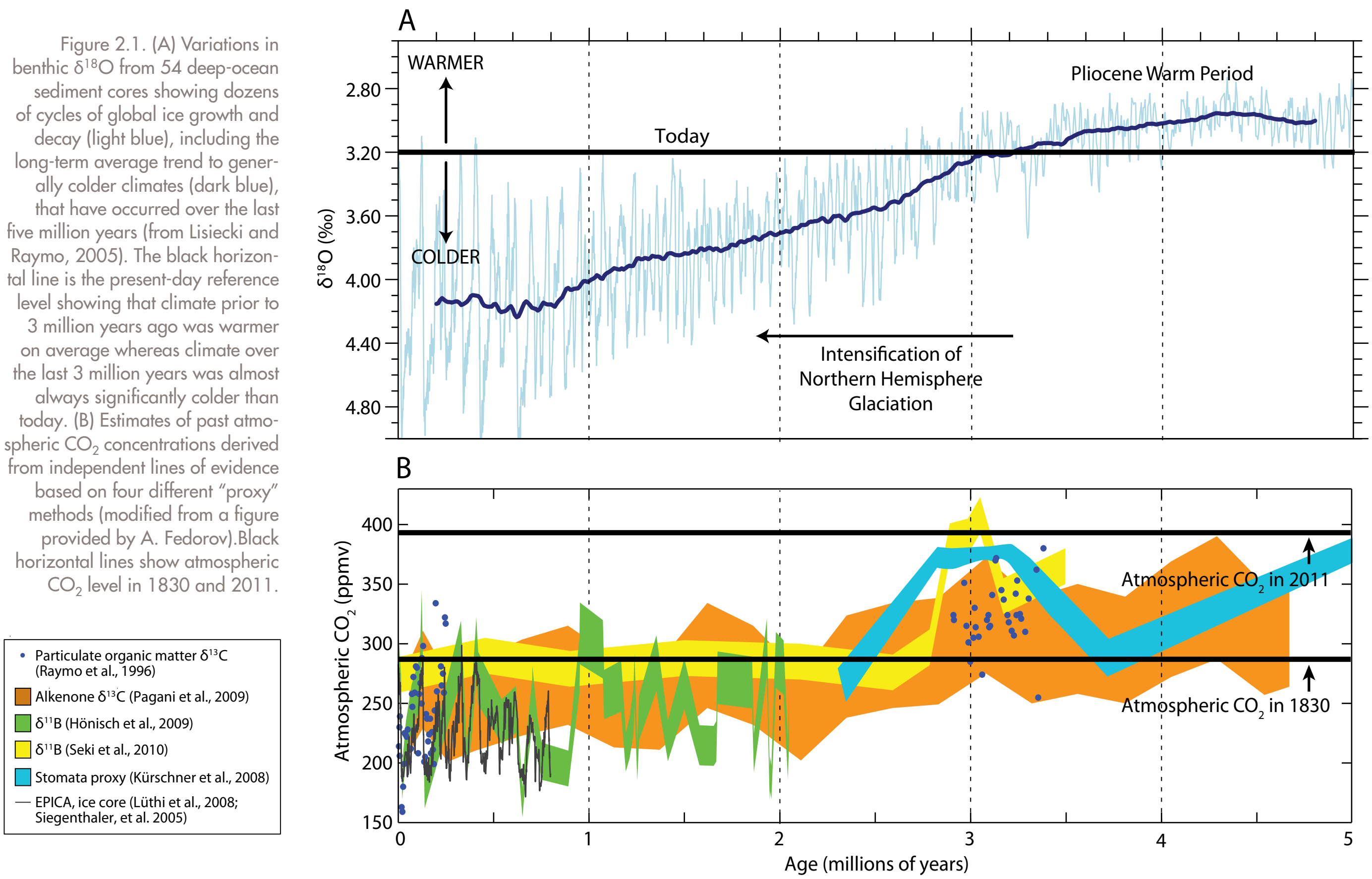


Figure 2.1. (A) Variations in benthic $\delta^{18}O$ from 54 deep-ocean sediment cores showing dozens of cycles of global ice growth and decay (light blue), including the long-term average trend to generally colder climates (dark blue), that have occurred over the last five million years (from Lisiecki and Raymo, 2005). The black horizontal line is the present-day reference level showing that climate prior to 3 million years ago was warmer on average whereas climate over the last 3 million years was almost always significantly colder than today. (B) Estimates of past atmospheric CO_2 concentrations derived from independent lines of evidence based on four different "proxy" methods (modified from a figure provided by A. Fedorov).Black horizontal lines show atmospheric CO_2 level in 1830 and 2011.

longitudinal, and depth transects, combined with longer and more-detailed temporal records, will allow increasingly detailed reconstructions of the spatial and temporal patterns of past climate change.

Gaining a long-term perspective on the climate system's response to greenhouse gases and other forcings is a goal shared with the Intergovernmental Panel on Climate Change (IPCC), the NSF Paleo Perspectives on Climate Change (P2C2) program, the International Geosphere-Biosphere Programme (IGBP), Past Global Changes (PAGES) project, EPOCA (European Project on Ocean Acidification), as well as numerous other observational ocean and atmosphere monitoring programs. In addition, collaborative polar paleoclimate programs include international ice coring efforts (such as the European Project for Ice Coring in Antarctica [EPICA]), integrated data-modeling initiatives like the Scientific Committee on Antarctic Research-Antarctic Climate Evolution (SCAR-ACE), and offshore efforts using alternative drill platforms including SHALDRIL (drilling along the Antarctic continental margin) and Antarctic Geological Drilling (ANDRILL). On land, synergistic paleoclimate efforts include the International Continental Scientific Drilling Program (ICDP), among others. Of all these programs, it is only through deep ocean drilling that we are able to recover time-continuous, high-resolution records of the warmer, higher-CO_2 climates of the deep past.

Challenge 1 | How does Earth's climate system respond to elevated levels of atmospheric CO_2?

Warming in the high northern latitudes has accelerated in recent decades as atmospheric CO_2 concentrations have risen, resulting in substantially diminished summer sea ice cover in the Arctic Ocean and increasing loss of the polar ice sheets over Greenland and western Antarctica. These changes are occurring at a faster pace than previously predicted, suggesting that parts of the Earth system are more sensitive and dynamic than indicated by the current generation of climate models. The potential exists for climate thresholds to be exceeded, especially at high latitudes where snow and ice albedo feedbacks are strongest. Understanding the risks of rapid climate change requires taking a long view of Earth's response to increasing atmospheric greenhouse gases. The geologic record below the seafloor extends beyond the instrumental and ice core records of the recent ice ages, to more distant time periods when atmospheric CO_2 was comparable to today's level (**Figures 2.1 and 2.2**) and to the much higher levels that are expected in the coming decades.

Drilling and Research Strategy

Scientific ocean drilling will allow us to explore conditions during past warm climate states at nearly all latitudes. Using new proxy methods that reveal a wealth of paleoenvironmental information (e.g., **Figure 2.1**), these studies will permit reconstruction of surface and deep ocean temperatures, ocean circulation, nutrient distribution, and ocean productivity. Importantly, multiple proxy methods can help us reconstruct ancient CO_2 levels beyond the age of the oldest ice cores, allowing us to study times characterized by the CO_2 levels predicted in the near future. These records of the ocean's physical, chemical, and biological response to past changes in greenhouse gases will enable us to: (1) improve estimates of global climate sensitivity to both sustained higher levels of greenhouse gases and to dramatic transient perturbations to the carbon cycle; (2) determine the magnitude of ice sheet and sea ice loss due to elevated greenhouse gas concentrations, including the underlying mechanisms that amplify polar warming; (3) understand how tropical temperatures, upwelling regimes, and El Niño variability behave in a high-CO_2 world; and (4) identify key physical and chemical processes that need to be better represented in predictive climate system models (**Box 2.1**).

Providing mechanistic explanations for observations derived from ocean drilling has long been a challenge for the climate modeling community. While exciting advances have been made in recent years, a number of fundamental data-model conundrums remain. Foremost among them is that most IPCC-class climate models underestimate climate sensitivity (defined here as the equilibrated global temperature response to a doubling of CO_2) relative to paleoclimatic indicators from the last 160 million years. Differences between observations and simulations of past warmer climates are most profound in the polar regions, where the models tend to severely underestimate the warming inferred from paleoproxies. This potential for dramatic amplification of polar temperatures under elevated CO_2 conditions is important for predictions of sea ice and permafrost melting, and the future stability of ice sheets.

The differences between north and south polar geography (a polar ocean versus a polar continent) offer an opportunity for ocean drilling to help resolve the complex linkages among the polar ocean, atmosphere, and high-latitude land surface processes. Achieving this goal requires high-resolution sampling from carefully selected, temporally overlapping pole-to-pole drilling transects.

Scientific ocean drilling explores times in Earth's past that were characterized by warmer climates than today, teaching us vital lessons about the causes, rates, and consequences of global warming on the Earth system.

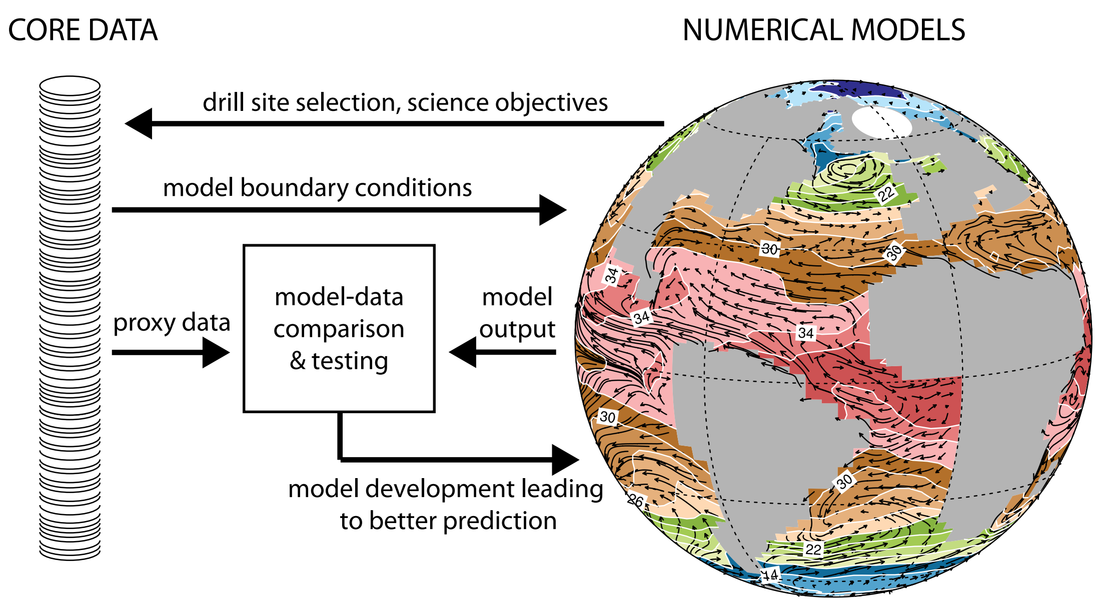
With such data we can better ground-truth Earth system models and quantify the strength of polar feedbacks. To date, a limited number of sites around Antarctica have been drilled, and only three deep-sea sites have been cored (to relatively shallow depths) in the central Arctic basin.

While the amplification of polar warming during past warm intervals appears to be underestimated by the current generation of climate models, the sensitivity of past tropical temperatures has commonly been over-estimated relative to proxy-based temperature estimates. Is it possible that the models are missing some moderating (negative) feedbacks in the low latitudes? Pole-to-pole transects will also allow determination of tropical temperature history as well as equator-to-pole temperature gradients under a range of past climate states and greenhouse gas concentrations. These data are essential for testing the fidelity of climate models that are now used to predict future warming.

Some climate trends and events, including the extreme warmth 61–45 million years ago, gradual late Eocene cooling, and the sudden appearance of a continental-scale Antarctic ice sheet around 34 million years ago, are correlative with inferred trends in atmospheric CO_2, in keeping with fundamental climate theory and model-derived cooling-glaciation thresholds (Figure 2.2). Climate

BOX 2.1 | MODEL-DATA INTEGRATION

Numerical climate, ocean, ice sheet, and Earth system modeling is becoming an increasingly important partner in ocean drilling research. Models can test data-driven hypotheses, provide physics-based explanations for observed phenomena, and fill spatial and temporal data gaps. They can also help guide the location of drilling targets, maximizing the potential for successful expeditions. In turn, data provided by drilling are needed to help reconstruct model boundary conditions and to evaluate model performance through comparison and testing. The goal is to iteratively improve both the models and the model/data calibrations. Ultimately, advancing models beyond basic climate scenario projections and toward prediction of our future climate change requires sufficient knowledge of Earth's prior responses to natural fluctuations in greenhouse gases and other climate forcings. Ocean drilling provides the only true capability to explore Earth's prior climate response to increases in atmospheric CO_2 levels that are on par with the increases occurring today.



change over the last 25 million years is more difficult to explain as a simple function of reconstructed CO_2 concentrations. For example, some Miocene CO_2 reconstructions (23–5.3 million years ago), derived from different proxy methods, show continually low concentrations (much like the last 2.6 million years). These low CO_2 concentrations make the relative warmth and presumed absence of orbitally paced Northern Hemispheric ice sheets during this time period enigmatic. However, other lines of evidence suggest that CO_2 levels during the Miocene were higher. This possible decoupling between CO_2 concentrations and climate variability over the last 25 million years may suggest an increased sensitivity to other climate forcings (e.g., tectonic or orbital) when background greenhouse gas concentrations are low and climate is relatively cool. For example, some climate feedback mechanisms, such as the strong positive snow/ice-albedo feedback, only operate in a climate cold enough to allow expansive continental snow cover, ice caps, and sea ice to exist, dramatically increasing the sensitivity of the poles to relatively modest forcings. Other greenhouse gases such as CH_4 and N_2O may also be important, perhaps varying in concert with CO_2. We know the relationship between CO_2 concentration and radiative forcing is logarithmic, so small changes in CO_2 may have a greater impact when initial concentrations are low. Improved confidence in CO_2 reconstructions for the pre-ice core era, when levels were comparable to where they will be in coming decades, will be critical for better constraining climate sensitivity.

Finally, during some intervals, like the mid-Pliocene warm period (3.3–3.0 million years ago), current proxy reconstructions suggest that atmospheric CO_2 levels were comparable to today (~30% higher than pre-industrial levels) (**Figure 2.1**). Yet, global mean sea

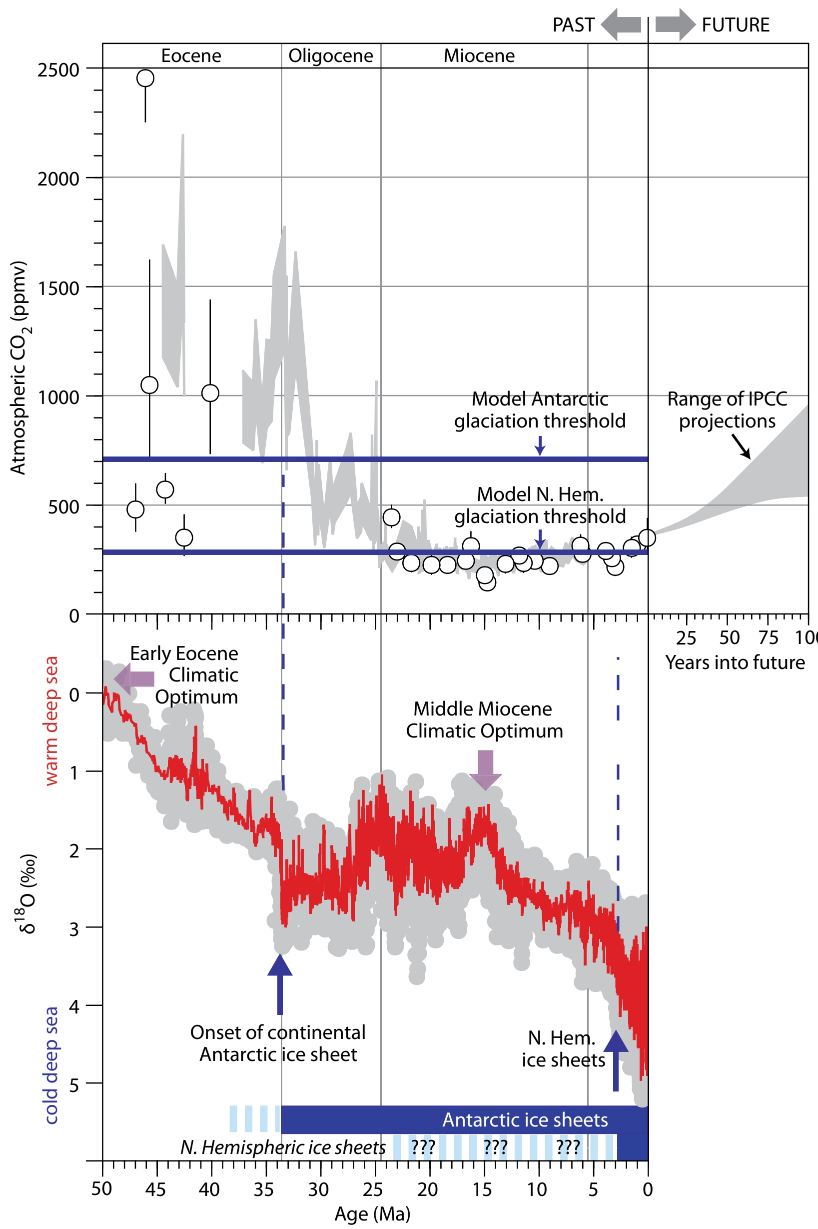


Figure 2.2. A summary of CO_2 and climate indicators spanning the last 50 million years. Blue along lower axis shows inferred presence/absence of north and south polar ice sheets. The benthic marine $\delta^{18}O$ record (red line; Zachos et al., 2001), an indicator of deep-ocean and high-latitude surface ocean temperatures, illustrates the long-term global cooling that has occurred over the last 50 million years. Over this same time period, proxy indicators suggest that atmospheric CO_2 (top panel) may have periodically exceeded 1000 ppmv prior to 35 million years ago. These estimates are derived from stable carbon isotope values of alkenones found in deep-sea sediment cores (gray band; Pagani et al., 2005) and estimates from boron isotope-pH reconstructions (open circles; Pearson et al., 1999). Model-derived CO_2-glaciation thresholds for Antarctica and the Northern Hemisphere (DeConto et al., 2008) are shown for comparison with the geologic record. Future IPCC projections of rising CO_2 over the next century fall within the range inferred for the earlier Cenozoic, illustrating the long-term context that only ocean drilling can provide.

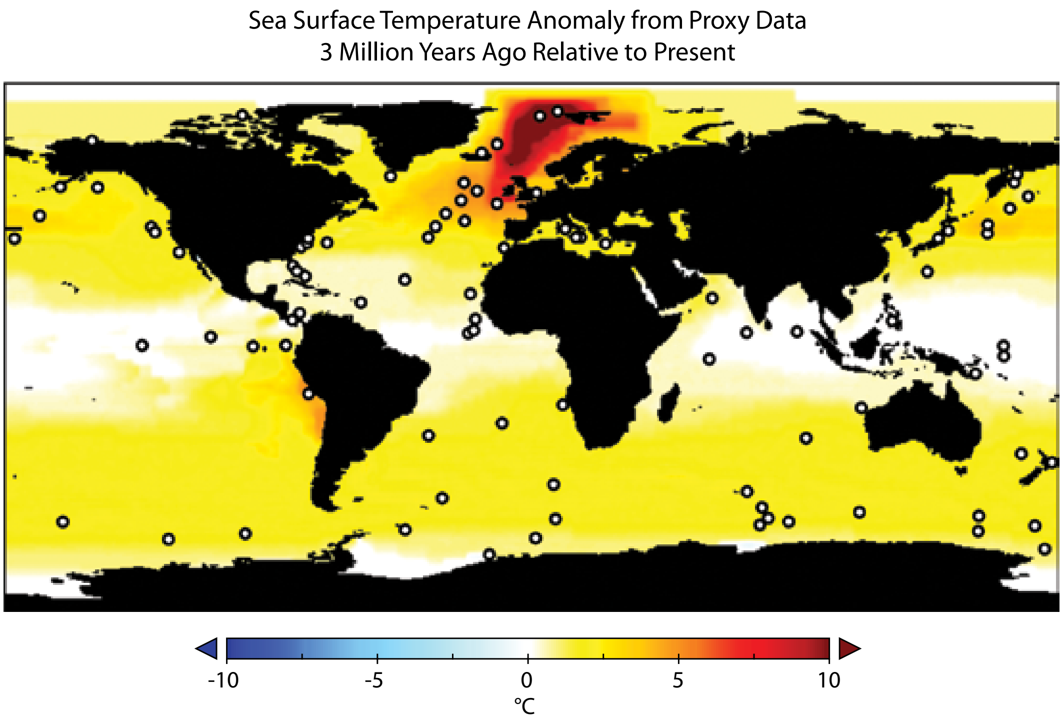


Figure 2.3. Difference between mean annual sea surface temperature averaged within peak interglacial periods from the time period 3.3–3.0 million years ago (Dowsett et al., 2010) and modern sea surface temperatures (from Reynolds and Smith, 1995). Warm colors imply sea surface temperatures warmer than today, with the most dramatic warming observed in the Northeast North Atlantic. Past sea surface temperatures are reconstructed using a variety of proxy methods from a global array of deep-sea cores (open circles).

surface temperatures were measurably higher than at present (**Figure 2.3**). Ocean drilling has shown that warm tropical Pacific surface waters expanded both poleward and eastward, with average conditions in the eastern Pacific resembling a persistent El Niño-like state (see **Challenge 3**). At high latitudes, sea surface temperatures were also warmer than today, especially in the area of the North Atlantic and Norwegian-Greenland Sea that is critical for deepwater formation (**Figure 2.3**). A drilling strategy targeting locations ranging from polar seas to low-latitude upwelling zones is needed to explain the behavior of the climate system during past episodes of global warmth. This strategy must be combined with continued development of ever more reliable proxies. Ocean drilling data will test the capabilities of models to simulate warm climates, help identify latitudinal and regional model biases, and determine if underlying mechanisms responsible for climate states like the Pliocene are likely to occur in the future.

Challenge 2 | How do ice sheets and sea level respond to a warming climate?

Mean sea level is expected to rise between 0.5 and 1.5 m by the year 2100, affecting coastal ecosystems and water supplies, and flooding densely populated coastal communities. In the last decade, most of the measured global mean sea level rise has been caused by thermal expansion of the ocean in response to global warming. In the future, melting of the Greenland and Antarctic ice sheets, containing the equivalent of ~64 m of sea level, pose a far greater threat. Satellite-based measurements show that the ice sheets have recently begun to lose mass at an accelerating pace (**Figure 2.4**). This melting is contributing about half of the current sea level rise, but ice sheets will become the largest contributor if the rate of mass loss continues to increase.

Long-term projections of sea level rise remain highly uncertain, primarily due to our poor understanding of the dynamic behavior of ice sheets during sustained warming. The instrumental record of sea level extends back only about 150 years, a period when global mean sea level rose by only ~0.2 m, far less than the rise predicted for the future. By contrast, the geologic record of sea level change contains information about the full range of sea level variability, from warm periods that were virtually ice free and characterized by sea levels many tens of meters higher than today, to periods when ice sheets covered most of North America and Europe, exposing the continental shelves and forming land bridges. By studying the full spectrum of climate states, we can better understand the dynamic behavior of ice sheets.

The deep-sea record reveals the rates at which ice sheets and sea level responded to past episodes of global warming, providing insight into how much sea level might change in coming decades.

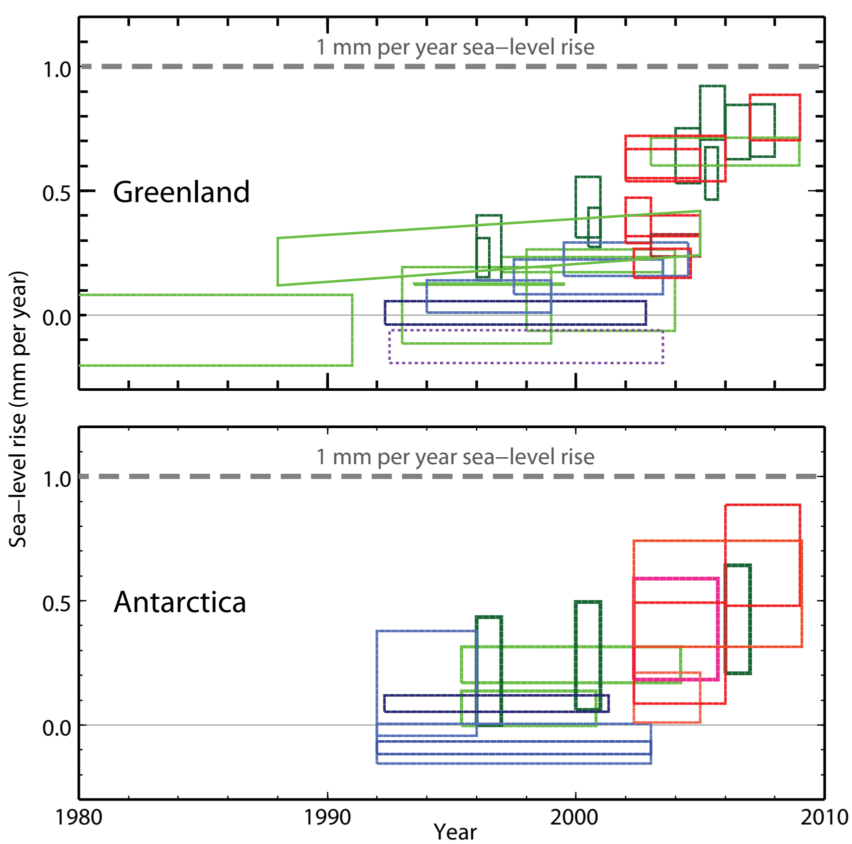


Figure 2.4. Estimates of equivalent sea level rise from (top) Greenland and (bottom) Antarctica polar ice loss over the last 30 years. Each box represents a range in equivalent sea level rise from an article reporting satellite data (colors represent different approaches). Sources listed in Bertler, and Barrett (2010).

Drilling and Research Strategy

The response of ice sheets to a warmer climate can be reconstructed from sedimentary records of relatively recent interglacial episodes when ice extent was similar, or slightly less than at present, and from much earlier times (34–3 million years ago) when climate was consistently several degrees warmer than today. During those earlier times, the Antarctic ice sheets appear to have been much more dynamic, with variations in ice sheet size capable of driving sea level changes of many tens of meters. Analysis of recently recovered ocean sediment cores suggests that the West Antarctic Ice Sheet (WAIS), containing about 4 m equivalent sea level, is particularly sensitive to relatively modest forcing (i.e., a few degrees of ocean warming) and may have collapsed many times over the last 5 million years (**Figure 2.5**). Estimates of sea level rise during warm intervals ~3 million years ago suggest the possibility of even larger changes (perhaps up to 30 m above present). The Greenland Ice Sheet and WAIS together account for only about 12 m of potential sea level, so estimates greater than 12 m imply a significant loss of ice from the much larger East Antarctic Ice Sheet, containing the equivalent of ~52 m of sea level.

Through scientific ocean drilling we can reduce the uncertainties in our understanding of the magnitude and rate of past sea level change. Did large sections of the East Antarctic Ice Sheet collapse the last time atmospheric CO_2 levels reached 400 ppm? What are the time spans over which past ice sheet collapses occurred, and how much warming was required to push them past their "tipping points"? To answer these questions, we need cores from high-latitude shelf and slope sites where sediment accumulates rapidly (**Figure 2.6**). Recovered cores will resolve the timing and amount of sea level rise and, in conjunction with glacio-isostatic

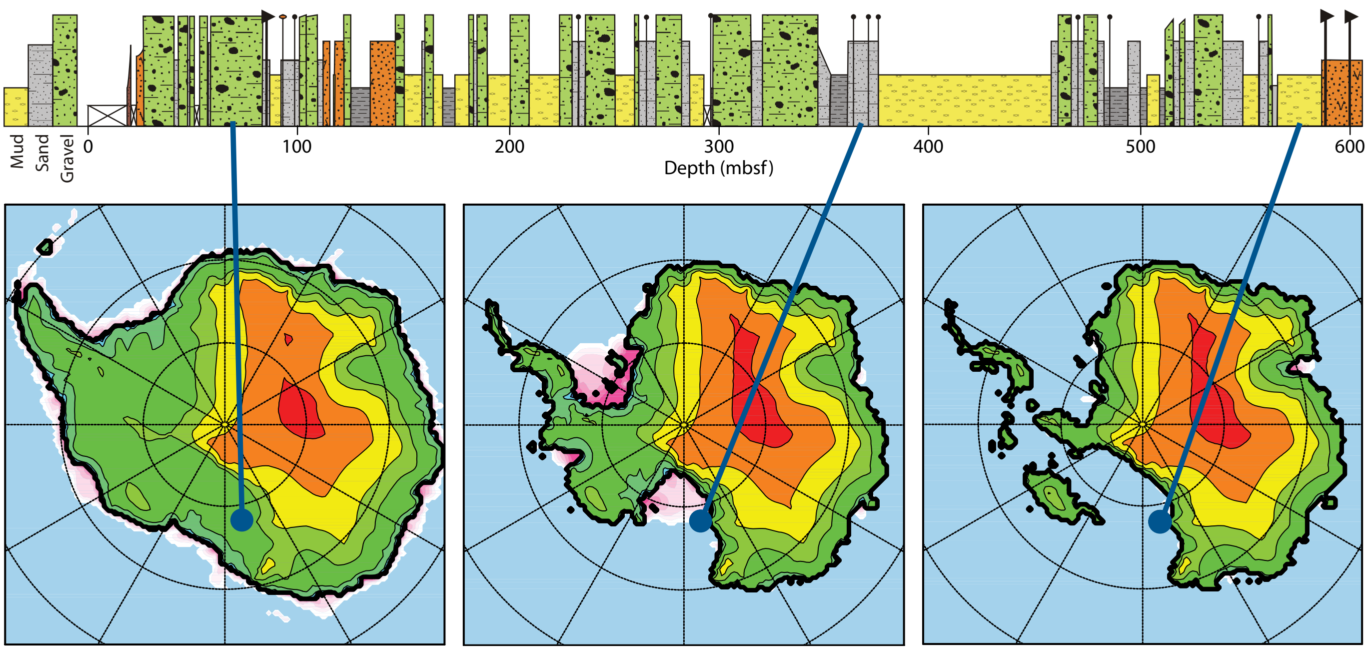


Figure 2.5. An example of data-model comparison between a sediment core recovered from the Antarctic margin (top and blue dots on maps; Naish et al., 2009) and snapshots from a model simulation of the Antarctic Ice Sheet spanning the last 5 million years (bottom; Pollard and DeConto, 2009). In the sediment core, diatomite (yellow) dominates during the older warmer Pliocene interval around 3 million years ago (~400 meters core depth), indicating open water and a smaller West Antarctic Ice Sheet (right panel). The presence of mud and sandstone (gray) at the drill site indicates a proximal ice sheet grounding line and an ice sheet configuration similar to today (middle). Diamictite (green), which records the advance of a grounded ice sheet over this site during glacial maxima, has become the dominant facies over the last 900,000 years (upper 80 meters of core), including at the last glacial maximum about 20,000 years ago (left).

modeling, the sources of the melting ice. This information is needed, along with land-based records, to constrain numerical ice sheet models that attempt to predict how ice sheets melt under warmer conditions. Such models, coupled with ocean and atmosphere general circulation models, will be crucial for projections of future sea level, with direct application toward planning for climate change impacts.

The processes leading to the collapse of ice sheets, and the timing and volume of meltwater released, can also be constrained by studying the geologic record of Quaternary glacial-interglacial transitions known as terminations (e.g., most recently from ~20,000 to ~8,000 years ago, and prior to that from ~138,000 to 128,000 years ago). During these periods, sea level rose rapidly by almost ~120 m at mean rates of ~8 mm/yr. Coral-reef-based sea level records recently recovered by ocean drilling in Tahiti suggest that this dramatic sea level rise (caused by melting land ice after the Last Glacial Maximum ~23,000 years ago) did not occur uniformly, but instead was punctuated by several centuries of extremely rapid rise (4 m/century on average; **Figure 2.7**) about 14,500 years ago. Such dramatically varying rates of melting imply the presence of thresholds within the dynamic behavior of ice sheets and provide a challenging test for ice sheet models used to predict future sea level rise.

Drilling of multiple sites around the globe, spanning several glacial-interglacial transitions, is needed to better constrain the timing and amplitude of sea level change that resulted in the disintegration of large ice sheets. To date, uncertainties in the rate and location of meltwater and iceberg influx during deglaciation have hindered a thorough evaluation of the response of ocean meridional overturning circulation to freshwater inputs. In addition, sea level change in response to ice mass changes is not spatially uniform, and that spatial heterogeneity can be used to great advantage. Local and regional mantle and crustal processes can change the position of the sea surface relative to the land. The redistribution of mass from land (ice) to sea (water) impacts sea level by deflecting both the ocean floor (through isostatic deformation) and the ocean surface (through changes in gravity). The relative magnitude of these isostatic and gravitational processes can be assessed by studying multiple, temporally

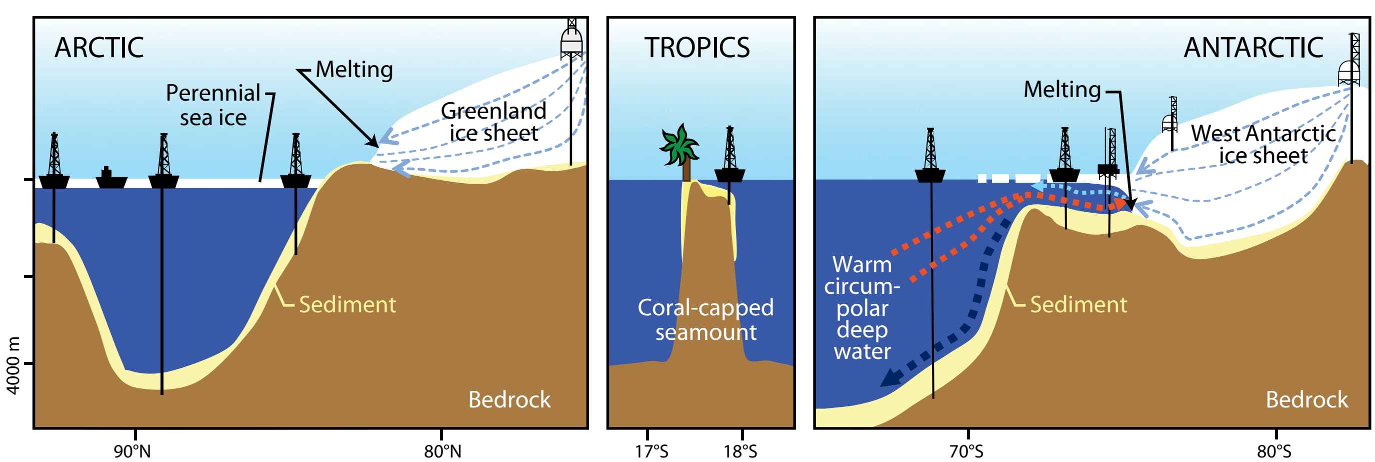


Figure 2.6. Proposed drilling strategy from pole to pole using International Ocean Discovery Program drilling platforms to collect records linking climate, ice sheet, and sea level histories on geologic time scales. The climate history derived from these records is used to ground-truth and test the performance of numerical ice-atmosphere-ocean models, thus improving their ability to project future sea level rise. Ice and coral records are best preserved over the last 100,000 years, Antarctic ice cores go back 850,000 years, and sediment records extend back tens of millions of years. Red arrows represent warm water flow beneath floating ice, recently recognized as a key factor in accelerating ice loss from West Antarctica. Elements of this figure were adapted from Schoof (2010).

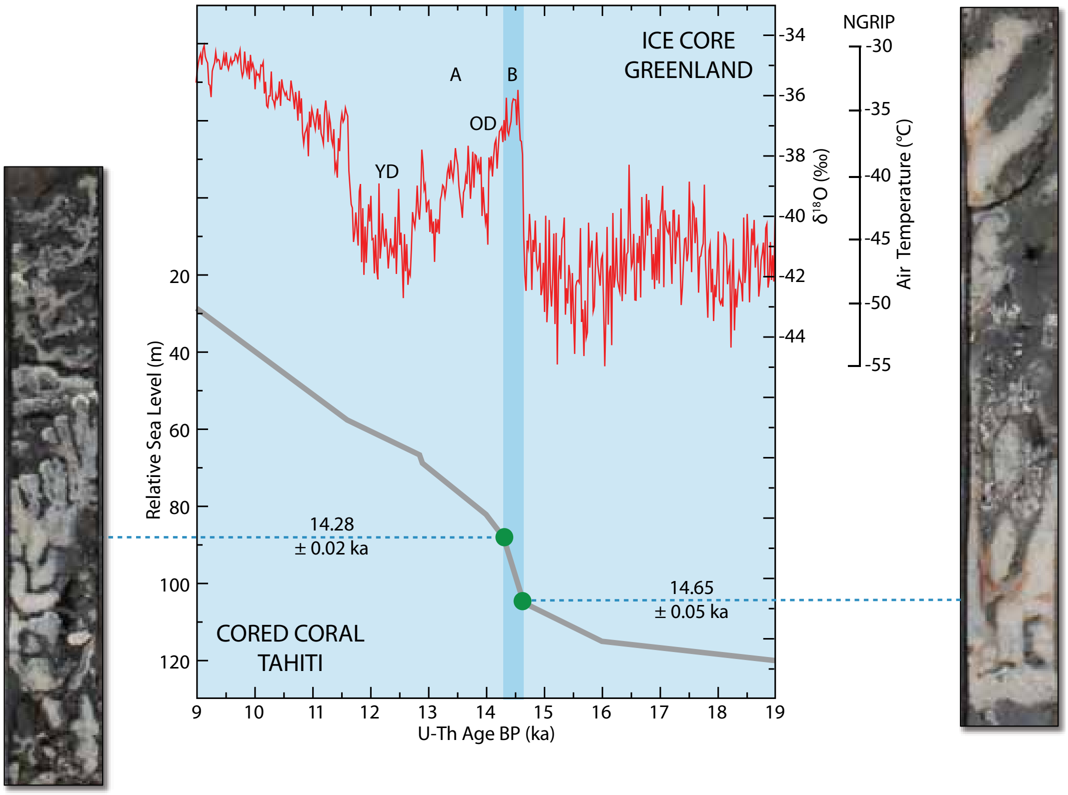


Figure 2.7. Reconstruction of the relative sea level (m) curve during the last deglaciation at Tahiti (P. Deschamps, CEREGE, *pers. comm.*, 2011). The U-series dating of the two reef cores recovered during IODP Expedition 310 (Camoin et al., 2007) demonstrates the coeval occurrence at 14.65–14.60 thousand years ago of Meltwater Pulse 1A (dark blue) and the dramatic high-latitude warming associated with the inception of the Bølling-Allerød (B, A) warm period (air temperature data shown from the NGRIP ice core from Greenland). The Older Dryas (OD) and the Younger Dryas (YD) cooling events recorded in the ice cores are also indicated.

overlapping sea level records recovered from a range of latitudes, in different tectonic and sedimentary settings and at varying distances from formerly glaciated regions. For example, samples from ancient coral reefs at a number of sites distant from former ice sheets will be necessary to constrain the total volume changes in land ice and the geographic partitioning of this volume between different ice sheets on different continents. Complementary drilling of open-ocean sediments at sites close to past ice sheets will provide more direct information regarding regional ice melt history and the timing of ice advance-retreat. Ultimately, the combination of these data with modeling techniques can be used to “fingerprint” the relative contributions of different ice sheets to past sea level change, providing more realistic scenarios for testing predictive models and a better understanding of ice sheet behavior in a changing world.

Challenge 3 | What controls regional patterns of precipitation, such as those associated with monsoons or El Niño?

Although interannual climate variability is the norm, with some years wetter or drier, warmer or cooler, the longer-term climate state may be changing in the face of current global warming.

Episodes of warming in the eastern tropical Pacific Ocean, called El Niño events, bring devastating floods to some regions and drought to other regions around the globe. These events exemplify the vulnerability of water resources to small changes in ocean temperatures and highlight a pressing societal need to understand what factors control the global hydrologic cycle. Four billion people in Asia, India, and Africa rely on the regular return of the monsoon, yet it is unclear how increasing greenhouse gas concentrations and global temperatures will disrupt, or amplify, this cycle.

Drilling and Research Strategy

When Earth's global average temperature shifts, temperature changes are not uniform. These changes have a regional complexity that result in changes in equator-to-pole and land-to-sea temperature gradients, as well as alterations in atmospheric and oceanic circulation, absolute humidity, and rainfall patterns. Scientific ocean drilling has yielded samples showing climate change during past warm periods such as the early to mid Pliocene (5–3 million years ago) when atmospheric CO_2 levels may have been about the same as today. At that time, warm tropical Pacific surface waters extended much further poleward and a permanent El Niño-like state existed in the equatorial region (characterized by the expansion of warm water southward over the upwelling zones off of Peru; compare top and bottom panels in **Figure 2.8**). If such a change were to occur again, it would have dramatic global hydrologic, economic, and social consequences (**Figure 2.9**).

The dynamic mechanisms that maintain conditions such as those reconstructed through ocean drilling have yet to be identified. One climate modeler has proposed that enhanced vertical mixing of the upper ocean, perhaps through increased hurricane frequency (**Figure 2.10**), may account for the larger Pacific warm pool and increased poleward oceanic heat transport. This hypothesis can be tested by drilling, and will yield samples and data that are needed to more accurately model and predict future global change.

Using ocean sediment cores (**Figure 2.11**), ice cores, and speleothems (cave stalagmites and stalactites), scientists have also identified

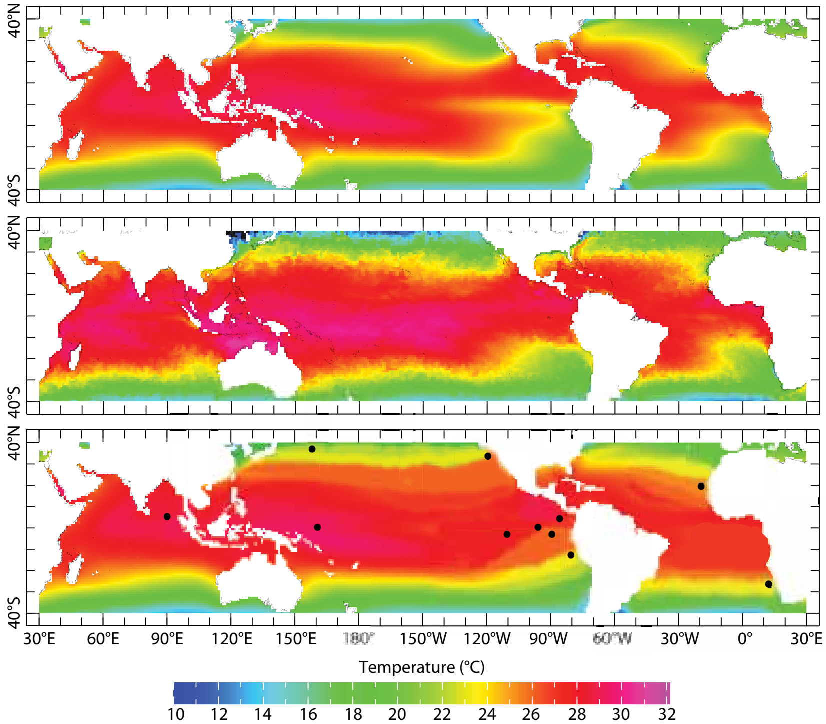


Figure 2.8. Comparison of modern annual average sea surface temperature (top; Locarnini et al., 2010), with sea surface temperature during the January, 1998, El Niño event (middle; Carton and Giese, 2008), and the Pliocene annual average sea surface temperature (bottom). The Pliocene reconstruction (representing ~4.6–3 million years ago) resembles a permanent El Niño-like state, with a tropical warm pool in the Pacific that was expanded relative to today both in the east-west and north-south directions. Pliocene data come from ocean drilling sites (dots on bottom panel; see Dekens et al., 2007, and references therein). Courtesy of C. Ravelo, University of California, Santa Cruz.

rapid and extreme millennial-scale variations in regional sea surface temperature and precipitation. These climate shifts are often large relative to the interannual variability of the background state and occur quickly, on the order of years to centuries. Scientific ocean drilling will obtain paleoclimatic records that can be used to determine whether these climate shifts are triggered by small perturbations in radiative forcing (e.g., solar cycles, greenhouse gases) or whether they are tied to the intrinsic variability of an ocean-climate system whose behavior depends on its mean state.

This drilling strategy has three components. First, by drilling continental margin sediments that contain terrestrial material transported by rivers mixed with marine sediment, it is possible to obtain continuous, well-dated records of both continental and oceanic change. New continental proxies offer great potential for obtaining detailed information regarding changes in terrestrial precipitation patterns and vegetation. By drilling ancient corals and sediments with annual layering, even seasonal to interannual climate variability will be examined within the context of long-term global climate change.

Second, drilling open-ocean sites will be crucial to reconstructing changes in past sea surface temperature gradients. These zonal and meridional temperature patterns are the primary determinants of cyclone formation and intensification, as well as climate zone size and position. These open-ocean records will also be used to examine the role that ocean circulation plays in generating and transmitting millennial-scale climate change events across the globe.

Third, ocean drilling will investigate the character of regional climate change across a range of time periods with different mean climatic states, solar forcing, and greenhouse gas concentrations. In this way, a mechanistic understanding of hydrographic

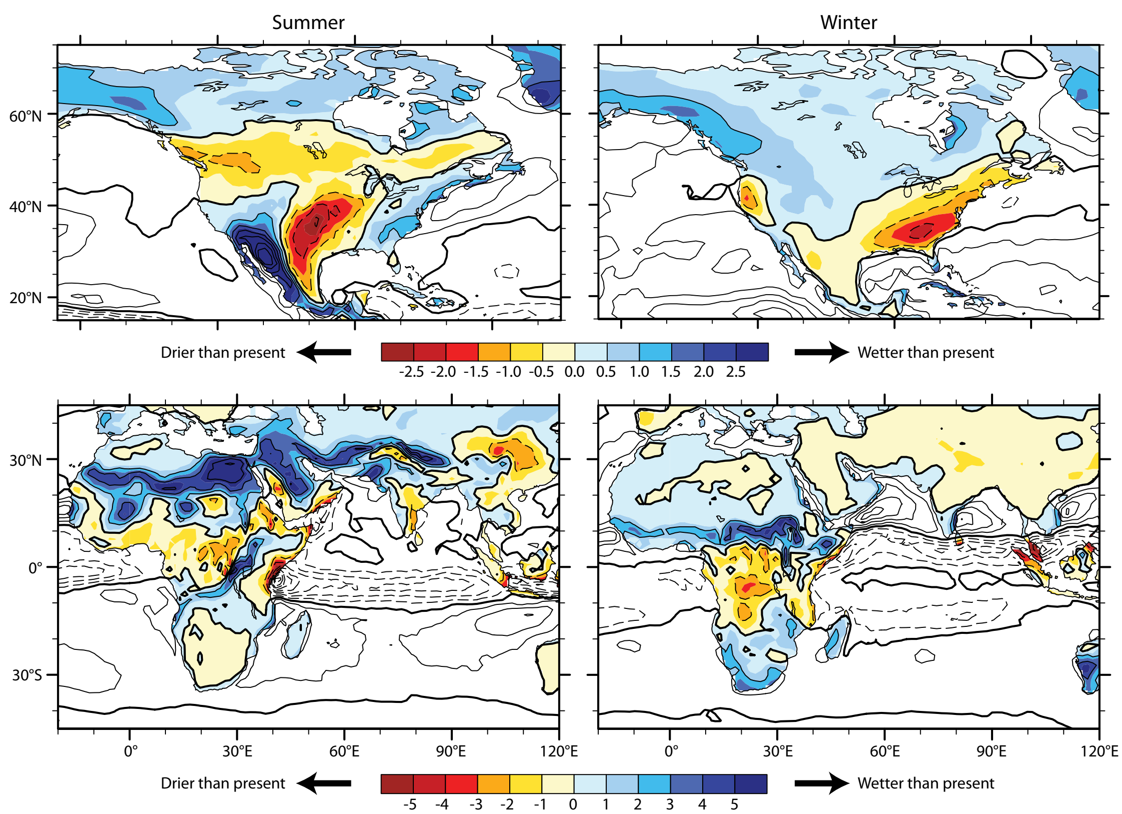


Figure 2.9. Impact of reduced Pliocene (~4.6–3 million years ago) sea surface temperature gradients, reconstructed from deep-sea sediment cores, on precipitation (mm/day) over North America in summer and winter (top panels) and over Africa and southern Asia (bottom panels). The sea surface temperatures were used as input into state-of-the-art numerical climate models and make predictions as to possible outcomes on the hydrologic cycle of a modest global warming similar to that observed during the Pliocene (e.g., Figure 2.1). After Brierley and Fedorov (2010).

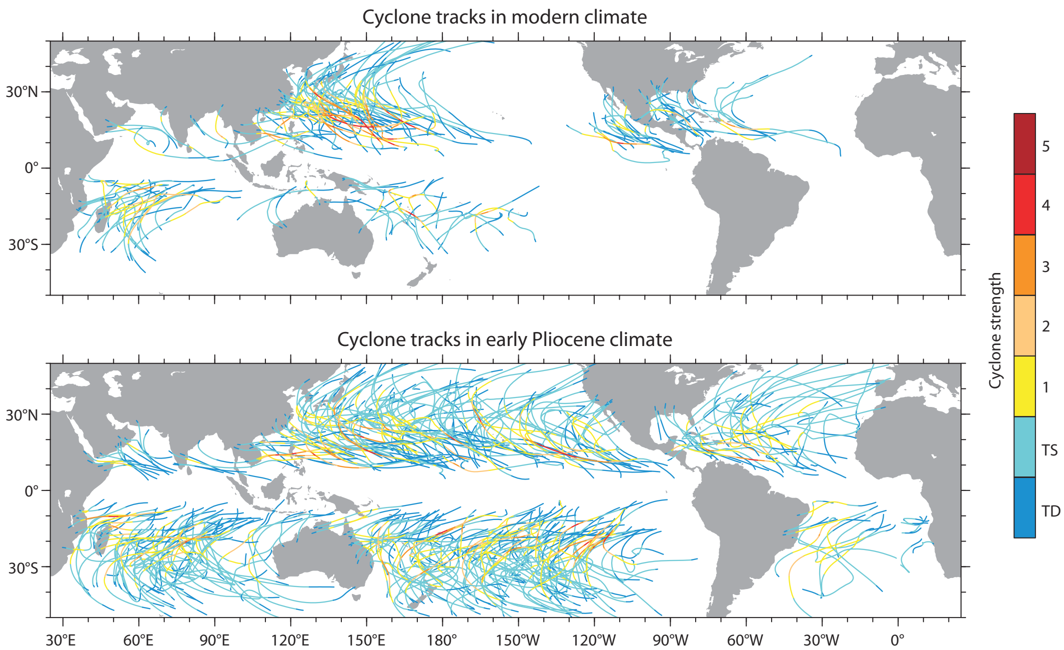


Figure 2.10. Model prediction of tropical cyclone distribution and intensity during the Pliocene warm period (representing ~4 million years ago) showing a dramatic increase in the number and geographic extent of tropical cyclones in a slightly warmer world. The colors indicate hurricane strength—from tropical depression (TD, blue), to tropical storm (TS, teal), to category-5 cyclones (red). The Pliocene model simulation used reduced meridional and zonal tropical sea surface temperature gradients as reconstructed using deep-sea sediments (e.g., Figure 2.9; see Fedorov et al., 2010).

change can be derived from data representing a large dynamic range of climate conditions and forcings, providing valuable insight into the possible future behavior of the hydrologic cycle.

Finally, scientific ocean drilling will also explore the role that tectonic-climate interactions played in Earth system history. Tectonic uplift of mountains can influence atmospheric circulation and continental climate by altering the position of the jet stream, by enhancing land-sea temperature gradients, by increasing monsoon strength and seasonality in some areas, and by increasing aridity through the development of rain-shadow effects in other areas. Steeper topography also leads naturally to greatly increased rates of mechanical erosion that, when combined with enhanced orographic precipitation, result in greater rates of chemical weathering that consume atmospheric CO_2 and lead to global cooling.

Climate, in turn, can have a reciprocal impact on mountains, as cooling can lead to expansion of mountain glaciers, which further increases erosion and weathering, leading to additional exhumation and isostatic adjustment. Feedbacks also result from chemical weathering through its influence on the availability of dissolved nutrients and, therefore, enhanced biological productivity. Over multimillion-year time scales, variations in regional monsoon systems are inextricably coupled to tectonic processes. Study of the history of Asian or Indian monsoons will require recovery of physical and chemical weathering records contained in nearshore margin and fan sediments.

Figure 2.11. Using annually layered sediments (called varves) in ocean basins near continental margins, such as the Cariaco Basin off of Venezuela, past climate and ocean dynamics can be studied in great detail. Ocean drilling results from the Cariaco Basin include clear indications of changes in rainfall, such as the strength and frequency of El Niño events, that had an impact on regional habitability and the Mayan civilization (e.g., Haug et al., 2003).

Challenge 4 | How resilient is the ocean to chemical perturbations?

Scientific ocean drilling has revealed the ocean's response to episodes of acidification and hypoxia ("dead zones") during times of past global warmth, providing insight into current and future ocean health.

Human activity has led to dramatically increased fluxes of fossil fuel carbon and fertilizers into the atmosphere and ocean, resulting in profound and easily measurable chemical perturbations to the environment. CO_2 absorption by the ocean has led to surface water acidification, which is a threat to the health of numerous economically important marine ecosystems, including coral reefs and coastal upwelling zones. Neutralization of this geologically instantaneous CO_2 input to the ocean carbon system will take tens of thousands of years but, in the shorter term, ocean acidification could take a devastating toll on calcifying marine organisms. Likewise, increased riverine fluxes of nitrogen into the ocean have caused eutrophication and oxygen-deprived dead zones, or hypoxia. Fish and crustaceans appear to be particularly sensitive to low O_2 levels, and even episodic expansion or recurrence of hypoxic zones can devastate fisheries. Marine biological responses to these perturbations can themselves influence both atmospheric greenhouse gas concentrations and climate, resulting in additional biological and climate perturbations (feedbacks). While instrumental data and real-time observations can characterize the short-term transient behavior of ocean chemistry and associated ecosystems, sediment cores are needed to understand the long-term behavior of these Earth systems, especially during intervals warmer than today.

Drilling and Research Strategy

The geologic record contains numerous intervals when abrupt increases in atmospheric CO_2 coincided with ocean acidification and warming (**Figure 2.12**). Study of this history can elucidate how individual species and entire marine ecosystems were perturbed by events too long and geochemically complex to mimic in the laboratory. Long-term biological responses to ocean acidification and hypoxia likely include both ecological adjustments (such as changes in organismal distributions) and loss of biodiversity through extinctions. Furthermore, using the geologic record we can look for the presence, during past events, of the physiological and ecological changes predicted by modern experiments (such as widespread

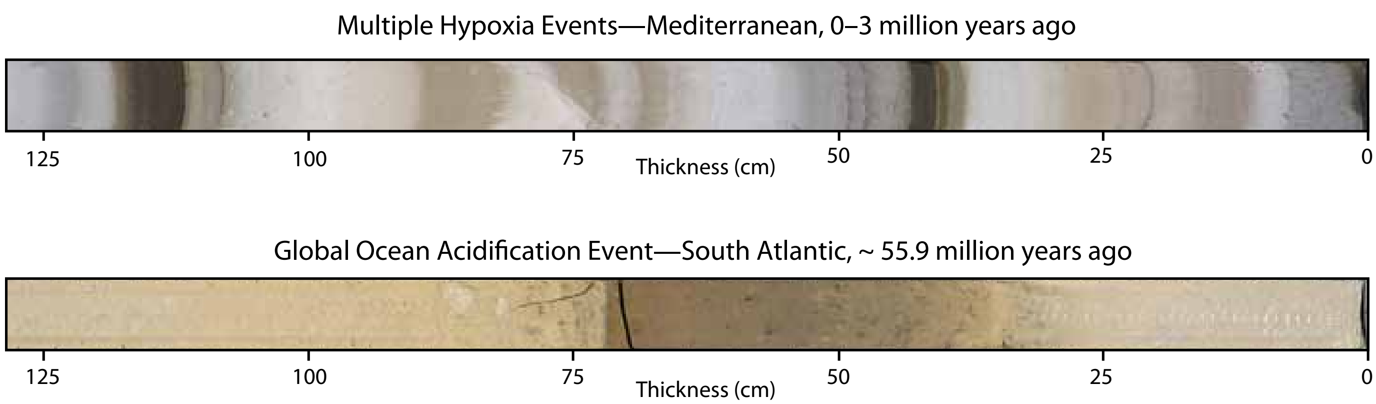


Figure 2.12. Deep-sea cores record dramatic global and regional ocean acidification and hypoxia. Hypoxia, or a pronounced decrease in water-column oxygenation, is expressed by dramatic increases in organic matter preservation that create sapropels (organic-rich sediments). These Mediterranean Sea (top, core from ODP Site 964) sapropels formed when abrupt surface water warming and freshening, driven by subtle variations in Earth's orbit around the sun, caused pronounced regional circulation changes. The dramatic dissolution of seafloor carbonate that created the red, clay-rich horizon shown in South Atlantic ODP core 1262 (bottom) was a global event that occurred at the Paleocene-Eocene boundary ~55.9 million years ago. This global ocean acidification event is believed to have been caused by the release of several trillion tons of carbon into the atmosphere due to thermal dissociation of marine methane hydrates following an ocean warming event. The next phase of ocean drilling must target those locations where sedimentation rates are high enough to preserve the details of how and where acidification and hypoxia develop in the ocean.

skeletal malformation and changes in ecosystem structure). In this manner, the history embedded in marine sediment complements laboratory experiments, documenting how the marine realm adjusts to global change.

Of central importance to ocean carbon chemistry research is quantifying how fast the ocean neutralizes excess CO_2 from the atmosphere. Rates of atmospheric CO_2 increase, oceanic pH changes, and Earth system recovery during past global warming and acidification events differ depending on the source, magnitude, and location of CO_2 injection (e.g., extreme volcanism, changes in size of the terrestrial biosphere, ocean overturning, or methane hydrate disintegration). For example, the Paleocene-Eocene boundary event 55 million years ago included a massive carbon release (3–6 trillion tons) that caused global warming and ocean acidification that lasted over 100,000 years. Remarkably, the rate of global change at the onset of the Paleocene-Eocene Thermal Maximum might have been comparable to the modern rate. While the ocean-climate system was different than today, valuable lessons can be learned about the impact of such a rapid perturbation on ocean geochemistry and ecosystems. Due to the extremely short time period over which anthropogenic carbon is being released, the impacts could be greater for many ecosystems than observed for similar systems in the fossil record.

Scientific ocean drilling will also be used to understand the connection between ocean chemistry and extreme internal and external forcings to Earth's surface, including catastrophic volcanic events and bolide impacts. Large igneous provinces, or LIPs, are huge accumulations of mafic igneous rocks that were erupted or emplaced within a few million years or less (see also **Challenge 9**). They released large amounts of trace metals and gases, including CO_2, H_2S, and SO_2, to the ocean-atmosphere system, triggering a chain of biogeochemical-climate feedbacks. These gigantic events in the geological past provide excellent case studies for understanding how ocean chemistry responds to major environmental perturbations.

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3. Biosphere Frontiers

Deep Life, Biodiversity, and Environmental Forcing of Ecosystems

CHALLENGES

5. What are the origin, composition, and global significance of subseafloor communities?
6. What are the limits of life in the subseafloor?
7. How sensitive are ecosystems and biodiversity to environmental change?

Samples recovered by ocean drilling permit study of Earth's largest ecosystems, offering insight into the origins and limits of the deep biosphere, evolution of marine microfauna through times of environmental change, and human origins.

INTRODUCTION

Earth's biosphere extends far below our planet's surface, including within sediments and rocks of the deep ocean. (**Figure 3.1**). This deep biosphere comprises a significant fraction of Earth's total living biomass. Scientific ocean drilling provides access to the deep biosphere, elucidating its origin, evolution, habitats, diversity, and biogeochemistry. Ocean drilling also generates detailed climate records that provide insight into the evolution of life on land—including humans.

The ocean biosphere plays an essential role in global climate. Marine microbes (Algae, Bacteria, Archaea) produce much of Earth's oxygen, and also capture and sequester carbon as they die and sink into the ocean's abyss. Variations in how much carbon is held and buried in these algal residues affect the amount of CO_2 in the atmosphere and, therefore, the extent of greenhouse warming. The organic carbon produced in the surface ocean that is ultimately buried in deep-sea sediments also provides source material for hydrocarbons.

Understanding marine ecosystems dynamics requires knowledge of photosynthetic productivity and how organisms near the base of oceanic food webs responded to environmental changes in the geologic past. Through study of the ocean's microscopic fossils and microbial compounds, we can learn about how long-term and abrupt changes in oceanic conditions affect the health and diversity of marine ecosystems. Marine fossils also preserve a global record of how individual species responded to environmental challenges through migration, extinction, and evolution.

Many microbes in the deep biosphere grow extraordinarily slowly. Reconciling a low rate of metabolic activity with its large total biomass is a major challenge in deep biosphere research, as is obtaining a basic understanding of the physiological capabilities and biogeochemical consequences of subseafloor life. Some communities deeply buried within sediments may be fueled by weathering rocks, whereas others acquire energy from hydrogen released through natural radioactive splitting of water. In either case, they are energetically independent of photosynthesis. Energy supplied by thermal degradation of long-buried organic matter and/or magmatic heating may support microbial communities in the deepest sedimentary biosphere. In contrast, microbes in igneous oceanic crust may be well connected with the ocean

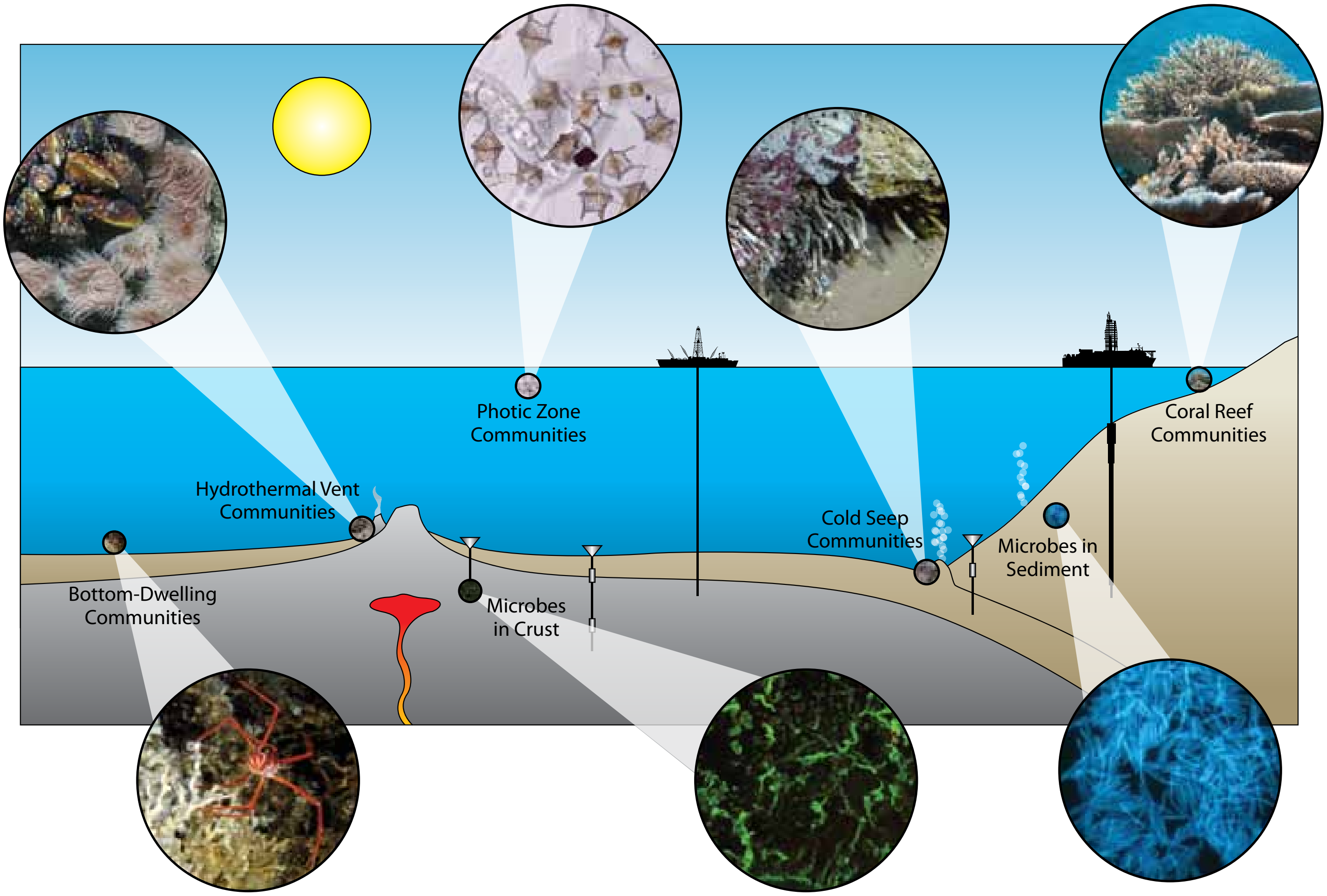


Figure 3.1 The presence and size of the deep biosphere may affect the Earth system in ways we have yet to appreciate. Microbes in extreme environments such as hydrothermal vents, mud volcanoes, and deep-sea hydrocarbon seeps are capable of producing organic carbon without the sun's energy. These chemosynthetic microbes also play an important, but yet quantitatively uncertain, role in the global carbon and other cycles. Photos from: Bottom Dwelling: Ross (2007; Figure 3); Hydrothermal Vents: Devey et al. (2007, Figure 2); Microbes in Crust: Orcutt et al. (2010); Photic Zone: M. Montresor, SZN/Alfred Wegener Institute; Cold Seep Communities: Vanreusel et al. (2009, Figure 6A); Microbes in Sediment: Figure 3.2B; Coral Reef: Coral Disease Working Group (2007; Figure 2).

through active hydrological systems that carry water, and perhaps microbes, rapidly through the crust. All of these discoveries are recent, and show that our knowledge of Earth's biosphere is incomplete.

Understanding the origins and evolutionary history of the deep biosphere, the mechanisms that fuel microbial growth, and how variations in subseafloor environments impact their abundance, will provide insight into the evolution of ancient life on Earth and inform ideas on life elsewhere in our solar system. To investigate and better understand the nature of life in these extraordinary environments, we need to sample fossil and living populations, measure metabolic activity, resolve physiological adaptations, and evaluate the role of the subseafloor biosphere in sediment and rock alteration, crustal hydrology, and biogeochemical cycles. These studies will be leveraged through coordination between scientific ocean drilling and continental projects, such as the International Continental Scientific Drilling Program, and groups organized to assess microbiological populations and function using terrestrial subsurface laboratories. Scientific ocean drilling will also aid ambitious international studies of the deep marine biosphere, such as the Deep Carbon Observatory.

Challenge 5 | What are the origin, composition, and global significance of subseafloor communities?

Ocean and continental drilling studies show that the subsurface biosphere is widespread, large, and genetically and geochemically diverse (e.g., **Figure 3.2**). Early work also suggests that subseafloor sedimentary and crustal microbes are genetically distinct from Earth's surface microbes. In addition, about 85% of the gene sequences from the subsurface microbial communities studied thus far belong to unidentified groups with unknown metabolic pathways. Major unknowns include the composition and diversity of most subseafloor communities, the processes by which subseafloor communities are established, the ease with which their constituent microbes disperse and find new resources, and the balance between the energy these communities derive from the surface biosphere and the energy they derive from Earth's interior. The pervasiveness of buried microbial communities and the nature of their activities suggest that they may play important roles in global biogeochemical cycles, mineral alteration, and the production and destruction of hydrocarbons in oil reservoirs and in sediments. By quantifying the rich variety of life and understanding microbial strategies for their survival on Earth, we can test predictions about kinds of life that may have existed in the deep past or on other planets. In this sense, these deeply buried chemolithotrophic communities provide a model for nonphotosynthetic life at times and in places that are otherwise inaccessible.

The deep subseafloor biosphere may be one of the largest ecosystems on our planet, driving subseafloor geochemical processes that affect ocean chemistry, the global carbon cycle, and the alteration of sediment and rocks.

Drilling and Research Strategy

Scientific ocean drilling and associated sampling, measurements, and experiments permit studies of the fundamental ecological, physical, and historical factors that affect deep, subseafloor ecosystems. Coring of entire sediment columns in a variety of marine environments will determine whether subseafloor sedimentary communities are typically assembled from microbes that were deposited on the seafloor and survived burial and passage through successive geochemical

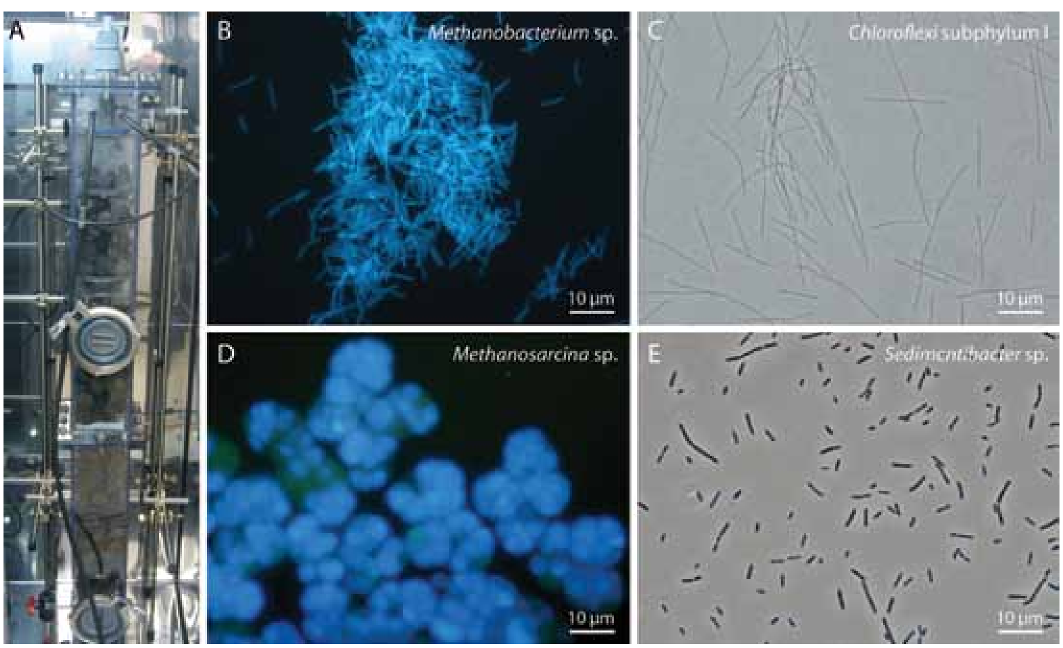


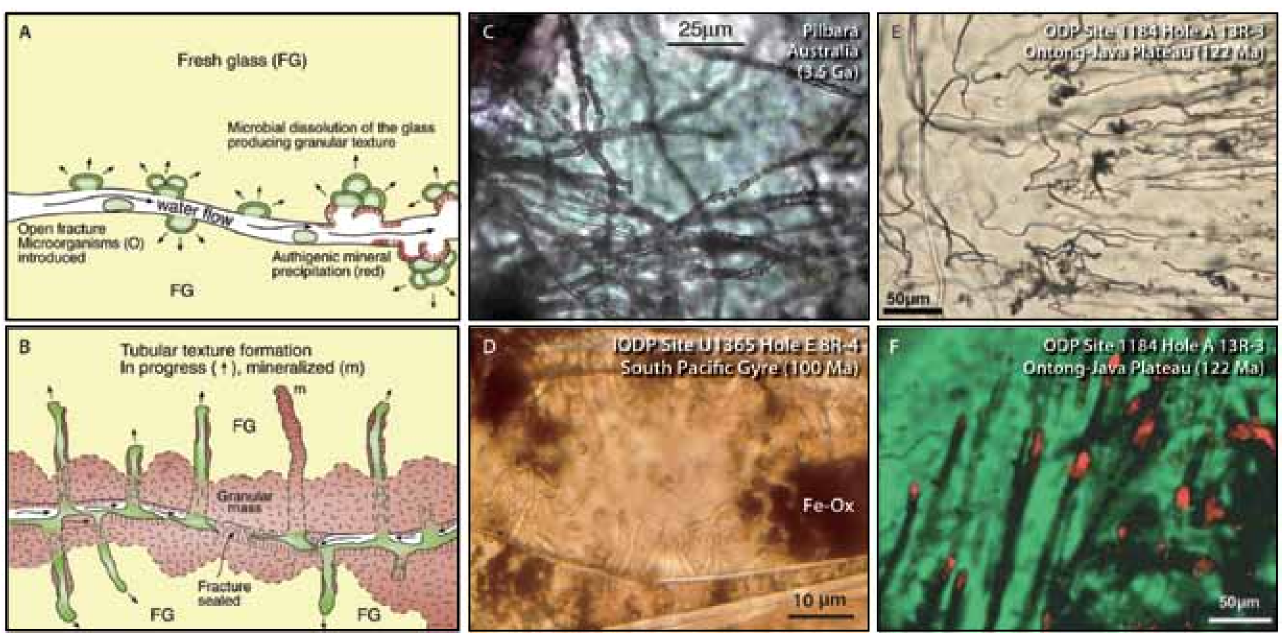
Figure 3.2. Cultivations of subseafloor sedimentary microbes using a flow-through bioreactor system customized for low energy and nutrient flux subseafloor environments. (A) The anaerobic bioreactor system. Phase-contrast microscopic image of archaeal isolates (B) *Methanobacterium* sp. and (D) *Methanosarcina* sp., and bacterial isolates (C) *Chloroflexi* sp. and (E) *Sedimentibacter* sp. All four strains were isolated from sediment cored at Site C9001 during the *Chikyu* shakedown expedition off Shimokita, Japan. Innovative cultivation techniques will help scientific ocean drilling to open a window to understanding of genetic, metabolic, and evolutionary characteristics of subseafloor life. Modified from Imachi et al. (in press).

zones, or if the communities migrated through the sediment in response to ongoing chemical changes. Studies of microbes in subseafloor environments may also improve understanding of marine microbial communities in general. For example, studies of anaerobic microbes deep in oxic sediment and thermophiles deep in cool sediment will improve understanding of microbial survival strategies, dispersal of microbial communities in the ocean, and, possibly, how communities assemble in the overlying water column.

Microbial communities have also been discovered in the basalt that makes up oceanic crust (**Box 3.1**). By drilling multiple sites along subsurface fluid-flow paths we can determine whether seawater flowing into rock fractures introduces these subseafloor microbes, or whether they migrate along flow paths from pre-existing communities in older rock, or from the overlying sediment. Integrating hydrological studies with microbiological and biogeochemical experiments (see **Box 5.1)** will help identify the kinds of organisms that colonize rock below the seafloor and how they use chemical gradients and mineralogy to sustain life.

BOX 3.1 | CONTINUITY OF LIFE—ANCIENT AND MODERN SUBSEAFLOOR LIFE

Distinctive features in volcanic glass have been interpreted as trace fossils of subseafloor life. It is hypothesized that microbial activity dissolves the glass, forming complex tubular features and precipitating minerals within the glass (A and B). Features like these have been found in 3.5-billion-year-old altered glass of the Greenstone Belt in Pilbara, Australia (C), in 100-million-year-old basaltic glass from the South Pacific Gyre (D), and in 122-million-year-old basaltic glass from the Ontong-Java Plateau (E and F). The distribution of these traces in ocean drill cores and the testing of their origin through multidisciplinary studies (including microbiology, molecular biology, geochemistry, hydrogeology, and mineralogy) and drillhole experiments (see Box 5.1 and Figure 5.5) will (1) extend our understanding of the modern deep biosphere to the history of life on Earth and (2) inform the search for life on other planets. Figures A–C from Staudigel et al. (2008), D from D'Hondt et al. (in press), and E and F from McLoughlin et al. (2009).



Scientific ocean drilling provides the means to investigate the relationship between microbial communities and numerous subseafloor biogeochemical processes, including sulfate and nitrate reduction, biogenic hydrocarbon and mineral production and destruction, and mineral oxidation and reduction. Drilling also permits examination of the physiological adaptations and community interactions that allow microbes to engage in these processes. By drilling into ocean margin sediment, we will improve our understanding of how organisms participate in the formation and destruction of marine and terrestrial hydrocarbon deposits (coal, peat). In regions of active serpentinization, we will investigate the extent to which that process supports (or does not support) subsurface life independent of photosynthesis (see **Box 4.2**). In regions of organic-carbon-rich anoxic sediment (e.g., upwelling regions) and organic-carbon-poor sediment (e.g., mid-Pacific gyres), drilling will increase our understanding of the extent to which mineral reduction or mineral oxidation, respectively, supports subseafloor life.

Finally, scientific ocean drilling will provide opportunities to capitalize on rapidly developing fields, such as metagenomics, which entails sequencing and analysis of DNA and RNA from entire communities of microbes collected directly from the environment (**Figure 3.3**). Techniques only recently developed by molecular biologists can be used to identify the metabolic activities and genetic compositions of individual cells. A major effort is needed to identify the key organisms responsible for subseafloor processes described above. This effort will enhance the rapid development of techniques for metagenomic analysis and for study of single cells.

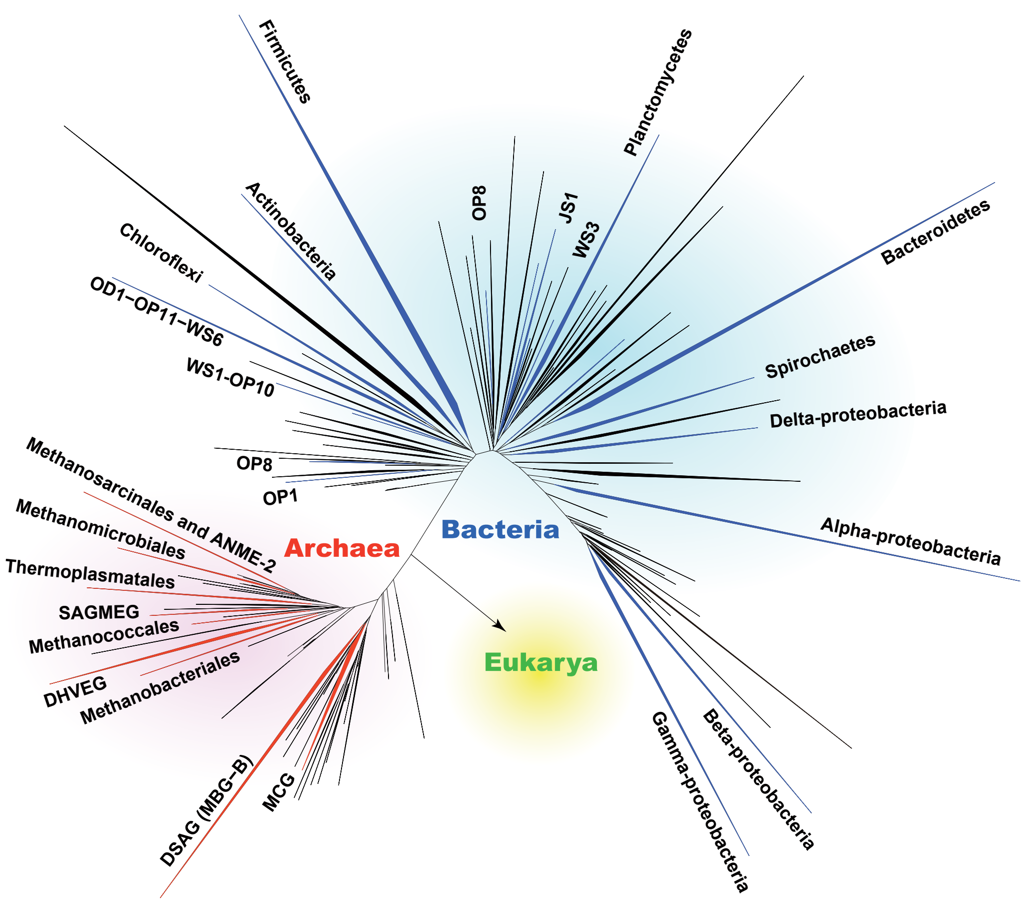


Figure 3.3. Phylogenetic tree of the three known domains of life on Earth (Archaea, Bacteria, and Eukarya). The tree is constructed by small subunits of ribosomal RNA genes, including sequences detected from samples recovered by scientific ocean drilling (Inagaki, 2010). Branches marked in red and blue, respectively, represent Archaeal and Bacterial phylogenetic groups that are frequently detected in subseafloor sediment. Most subseafloor species are distinct from species known in the surface world. The physiology, distribution, and ecology of these subseafloor species, and the many subseafloor species yet to be discovered, remain to be demonstrated through future scientific ocean drilling.

Challenge 6 | What are the limits of life in the subseafloor?

Scientific ocean drilling is helping to resolve the limits of life on Earth today, and the conditions and processes that may have favored the origin of life on Earth or elsewhere in the solar system.

Life is present in nearly all natural environments on Earth. Potential limiting factors include high temperature and pressure, pH extremes, and insufficient access to nutrients, carbon, or energy (e.g., insufficient food [electron donors] or oxidants [electron acceptors]). A major unresolved problem is how microbial communities find sufficient energy to power life over geologic time in extreme environments. Subsurface microbial communities may have special adaptations for long-term survival where energy and nutrients are limiting. Metabolic rates in subsurface microbes are many orders of magnitude lower than metabolic rates observed in microbial cultures and in microbes in surface sediments. Such differences challenge our current understanding of where and how life can exist, and what defines life in general. In addition, subseafloor communities using different energy sources may coexist, with one living on the reaction products of the other. By studying the evolutionary adaptations that allow microbes to persist with extremely low access to energy and nutrients, we will significantly expand our understanding of the possibility of evolution and habitability of other planets.

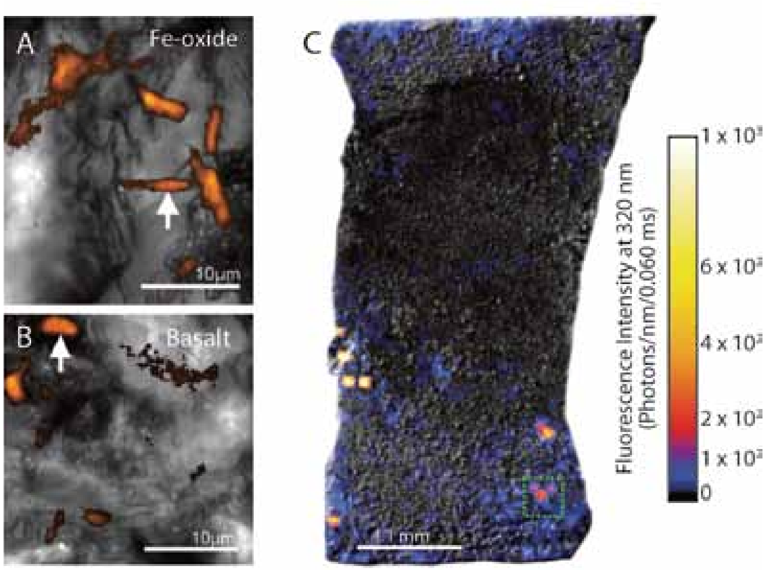


Figure 3.4. A new technology for life detection using a deep-UV laser induced by native fluorescence. Microbial cells are visible as orange regions in deep-UV native fluorescent images of (A) iron oxide, (B) basalt, and (C) a basalt chip from Lo'ihi Seamount. The photo is overlaying an image of visible and native deep-UV fluorescence. Note the change in scale from panels A and B to panel C. Figures modified from Bhartia et al. (2010).

Drilling and Research Strategy

The limits of life are presently understood by reference to laboratory "record-holders"—energy-unlimited pure cultures that are pushed to their biochemical breaking points, with all but the tested parameters optimized. While such studies are unquestionably useful, they fail to capture the natural world's complexity. Full understanding of these effects requires that we examine the distribution of populations in natural settings where organisms may be simultaneously challenged by multiple factors and where symbiotic relationships may support adaptation and survival.

Ocean drilling can deliver fundamental information about the limits of habitability by exploring subseafloor life at the "fringe." Subseafloor environmental gradients span a wide range of nutrient availability, food availability (e.g., organic matter, reduced metal, dissolved hydrogen), oxidant availability (e.g., oxygen, sulfate, oxidized metal), temperature, salinity, porosity, pH, and connectivity to subsurface fluid reservoirs. Core samples recovered by drilling will enable characterization of the microbial populations that have adapted to the diverse habitats defined by the varying combinations of these properties (**Figure 3.3**). By detecting and quantifying life in cored materials, we can identify the limits of the habitable zone in Earth's deep environment (**Figures 3.4 and 3.5**).

Two examples highlight ways in which scientific ocean drilling will advance understanding of the limits to life. First, measuring the increase in temperature with subseafloor

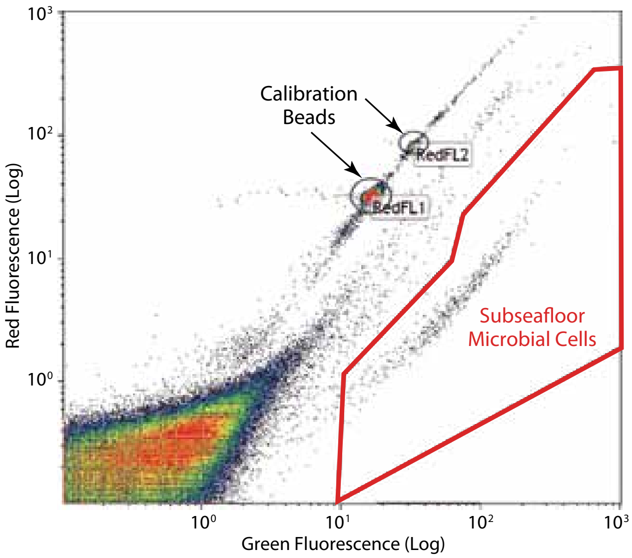


Figure 3.5. An example of new technology that may accelerate microbiological studies of subseafloor life through scientific ocean drilling. Microbial cells from subseafloor sediment can be automatically detected and their abundance can be quantified using an automated flow cytometry system (Morono et al., 2009). Microbial cells are in the region outlined in red on the right side of the figure. The colorful region in the lower left is due to fluorescence of sedimentary minerals.

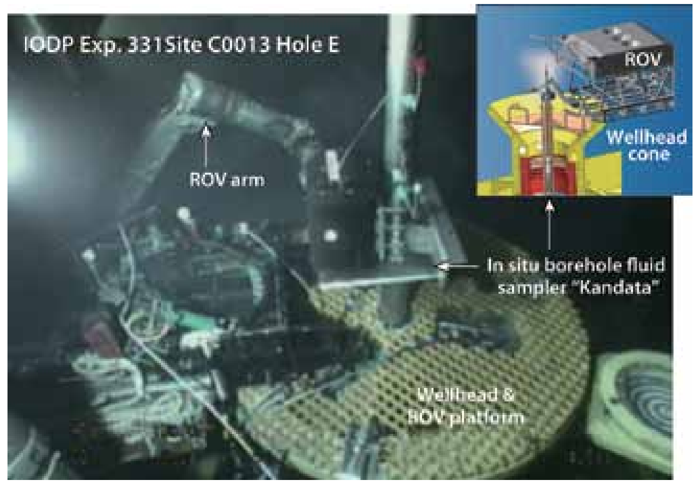


Figure 3.6. Borehole experimentation in an active hydrothermal field. The portable in situ borehole fluid sampler "Kandata" was deployed in the Okinawa Trough hydrothermal field during IODP Expedition 331. After drilling with D/V *Chikyu*, the borehole was cased to 40 m below the seafloor, and high-temperature (>250°C) hydrothermal fluid began to discharge from the wellhead. Inset: a schematic illustration of the "Kandata" operation at the cased and sealed borehole. The fluid sampler was hung in the borehole on a wireline by the ROV *HyperDolphin*. The borehole fluid is captured to understand how fluid-mineral interaction, temperature, and flow rate affect habitability in the hydrothermal field. Figure courtesy of K. Takai, JAMSTEC.

depth while simultaneously recovering sediment samples in a variety of locations worldwide will document the adaptations that permit life under different conditions. Deep drilling of sedimentary sequences rich in organic matter will allow exploration and understanding of the thermal limit to life for organic-fueled organisms. Deep drilling into aquifers heated magmatically, and into deep, hot sediment having little organic matter, will permit exploration and understanding of the thermal limits of life for organisms that are fueled by rock alteration or by hydrogen released by radiolysis, the natural radioactive splitting of water. Second, evidence is accumulating that organic-fueled subseafloor life can survive on extraordinarily low fluxes of energy for long time periods. The extent to which these slow-living organisms reproduce and evolve in situ, the physiological adaptations that allow their long-term maintenance of cellular functions for survival, the structure of their communities, and the extent to which similarly slow-living organisms inhabit other subseafloor environments are all unknown.

Shipboard study of microbial populations recovered in cores from diverse environments, combined with growth experiments in subseafloor in situ laboratories (**Figures 3.6 and 5.5**) and shore-based laboratory studies of the cellular biochemistry of recovered organisms, will yield new insights into the limits of life.

Challenge 7 | How sensitive are ecosystems and biodiversity to environmental change?

The ocean hosts one of the largest ecosystems on Earth, and its fossiliferous sediments are excellent recorders of past changes in the ocean, climate, and biodiversity.

Ocean ecosystems are being altered by numerous environmental stressors, including climate change, rising temperatures, hypoxia, acidification, and overfishing. Species migration caused by changing environmental conditions, and the subsequent competition between native and immigrant species, may result in speciation or development of new adaptive traits. In other cases, existing species and groups of species will go extinct. Numerous studies of biological systems show that abrupt changes in globally important ecosystems can occur in response to rapid environmental shifts. The challenge is to determine where and when "tipping points" could occur in the near future.

Drilling and Research Strategy

The history of biodiversity (including origination and extinction of species, the rates of species turnover, and stasis) as well as the relationships between biodiversity and environmental change can only be quantified and modeled through analyses of the fossil record (**Figure 3.7**). Ocean sediments preserve records of biotic and environmental change at annual-to-decadal scale resolution, going back tens of millions of years (**Figure 2.12**). These records are increasingly important for resolving the pace and amplitude of abrupt climate change and documenting ecosystem sensitivity to a variety of environmental perturbations, including those changes currently underway in the ocean. For example, studies of the warm Pliocene (~5 to 3 million years ago) will yield insights as to how marine ecosystems changed when Earth was only a few degrees warmer than today, global sea level was higher, and atmospheric CO_2 levels were comparable to modern values (**Figure 2.1**).

Analyses of deep-sea cores increasingly suggest that an astronomical metronome—the wiggles in Earth's orbit about the sun—may have fundamentally influenced the diversification and abundance of life on Earth. Addressing whether there are such long-term cycles in Earth's biological productivity and species turnover requires recovery of multimillion-year-long core sequences with excellent age control—records that are present only in the deep ocean. Precise age control permits global correlation of past events, which is essential for stitching together complete records from critical time periods. The marine fossil record accessible through drilling makes possible studies of the timing of worldwide extinction and speciation rates, long-distance oceanic migration rates in response to climate change, and the speed of threshold shifts within ecosystems. From these observations, we will be better equipped to evaluate and predict the dynamic response of ecosystems to future climate changes and test fundamental ecological theories involving adaptation, speciation, migration, and extinction.

In addition to acquiring records of how ecosystems responded to changes in insolation in response to Earth's orbital perturbations, ocean drilling will recover intervals of past rapid climate change particularly relevant to the study of marine ecosystems, including oceanic anoxic events, hyperthermal events, Antarctic glaciation events, and extremely rapid glacial terminations. Through geochemical, sedimentological, and paleontological studies of sediments and microfossils, we can reconstruct past oceanic conditions, including environmental parameters such as temperature, salinity, pH, carbonate saturation, and oxygen content. To understand

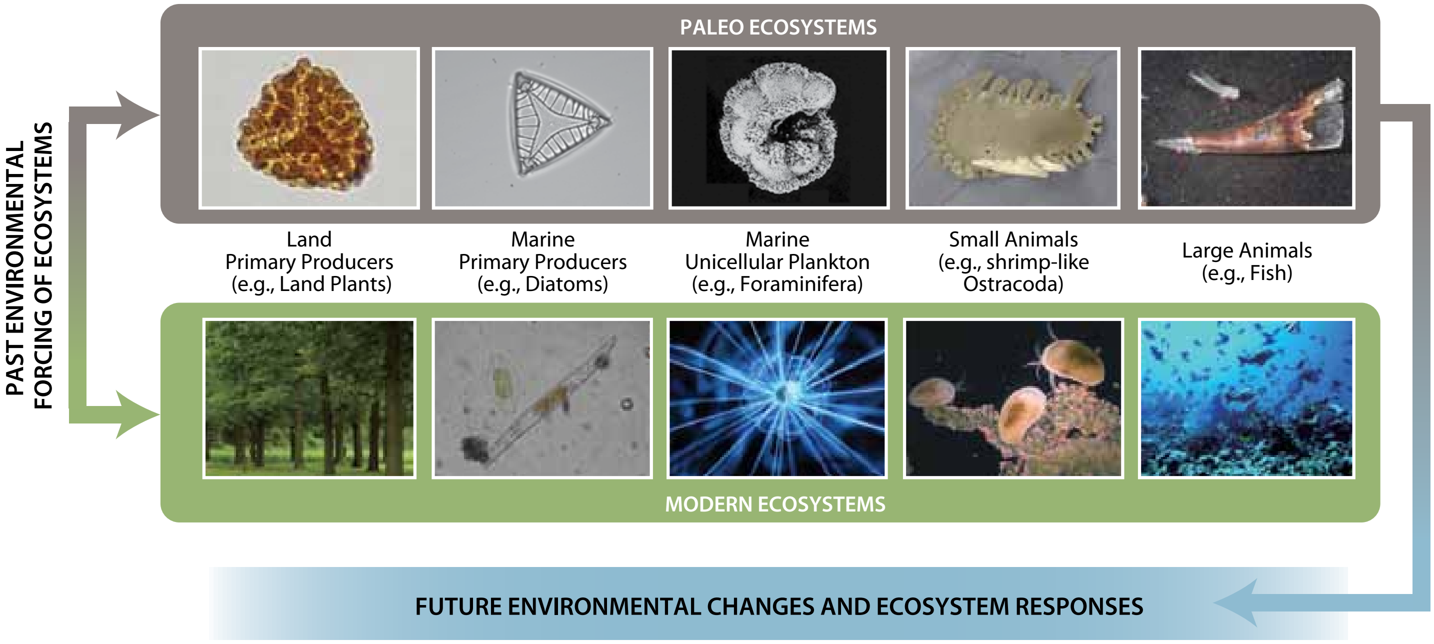


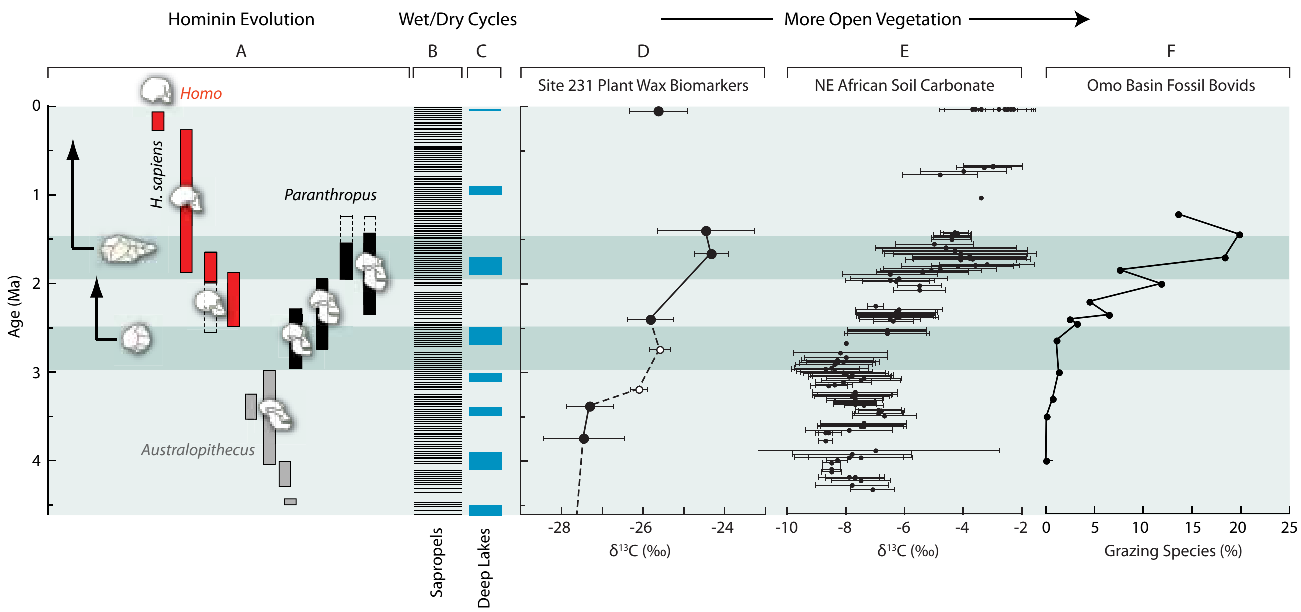
Figure 3.7. Examples of fossil organisms with an abundant deep-sea fossil record (top row) and living examples of the organisms that produce the fossils (bottom row). Left to right: pollen (land plant), diatom (photosynthetic algae), foraminifera (single-celled heterotroph organism), ostracod (small benthic animal), fish. The abundance and diversity of these fossils represent all levels of the food chain, permit detailed reconstruction of oceanic ecosystems, and provide important information about land ecosystems. In addition, the chemical composition of the fossils directly records environmental conditions, such as seawater temperature, salinity, and oceanic productivity. Credits: (top, left) Iwai et al. (2001); (top, second from left) Courtesy of J. Barron, USGS; (top, middle) Olsson et al. (1999); (bottom, second from left) from http://arch.ced.berkeley.edu/hiddenecologies/?page_id=170; (bottom, middle) Courtesy of H. Spero, University of California, Davis.

the interplay between biotic evolution and the global climate system, drill sites will be located in areas that have high sedimentation rates, enabling recovery of materials with excellent age control. Numerous methods will be used to analyze core material to obtain detailed information on the environmental conditions when the sediments were deposited. To obtain information on ocean stratification and circulation, drilling will be along depth transects at climatically sensitive locations chosen in cooperation with climate modelers.

Finally, human evolution and the development of ancient societies has been closely tied to past climate change (**Box 3.2**). Improving knowledge of human origins requires targeted drilling around the African continent and in oceanic areas along the pathways of human migration into Asia, Australia, and the South Pacific. Pollen, dust, and other land-derived materials in deep-sea cores provide a record of ecosystem and environmental change on nearby continents (**Figure 3.7**). To understand how human societies have fared through past abrupt climate changes, cores are needed in areas near the centers of human social development—the Persian Gulf, the Mediterranean, South America, and Southeast Asia. Ocean drilling can provide a global environmental framework within which to understand the factors that led to the evolution of our species, the rise of some ancient societies, and the collapse of others.

BOX 3.2 | HUMAN EVOLUTION

The fossil record of human evolution is punctuated by two events that shaped much of who we are today. These events, centered near 2.8 and 1.8 million years ago (Ma), include the emergence of the Homo lineage, extinction of ancestral lineages, appearance and refinement of stone tools, meat processing, and a marked increase in brain size (panel A, green horizontal bars). Environmental hypotheses of faunal evolution propose that climate shifts create ecological selection pressures that can ultimately result in speciation and extinction ("turnover") events. Marine sediment records of African paleoclimate change recovered by ocean drilling indicate marked changes in African climate over this interval. These records show that in addition to the persistent, wet-dry monsoonal cycles (panel B), a drying trend commenced in East Africa near 3–2.5 Ma, reaching driest, most open conditions between 2.0–1.5 Ma (panels D,E). Other mammals sharing the landscape with our ancestors such as antelopes (and other ungulates) also show marked evolutionary and adaptive change at these times (panel F). Figure adapted from deMenocal (2011), doi:10.1126/science.1190683, reprinted with permission from AAAS.



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4. Earth Connections

Deep Processes and Their Impact on Earth's Surface Environment

The dynamic processes that create and destroy ocean basins, shift the position of continents, and generate volcanoes and earthquakes extend from Earth's core to its atmosphere, and are fundamental for understanding global change within the context of planetary evolution.

CHALLENGES

8. *What are the composition, structure, and dynamics of Earth's upper mantle?*
9. *How are seafloor spreading and mantle melting linked to ocean crustal architecture?*
10. *What are the mechanisms, magnitude, and history of chemical exchanges between the oceanic crust and seawater?*
11. *How do subduction zones initiate, cycle volatiles, and generate continental crust?*

INTRODUCTION

Geochemical exchanges among the solid Earth, ocean, and atmosphere have influenced Earth's surface environment throughout its history. Flows of material and energy among global reservoirs drive long-term changes in Earth's structure and composition, cause volcanism and tectonism, and create hospitable environments for the development and evolution of life. Long-term upward flow of the mantle, decompression melting, and emplacement and eruption of magmas create oceanic crust, which underlies two-thirds of Earth's surface. New crust is altered over millions of years by chemical exchange with seawater. Subduction and dehydration of altered oceanic crust triggers the melting and magmatism that forms volcanic arcs, and enhances the vigor of mantle circulation through reduction in viscosity. At shallower depths, fluids released from subducting plates influence the nature of slip behavior and seismic activity at convergent plate boundaries.

The mantle is the largest geochemical reservoir on Earth, yet its composition remains poorly understood because of lack of direct sampling. A combination of heating by radioactive decay at depth and sinking of tectonic plates back into the mantle at subduction zones drives upper mantle convection over long time scales. However, there is evidence that plate tectonic processes observed today have been eclipsed at times in Earth's history by episodes of massive magmatic outpourings in small areas. These events may occur when hot mantle ascends rapidly from great depth to erupt on Earth's surface, forming oceanic plateaus and continental flood basalts (so-called large igneous provinces, or LIPs). The causes and environmental consequences of catastrophic magmatism remain speculative. Likewise, the processes that initiate new plate boundaries, a first-order problem in Earth dynamics, are poorly understood. For example, although continental rifting that forms new divergent plate boundaries can occur with little magmatic activity, this process is most commonly associated with extensive volcanism, suggesting a strong mantle influence. Similarly, at convergent plate boundaries, the initiation of subduction and formation of volcanic arcs remain enigmatic.

Convection is not restricted to the mantle, and occurs within the liquid-metal outer core, giving rise to Earth's strong magnetic field. Igneous rocks and sedimentary sequences record short- and long-term magnetic field

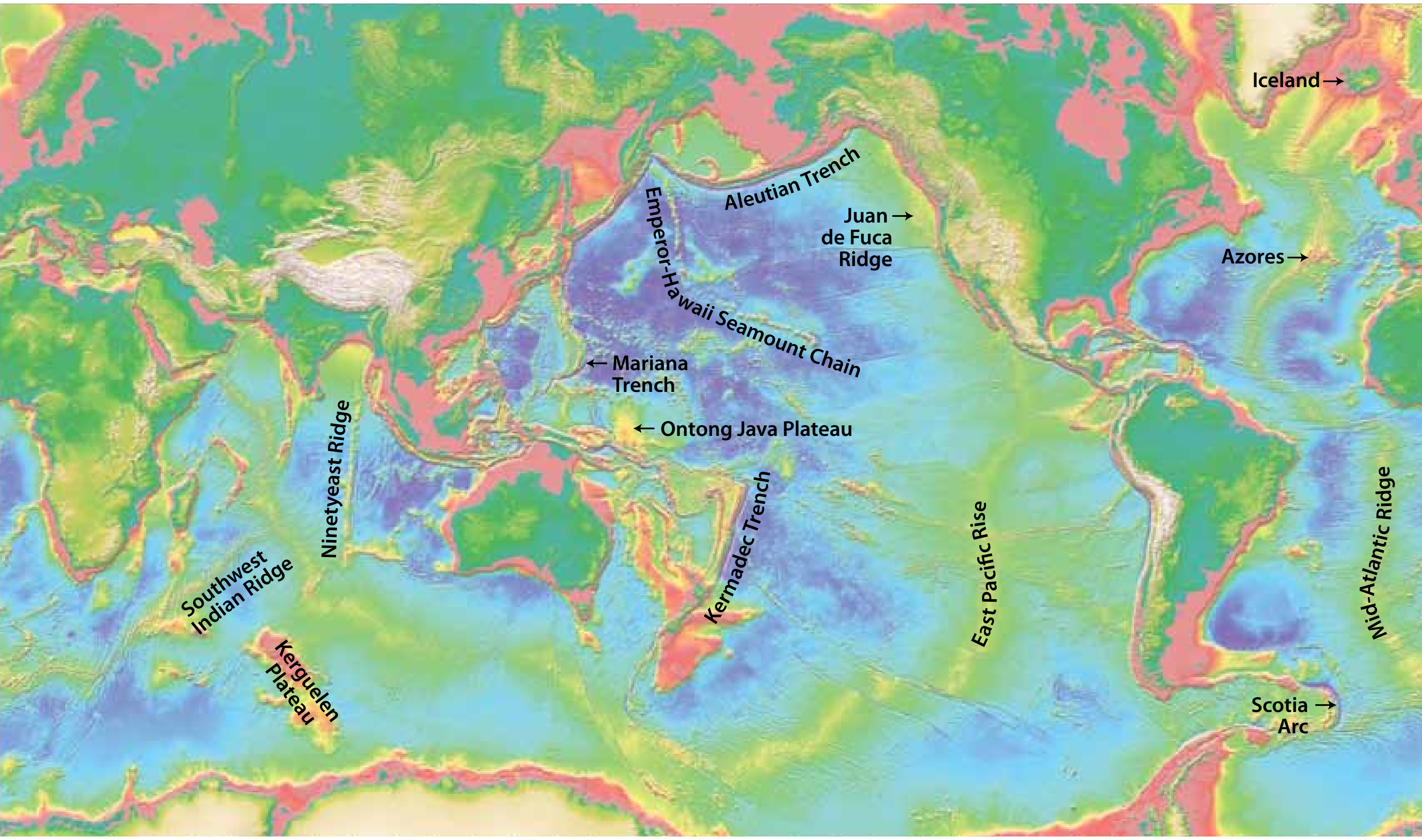


Figure 4.1. Map of the global seafloor illustrating a rich variety of topographic features that would be apparent if the ocean was drained of water. The bathymetry of the ocean floor and the geophysical and geochemical character of the oceanic crust provide a ~200 million year record of tectonic and magmatic processes influencing the lithosphere, Earth's rigid outer shell. Features labeled "ridge" or "rise" are seafloor spreading centers, where new oceanic lithosphere is created, whereas features labeled "trench" are subduction zones where one plate plunges below another and is recycled into the mantle. Also apparent on this image are seamount chains and large igneous provinces, both of which are thought to have derived heat and associated magmatic activity from the rise of plumes from deep within the Earth. Map of global seafloor topography from satellite imagery by W. Smith and D. Sandwell, available at: http://www.ngdc.noaa.gov/mgg/image/seafloor.html.

variations, providing quantitative constraints on the timing and rates of planetary processes, and yielding important clues concerning how the geodynamo functions (**Box 4.1**). The coincidence of anomalous magnetic field behavior and massive volcanism through Earth history could be indicative of a causal link, but this hypothesis remains to be tested.

Studies of the oceanic lithosphere, our planet's solid outer layer that includes the crust and the rigid part of the upper mantle, are essential for understanding the influence of deep processes on the shallow Earth environment. The oceanic crust, created principally at mid-ocean ridges, forms a thin veneer above the mantle and includes edifices such as seamounts, volcanic islands, massive oceanic plateaus, and island arcs (**Figure 4.1**). Melting processes that generate these features provide nuanced records of the mantle's thermal state and composition. Altered oceanic crust records cumulative geochemical exchange with the ocean (**Figure 4.2**). The continued recycling of water between Earth's interior and surface reservoirs shapes our planet, helps maintain distinct continental and oceanic realms, and is critical to the movement of carbon and nutrients between shallower and deeper biomes. Drilling is an essential tool for unraveling and understanding the geologic, geochemical, magmatic, and hydrological processes responsible for development and evolution of these solid Earth systems.

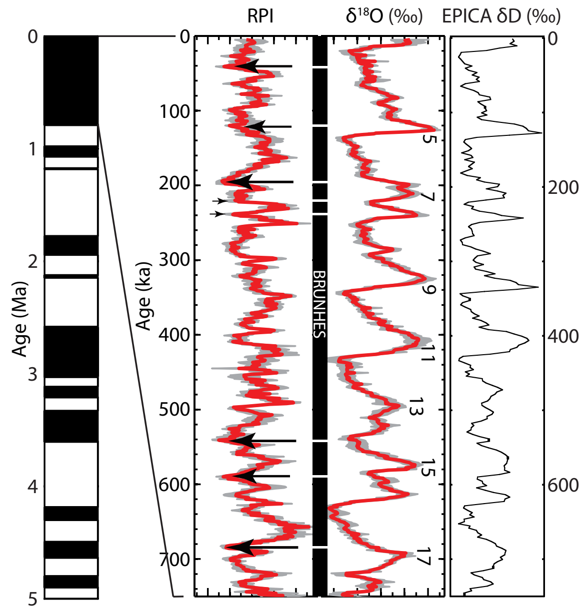
The Earth Connections theme links conditions and processes active today with those that have shaped our planet for billions of years. Climate and ocean change depend

directly on the rate of seafloor spreading, mantle and lithospheric outgassing, and the construction of topography associated with mountain-building events. Some of the earliest life on Earth is likely to have developed at interfaces where rock, heat, and fluids mix; close genetic descendants of these early organisms are found today in similar settings. Processes described in Earth Connections are responsible for immediate geohazards, and for the development of mineral resources that are essential to modern societies. The fundamental importance of these systems and processes has led to a confluence of interest among national and international research programs. The International Continental Scientific Drilling Program (ICDP) explores related questions mainly on land. The InterRidge program helps to initiate projects associated with seafloor spreading and evolution, and the Deep Carbon Observatory seeks to understand the nature of carbon processing within Earth. InterMARGINS is focused on continental margin studies, including understanding the nature of rifting, cycling of sediments and fluids at subduction zones, and associated geohazards. All of these programs, and numerous others, depend on scientific ocean drilling to acquire high-quality samples and data from deep below the seafloor, and to develop and deploy sensor and sampling systems that allow transformative understanding of these processes.

Figure 4.2. Delicate branching chimney structure venting high-temperature fluids from the Satanic Mills Chimney Field, PACMANUS Site, Bismarck Sea, Papua New Guinea, provides a stunning example of the flow of chemicals and energy between the solid Earth and ocean, and how hydrothermal systems sustain diverse and surprising ecosystems. Conduit diameters are ~10 mm. Video image from the Japanese *Shinkai 6500* submersible, courtesy of the Commonwealth Scientific and Industrial Research Organisation.

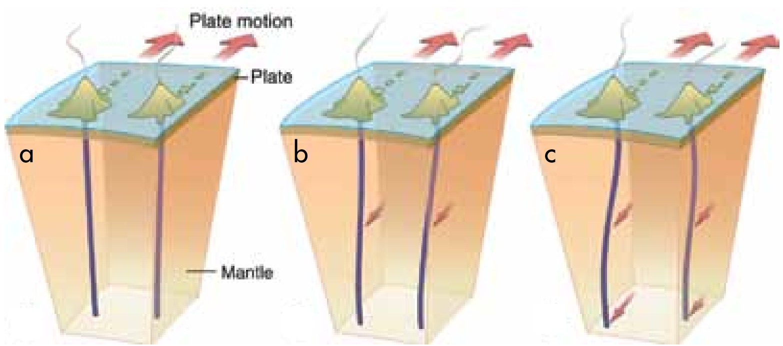
BOX 4.1 | MAGNETISM AND THE GEODYNAMO

The magnetic field is one of the most enigmatic properties of the physical Earth. It is constantly changing, yet on average it is remarkably stable, being approximated by a bar magnet at the center of the Earth. It acts as an umbrella, shielding us from cosmic radiation, and as a guide, pointing roughly toward North. Yet some of its more spectacular behavior includes completely flipping its polarity during "reversals,"and wandering rapidly during "excursions," and constantly changing intensity. The timing of polarity reversals has served as the backbone of the geological time scale for decades. Now, emerging records of excursions and relative paleointensity (RPI) can be added to the chronostratigraphic toolbox, and can be correlated to marine and ice-core isotopic records (top figure) within intervals of uniform magnetic polarity. The time-calibration of these global attributes of the magnetic field (using the power of astrochronology) remains a critical task that can only be adequately accomplished through ocean drilling. Precise global stratigraphic correlation remains elusive, is one of the great challenges in paleoceanography, and is essential for deciphering regional leads and lags in the climate system.



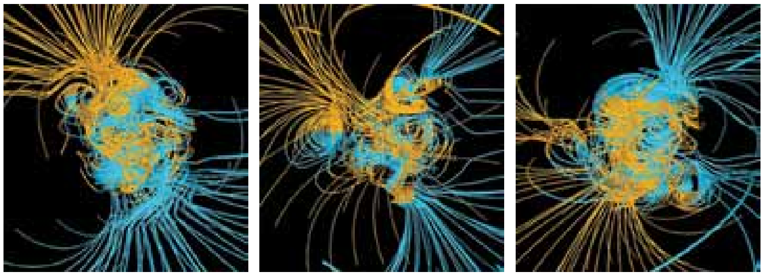
Left: Geomagnetic polarity record for the last 5 Myrs (black: normal polarity, white: reverse polarity). Right: Stack of relative paleointensity (RPI) and oxygen isotope data ($\delta^{18}O$) from deep-sea sediments with 2σ error (Channell et al., 2009) for the last 750 kyr compared to the deuterium isotope data (δD) from the Dome C Antarctic ice core (Jouzel et al., 2007). Arrows indicate documented magnetic excursions associated with RPI minima. Marine isotope stages are numbered.

Despite the ever changing nature of the geomagnetic field, the fact that it averages to a centered bar magnet has been central to plate tectonic reconstructions for decades. Yet things are not as simple as they were once thought to be. Reconstructions have traditionally been tied to the so-called "hotspot" reference frame, constructed using the locations of persistent points of volcanic activity such as the sources of the Hawaiian and Line Islands and Iceland. It has become increasingly clear that these volcanic sources may not be "fixed" in the mantle, but drift with respect to one another and to the Earth's spin axis (middle figure). These motions are essential clues to the dynamics within the deep Earth, but are as yet poorly documented.



Views of hotspot plumes and overriding plate motion. (a) Plumes are fixed and not affected by mantle flow. (b) Plumes are fixed at their base but affected by mantle flow during ascent. (c) Plumes are not fixed at their base and are affected by mantle flow. From Stock (2003).

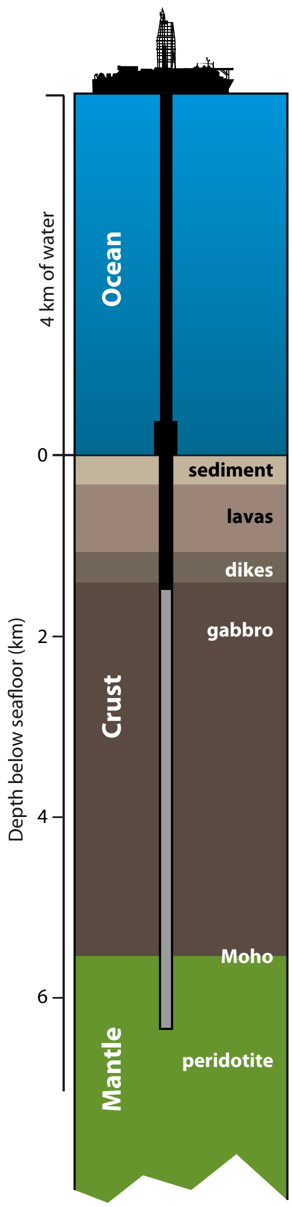
Understanding the origin of the Earth's magnetic field itself remains a challenging research area. Available computers strain to produce numerical models (bottom figure), and computer speeds remain inadequate for realistic simulations. It is imperative to "ground truth" the numerical simulations with "real" data from high-sedimentation-rate deposits located around the globe that have recently been shown to provide rich archives of magnetic field behavior.



Numerical simulation of magnetic flux lines within and emanating from the core during a simulated polarity reversal. Courtesy of G. Glatzmaier, University of California, Santa Cruz.

Challenge 8 | What are the composition, structure, and dynamics of Earth's upper mantle?

Enhanced capabilities will enable drilling of a complete section of oceanic crust, determination of the nature of the Moho, and recovery of pristine samples of Earth's mantle—a scientific ocean drilling goal for many decades.



The mantle is Earth's largest geochemical reservoir (~68% by mass), extending from the base of the rocky crust to the top of the metallic core. Understanding the mantle is essential for interpreting Earth's long-term evolution because of the mantle's sheer size, and because all oceanic crust, and much of the continental crust, is derived from partial melting of mantle rock. Much of what we know about mantle structure and function is inferred from geophysical measurements and analysis of samples recovered in settings where mantle rocks have been uplifted close to the surface. Evidence that the upper mantle is highly variable in composition comes mainly from mantle rock fragments brought to the surface by ocean island and continental volcanoes, and altered mantle rocks exposed by deep faults on and near mid-ocean ridges. Seismic anisotropy within the uppermost mantle may indicate the alignment of minerals as a result of mantle flow, as well as differences in thermal and geochemical state. The only way to decipher melting processes that generate magmas and form the crust at seafloor spreading centers, and to evaluate the unaltered composition and variability of mantle rocks, is to drill through the crust and into the upper mantle at a single location.

Drilling and Research Strategy

The scientific ocean drilling community is now poised to penetrate and sample a complete section of oceanic crust and underlying upper mantle (**Figure 4.3**). The technology required poses challenges (**Chapter 7**), but major scientific milestones will be met using a stepwise approach, with science and drilling engineering proceeding in tandem. Directional coring launched from suitable points near the base of the crust will allow sampling of the upper mantle along multiple drilling trajectories. This strategy will provide lateral sampling for heterogeneity, and maximize the volume of material obtained from individual boreholes.

Figure 4.3. Cartoon showing known and inferred stratigraphy around ODP/IODP Hole 1256D in the eastern equatorial Pacific Ocean, on the east flank of the fast-spreading East Pacific Rise. Depth of penetration thus far by scientific ocean drilling is shown in black; section of hole shown in gray indicates additional penetration that would be required to achieve a complete penetration of the oceanic crust and uppermost mantle. Note that the drillship would be about 100 times smaller if it were drawn to scale.

Drilling through the oceanic crust and into the mantle will provide access to the Mohorovičić discontinuity ("Moho"), a step increase in seismic velocity that has long been thought to represent the boundary between rocks formed from mantle melt (the crust) and rocks below from which melts migrate (the residual mantle). Testing this hypothesis, and understanding subtle seismic layering within the crust, will greatly enhance scientists' ability to extrapolate from borehole observations across ocean basins. Drilling will also provide key constraints on models used to quantify fundamental properties of the mantle, including temperature, viscosity, and flow directions.

Access to mantle material will allow researchers to move beyond idealized models of mantle melting and examine how multiple melting events and melt-rock reactions occur. Melt inclusions trapped in single minerals within lavas show remarkable variations in composition, suggesting that a wide range of melt compositions are produced initially, but are later homogenized in magma chambers or lenses before being erupted. Recovery of pristine mantle samples will provide a mineralogical and geochemical history of mantle processes that will help to constrain Earth's bulk composition and long-term planetary evolution (**Figure 4.4**).

Selection criteria for a location for drilling to the mantle include a typical thickness (5–7 km) and seismic structure for the crust, a well-defined seismic Moho structure (**Figure 4.5**), robust seismic anisotropy within underlying mantle, and a simple geological history far removed from complications caused by intraplate volcanism. Three potential areas have been identified in the Pacific Ocean: off Northwest Hawaii, off Central America, and off Baja California. Further seismic studies of these areas are planned for 2011–2012; one area is the target of a pilot hole that will be deepened beyond its current depth of 1.5 km in 2011.

Drilling through the oceanic crust and into the uppermost mantle has become a rallying point for researchers spanning a broad range of disciplines and interests. There is consensus that achieving this goal is essential, and that numerous related problems and questions can be addressed in concert with development of a deep mantle borehole. A mantle hole will be designed and deepened in stages and in association with several relatively deep crustal boreholes drilled nearby (as necessary to develop an understanding of crustal conditions and prepare casing and drilling systems). This strategy will also provide opportunities for multidisciplinary collaboration and achievement of goals that are important to other ocean drilling themes. Ultimately, this effort will engage new communities in scientific ocean drilling, including planetary geologists, computational mineralogists, experimental petrologists, and exobiologists.

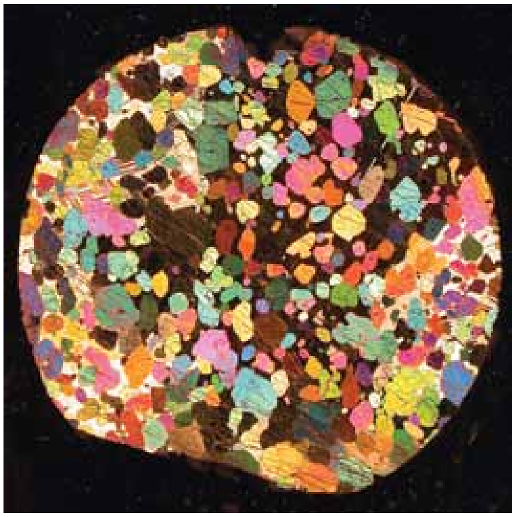


Figure 4.4. Photomicrograph of an intrusive rock from the deep oceanic crust observed in cross-polarized light. The brightly colored olivine crystals preserve a record of deep crustal and mantle processes that can be deciphered with state-of-the-art trace element, isotope, and gas analyses. Photo is ~20 mm across. Courtesy of Benoit Ildefonse, Université Monpellier.

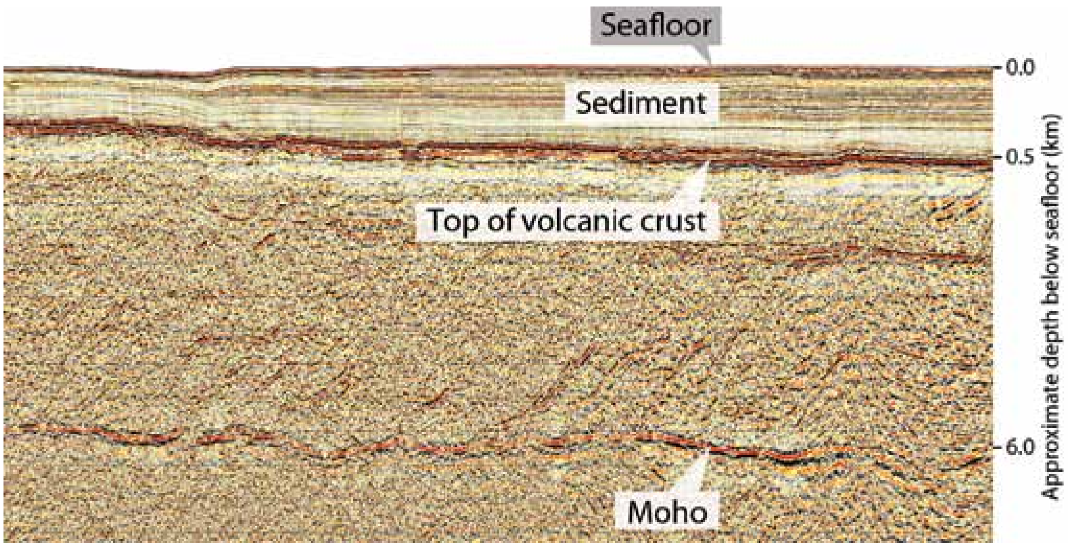


Figure 4.5. Seismic reflection profile showing crust formed at a fast-spreading mid-ocean ridge on the Pacific Plate that has a well-imaged seismic Moho, the seismic boundary thought to separate crust from mantle. Penetration of a full crustal section in an area such as this would extend across the Moho and into the upper mantle rocks below. Depth is approximate, and is based on this travel-time section. Courtesy of S. Kodaira, JAMSTEC.

Challenge 9 | How are seafloor spreading and mantle melting linked to ocean crustal architecture?

Seafloor exploration has demonstrated that oceanic crust is not uniformly layered everywhere. Drilling into sections of exposed deep crust and mantle at slow-spreading ridges will test three-dimensional models of crustal architecture.

Scientific ocean drilling, combined with seafloor mapping, geophysical experiments, and numerical modeling, have radically transformed our view of how oceanic crust is generated at mid-ocean ridges. We now know that magmatic and tectonic processes interplay in many ways, and that multiple mechanisms are responsible for creating new oceanic crust. Early textbook models of oceanic crust were inspired by observations of ophiolites—slices of ancient oceanic crust exposed above sea level. These models depicted upper oceanic crust as a uniform, layered sequence of basaltic lavas and dikes, and a lower intrusive crust composed of gabbros. Results from drilling the upper 1.5–2 km of oceanic crust formed at intermediate- to fast-spreading ridges in the Pacific Ocean are broadly consistent with the ophiolite model (with considerable variability in the thickness and alteration of upper crustal layers), but the lower crust remains poorly sampled.

In contrast, crust formed at slower-spreading centers, which comprise the majority of the global mid-ocean ridge system, differs substantially in composition and architecture from that of faster-spreading crust. At slow-spreading ridges, mantle melting produces insufficient magma to form the full layered sequence observed in crust produced at faster spreading rates. However, crustal-scale faulting is more prevalent, exposing mantle rocks at the seafloor (**Figure 4.6**). It is estimated that 25% of the rocks exposed at slow-spreading ridges may be mantle rocks. These rocks are highly reactive with seawater, making them important for the geochemical cycling of elements such as lithium and boron. In addition, hydrothermally altered mantle rocks (serpentinites) may be a major unexplored carbon reservoir, critical to understanding the global carbon cycle (**Boxes 4.2 and 5.3**).

Lithospheric magmatic and tectonic processes also influence crustal architecture in other parts of the ocean basins. When continents break apart to form new ocean basins, they do so with either widespread volcanism accompanying the transition from continental to oceanic crust (volcanic rifted margins), or with little volcanism but widespread tectonism that results in exposure, weakening, and alteration of mantle rock (nonvolcanic rifted margins). There are also extremely active volcanic systems that develop at plate boundaries and within plate

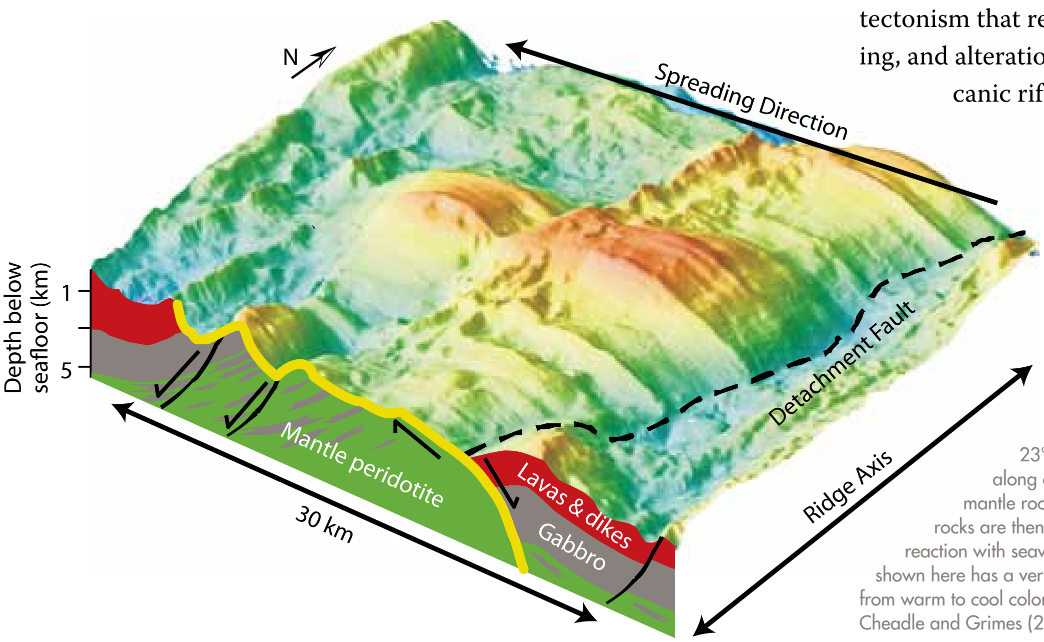


Figure 4.6. A three-dimensional view of a segment of the slow-spreading Mid-Atlantic Ridge at 23°N showing how large-scale movement along a detachment fault exposes blocks of mantle rock (peridotite) at the seafloor. The mantle rocks are then commonly altered to serpentinite by reaction with seawater. The dome-shaped uplifted block shown here has a vertical extent (shown by the gradation from warm to cool colors) exceeding 3 km. Modified from Cheadle and Grimes (2010).

interiors that erupt intermittent, massive volumes of lava over geologically brief periods ("hotspots"). Many LIPs emplaced in ocean basins are associated with plumes originating in the upper or lower mantle, and their emplacement may have contributed to periods of rapid global climate change (**Challenge 2**).

Drilling and Research Strategy

Understanding links among seafloor spreading, mantle melting, and ocean crustal architecture requires scientific ocean drilling to recover rocks and downhole data. As described in **Challenge 8**, the International Ocean Discovery Program plans to sample a complete, intact section of fast-spreading oceanic crust, from the extrusive lavas to the Moho. Because crust formed at fast spreading rates is relatively uniform, a single deep hole will advance understanding of many processes that have "paved" two-thirds of Earth's surface in the last 200 million years. This sampling will allow researchers to quantify the bulk composition of a large part of the oceanic crust, resolve chemical connections between melts coming from the mantle and what is sampled at and near the seafloor, and test competing models of magmatic accretion. Collateral benefits to drilling include permitting estimates of hydrothermal fluid and solute fluxes, calibration of regional seismic measurements, resolution of the origins of marine magnetic anomalies, and more accurate estimates of chemical fluxes into the mantle at convergent margins.

To gain a better understanding of processes, composition, and architecture at slower-spreading ridges, drilling of a single deep hole should be complemented by drilling through "tectonic windows" in slow- and ultraslow-spreading crust where faulting exposes the deep crust and mantle. This drilling strategy would test three-dimensional models of the oceanic crust developed through seismic surveys and ocean-bottom mapping of rock outcrops. Shallow coring will address important questions regarding mantle melting, depletion, and fertilization, and the geometries of melt and mantle flow. Regional mantle heterogeneity can be addressed by drilling transects of offset holes across large mantle exposures. Access to altered mantle rocks exposed by faulting in slow-spreading environments will also allow quantification of chemical exchanges and biological processes associated with serpentinization (**Box 4.2**). Deeper crustal drilling in these settings, where the shallow crust is either removed by faulting or never developed initially, will resolve whether the Moho is a lithologic, alteration, or tectonic boundary, and how the nature of the Moho varies in space and time.

Scientific ocean drilling is also essential for resolving the processes responsible for continental rifting and localized, sustained outpourings of lava that lead to the formation of LIPs. It provides the only opportunity to penetrate thick sediments at continental margins where the transition from continental breakup to steady-state seafloor spreading is buried. Geological histories developed using core samples and other downhole information can be used to test and calibrate ocean basin formation models. Drilling LIPs, hotspot tracks, and other features created by focused magmatic activity will reveal the timing and distribution of these systems, the duration of shorter- and longer-term magmatic episodes, and the nature of mantle heterogeneity and large-scale mantle convection processes (linking **Challenge 9** to **Challenge 8**).

Challenge 10 | What are the mechanisms, magnitude, and history of chemical exchanges between the oceanic crust and seawater?

Scientific ocean drilling will help to unravel the geochemical consequences of seawater interactions with the oceanic crust during hydrothermal alteration and the contribution of these processes to global geochemical budgets and reservoirs.

The chemical and isotopic composition of seawater reflects the dynamic balance among fluxes dominated by riverine inputs, lithospheric fluid exchange, and biological cycling. These fluxes depend on global geologic processes, such as seafloor spreading, lithospheric cooling, mountain building, changing climate, and the evolution of biological systems. The discovery of high-temperature ("black smoker") hydrothermal vents at seafloor spreading centers ~35 years ago confirmed that large quantities of seawater-derived fluids circulate through the oceanic crust, transferring mass and heat between the lithosphere and ocean. Subsequent studies have shown that an even larger quantity of fluid flows through the oceanic crust on mid-ocean ridge flanks, but at much lower temperatures. Collectively, these systems extract as much as one-third of the heat associated with lithospheric cooling. The chemical exchange between circulating fluids and rocks has helped to buffer changes in ocean chemistry through geologic time, and also influences the properties and evolution of oceanic crust itself, and through subduction, the mantle and arc magmas. Material that eventually is recycled back into the deeper mantle carries with it a history of hydrothermal activity.

Although the nature of individual fluid-rock reactions that occur during hydrothermal alteration of oceanic crust is generally understood, the magnitude and distribution of chemical exchange remain poorly quantified, as does the balance between higher- and lower-temperature fluid flows and the variability in reactions that occur across a range of seafloor ages. In addition, recently identified mechanisms that accommodate extension along portions of slow-spreading mid-ocean ridges expose vast swaths of deep crustal and upper mantle rocks to seawater, implying that processes such as serpentinization may impact seawater chemistry and geochemical and biogeochemical cycles (**Box 4.2**).

Drilling and Research Strategy

Fluids leave a record of seawater-rock exchange through chemical and isotopic changes, the formation of alteration minerals, and variations in lithospheric physical properties. Drilling and sampling oceanic crust of a variety of ages will quantify the timing, duration, and extent of fluid-rock exchange, as well as the oceanic crustal contributions to the geochemical cycles of important elements such as strontium, magnesium, potassium and carbon. The seawater-rock exchange that produces black smoker vents occurs at high temperatures (>300°C). Because these systems extract thermal energy from magma, associated reactions occur mainly in young crust close to seafloor spreading centers and on ridge flanks associated with hotspot volcanism. Estimates of fluid and geochemical fluxes during high-temperature hydrothermal circulation can be made by drilling and sampling the time-integrated products of fluid flow present in shallow lavas and sheeted dikes, and comparing these samples and data to independent estimates made from seafloor and water-column studies of vent fluids.

Seawater-basalt exchange occurs at relatively low temperatures (<100°C) for many geochemical tracers, such as magnesium, carbon dioxide, and iron, through the alteration of volcanic glass and minerals and the formation of secondary alteration phases such as clay minerals, iron hydroxides, and carbonates. These low-temperature exchanges occur wherever seawater is able to enter the oceanic crust on ridge flanks, and can continue even in crust buried beneath thick sediments if there is sufficiently high crustal permeability and lateral driving forces between areas of basement exposure (e.g., seamounts, fracture zones, LIPs). Departures from the predicted lithospheric cooling curves indicate that, on average, ridge flank flow plays a discernible role in the advection of heat from the basement out to at least 65 million years, but numerous studies have found that fluid, thermal, chemical, and biological redistribution and exchange can continue in crust that is well over 100 million years old (**Figure 4.7**). Quantifying the extent and timing of low-temperature exchange requires drill holes that penetrate well into the zone of extrusive volcanism (300–500 m). At present, there are few basement samples from sites 20–70 million years old, a period of significant thermal and hydrogeologic transition. Drilling will provide essential information on how the crust ages, as well as better age resolution for investigations of past seawater chemistry based on crustal alteration. The

BOX 4.2 | SERPENTINITE SEAS

Deep faulting at slow-spreading mid-ocean ridges exposes mantle rocks at and near the seafloor, allowing them to react with seawater. The resulting serpentinization alters dry, dense, mechanically strong and poorly magnetic mantle peridotite into a low-density, weak, highly magnetic rock with >10% water. The weak serpentinite allows the oceanic lithosphere to fail, exposing even more mantle rocks that can react with seawater. Serpentinized mantle peridotites make up a significant proportion (~25%) of the ocean floor at slow-spreading ridges and at ridge-transform intersections. Serpentinization occurs throughout the plate tectonic cycle, from continental breakup to plate subduction. The conversion of peridotite to serpentinite is exothermic and can contribute to sustaining low-temperature hydrothermal systems. Serpentinization produces hydrogen and abiotic methane, which are basic nutrients for exotic food webs, and acetate, formate, and alkaline fluids. Mixing of these alkaline fluids with seawater results in carbonate precipitation. The formation of large carbonate structures such as the Lost City springs on the Mid-Atlantic Ridge has close parallels with ancient calcite deposits within mantle rocks in on-land sections of oceanic lithosphere (called ophiolites), and may provide guidance for novel approaches to sequester carbon dioxide (Box 5.3). Microbial communities around serpentinized mantle may be adapted to conditions that mimic those of the early Earth.

Seen on the right of this photo is serpentinite bedrock (dark black-brown) with the remnants of old carbonate seeps growing out of near-vertical serpentinite walls at the Lost City hydrothermal field in the Atlantic. Seen on the left is part of a several-meter-tall carbonate pinnacle growing from a larger fissure. A blue cut throat eel (nonvent endemic) can be seen toward the top middle of the photo. Courtesy of D. Kelley, University of Washington, and the 2005 Lost City Team, NOAA, URI-IAO, and IFE.

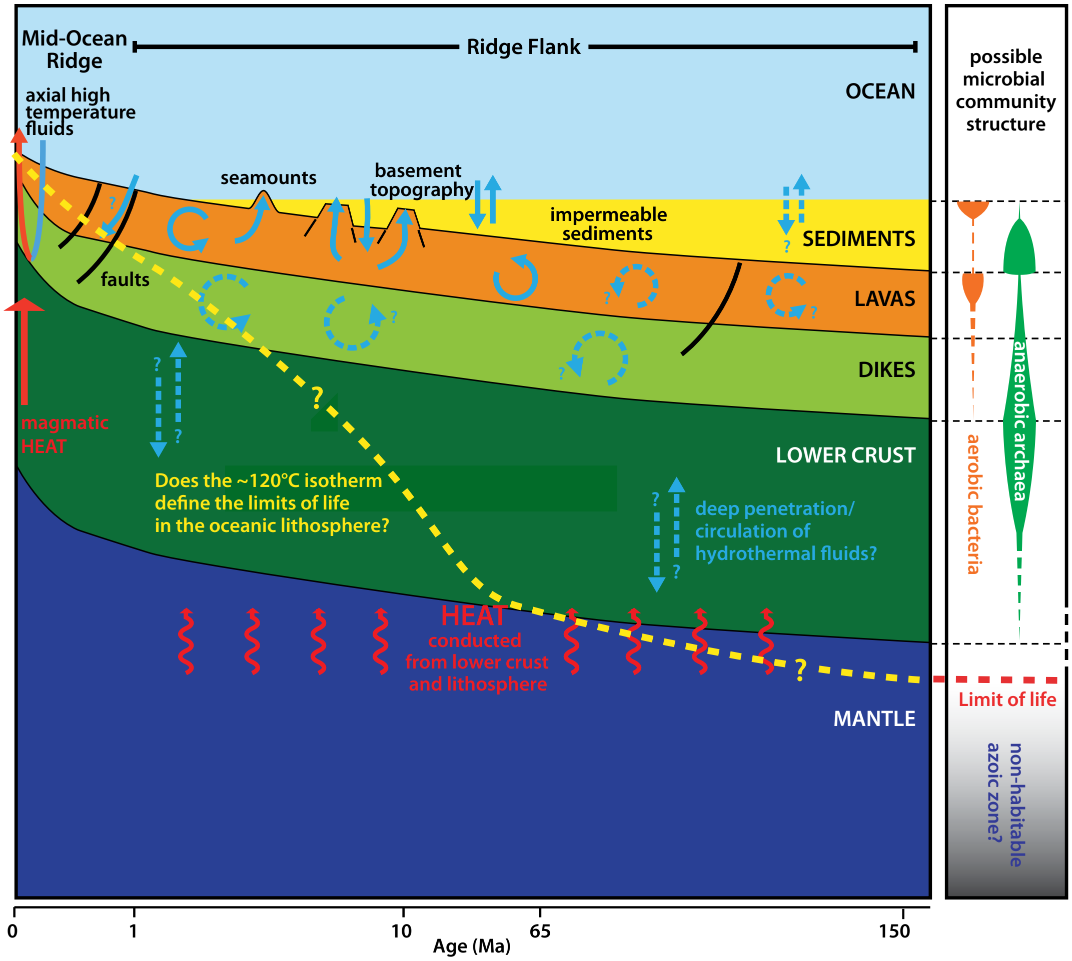


Figure 4.7. Schematic architecture of a mid-ocean ridge flank (not to scale) illustrating the parameters that may influence the intensity and style of hydrothermal circulation, such as faults, seamounts, basement topography, and impermeable sediments that isolate the crust from the ocean. Arrows indicate heat (red) and fluid (blue) flow. The yellow dashed line is a hypothetical trajectory of the 120°C isotherm as oceanic crust moves away from the ridge crest. Modified from a figure provided by R. Coggon, Imperial College London, D. Teagle, University of Southampton, and K. Nakamura, AIST.

ultimate goal is to drill a series of ocean-basin-wide transects that follow plate tectonic flow lines, extending from "zero-age" mid-ocean ridges out to 100 million-year-old crust or older. These transects should be planned across a range of seafloor spreading rates and tectonic and magmatic styles. Careful analysis of drill cores and downhole logs, coupled with state-of-the-art geochronology and seafloor mapping, can provide independent records of the rates, magnitudes, and distribution of chemical alteration in the oceanic crust, and the influence of lithospheric alteration processes on ocean chemistry through time.

Challenge 11 | How do subduction zones initiate, cycle volatiles, and generate continental crust?

Subduction zones are the primary sites where material from Earth's surface is recycled into Earth's interior. The oceanic lithosphere, including trapped water and carbon dioxide, is subducted into the mantle at deep-sea trenches where heat and pressure release a significant (but poorly known) fraction of volatile constituents. These volatiles drive melting in the mantle above the subducting plate, and the resulting magmas ascend, crystallize, degas, and erupt. The most explosive volcanic eruptions on Earth are associated with subduction. In addition to posing an immediate hazard to nearby populations and ecosystems, these systems facilitate the violent expulsion of water, gases, and magma from the interior of the planet, thereby recycling volatiles back to Earth's exterior and generating new crust in the overlying plate (**Figure 4.8**). Originally in the form of submarine and island arc volcanoes, such juvenile crust eventually matures into continents, which are unique in our solar system, ancient on our planet, and essential for the development of terrestrial ecosystems.

At convergent plate boundaries, oceanic lithosphere is subducted, resulting in release of volatiles, melting in the mantle, and the world's most explosive volcanic eruptions, large earthquakes, and tsunami.

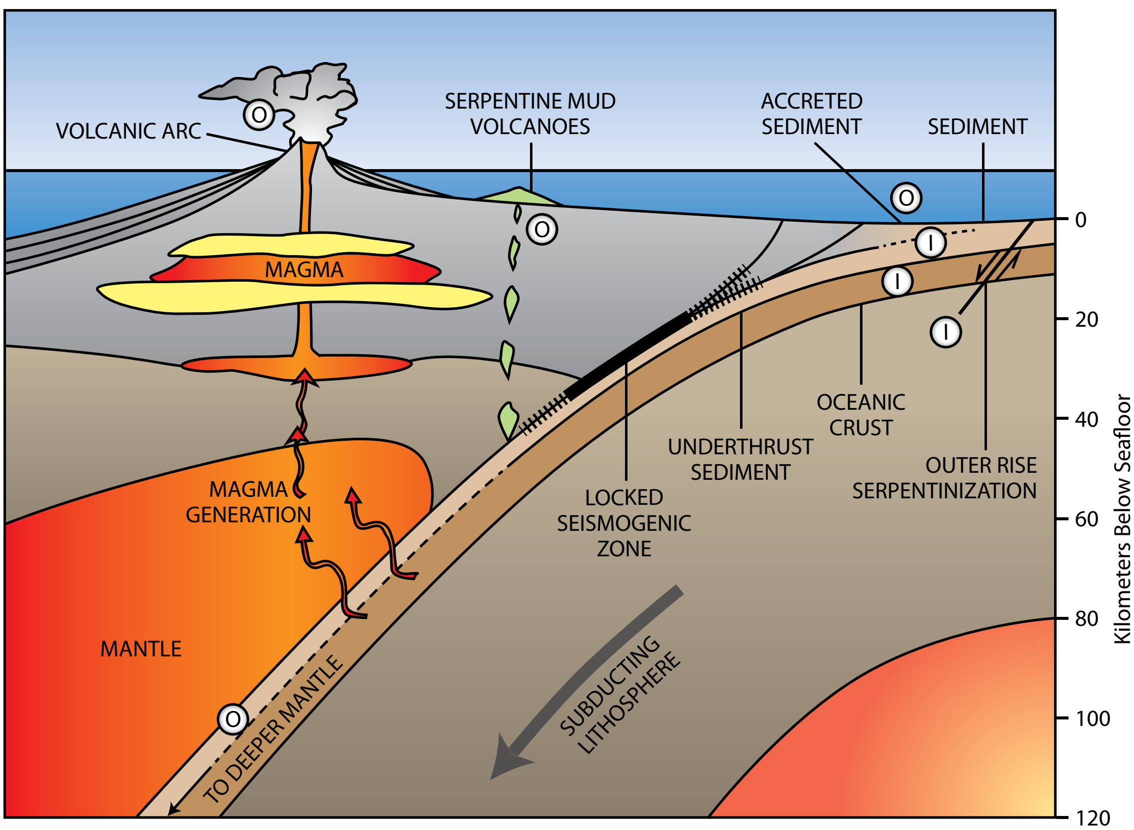


Figure 4.8. Cartoon of a subduction zone showing major inputs (I), outputs (O), fluid and melt pathways, and arc crust structure. Oceanic crust is covered by a thick accumulation of marine sediments and has been extensively altered by millions of years of hydrothermal circulation, including microbial and abiotic reactions. Outer rise faults may hydrate subducting mantle lithosphere, and the resulting serpentine is a major potential water input to the subduction zone. Fluids (H_2O and CO_2) from sediments and altered volcanic rocks escape into the accretionary prism, overlying plate, and mantle wedge during subduction, leading to formation of cold seeps and mud diapirs on the forearc, great earthquakes in the locked seismogenic zone, and mantle melting below the volcanic arc. Magmas generated in the water-fluxed mantle wedge may stall and freeze, creating future continental crust, or erupt explosively and provide a drillable record of the net recycling and crustal growth process.

Several models have been proposed to explain how subduction begins, including spontaneous foundering of oceanic lithosphere along regions of pre-existing weakness such as fracture zones, subduction jump and/or polarity reversal following plate collision, or imposition of stresses associated with global plate reorganization. Once initiated, the efficiency with which subduction zones function is critical to the maintenance of our habitable planet. If a substantial portion of the subducted water was not returned to the surface, our planet would become very inhospitable. Likewise, the subduction of carbonates in marine sediments and oceanic crust removes carbon dioxide from the surface realm. If this carbon were not delivered back to the atmosphere via volcanism, it would change the net budget of this critical greenhouse gas over long time scales. Thus, subduction links Earth's volcanic and climate cycles.

The approximately andesitic (intermediate-silica) composition of the continental crust has long been cited as evidence that this crustal type is produced by arc magmatism. Arcs are currently the only tectonic location where andesite is generated in significant volumes. High-resolution seismic images suggest that much of the middle crust in volcanic arcs has physical properties consistent with andesite, but these same arcs generate magmas having a wide diversity of bulk compositions. This observation raises important questions about the melting and magmatic processes that give rise to observed patterns and types of eruptive volcanism.

Drilling and Research Strategy

Testing models of subduction zone initiation requires a multidisciplinary approach and judicious selection of drilling sites in areas where subduction is incipient or in initial active stages, and recovery of geological materials that record the earliest stages of subduction, trench formation, and arc volcanism. In many cases, samples must be recovered from beneath thick accumulations of marine and arc-derived sediments. Cores recovered from sites adjacent to arc edifices can provide a chronology of the geochemical evolution of volcanic products, from initial arc establishment to maturity and the waning of volcanism. Advances in microanalysis enable petrologists to determine absolute dates and geochemical and isotopic signatures from tiny samples of volcanic glass shards, so the temporal evolution of island arcs can be deciphered. For example, recent studies of ash recovered from drilling the western Pacific Ocean arcs identified distinct geochemical trends resulting from variations in magma source inputs, changes in subducted components, and variable extents of interaction with the overriding plate.

The global cycles of water and carbon through subduction zones remain poorly understood, including contributions from hydrous alteration phases and carbonates that form in the oceanic crust as it ages. Resolving fluxes of these materials into and through subduction zones remains a key goal of scientific drilling studies. The recent discovery of deeply penetrating faults on the outer side of the trench, sometimes associated with anomalously low seismic velocities in the mantle beneath the downgoing plate, has raised the possibility that there is much more hydration and alteration of the mantle than previously realized. The presence of active serpentinite mud volcanoes in the Mariana forearc (**Figure 4.9**) indicates that serpentinization is an important process at depth. Drilling provides the only means to recover samples and fluids from depth in areas of known or hypothesized serpentinization, and will allow a quantitative assessment of how deeply penetrating faults may guide fluids to depth, through drilling, sampling, and monitoring experiments.

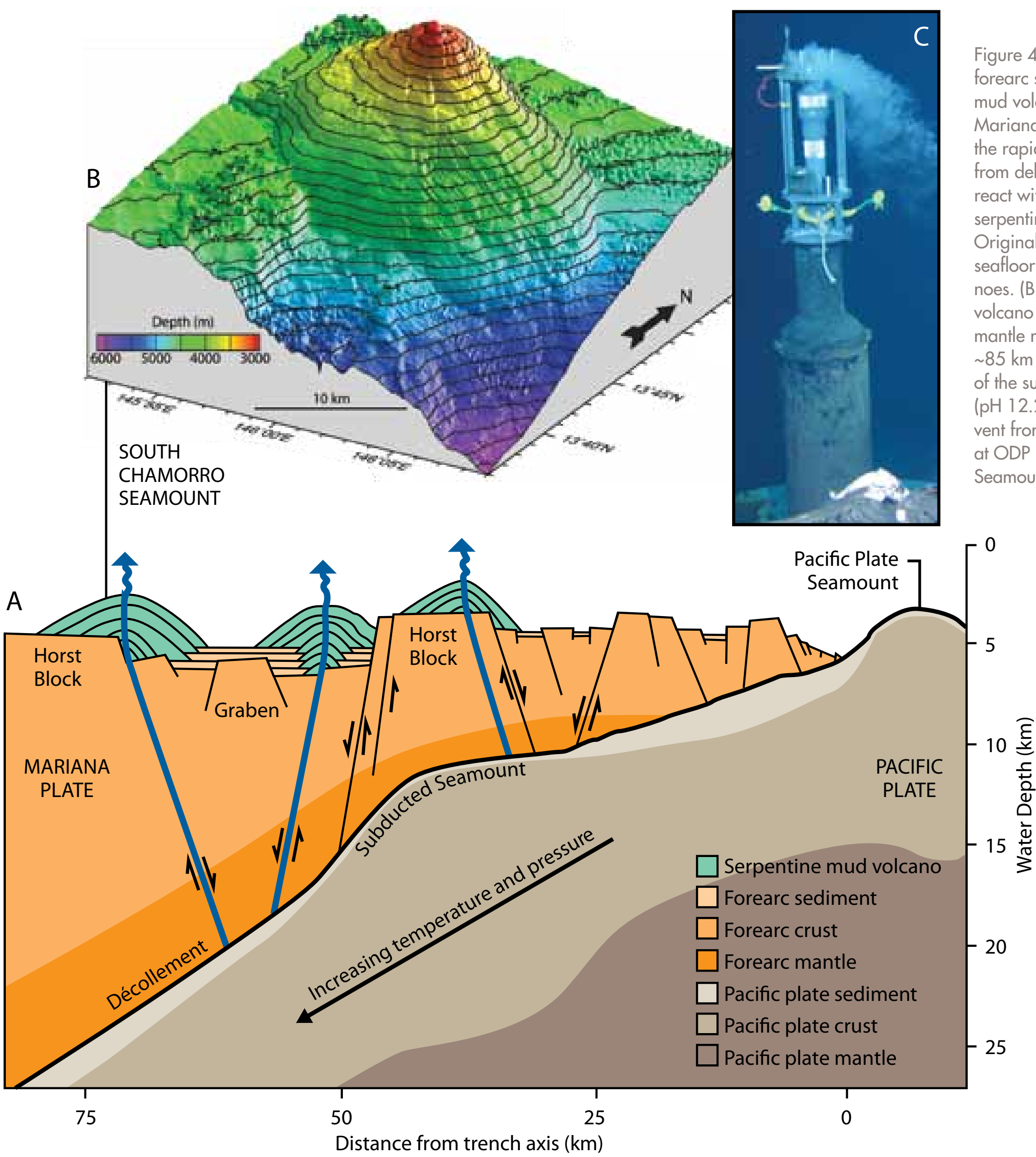


Figure 4.9. (A) Cross section of the Mariana forearc showing the formation of serpentine mud volcanoes. Deep-seated faults in the Mariana plate above the downgoing slab allow the rapid rise of fluids from depth that result from dehydration reactions. Ascending fluids react with the overlying mantle to produce serpentine, hydrogen, and alkaline fluids. Original and reacted materials rise to the seafloor and form serpentinite mud volcanoes. (B) South Chamorro Seamount is a mud volcano composed of serpentinized forearc mantle rock and slab-derived schist, located ~85 km from the trench, 25 km above the top of the subducting plate. (C) Highly alkaline (pH 12.2) and sulfate- and methane-rich fluids vent from a long-term borehole observatory at ODP Hole 1200C on South Chamorro Seamount. Modified from Wheat et al. (2010).

Understanding links among subduction, arc volcanism, and continental crust formation requires drilling transects of sites through active and ancient sedimentary, volcanic, and crustal systems. Temporal records of magmatic output are crucial for identifying the deep magmatic processes that can lead to development of bulk andesitic arc crust because the crystal cargo accompanying this output carries its genetic legacy. Recovered material will reveal the relative contributions to arcs from the mantle and sedimentary, igneous, and residual mantle portions of the subducted oceanic lithosphere, and help test models of continental crust formation.

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5. Earth in Motion

Processes and Hazards on Human Time Scales

Many fundamental Earth system processes, including those underlying major geologic hazards, occur at "human" time scales of seconds to years, requiring new sampling, downhole measurement, monitoring, and active experimental approaches.

CHALLENGES

12. What mechanisms control the occurrence of destructive earthquakes, landslides, and tsunami?

13. What properties and processes govern the flow and storage of carbon in the subseafloor?

14. How do fluids link subseafloor tectonic, thermal, and biogeochemical processes?

INTRODUCTION

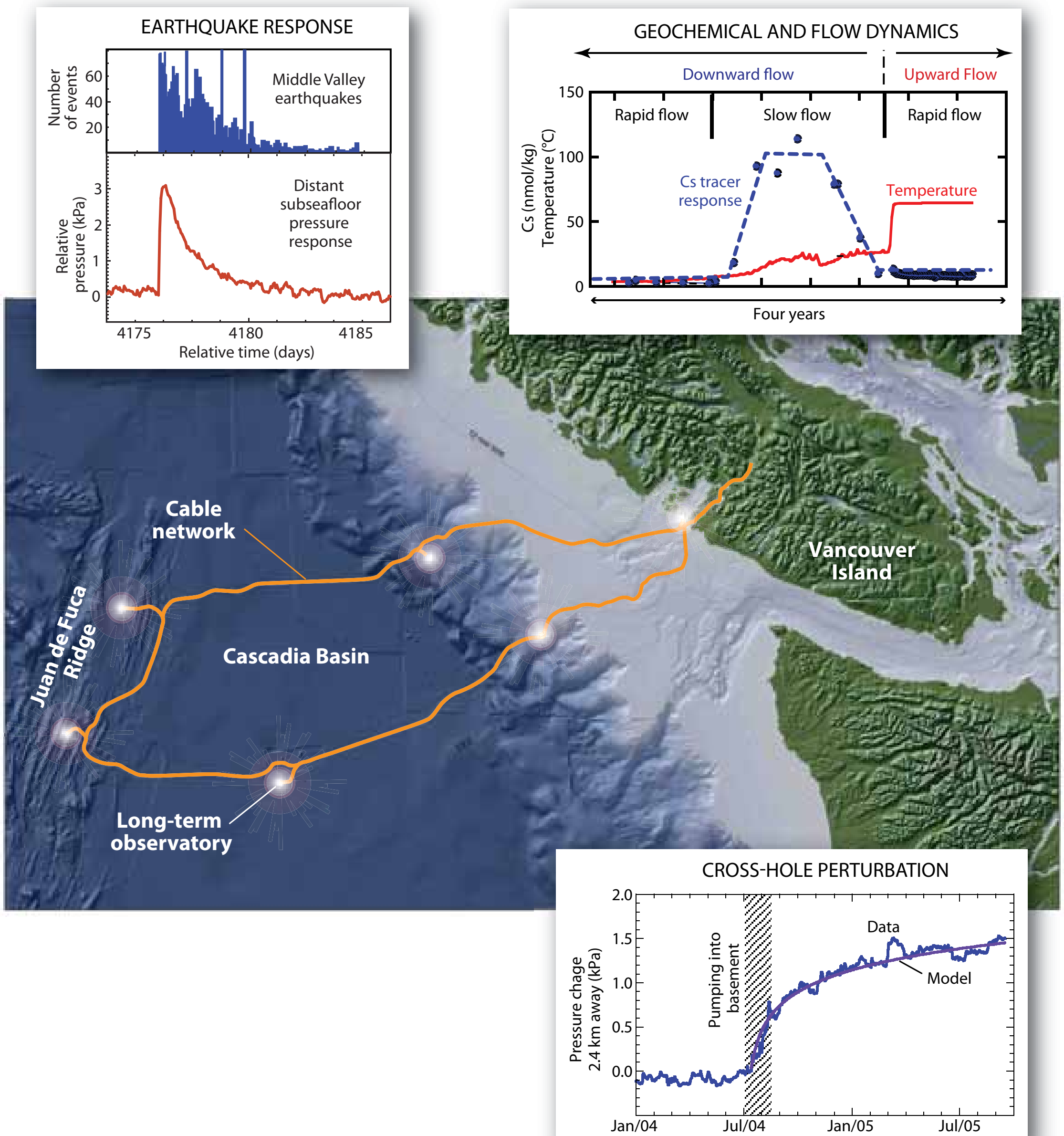
Dynamic processes act on Earth's lithosphere over a range of spatial and temporal scales, from the accumulation and release of strains that cause earthquakes, landslides, and tsunami, to the cycling and storage of carbon in subseafloor sediments and the igneous crust, to the flows of heat, solutes, and microbial materials between oceanic and subseafloor realms. Fluids are essential to many of these processes, influencing the locations, magnitudes, and timing of seismic events; the focused transfer of mass and energy within and across the seafloor; the development, accumulation, and movement of carbon; and the establishment and maintenance of a vast subseafloor biosphere. These dynamic interactions have occurred throughout Earth history, and they are directly observable in many settings only through scientific ocean drilling and borehole experiments.

Recent advances in downhole measurement tools and the establishment of long-term borehole observatories have transformed our understanding of coupled lithospheric-hydrologic-biological systems, particularly by enabling continuous, high-frequency monitoring and active experiments (**Box 5.1**). Time-series observations add a new dimension to drilling, coring, and sampling by quantifying dynamic in situ conditions and defining the rates and patterns of system response to natural and induced perturbations. A continued presence in the subsurface will allow completion of carefully designed experiments to understand numerous processes, from the rates of fluid flow and microbial activity, to the efficacy of potential carbon storage and sequestration in subseafloor reservoirs. Recent capabilities introduced by riser-based drilling are permitting ever-greater access to rocks, sediments, and fluids within tectonically active environments such as fault zones (**Figure 5.1**).

Development of these capabilities is fundamentally changing the nature of scientific inquiry during ocean drilling. Instead of looking at the rock record as recovered during drilling, we are measuring active processes as they occur. Subseafloor boreholes established as long-term observatories also comprise a valuable legacy for current and future generations, allowing the installation and use of new experimental tools as they are developed, and greatly extending the return on investment for ocean drilling operations. Many of the emerging research directions described

BOX 5.1 | MULTIDISCIPLINARY EXPERIMENTATION AND MONITORING IN THE SUBSEAFLOOR

A new generation of combined borehole observatories that collocate hydrologic, thermal, biological, and geodynamic measurements are emerging as powerful tools to explore linked lithospheric, hydrogeologic, and microbial systems. In this example from the northeastern Pacific Ocean, both active perturbation experiments and continuous and high-frequency monitoring are underway. Similar studies have been initiated or planned in other parts of the world, including convergent margins offshore Japan and Costa Rica. Data examples are superimposed on a cartoon showing the NEPTUNE Canada cabled observatory network, and include (clockwise from upper left): borehole pressure response at a crustal site to a cluster of seismicity at a distant spreading center (Davis et al., 2001), geochemical and thermal records showing the dynamics of downhole and uphole flow and crustal exchange (Wheat et al., 2010), and the hydrologic response to a perturbation from basement operations at one crustal site, which produced a long-term pressure response at another crustal site 2.4 km away (Fisher et al., 2008). Additional examples of borehole observatory experiments are highlighted throughout this chapter. Map and network geometry background figure courtesy of NEPTUNE Canada.



in this chapter provide natural links to other research programs and initiatives, including the European Seafloor Observing Network (ESONET), Dense Oceanfloor Network for Earthquakes and Tsunamis (DONET), and EarthScope, extending from the ocean to the continents. Similarly, scientific ocean drilling has an essential role to play in collaborative studies of Earth's carbon reservoirs, leveraging complementary goals, specialized expertise, and tools being developed through national and international programs. The development of new, real-time technologies also presents innovative opportunities for outreach and engagement. These systems will allow researchers, students, and the public at large to establish a virtual presence in the subseafloor from their offices and homes, extending the community of stakeholders in these studies. This work will be critical in coming decades for understanding the complex dynamics of geohazards and other Earth processes that occur on human time scales.

Figure 5.1. Rigging the riser during *Chikyu* operations for the Nankai Trough Seismogenic Experiment (NanTroSEIZE) in 2009. The Nankai subduction zone off the eastern coast of Japan has a 1400-year-long recorded history of magnitude 8+ earthquakes recurring about every 120 years. Riser drilling brings new capabilities to scientific ocean drilling, including downhole measurements of pore pressure and stress, and deep penetration in unstable formations to allow sampling of active fault zones. These measurements are enabling Earth scientists to gain a better understanding of how, when, and why great earthquakes occur. Photo courtesy of Y. Kano, Kyoto University.

Challenge 12 | What mechanisms control the occurrence of destructive earthquakes, landslides, and tsunami?

Improving our understanding of when, where, and how great earthquakes occur is among the most urgent and challenging tasks facing modern Earth science.

Earthquakes can devastate heavily populated coastal areas from both ground shaking and tsunami, as evidenced by the tragedies in Indonesia in December 2004 and more recently in Japan in March 2011. Great subduction zone earthquakes account for over 90% of global seismic energy release, and represent the greatest natural hazard to life and property for major coastal population centers. Submarine landslides and catastrophic volcanic flank collapse (and associated tsunami) also pose significant risks to coastal populations and to seafloor infrastructure. Together, these processes comprise the only large-scale natural hazards for which no short-term prediction methods exist.

The processes and rock properties that govern earthquake nucleation, propagation, and energy budgets remain enigmatic. In particular, the relationships between rock physical properties, fault zone architecture and composition, in situ conditions, and fault slip behavior are not well known. As a result, we do not understand why some earthquakes grow into rare giant events (M_w ~9; e.g., Sumatra in 2004 and Japan in 2011) whereas others in similar areas are much smaller, or why some earthquakes lead to coseismic slip that offsets the seafloor, giving rise to destructive tsunami. Although monitoring in some environments suggests that pore pressure conditions and fault and wall rock permeability, porosity, and elastic moduli can all vary systematically immediately following earthquakes and through the interseismic period, observations are sparse and our process-based understanding of these phenomena is limited.

Recent data from geodetic and seismological networks show that strain release at lithospheric plate boundaries spans a much wider range of slip rates than previously recognized, from the tectonic (creep), to months-years (slow slip), to days-weeks (episodic tremor and slip), to low-frequency earthquakes, to "normal" earthquakes that last seconds to minutes (**Figure 5.2**). The underlying mechanisms that govern the nature of slip, and determine why there is such a rich variety of behavior along plate boundaries, remain undiscovered. Some hypotheses suggest that pore fluid pressure and rock frictional properties may provide fundamental controls on the earthquake cycle, but to date these properties have not been measured in situ because of lack of drillholes in appropriate locations.

Understanding controls on the timing, size, nature, and effects of submarine landslides and volcanic collapse is equally important for characterizing associated hazards. Earthquakes or volcanism can drive slope failure (**Figure 5.3**). Hydrodynamics along ocean margins may precondition certain systems to failure, anthropogenic impacts may trigger failure, methane hydrate dissociation driven by climate may generate landslides, and landslides may naturally recur, driven entirely by the internal dynamics of pore pressure and stress evolution. Recent submarine exploration of arcs and back-arc basins has also revealed volcanic calderas symptomatic of explosive syn-eruptive collapse and present as yet unquantified volcanic- and tsunami-related hazards.

Drilling and Research Strategy

Scientific ocean drilling is well positioned to elucidate earthquake and faulting processes through direct sampling and in situ measurement within active systems, including continuous, real-time monitoring (**Box 5.2**). Of particular interest is capturing parts of the earthquake cycle where and when transients may be observed, such as in fault zones approaching rupture, or along faults that have recently ruptured and are regaining strength. Understanding processes that underlie geologic hazards also elucidates the longer-term tectonic and geochemical evolution of the ocean floor. For example, crustal seismicity may be associated with hydration and serpentinization of the oceanic lithosphere (**Box 4.2**), which subsequently influences the tectonic and earthquake behavior of subduction zones and the global cycling of carbon (**Box 5.3**). Similarly, the processes that govern the mass fluxes, geochemical evolution, and construction of island arcs also impact volcanic eruptive and sector collapse hazards. Development of subseafloor geohazard observatory networks, linked through cables, buoys, satellites, and other communication tools (**Boxes 5.1 and 5.2**), presents an opportunity to resolve and adapt to abrupt Earth system processes.

Ocean drilling and experiments will expand our understanding of the timing, size, and nature of geohazards by providing access to the subseafloor to sample materials, measure properties, and monitor subsurface conditions. Coring, logging, and sampling will

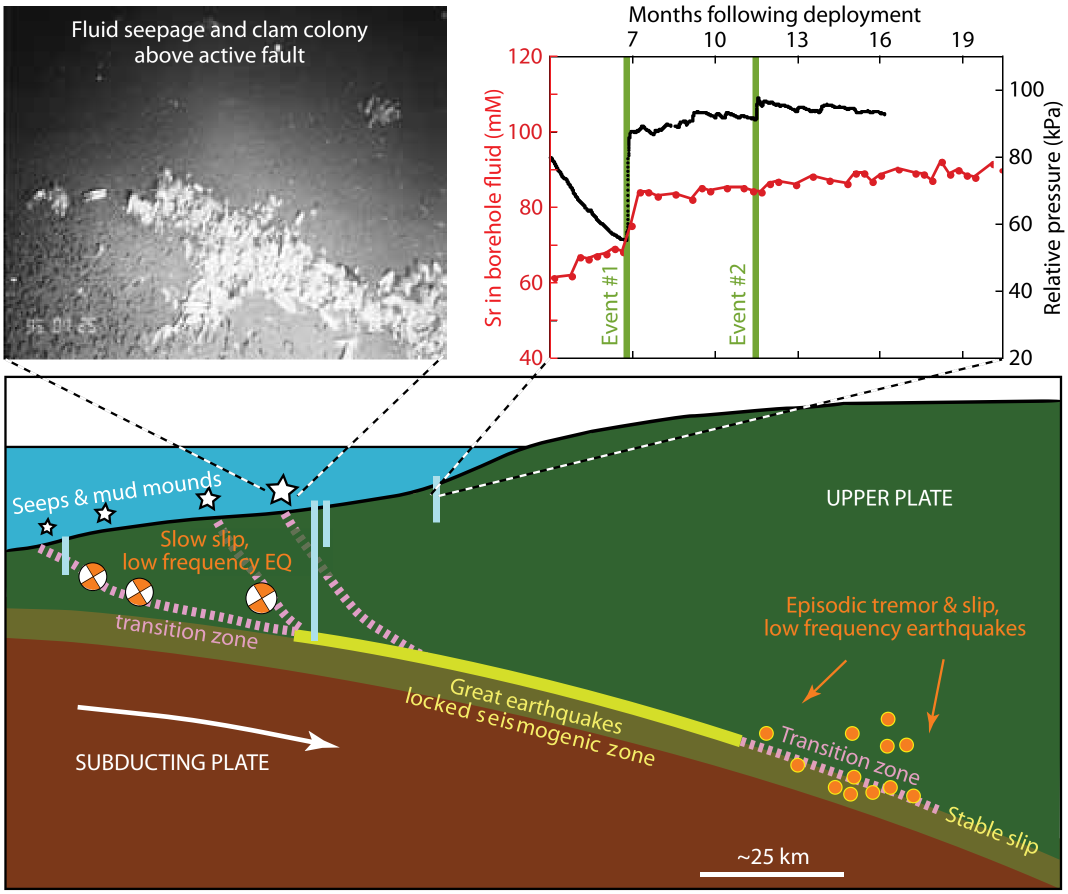


Figure 5.2. Schematic cross section of a subduction zone showing the locations and diverse styles of earthquake slip observed along subduction megathrusts. The locations and sense of slip for slow-slip events and very-low-frequency earthquakes (VLFE) in the shallow subduction zone outboard of the locked seismogenic zone (orange and white symbols) are consistent with their occurrence along major splay faults within the upper plate (after Ito and Obara, 2006; Obana and Kodaira, 2009). These splay faults are associated with cold seeps at the seafloor (photo, top left), suggesting that fluids may play a role in their slip behavior. The source regions of shallow slow slip and VLFE events, along with the shallowest portion of the megathrust that slips coseismically (yellow line), are likely within the reach of ocean drilling. Deep slip behavior along the subduction interface includes episodic tremor and slip, as well as slow-slip events (orange circles). Monitoring of seismicity and fluid conditions in boreholes (shown schematically in blue) is an essential component in characterizing and understanding these newly discovered phenomena. Photo at top from Ogawa et al. (1996); schematic diagram adapted from Saffer and Tobin (2011).

be extended across seismogenic faults and slope failures at depths where slip occurs, illuminating the composition and structure of seismogenic and tsunamigenic faults and failure surfaces. Sampling and dating of event deposits and volcanic ashes will help determine the timing and size of past geohazards, ultimately allowing determination of earthquake and landslide recurrence intervals. Downhole measurements will quantify in situ conditions that control rock failure, including pore pressure, temperature, and stress. Borehole observatories will be installed to monitor strain, pore fluid pressure, and seismicity through the earthquake cycle. These measurements will help resolve processes controlling the initiation and triggering of fault slip and slope failures, identify potential precursory phenomena, understand the dynamics of slip and post-failure recovery, and characterize links between volcanic and earthquake hazards (**Box 5.2**). Borehole measurements will also resolve the spectrum of fault slip behaviors and define locations of interseismic strain accumulation. Linking borehole observatories to cabled seafloor networks will provide real-time access to subseafloor data, allowing assessment and analysis as processes unfold. Long-term, interdisciplinary studies such as these were begun during earlier phases of scientific ocean drilling, particularly offshore of Japan and western North America (e.g., **Box 5.1**). Studies of these regions will continue to be important for resolving processes related to earthquakes, landslides, and tsunami, and additional programs will be developed in other areas of high geohazard risk.

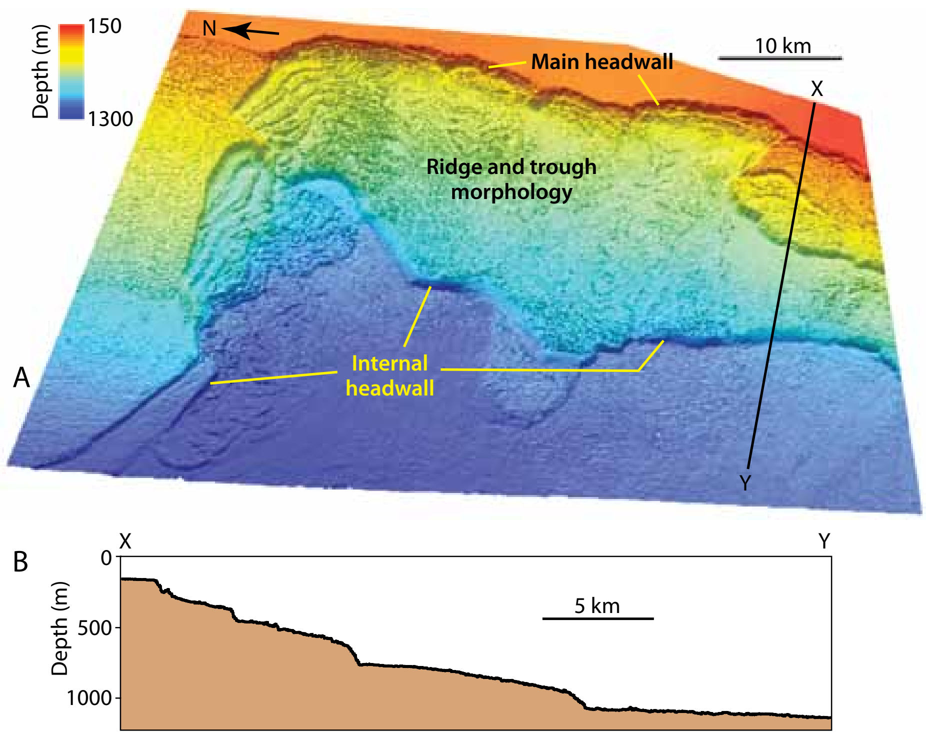
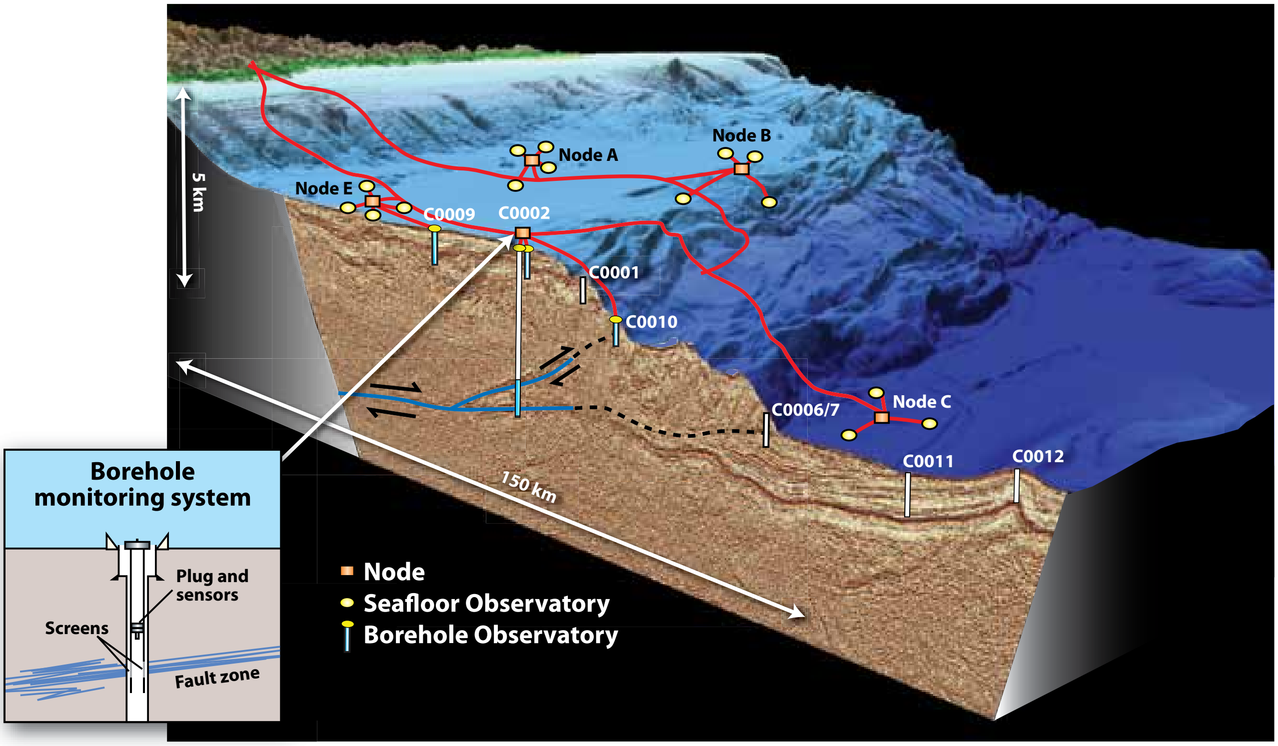


Figure 5.3. (A) Shaded relief bathymetry image of the central part of the upper Storegga Slide, a huge landslide that unleashed a major tsunami offshore Norway. (B) Depth profile across the slide. From Masson et al. (2010), Figure 1. Reprinted with kind permission from Springer Science+Business Media.

BOX 5.2 | A STETHOSCOPE ON EARTHQUAKE FAULTS

Borehole observatories spanning the source zone of subduction earthquakes and tsunami—like the ones shown here now being installed by the Integrated Ocean Drilling Program as part of the Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE)—allow in situ monitoring of conditions at depth. Measurements include strain, seismicity, pore-fluid pressure, fluid composition, and temperature, and enable small earthquakes and transients to be resolved in great detail. Borehole observatories offer a markedly clearer view of earthquakes and strain than is possible with remote land-based or even seafloor monitoring, and provide reliable measurements of in situ conditions and their variations with time, ultimately helping to define how, where, and why strain accumulation and release occur. This continuous, high-frequency monitoring becomes even more powerful when connected to real-time seafloor data networks like the collocated Japanese Dense Oceanfloor Network System for Earthquakes and Tsunamis (DONET) cabled observatory. Existing and planned cabled seafloor networks (e.g., DONET, NEPTUNE Canada, and the US Ocean Observatories Initiative offshore western North America, and the European Seafloor Observatory Network [ESONET] in the Mediterranean), tied to borehole observatory installations, represent a new approach for earthquake research. Scientific ocean drilling is critical to these efforts, and is also contributing directly to earthquake early warning systems. Inset from Expedition 319 Scientists (2010).



Challenge 13 | What properties and processes govern the flow and storage of carbon in the subseafloor?

The flow and storage of carbon below the seafloor link climatic, biologic, solid Earth, and hazard research across a wide range of spatial and temporal scales.

Sedimentation, deformation, hydrocarbon generation and accumulation, slope stability, crustal carbonation, and complex biological communities are intricately connected throughout the global ocean. These connections are fundamental to addressing increasing demands on available resources, understanding the influence of gas hydrate deposits on slope instability, and quantifying the impacts of excess CO_2 delivery to the atmosphere. The extent, resource potential, and hazards presented by gas hydrates have global implications for human populations and important ecosystems. Making progress in these fields requires that we determine the quantities of carbon stored below the seafloor in various forms and the rates of carbon transfer in and out of the seafloor, and evaluate whether there are carbon sequestration opportunities along continental margins and in the deep sea. These studies will also provide fundamental information on hydrologic, mechanical, and biogeochemical processes occurring within the subseafloor.

Drilling and Research Strategy

The global gas hydrate reservoir is thought to exceed the known extent of conventional hydrocarbons (oil, gas, and coal combined), and to pose numerous environmental challenges. Hydrate deposits are highly dynamic and sensitive to changes in pressure, temperature, and flows of carbon from depth. Hydrate dissociation in the geologic past released large volumes of methane into the ocean and atmosphere, and may have led to abrupt climate changes. Rapid hydrate decomposition may trigger local and regional slope failure along continental margins (**Figure 5.3**). Scientific drilling is critical for resolving flows of carbon through gas hydrate systems, recovering core material, determining in situ hydrate distribution (**Figure 5.4**), and monitoring changing properties and conditions through time.

There is growing interest in developing methods for removing excess CO_2 from the atmosphere and depositing it in geologic

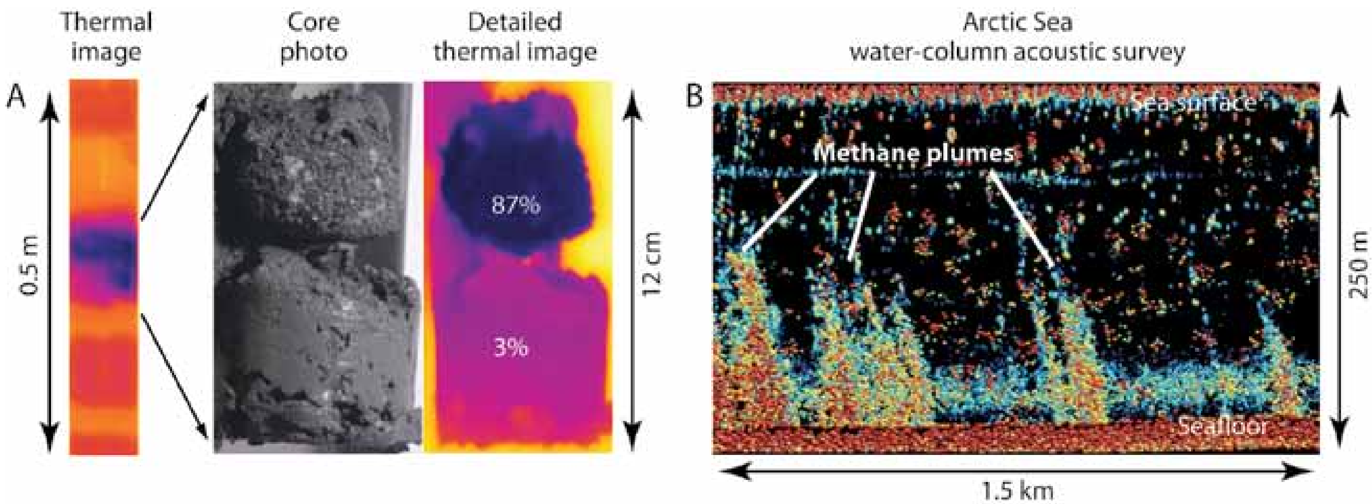
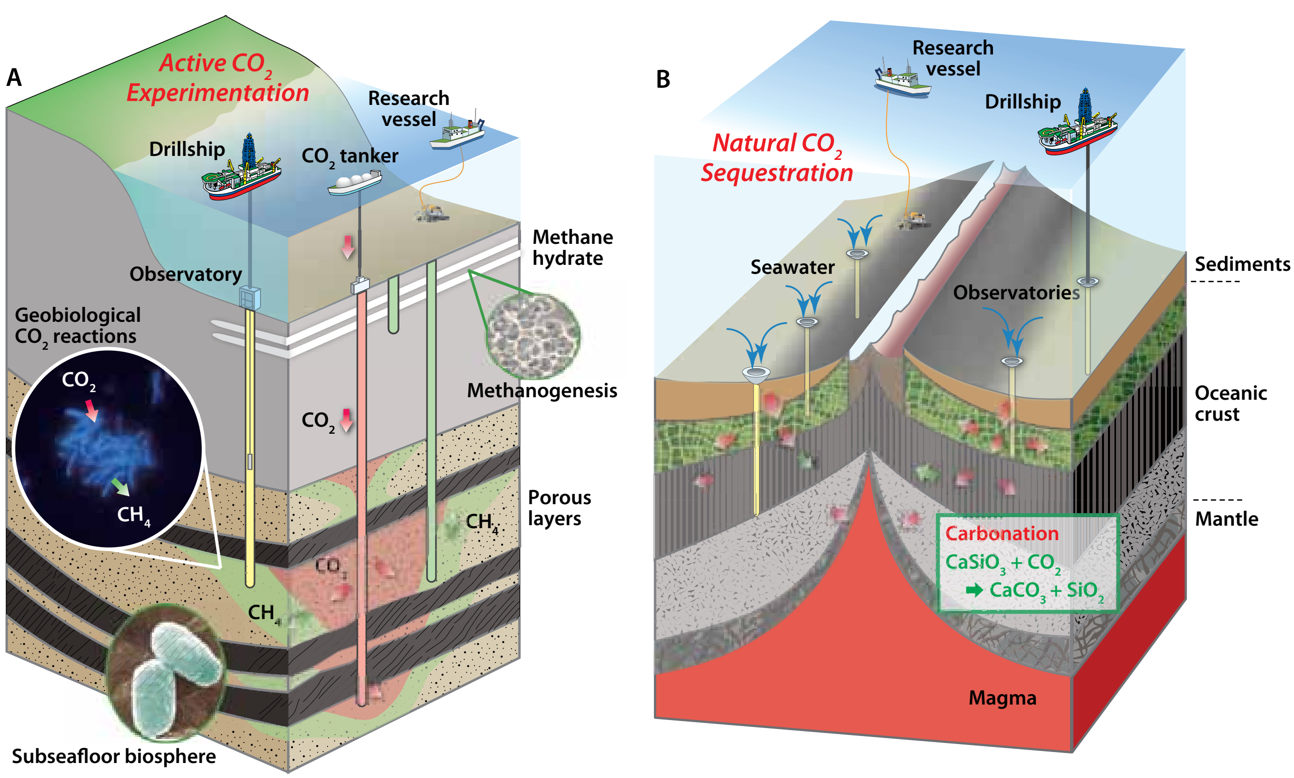


Figure 5.4. New tools are being developed to assess the distribution of gas hydrate in marine sediments. (A) The panels show how thermal anomalies (detected with an infrared camera) were used to identify areas of hydrate concentration immediately following recovery of core materials. Subsamples were collected and analyzed separately to assess the quantity of hydrate present at a centimeter scale, and to understand what controls its distribution. Studies such as these are important for determining where and why large movements of gas from subseafloor hydrates to the overlying ocean may occur. From Torres et al. (2008). (B) This water-column acoustic image from the Arctic Sea shows plumes of methane gas rising from subseafloor hydrate deposits as a result of warming bottom water. Drilling, sampling, and experiments can help to resolve why, where, and how rapidly similar processes may occur. From Westbrook et al. (2009).

reservoirs, a form of geoengineering known as carbon sequestration (Box 5.3). This approach may be necessary, even if there were an immediate and efficient shift to energy sources that do not emit CO_2, in order to limit impacts from excess carbon released to the atmosphere and ocean over the last 150 years. Pilot studies are underway at sites on land, but researchers are also evaluating the potential for storing carbon in the subseafloor. Several kinds of seafloor reservoirs offer the potential for large-scale CO_2 storage, including

BOX 5.3 | SUBSEAFLOOR CAPTURE AND STORAGE OF CO_2

In situ monitoring and perturbation experiments enabled by scientific ocean drilling offer an opportunity for fundamental research on geological capture and storage of CO_2 in both sedimentary formations (panel A) and the igneous crust (panel B). Borehole experiments are needed to measure key subseafloor physical properties that control fluid migration, particularly permeability, porosity, fracture density and orientation, and storage (compressive) properties (e.g., Figure 5.6). Continuous access for sampling and monitoring will assess the extent, distribution, and rates of microbial processes and fluid-rock interactions that may contribute to successful carbon sequestration through a natural CO_2/organics-bioreactor system. Borehole observatories shown in panel A are sealed for injection and monitoring. Several observatories shown in panel B are open, allowing cold ocean bottom water to be drawn into the permeable crust (blue arrows) by a runaway hydrothermal "siphon," established during the drilling process. Ocean drilling provides a means to evaluate carbon capture and sequestration schemes based on carbonate-producing fluid-basalt or peridotite reactions, to monitor plume migration and fluid geochemical evolution through time, and to investigate the potential for enhancing natural carbonation processes. Active borehole experimentation will be required to assess the local impacts of small-scale CO_2 injection; eventually, full-scale trials will be required, substantially expanding available observational data on the behavior of supercritical CO_2 storage, with important benefits for managing Earth's environments and sustaining natural resources. (See House et al., 2006; Goldberg et al., 2008; Kelemen and Matter, 2008.) Figure courtesy of F. Inagaki, JAMSTEC.



depleted oil and gas fields, brine-filled aquifers, and multiple levels of the oceanic crust. The potential for carbon storage in the oceanic crust is particularly intriguing, as this reservoir is large, known to contain extensive and widely connected zones of elevated permeability, isolated from the overlying ocean in many places by relatively thick and continuous (low-permeability) sediments, and offers the potential for rapid carbonation and other forms of mineralization that could contribute to long-term chemical and physical trapping. In fact, large-scale serpentinization and other forms of carbonation occur naturally in the oceanic lithosphere and likely played a major role in global carbon cycling in the geologic past (**Box 4.2**). Scientific ocean drilling can facilitate pilot studies of subseafloor carbon sequestration, in collaboration with national or other international programs, helping to resolve the nature of permeable networks, the extent and rates of mineralization and trapping, and the influence and impacts of subseafloor microbial communities on long-term CO_2 storage (**Box 5.3**).

Studies of gas hydrates, serpentinization, and CO_2 sequestration will benefit from the establishment of subseafloor observatories and the linking of these systems to data and power networks. Borehole observatories provide long-term and continuous sampling, and opportunities for both monitoring and active experiments. For example, recent monitoring in borehole observatories led to the discovery of unexpected geomechanical and hydrologic phenomena, changing our view of how lithospheric stresses and hydraulic signals are transferred over long distances, and how pressure anomalies are distributed with depth (**Box 5.1**). Researchers have also initiated controlled perturbation experiments and monitored formation response. These kinds of active experiments allow spatial and temporal control of observational scales, and the simultaneous and focused use of multiple tools and techniques yields a systems-based understanding of coupled processes and complex dynamics. Active experiments permit evaluation of hydrologic compartmentalization, anisotropy, and lateral continuity below the seafloor, and associated variations in biogeochemistry and microbial characteristics. These properties are fundamental, in turn, for evaluating the extent of hydrate carbon in storage, and determining whether large-scale sequestration within seafloor reservoirs is feasible.

Challenge 14 | How do fluids link subseafloor tectonic, thermal, and biogeochemical processes?

The oceanic lithosphere is the largest aquifer on Earth, containing a volume of fluid equal to that stored in all ice caps and glaciers.

Fluids play fundamental roles in numerous global processes, including heat loss from the solid Earth, mineral deposition, stress accumulation and release (earthquakes, landslides) near populated areas, and carbon and nutrient cycling in coastal waters. Flowing fluids support submarine biomes (**Box 3.1**) and exotic seafloor communities (**Figure 4.2**), contribute to seismicity and crustal cracking and cooling, control patterns of lithospheric alteration (**Figure 4.7**), and transfer volatiles to and from subduction zones (**Figure 4.8**). The submarine hydrogeologic cycle is also linked to groundwater systems on land, including massive flows between terrestrial and marine realms across continental margins. Coastal aquifers that extend into continental shelves support major population centers around the world, but in many cases these resources were emplaced during sea level low stands, making them essentially nonrenewable on human time scales. Additional saline fluids are pumped back and forth across the seafloor by tidal and other processes. Fluid flow through sediments and rocks of continental margins, subduction zones, and the oceanic lithosphere is a poorly known part of the global hydrologic cycle. Quantifying and understanding these fluid-mediated systems and processes requires the collection of sediment, rock, and fluid samples and in situ measurements, including time-series measurements of system responses to natural and induced perturbations.

Drilling and Research Strategy

Drilling is the only available means for collecting critical samples and data, integrating across spatial and temporal scales, and establishing a long-term presence within the subseafloor hydrologic realm (**Figure 5.5**). Data from recent ocean drilling experiments on ridge flanks document changes in formation

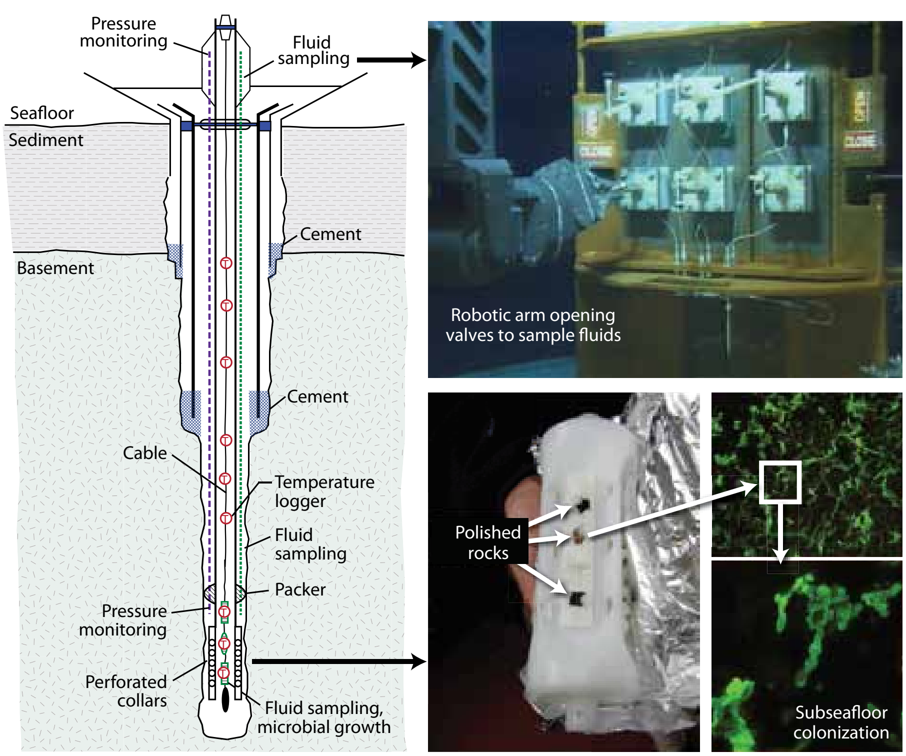


Figure 5.5. Schematic showing a long-term, subseafloor observatory (CORK, left; Fisher, et al., 2011b) and examples of system servicing (top right) and experiments (lower right). Seafloor and subseafloor instruments are installed when the observatory is initially deployed by a drillship, and can be recovered and replaced using a submersible or remotely operated vehicle (upper right; photo courtesy Woods Hole Oceanographic Institution). Valves, samplers, and data loggers on the well head are accessed to download data and collect samples. Downhole instruments are deployed for long-term fluid sampling and for subseafloor microbial colonization (lower right), which will allow the collection of relatively pristine communities from this remote biome. Collection of microbes and high-quality fluid samples is generally not possible without establishment of an observatory, because of the influence of drilling, coring, and other operations.

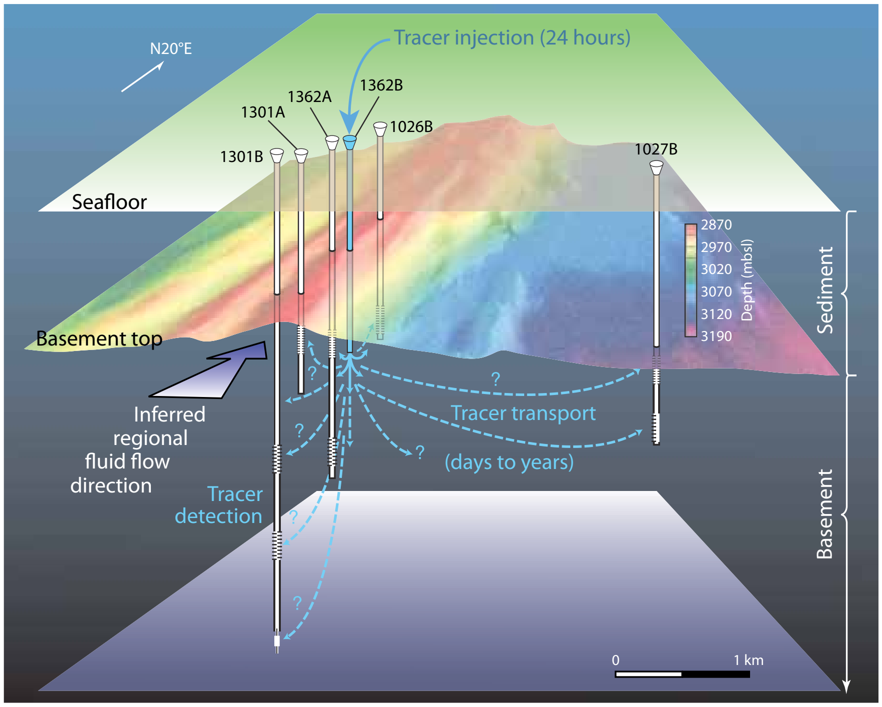


Figure 5.6. Multidisciplinary experiments using networks of subseafloor observatories include cross-hole hydrogeologic testing and injection of multiple tracers from a central borehole, with pressure and temperature monitoring and fluid sampling in surrounding boreholes distributed in multiple directions and distances. Samples and data will be collected during active system perturbation using the drillship, and during subsequent years using long-term borehole observatories serviced with submersibles and remotely operated vehicles. The nature of cross-hole, multidirectional response provides critical information on subseafloor fluid pathways, natural patterns of circulation, and coupling among fluid, thermal, chemical, and biological components of the crustal system From Fisher et al., (2011a).

fluid pressure, temperature, and composition in response to regional strain events, such as earthquakes and dike intrusion (**Box 5.1**), and have led to increased appreciation of the heterogeneity, scale dependence, and dynamic nature of the crustal fluid reservoir. Borehole measurements from plate boundaries at subduction zones, including those from long-term subseafloor observatories, have revealed links between fluid composition and transient flow rates, driven by the coupling between hydrology and strain from earthquake events. More generally, comparisons of present-day formation fluids and the integrated record of sedimentary and rock alteration provide essential constraints on the rates and locations of plate aging processes.

Despite recent progress, numerous fundamental questions about subseafloor hydrologic systems remain poorly resolved. For example, characteristic rates of fluid transport, and how these rates vary with location and flow direction, remain largely unknown. The lateral and depth extent, distribution, and geometry of flow paths, and the temporal evolution of fluid flow systems are poorly constrained. As a result, we have little information about the quantitative coupling between hydrologic, mechanical, chemical, and biological properties and processes. Models and sophisticated analytical techniques used to simulate these systems require calibration and verification so that results from local studies can be extended globally.

Future progress will be made in these areas through fluid sampling and active testing, including single and multiple borehole experiments to quantify the nature and rates of in situ microbiological colonization (**Figure 5.5**) and to resolve directional permeability and chemical transport properties (**Figures 5.5 and 5.6**). Long-term observations of subseafloor hydrogeologic systems, as part of both monitoring and active experimentation, are transforming our view of fluid-sediment-rock-microbial interactions. Continued development of drilling, sampling, and sensor technology will help with collection of data and materials from increasingly challenging environments, including those experiencing high temperatures and rapid rates of strain.

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6. Education and Outreach
Preparing for the Future

The International Ocean Discovery Program will train the next generation of Earth system scientists and elevate the public's understanding of our planet to enable informed decision making and inspire environmental stewardship.

Scientific ocean drilling exemplifies integrated science through the application of geology, physics, chemistry, biology, mathematics, and engineering to solve Earth system problems. Scientists on board *JOIDES Resolution*, *Chikyu*, and mission-specific platforms represent all of these disciplines, and they work together to achieve shared scientific objectives. The International Ocean Discovery Program will apply this multidisciplinary, integrative, collaborative approach to understanding how Earth works to its education and outreach initiatives.

Drilling research vessels with state-of-the-art laboratories, core repositories on three continents, openly accessible data, and thousands of scientists, marine technicians, and other professionals who actively participate in the program are all valuable assets that will contribute to education and outreach. Education and outreach activities are focused in three main initiatives. These initiatives are supported (in part) by member countries' national programs, along with additional activities aligned with national priorities.

Training the Next Generation of Scientists

Tackling the challenges of global climate change, energy and water resources, and geohazards requires a workforce able to function in highly technical, interdisciplinary, and international settings. The International Ocean Discovery Program will be an excellent training ground for such a workforce. Each drilling expedition includes an international group of scientists who collaborate in very sophisticated laboratories to integrate a wide variety of data types to solve complex Earth system science problems. Working in multidisciplinary teams and considering diverse perspectives has been a hallmark of scientific ocean drilling. Drilling expeditions will continue to include early-career scientists

Figure 6.1. Since 2007, ECORD has been sponsoring summer schools for graduate students and early-career scientists focusing on Integrated Ocean Drilling Program research themes. The ECORD Bremen summer school takes advantage of the unique facilities offered by the Bremen Core Repository to combine lab exercises on "shipboard" methodologies as well as lectures and interactive discussions on scientific drilling. The Urbino Summer School in Paleoclimatology combines lectures, exercises with data investigations and presentations, and field experiences. Photos courtesy of IODP/ECORD.

and graduate students who will work closely with and learn from people who will become mentors, colleagues and, perhaps, employers (**Figure 6.1**). Most shipboard scientific participants continue research on shore, strengthening the ties developed during sea-going expeditions.

Fostering Stewards of the Planet

Inspiring a sense of environmental stewardship and an interest in science begins in homes and classrooms. The International Ocean Discovery Program's combination of international collaboration, innovative

BOX 6.1 | SCHOOL OF ROCK

Since 2005, the US-sponsored Deep Earth Academy has conducted five School of Rock programs on board *JOIDES Resolution* or at the Gulf Coast Repository at Texas A&M University. During each of these one-to-two week immersive, experiential, and residential programs, approximately 15 educators from around the world work with scientists, real core material, and laboratory technology to learn how ocean drilling data reveal clues about Earth's history. The School of Rock actively engages traditional and informal educators by: (1) accessing and using a broad sampling of the vast ocean drilling database, (2) developing a range of age-appropriate and audience-friendly Earth system science activities for classrooms and museums, and (3) recognizing that the findings of scientific ocean drilling have great relevance to understanding Earth history and its processes. The Deep Earth Academy's School of Rock is one model for bringing scientific discoveries and research data to the broader public through active learning. Photos courtesy of IODP/USIO.

Figure 6.2. Visitors line up on the Kobe, Japan, pier for a *Chikyu* tour that includes ships laboratories and the bridge. The number of visitors to the drill-ship passed the 100,000 mark by 2010. Photos courtesy of IODP/JAMSTEC.

technology, and cutting-edge exploration can serve as an efficient vehicle to teach students about the nature of science. Emphasis will be on connecting to homes and classrooms using high-quality, hands-on activities that use scientific ocean drilling information to teach Earth systems processes and history. The program's web site will host outstanding educational materials developed through national programs and international collaborations. The program will help science educators to develop new materials for use in the classroom and in informal settings such as museums, nature centers, and national parks by providing them with access to expertise, photos and graphics, and other resources. The International Ocean Discovery Program will also develop multimedia materials for classroom use, port calls, core repository visits, and other public forums.

As in the past, the program will take advantage of port calls to bring the public on board the drillships (**Figure 6.2**). Core repositories will host tours for school groups, workshops, and other educational activities. More comprehensive programs for educators, such as those conducted on board *JOIDES Resolution* or at core repositories (**Box 6.1**), will last two weeks or more.

Informing and Inspiring the Public

The International Ocean Discovery Program will use the most exciting and relevant discoveries and technological achievements to inform and inspire citizens about Earth system science. The program will use partnerships with leading public institutions such as science and art museums, and web-based media and social networking tools, to design and implement public communication activities.

A major part of this communications effort will build on the Integrated Ocean Drilling Program's successes in linking classrooms and other venues to the drilling platforms electronically (**Box 6.2**). The new program will also expand its global educational presence through providing free "apps" for smart phones and digital notebooks, and it will make use of other electronic media as new technologies become popular.

The rising public awareness of the impact of global environmental change on everyday life combined with 21st century technology offers an opportunity for Earth scientists to take center stage in the international arenas of research, policy, and education. As physicians of the planet, Earth scientists will increasingly be relied upon by society to interpret Earth's signals and warning signs, to evaluate resource shortages, and to advise on planning for the sustainable future of our economy, security, and well-being. With this extraordinary opportunity at hand, the International Ocean Discovery Program will support the global Earth and life sciences communities by making the critical connections between Earth system science and society through coordinated national and international public engagement programming.

BOX 6.2 | DRILLING VESSELS AS EDUCATION PLATFORMS

Since 2009, the Integrated Ocean Drilling Program has been bringing the public on board *JOIDES Resolution* in real time through value-added, expedition-based education programs via ship-to-shore video broadcasts and Web 2.0 communication tools linked to the ship's public web site (http://www.joidesresolution.org). The web site is filled with scientists' blogs, games, and videos for all ages. Originally targeted at middle school students and family audiences, the site and its associated social media (YouTube, TeacherTube, Flickr, Twitter, and Facebook) have a growing audience that includes university students and other adults. To date, 200 live video interactions and webinars have been streamed from *JOIDES Resolution*, with more than 10,000 participants worldwide.

The program is also using social media to provide information on the whereabouts of *Chikyu* and what the scientists are up to while at sea during Integrated Ocean Drilling Program expeditions on that vessel through "*Chikyu* TV" and *Chikyu* "tweets" (e.g., http://www.jamstec.go.jp/okinawa2010/e).

7. Implementation

The International Ocean Discovery Program will have access to three types of drilling platforms operated by the United States, Japan, and a European consortium.

The scientific community has developed an ambitious agenda for the International Ocean Discovery Program. The new program plans to conduct expeditions that will study the complex interactions of Earth systems, observe Earth processes in real time, provide pristine samples critical for emerging fields of life science, and establish a basis for predictive Earth system modeling. Achieving these goals requires access to advanced and diverse drilling capabilities and associated facilities for pre-drilling surveying of drilling targets, borehole characterization, and long-term monitoring. The group of researchers and engineers engaged in this scientific enterprise also need access to sophisticated laboratory facilities. Given the scale of these scientific challenges, only a coordinated international effort can provide the financial and intellectual resources required.

During the current Integrated Ocean Drilling Program, membership increased to 24 nations from four continents. Institutions worldwide are involved through their participating scientists and research facility use. Earlier phases of international collaboration in ocean drilling have developed a global network of participants who are prepared to advance the science plan for the International Ocean Discovery Program.

DRILLING CAPABILITIES

The International Ocean Discovery Program will face drilling, coring, and downhole logging challenges of three principal types:

A. Deep drilling (2–7 km) into the ocean floor or at continental margins at a limited number of locations
B. Multiple holes drilled into the ocean floor, penetrating from shallow (~100 m) to intermediate depth (~2 km), often with a goal of ~100% core recovery down to 500 m or more
C. Drilling in extreme environments, such as shallow water (<100 m) and the high Arctic

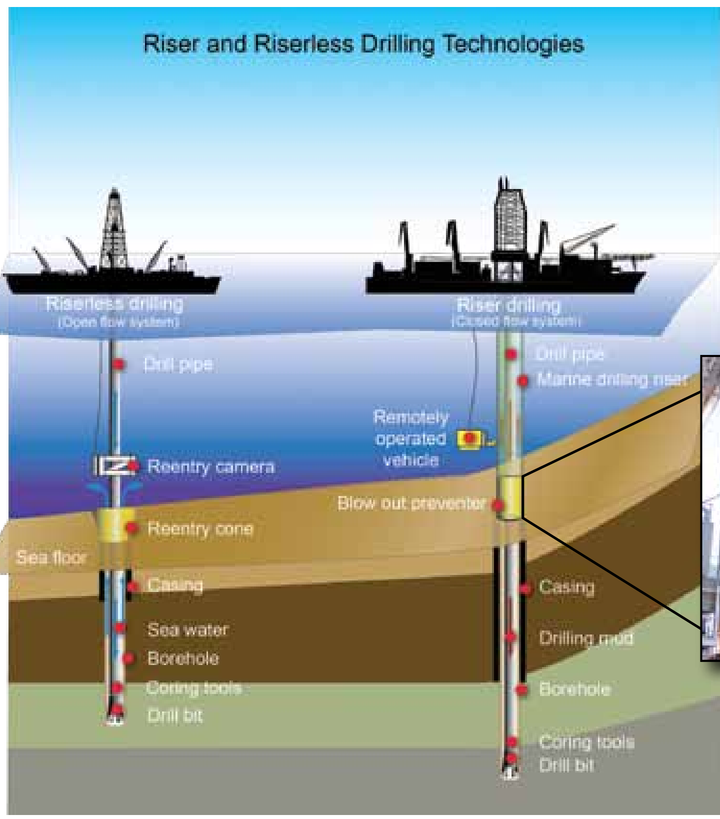
No single drilling platform can meet all of these requirements. The International Ocean Discovery Program will use two principal platforms: the riser-equipped D/V *Chikyu* and the riserless D/V *JOIDES Resolution*. Riser capability permits closed-hole drilling with mud circulation; riserless drilling is conducted in open holes (**Box 7.1**). *Chikyu* and *JOIDES Resolution* will be complemented by mission-specific platforms (MSP) to be chartered on a case-by-case basis to address targets in special environments (see **Boxes 7.2–7.4** for platform details). With a planned development of *Chikyu's* riser drilling capacity from its current 2.5 km to 4 km+ water depth, the program will possess the necessary drilling capabilities to conduct the full range of experiments proposed.

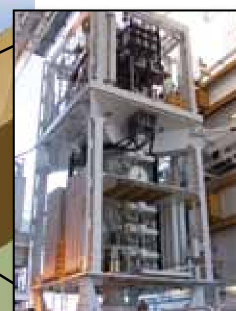
In general, type (A) projects will be conducted by *Chikyu*, type (B) by *JOIDES Resolution*, and type (C) by MSPs, although there will be some overlap. Importantly, the study of the different science themes requires access to all three platforms (**Table 7.1**).

BOX 7.1 | RISER AND RISERLESS OCEAN DRILLING

Major deep-sea drilling and coring can be conducted in either closed-hole (riser) or open-hole (riserless) mode.

In riser drilling, a large-diameter steel pipe (riser) is connected to the drilling platform and the seabed, with the drill pipe run within the riser. Drilling mud is pumped down the drill pipe and returned outside of the drill pipe contained by the riser. Mud density is controlled to keep the hole from collapsing by balancing formation pressure. Mud use can also improve core recovery and keep the hole clean by lifting drilling fragments ("cuttings") to the surface. These cuttings can be used for scientific examination, however, in most applications, cuttings cannot substitute for cores. Riser drilling is needed for deep holes and for difficult formations (e.g., salt, ones that are over pressured). If a hole has any risk of containing hydrocarbons, the riser technique allows for the deployment of a blow-out preventer. Setting up a deepwater riser can take many days to weeks, and is sensitive to weather and sea conditions. Thus, a riser system would not be used for multiple shallow holes.





In riserless drilling, seawater is circulated downward through the drill pipe and upward through the open hole. If needed, mud can be pumped through the drill pipe to clean the hole, but it cannot be returned to the platform and reused. Open-hole drilling typically can be initiated within hours or one day upon arrival at the site. Both riser and riserless modes permit multiple re-entries into an existing hole. Scientific ocean drilling has successfully drilled in riserless mode to 2-km depth in various settings, with the deepest hole being 2111-m deep into Pacific oceanic crust.

D/V *JOIDES Resolution*

During 2006–2008, the National Science Foundation invested approximately $115 million USD in the modernization of the riserless drilling vessel *JOIDES Resolution*, extending her lifetime 20 years to 2029 (**Box 7.2**). *JOIDES Resolution* is leased from industry on a long-term, 12 months per year contract, which is renewable for the period 2013–2023.

The hallmarks of *JOIDES Resolution* are global mobility and efficiency of drilling, generally resulting in the lowest possible cost per meter of core. Improved advanced piston coring provides complete or near-complete core recovery even in very lithified sediments (**Box 7.2**), enabling collection of high-fidelity paleoceanographic and paleoclimate records to great depths.

The versatility and operational flexibility of the riserless *JOIDES Resolution* make this platform the community's choice for a global drilling vessel, including for high-latitude operations outside of truly ice-infested waters. For most applications up to ~2-km subseafloor drilling depth (maximum depth yet untested) that do not require a riser, *JOIDES Resolution* will be the program's primary drilling tool across all research themes (**Table 7.1**).

Generic Targets for JOIDES Resolution *Drilling*

JOIDES Resolution drilling will span all themes of the science plan (**Table 7.1**). Experiments are expected to range in length from weeks to six or more months, often with multiple holes in close proximity or along transects. In general, the lead times for these projects will be less than the planned deep-drilling efforts by *Chikyu,* which may require five or more years of preparation.

Climate and Ocean Change. The approximately 50 months of climate research (**Table 7.1**) will include high-, medium-, and low-latitude drilling in every ocean except the Arctic. Drilling will include selected depth transects or arrays of mostly moderately deep (< 1 km) holes within regions important to understanding critical paleoceanographic, atmospheric, and hydrologic conditions. Sediment drifts will provide exceptionally high-resolution sampling sites if multiple holes, chosen on the basis of high-resolution seismic data, are drilled. Studies addressing regions of coupled ocean-continent climate systems will be linked to onshore lake studies conducted within the framework of the International Continental Scientific Drilling Program.

Biosphere Frontiers. Deep biosphere research will develop quantitative assessments of the spatial distribution of microbial activity at scales ranging from microscopic to regional, and will study metabolism mechanisms, genomics, limiting factors for microbial life (e.g., temperature, pressure, energy), and the origin of deep microbial life (i.e., downward migration and adaption versus in situ development). Investigations of specific evolutionary events in time will address environmental forcing of evolution (e.g., East Africa environment and hominid evolution; extinction events). A wide distribution of diverse sample settings within the ocean is expected, with drilling depths ranging from shallow to potentially 2+ km.

Earth Connections. The estimated 25 months of drilling conducted by *JOIDES Resolution* for Earth Connections will include shallower targets in the crust than those addressed by *Chikyu*. These sites will allow study of the structure of mid-ocean spreading ridges,

THEME	MONTHS			
	Chikyu	*JOIDES Resolution*	MSP	Total
Climate and Ocean Change	5	50	10	65
Biosphere Frontiers	5	20		25
Earth Connections	25	25	5	55
Earth in Motion	15	25	5	45
Total	50	120	20	190

Table 7.1. Initial estimates of platform drilling in increments of five months. Although distributed across the different science plan themes, many drilling expeditions will address multiple themes. The target is full 12 months/year *JOIDES Resolution* operation, varying between 8 and 12 months due to logistical and fiscal constraints, and five months/year of *Chikyu* operations. One mission-specific platform (MSP) operation (two months average) per year is expected. The actual amount of drilling time within each theme will depend on proposal pressure and readiness of each project, including site characterization and borehole instrumentation.

BOX 7.2 | RISERLESS PROGRAM PLATFORM D/V *JOIDES RESOLUTION*

After 133 scientific drilling expeditions since 1985 and a major refit (2006–2008), *JOIDES Resolution* features a completely redesigned multifloor laboratory facility. This 143-m-long drilling vessel can transit the Panama Canal and can operate in water depths ranging from 75 to 8200 m. *JOIDES Resolution*'s comprehensive transformation included replacement of all structures forward of the rig floor and refurbishment, upgrade, or replacement of all major drilling and downhole logging systems. The majority of the science systems were renovated or replaced to provide state-of-the-art support for core processing, description, and onboard and post-cruise investigations. The analytical chemistry and microbiology labs feature the latest-generation instruments for quantifying molecular, elemental, and ion constituents. Seven core loggers provide rapid and nondestructive capture of physical properties and include an image logger and a natural gamma ray logger that far exceed earlier capabilities. The new, integrative framework captures descriptive and interpretive core information that is stored in a state-of-the-art data management system. Following *JOIDES Resolution*'s transformation, three high-resolution paleoceanographic expeditions have been completed to date, along with investigations into the evolution and formation of a large igneous province, mantle dynamics, global sea level change, Antarctic glaciation history, subseafloor hydrogeology, and microbiology. Successful coring in these dramatically different environments was made possible by *JOIDES Resolution*'s diversified ensemble of coring tools. During these expeditions, *JOIDES Resolution* set new coring records, including advanced piston coring to a depth of 458 m and drilling the deepest scientific ocean sediment hole (1928 m into the seafloor). Photos courtesy of IODP/USIO.

ocean floor geochemistry, incipient formation of island arcs, the cycling of elements within subduction systems, and geochronology to constrain geodynamic events. Drilling into tectonically exposed mantle at or near the seafloor will complement deep drilling through the crust to the mantle by *Chikyu*. Drilling locations in the Pacific, Indian, and Atlantic Oceans are anticipated.

Earth in Motion. The 25 months of observatory/geohazards work by *JOIDES Resolution* will be in addition to an expected 15 months of *Chikyu* drilling in this field. *JOIDES Resolution* work will include establishing a number of subseafloor observatories to address geochemical fluxes and fluid movements in various settings, in situ slope stability, and the history of potentially tsunami-generating submarine landslides. Drilling through the shallower parts of earthquake-generating systems, including seismogenic faults that have recently generated large displacements, will also be considered. Locations may include the Pacific, Atlantic, and Indian Oceans, and related marginal seas. Locations offering cabled network connection to land offer particular advantages.

D/V *Chikyu*

Chikyu, in the top class of deep-sea drilling vessels (**Box 7.3**), currently has a riser-drilling capability of 2.5-km water depth. Expanding this capability to 4 km+ water depth is a major engineering challenge that ranks high on the Japanese government's list of new science facilities. This enhanced capability will allow the vessel to expand deep crustal drilling into earthquake-prone tectonic plate boundaries and Earth's mantle. The 50 months of *Chikyu* drilling time (**Table 7.1**) is essential for achieving new and long-standing goals within planetary sciences and earthquake research. Due to the nature of riser drilling, *Chikyu* is most efficiently used for deep drilling of a single or a few holes at one site.

Generic Targets for Chikyu *Drilling*

Deep-drilling projects are technically and logistically demanding and may require five or more years of lead time for science planning, acquisition of detailed site-specific data, engineering development, well design, and logistical preparations for operations. Initial planning for future deep-drilling projects for *Chikyu* has therefore already begun. Operational targets include two major missions within the Earth in Motion and Earth Connections themes, respectively: (1) the SEIsmogenic Zone Experiment (SEIZE) in settings within the Pacific that are complementary to the ongoing Nankai Trough SEIZE (NanTroSEIZE), and (2) sampling Earth's mantle below fully developed oceanic crust in the eastern Pacific. The implementation of SEIZE and mantle drilling is tentatively estimated to require on the order of 40 months of drilling (**Table 7.1**).

Other possible *Chikyu* targets include deep sedimentary systems that record, for example, the uplift of the Himalayas and development of the Asian monsoon, and sedimentary systems harboring microbial life in environments that require riser drilling, such as hydrocarbons or salt-bearing sequences. The scientific priority for initial *Chikyu* drilling will need to be developed during 2012–2013. Deep mantle drilling is not anticipated to start before about 2017 due to site survey needs and requires development of the 4+ km deep-water riser capability.

Mantle Drilling. Scientific planning for drilling into the mantle was initiated by a major workshop in 2006 and brought to a mature stage during 2010 through two dedicated workshops (http://www.iodp.org/workshops), one of which was held jointly with the Deep Carbon Observatory initiative supported by the Alfred P. Sloan Foundation. JAMSTEC plans to deploy its main geophysical research vessel R/V *Kairei* to the eastern Pacific to obtain detailed seismic images of possible

BOX 7.3 | RISER PROGRAM PLATFORM D/V *CHIKYU*

The 210-m-long (56,752 tons) D/V *Chikyu* is a purpose-built riser drilling vessel owned by JAMSTEC and operated for IODP by CDEX. *Chikyu* was completed in 2005, can accommodate up to 200 people (marine, drilling operations, lab technicians, and scientists), and has a range of approximately 20,000 nm. The 70.1-m-high, dual drill string derrick can handle up to 12 km of drill string. The current riser capability is 2.5 km of water, with plans to expand to 4 km+ during the new drilling program. The ship's powerful six thrusters can keep it in position in currents over 3 kts and in more than 23 m/s wind speed. It can deploy a 380-ton heavy blow-out preventer capable of withstanding pressure of 103 MPa. The riser system can be equipped with so-called fairings to reduce vortex-induced vibrations in the riser system when operating under the influence of strong currents. A unique, real-time riser vibration monitoring system is being developed to further support riser drilling under the most challenging conditions. *Chikyu* is equipped with a suite of state-of-the-art laboratories providing the same core measurements as *JOIDES Resolution* (see Box 7.2). In addition, *Chikyu* has a CT-scanning capability that provides 3D imaging of the cores before they are split into working and archive halves, as well as a laser ablation ICP-MS for elemental analysis at the microcrystalline level. *Chikyu* also has a system to sample and analyze the small pieces of rock material (cuttings) that are brought to the surface by the circulating drilling mud during riser drilling. Finally, *Chikyu* can also operate in riserless mode. The ship suffered damage from the massive tsunami associated with the Great East Japan Earthquake of March 11, 2011, but is expected to be fully operational by mid 2011 after drydock repair. Photos courtesy of IODP/JAMSTEC.

target zones identified through the workshops. Likewise, in order to advance well design and engineering development necessary for deep drilling into the mantle, the Integrated Ocean Drilling Program central management office has contracted with an industry consultant company to conduct a study of the most efficient drilling technologies, and the sensitivity of the mantle drilling project to variables such as water depth, total depth, temperature regime, and amount of coring. Preliminary results (April 2011) of this study suggest that innovative applications of existing technology will allow riser drilling into oceanic crust in water depths of 4+ km.

Seismogenic Zone Drilling. In spring 2011, the Integrated Ocean Drilling Program targeted the seismically active subduction zone system offshore Costa Rica, Central America, for riserless drilling as part of the ongoing SEIZE effort. To aid in planning for possible deep riser drilling, the US-owned R/V *Marcus Langseth* conducted a major three-dimensional seismic survey of this subduction system to complete imaging of the deeper parts of the system. Another well-imaged and remarkably shallow seismogenic zone offshore of the North Island of New Zealand shows frequent occurrence of so-called slow-slip seismic events. Thus, this region may also offer unique opportunities for sampling and for borehole observations of a full earthquake cycle within a finite time period.

The March 11, 2011, magnitude 9.0 mega-earthquake offshore northern Honshu, Japan, moved a whole plate boundary segment, resulting in a devastating tsunami and a high number of aftershocks (452 > M_w5 as of May 13, 2011). The current drilling program has formed a rapid-response group to evaluate what could be learned from sampling and measuring properties within the subseafloor region of recent failure, to evaluate fault zone strength and the generation of frictional heat. Another region of potential interest and preliminary readiness includes the Sumatra subduction system, which experienced a similar-scale seismic event that started with the December 26, 2004, mega-earthquake. Each of these seismic systems might take six, to as much as 18, months of drilling. Hence, only one or two may be studied by riser drilling within the scope of this 2013–2023 science plan.

Mission-Specific Platforms

Some scientific targets critical to accomplishing the goals of this science plan are located in regions characterized by geological formations that are difficult to drill or by extreme environmental conditions. Such targets require the use of mission-specific platforms. MSPs are chartered from industry according to the specific needs, and have been very successfully employed by the European Implementing Organization (ESO) within the current program (e.g., the high Arctic, carbonate platforms and coral reefs, and shallow continental shelves with poorly consolidated sediments [**Box 7.4**]).

Generic Projects for MSPs

Arctic Ocean. Recovering core from the high Arctic is a top priority of the International Ocean Discovery Program. Such samples will address climate-related research as well as the tectonic history of this ocean basin (**Figure 7.1**). It is expected that a minimum of two Arctic drilling expeditions will be required to achieve essential goals in high-latitude paleoceanography and regional tectonics. The Arctic subbasins may provide information critical for answering oceanic gateway questions relevant to poleward heat transport as high-latitude climate evolved from subtropical, to warm temperate, to its current ice-covered state. Furthermore, the wide Arctic continental shelves may contain vast amounts of shallow gas hydrates that may be very sensitive to global warming. The scientific case can be made for significantly

BOX 7.4 | THE USE OF MISSION-SPECIFIC PLATFORMS IN SCIENTIFIC OCEAN DRILLING

Mission-specific platforms (MSPs) are assembled by contracting platform and scientific services on a case-by-case basis to meet unique requirements, and require long-term planning and contracting. Four MSP expeditions were conducted by the Integrated Ocean Drilling Program between 2004 and 2010, with one more to be completed in 2012. During the 2004 Arctic coring expedition, two supporting icebreakers protected an icebreaker carrying a temporary drill from the heavy drift ice of the central Arctic Ocean. Cores to more than 400 m below seafloor in 1300-m water depth were obtained and provided the first glimpse into many unknowns of this unexplored ocean. Coring in the shallow reef environments of Tahiti and Great Barrier Reef by MSPs provided high-resolution records of past ocean conditions and post-glacial sea level rise. In both cases, dynamically positioned drilling vessels with purpose-fitted drill rigs were deployed, and provided much improved recovery rates compared to those obtained in the past. In some cases, interannual resolution of past sea surface temperatures was possible. Drilling on the inner, shallow part of the New Jersey shelf required the use of a three-legged lift boat. Not affected by tide or swell, a successful coring and downhole logging program through loosely consolidated shelf sediments was achieved. In the future, ESO will broaden the range of platforms and coring tools to include seabed drills. Research vessels could then be used as the operational platforms and narrow-kerf diamond coring technology could be extended to deep water. Due to restricted space on MSPs, the full analysis of cores and offshore data takes place at the Bremen Core Repository by the entire scientific party. Photos courtesy of IODP/ECORD.

more expeditions than covered in this implementation plan, but progress necessarily will be constrained by the difficult and expensive logistics of operating in this area. There are currently discussions at the European level to build a new scientific icebreaker, *Aurora Borealis*. Such a vessel would be a great asset for use as an MSP to drill in the Arctic in addition to already proven techniques using multiple icebreaking platforms working in tandem (**Box 7.4**).

Other additional MSP targets may include carbonate platforms, offshore freshwater reservoirs, proximal records of continental ice shields (e.g., Antarctica), submarine slopes, and young volcanic formations at mid-ocean ridges.

Additional Funding for Drilling Platform Time and Related Experiments

Raising supplementary funds in support of drilling and related experiments (e.g., observatories or expanded geophysical characterization) will be pursued on a project-by-project basis. The current Integrated Ocean Drilling Program includes a riser-drilling project funded by nonprogram funds (~$20 million USD) procured from a domestic (Japanese) competitive science program. In 2011, the Gordon and Betty Moore Foundation is supporting a riserless drilling and observatory program at a ~$3 million USD level. In 2009, the International Continental Scientific Drilling Program (ICDP) contributed financially to the implementation of MSP drilling along a continent-shelf drilling transect off New Jersey. Such collaborations provide a model for future ICDP-IODP interactions, possibly including drilling into the Chicxulub impact crater within the Gulf of Mexico. The

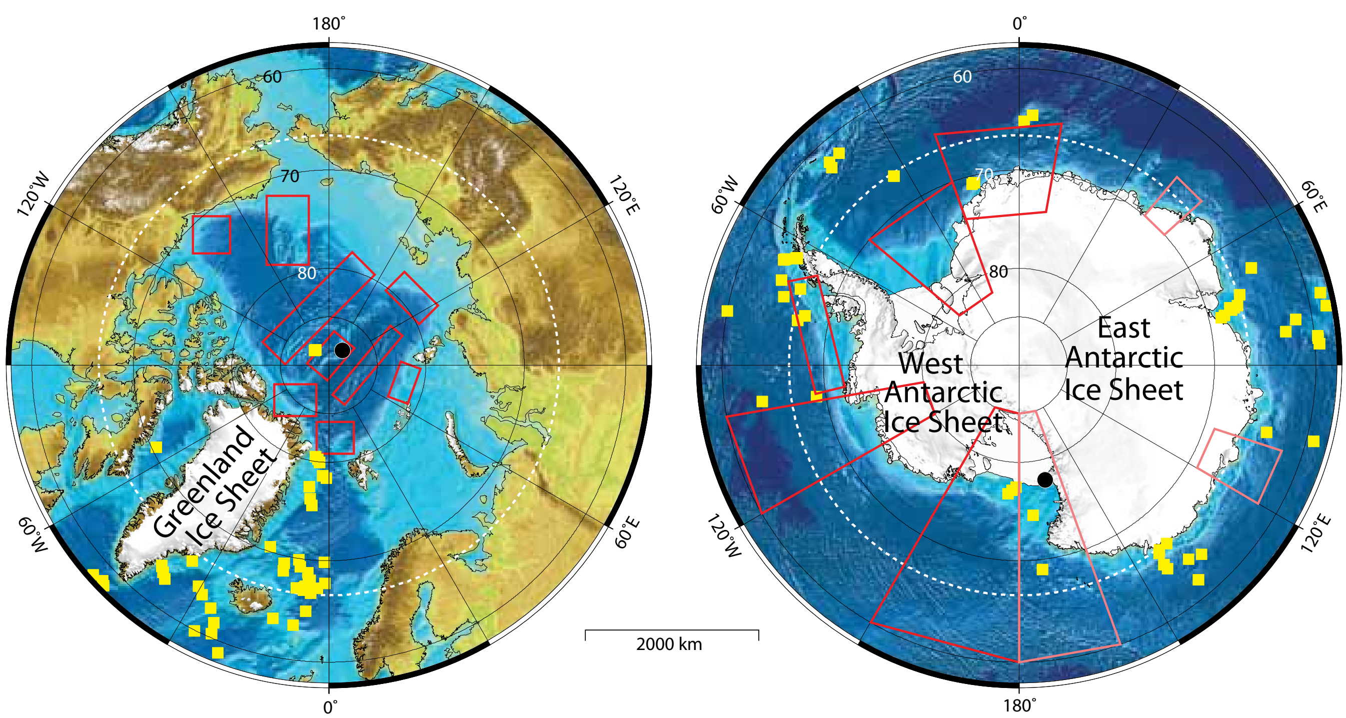


Figure 7.1. The Arctic (left) and Antarctic (right) regions displayed in polar stereographic projection. Yellow squares are previous scientific ocean drilling sites, and red open boxes are key areas for future drilling based on INVEST white papers. The black dot in the central Arctic Ocean (left) is the location of the one IODP ACEX drilling site, and the black dot near the edge of the Ross Ice Shelf (right) is the first ANDRILL project site, AND-1.

recently funded NSF Science and Technology Center focused on Dark Energy Biosphere Investigations (C-DEBI) grew out of prior ocean drilling and requires access to the sub-seafloor to meet its objectives. Collaboration between ocean drilling and the Deep Carbon Observatory on deep crustal drilling may leverage additional fiscal and intellectual support for the drilling program. Gas hydrate studies represent another prospective area of collaborative efforts and funding with other research programs and institutions. Support from the European Commission will be solicited for MSP operations addressing science themes identified in their new Framework Program 8.

Complementary funding from program countries on projects of special scientific or strategic interest to them is envisaged to further augment funding of *JOIDES Resolution* and *Chikyu.* In particular, this type of fiscal contribution may be most relevant to existing and new members representing emerging economies that have a growing interest both in basic research and in identifying the potential for natural resources in their regions.

SCIENTIFIC COMMUNITY, SITE CHARACTERIZATION, AND CORE ARCHIVES

The scientific community writes proposals, carries out drill site characterization, develops borehole instrumentation, and provides the intellectual capacity to meet program goals.

The successful outcome of scientific ocean drilling expeditions depends on member countries contributing additional scientific resources separate from the program membership fees and drilling-platform costs. This contribution includes intellectual as well as material resources in a number of areas.

Drill Site Characterization

Characterization of drill sites and observatory locations is critical for drillhole planning, safety, and environmental protection, and for establishing a three-dimensional setting of the cores and observations from the largely one-dimensional drill hole. For large and complex experiments, such as the study of seismogenic plate boundaries, pre-drilling activity typically entails detailed three-dimensional seismic surveys that can be achieved by the US-based R/V *Marcus Langseth*, the Japanese R/V *Kairei* (**Figure 7.2**), or by commercial companies. However, for most drilling operations, site characterizations using two-dimensional seismic surveys and other conventional geophysical and bathymetry data will suffice. Facilities for the collection and analysis of such data are readily available within most ocean drilling member countries. Program funds may be used for special surveys required for environmental and safety assessment. Remotely operated and autonomous underwater vehicles, human-occupied submersibles (e.g., *Nautile*, *Alvin*, *Shinkai 6500*), and a variety of seafloor mapping tools available within a number of the member countries will be critical for pre-drilling investigations and for installation and servicing of borehole observatories.

Scientific Community Resources

Each year, approximately 200 scientists are needed to participate in drilling expeditions where they provide critical early sample and data analyses at sea. On-shore requirements include hundreds of thousands of sample analyses, as much as 10 km of high-resolution continuous core scanning, and microbiological processing of several thousands of samples. In the past, ocean drilling's broad membership base has successfully delivered these resources. With recent and expected increases in membership, and new scientific networks forming in emerging fields of ocean drilling science, these "in-kind" contributions by member countries are expected to match future needs. The drillships' operators will supply the initial, platform-based technical and scientific support staff for core handling, for downhole logging, and for oversight and archiving of primary hole and core measurements and documentation provided by the 25–30 shipboard scientists on each expedition.

Microbiology

Both Japan and the United States recently initiated major programs that will support activities planned for the new drilling program in the emerging field of the subseafloor biosphere. Prominent among them are JAMSTEC and the Kochi Core Center in Japan, and the University of Southern California-hosted C-DEBI network. Other supportive institutions include the Center for Geomicrobiology at Aarhus University in Denmark, Cardiff University in the UK, MARUM at the University of Bremen, Germany, and IUEM and IFREMER in Brest, France.

Subseafloor Observatories

The technology and scientific community engaged in subseafloor observatory science has developed from within the ocean drilling community. This field is pushing toward greater depths with higher temperatures

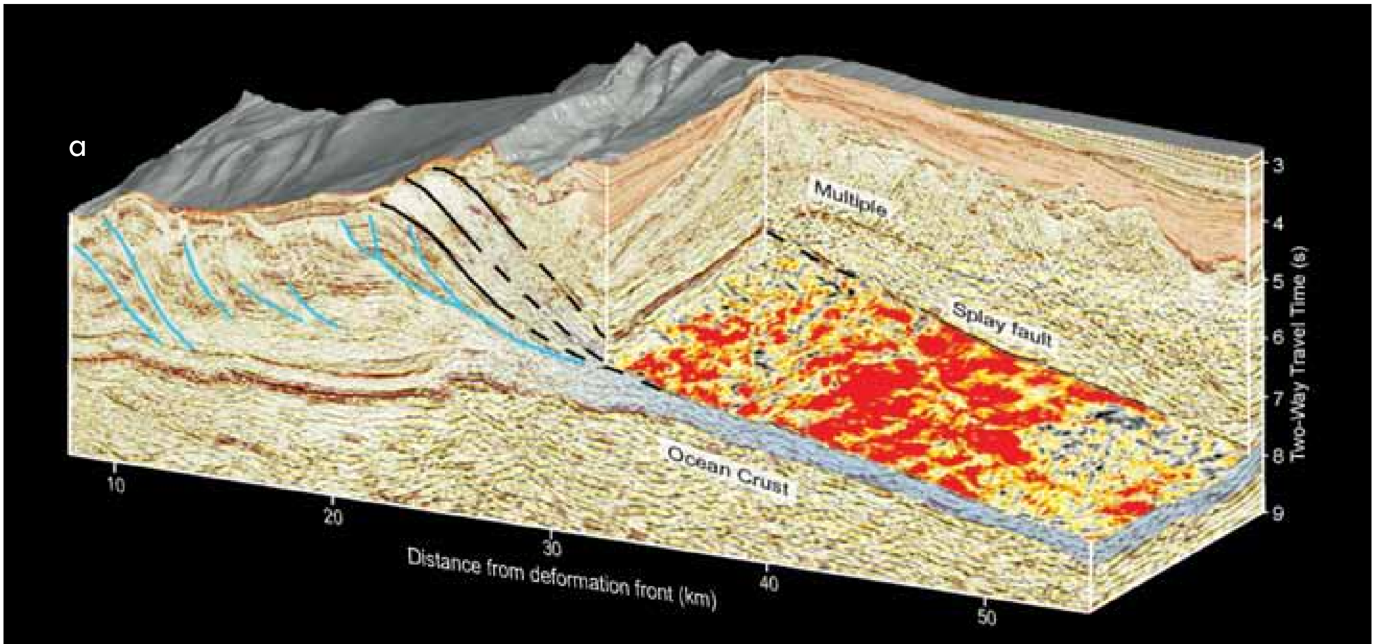


Figure 7.2. Advanced seismic 3D-imaging of a drilling target, such as (a) the seismogenic zone offshore Honshu, Japan (courtesy of N. Bangs, University of Texas at Austin), requires access to research vessels of the class of (b) the US R/V *Marcus Langseth* and (c) the Japanese R/V *Kairei*. The depth to the fault plane carved out in the 3D data block varies from approximately 5 km (up-dip end) to about 7 km.

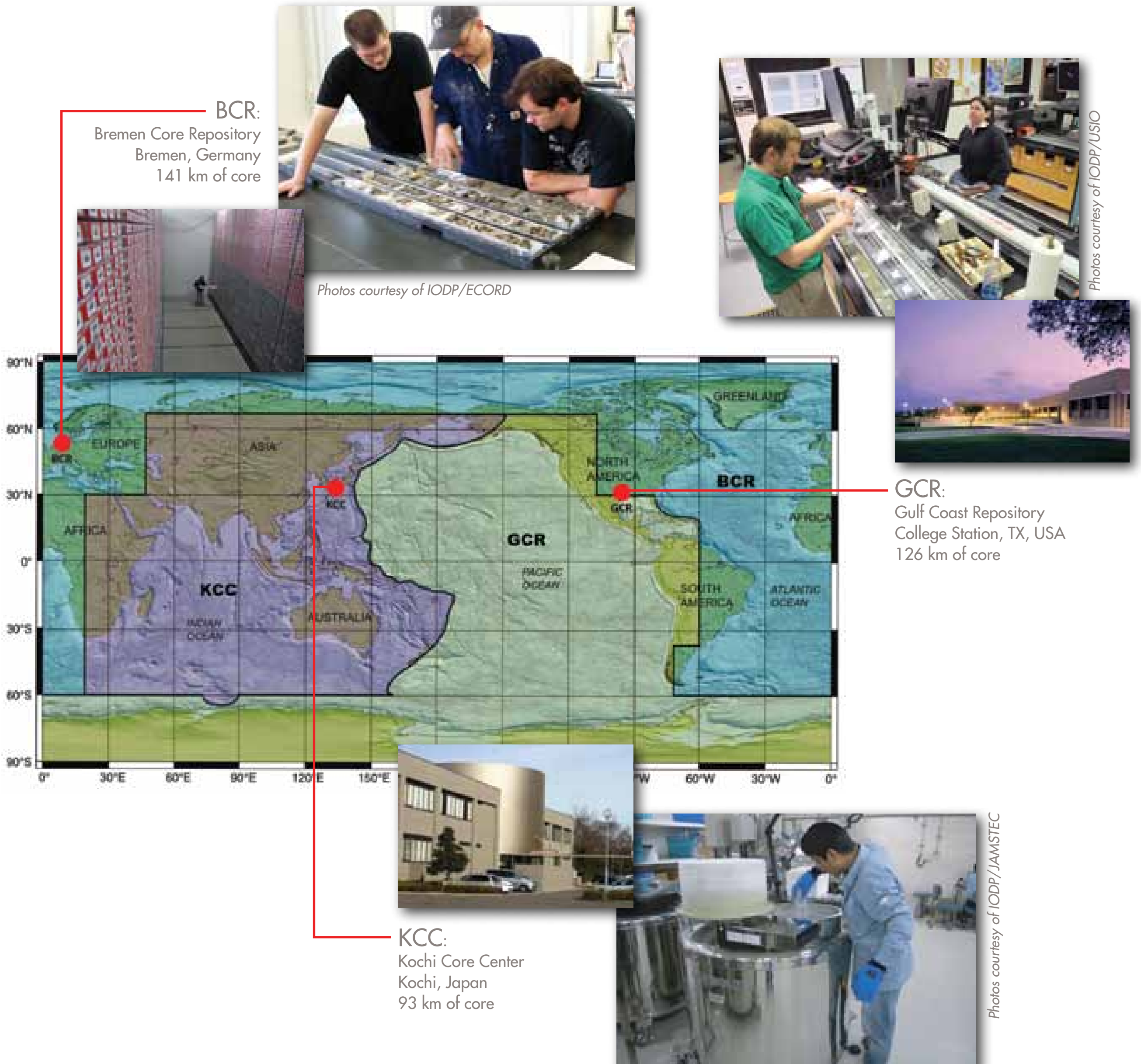
and pressures, and expanding from collecting fluid and temperature data, to including time series of chemistry, biological activity, and strain, as well as seismic data. Recently, opportunities to link subseafloor observatories through cabled networks for real-time monitoring have been pursued offshore Japan and western North America. Europe and China are developing plans for similar networks. This opportunity to establish a permanent observatory presence below the seafloor will be coordinated with seabed and water-column observatories (e.g., NEPTUNE Canada, the Ocean Observatory Initiative, DONET, and the European Multidisciplinary Seafloor Observatory).

Core Repositories

The scientific ocean drilling community operates three regional core repositories (**Box 7.5**). The combined core length archived in the three repositories totals 360 km (as of February 2011). These cores, an invaluable archive of Earth's history and climate, are subject to strict documentation and curation standards developed and maintained over four decades. Following a one-year sampling moratorium reserved for the scientists engaged in the recovery and description of the cores, this material is available to any researcher worldwide, provided that well-documented research plans are submitted.

BOX 7.5 | IODP GLOBAL DEEP-SEA CORE REPOSITORIES

Scientific ocean drilling cores dating back to the start of the Deep Sea Drilling Project (1968) are kept in three regional core repositories: the US Gulf Coast Repository (GCR) in College Station, Texas; the Bremen Core Repository (BCR) at the University of Bremen, Germany; and the Kochi Core Center (KCC) at Kochi University, Japan. By early 2011, these core centers archived a total of 360 km of deep-sea core from all ocean basins. Because MSPs do not have the same comprehensive laboratory facilities as the two main drilling platforms, cores from these expeditions are described at the BCR which has a comprehensive core-processing lab. Advanced analytical facilities are also available at the KCC, including high-resolution XRF scanning of cores, mass spectrometry facilities, and unique storage of microbiological samples in liquid nitrogen tanks. The GCR also offers high-resolution scanning of cores. Cores in all three repositories are kept under controlled climate conditions (temperature and humidity) and curators oversee the sampling of the working-half cores. A standing committee chaired by the Central Management Office oversees any use of the archive-half of cores.



The length of new core material that will be acquired by the International Ocean Discovery Program is estimated to be around 200 km, and is manageable with a modest increase in core storage capacity. The operations cost of the global core repositories will be borne by the core funding of the new drilling program

Data Management and Information Services

The International Ocean Discovery Program will further develop the Scientific Earth Drilling Information Service (SEDIS). It will be used as the common data and information portal. The SEDIS concept aligns with multinational data initiatives, such as the Global Earth Observation System of Systems (GEOSS) and the World Data System (WDS) of the International Council for Science (ICSU), that endorse federated system data services, including long-term preservation and publication of data as recommended by OECD.

SEDIS provides a single point of access to expedition-generated core descriptions, core measurements, logging data, publications, and post-expedition data. Each of the three platform providers is responsible for its own data management activities through its own data system during the data collection and moratorium period. SEDIS harvests metadata from the platform providers' data systems to enable searching and browsing of the distributed data sets. SEDIS is built on open-source components and uses international standards and protocols for metadata and data. Data sets and publications are referenced by digital object identifiers (doi's).

SEDIS will serve as the basis for the data and information infrastructure for the International Ocean Discovery Program and will ensure the long-term preservation and availability of legacy data from the Deep Sea Drilling Project, Ocean Drilling Program, and the current Integrated Ocean Drilling Program. SEDIS will be further developed, adding web-based services for data retrieval and data display in support of broader, multi-disciplinary use of program findings. SEDIS also includes access to other ocean-drilling-relevant data from terrestrial or lake drilling programs and will provide links to other networks such as WDS or GEOSS.

The Integrated Ocean Drilling Program publishes its initial drilling results and core descriptions on the web. Short, peer-reviewed summaries of initial scientific results are presented in the journal *Scientific Drilling*, published jointly with the International Continental Scientific Drilling Program. All post-drilling research is published in the open, peer-reviewed literature (**Table 1.1**) and is tracked by SEDIS. The International Ocean Discovery Program plans to use similar avenues to disseminate scientific results.

DEVELOPMENT OF DETAILED SCIENTIFIC EXPERIMENTS

Drilling proposals that detail how to advance this science plan will be submitted by individuals and investigator groups to the Central Management Office. This office will host an independent scientific advisory structure that will review proposals, request proposal improvements, and, annually, recommend projects for execution. The new program will remain responsive to scientific breakthroughs and opportunities.

Proposal Development

It is expected that approximately 75–100 highly competitive proposals will be needed to realize the goals of this science plan over its 10-year duration. Current proposal pressure exceeds this requirement by a wide margin (**Figure 7.3**). Some proposals may require as much as 25 months of drilling (e.g., reaching the mantle), whereas the vast majority will require ≤2 months of at-sea operations. Currently, about 100 active proposals are in the program review system, of which fewer than 10 per year can be accommodated. A select number of the existing proposals, together with new proposals submitted for the proposal deadline of October 1, 2011, will form the basis for the initial years of the new program. Considerable activity in preparation for possible deep crustal riser drilling (e.g., mantle drilling, seismogenic zone) is already underway and will be intensified during 2012–2013.

Drilling experiments have grown larger and have become more complex and multidisciplinary, often requiring collaborative efforts among disparate science communities. The new program will support development of such complex projects through programmatic workshops that engage multidisciplinary and/or multiprogram audiences. The latter will include other drilling programs (e.g., ICDP, ANDRILL) and nondrilling programs such as PAGES, GeoPRISMS, EarthScope, cabled observatories (e.g., NEPTUNE Canada, DONET, Ocean Observatories Initiative, European Multidisciplinary Seafloor Observatory), and microbiological networks like C-DEBI.

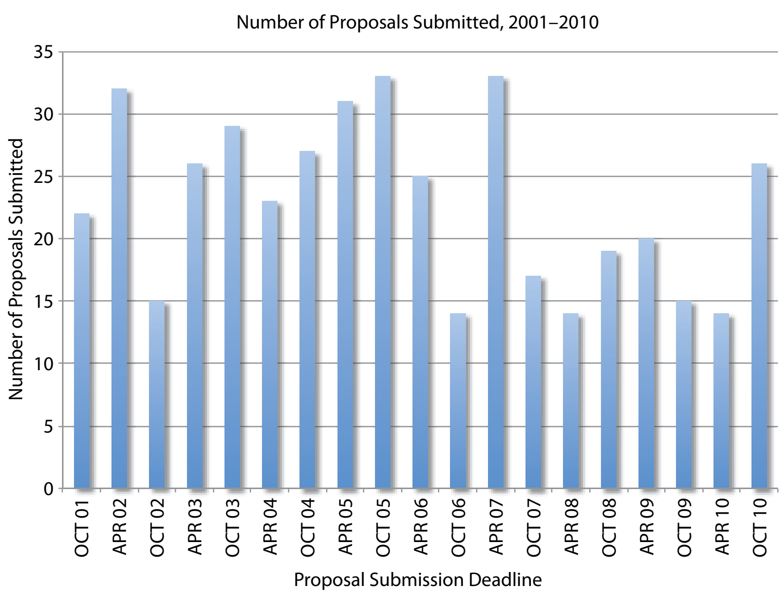


Figure 7.3. Number of drilling proposals submitted during year 2000–2010. As of early 2011, the number active proponents for these proposals is 1120.

Securing Scientific Staffing

Each drilling expedition typically involves up to 30 scientists covering a spectrum of specialties. On an annual basis, this amounts to as many as 200 scientists. These participants will be selected from the member countries based on national, competitive nomination systems. Member nations provide funding for shipboard scientists, support that represents a significant contribution to the program. Participating in drilling operations at sea is one of the most fundamental and valued program membership benefits for scientists. It is widely recognized as an important opportunity to train a new, globally oriented generation of Earth and life scientists.

PROGRAM GOVERNANCE AND OPERATIONS

Program operations and governance will be conducted through a number of entities with mandates and roles based on past and ongoing scientific ocean drilling experiences. The key structural components are a Program Governing Board (PGB) representing all funding agencies supporting the program, a Central Management Office (CMO), a Scientific Advisory Structure (SAS), and Implementing Organizations (IOs). The CMO will serve as the science and program integrating entity, and will support the PGB in its program oversight.

Program Governing Board

The Program Governing Board has the ultimate program authority. It will monitor and oversee the program's overall progress and its funding requirements, and determine membership fees, entitlements, and responsibilities. Specifically, within the larger framework of the program's long-term plan, it will review and determine funding levels for the annual program plan, including desired expeditions, submitted by the CMO.

Central Management Office

The Central Management Office (currently IODP Management International, or IODP-MI Inc.) will host and administratively support the independent SAS. Working with the platform operators (IOs) and the SAS, the CMO will compile long-term program scenarios and annual program plans with detailed scientific, technical, and fiscal information for the PGB to consider. The CMO is charged with integrating science planning, operations, and data output across the program, organizing achievement reviews, and supporting program-wide outreach. It will receive advice on scientific priorities and achievements from the SAS and from external review committees as needed.

Scientific Advisory Structure

The independent SAS will include approximately 100 scientists and engineers appointed and supported by program member nations. The SAS, working on the principle of peer review, is charged with in-depth reviews of all scientific proposals submitted to the program. Criteria for a successful proposal include scientific excellence, contributions to advancing the goals of the science plan, transformational nature of the science, and implementation feasibility. The SAS will also review and approve annual and long-range science implementation plans, engage in reviews of scientific achievements, and assist in identifying emerging or underrepresented areas of research. It works closely with the CMO and provides reports to the PGB.

US Implementing Organization

The US Implementing Organization (USIO) is responsible for science operations on the drilling vessel *JOIDES Resolution* (**Box 7.2**). The Consortium for Ocean Leadership, in partnership with Texas A&M University (TAMU) and Lamont-Doherty Earth Observatory of Columbia University (LDEO), form the USIO. The USIO is currently supported through a systems integration contract with the US National Science Foundation and a contract with IODP-MI to deliver technical, operational, and financial management of *JOIDES Resolution* activities. Services provided by TAMU include vessel and drilling operations; maintenance and support of ship- and shore-based science laboratories, data management, and publications; and housing of the Gulf Coast Repository. Through the LDEO, the USIO also provides downhole geophysical measurement (logging) services, and development of new types of borehole logging instruments. As of April 2011, the partners within the USIO have operated 133 *JOIDES Resolution* expeditions since 1985.

Center for Deep Earth Exploration

The Center for Deep Earth Exploration (CDEX) is hosted by the Japan Agency for Marine-Earth Science and Technology (JAMSTEC), the biggest oceanographic center in Asia and owner of the drilling vessel *Chikyu* (**Box 7.3**). CDEX was established in 2003 and, as of April 2011, has operated *Chikyu* during nine Integrated Ocean Drilling Program expeditions. CDEX has contracted onboard drilling and ship operation to Mantle Quest Japan, a joint company of Japan Drilling Company and Nippon Yusen Kabushiki Kaisha, established in 2009 to provide ship and drilling crew for *Chikyu* operations. In-house CDEX staff are responsible for engineering development, drilling planning, expedition logistics and management, data management, and education and outreach activities. CDEX also operates the Kochi Core Center, one of the program's three core repositories. CDEX is funded through JAMSTEC based on an ocean drilling budget provided by the Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT), and has a contract with IODP-MI for delivery of a number of drilling-related science services, including shipboard science support, geophysical logging, borehole observatory development, and core curation.

ECORD Science Operator

The ECORD Science Operator (ESO) is responsible for procurement of suitable platforms for MSP operations (**Box 7.4**), and offshore and onshore science operations relating to MSP projects. Additionally, ESO provides offshore, containerized laboratories, support staff, data management, and curatorial services during MSP operations. The three ESO partners are the British Geological Survey in the UK, the University of Bremen in Germany, and the European Petrophysics Consortium (EPC). The University of Bremen Institute for Marine Environmental Sciences (MARUM) hosts the Bremen Core Repository, one of the three regional scientific ocean drilling core repositories.

COVER CREDITS

BACKGROUND EARTH. Using a collection of satellite-based observations, scientists and visualizers stitched together months of observations of the land surface, oceans, sea ice, and clouds into a seamless, true-color mosaic of every square kilometer (.386 square mile) of our planet. Credit: NASA Goddard Space Flight Center Image by Reto Stöckli (land surface, shallow water, clouds). Enhancements by Robert Simmon (ocean color, compositing, 3D globes, animation). Data and technical support: MODIS Land Group; MODIS Science Data Support Team; MODIS Atmosphere Group; MODIS Ocean Group Additional data: USGS EROS Data Center (topography); USGS Terrestrial Remote Sensing Flagstaff Field Center (Antarctica); Defense Meteorological Satellite Program (city lights). Image from http://visibleearth.nasa.gov/view_rec.php?id=2431

GEOHAZARDS. Debris and standing water left from tsunami, northwestern Sumatra, January 21, 2005. Image from http://walrus.wr.usgs.gov/tsunami/sumatra05/Banda_Aceh/0708.html

BIOSPHERE. Microbes in crust. Credit: Orcutt B.N., W. Bach, K. Becker, A.T. Fisher, M. Hentscher, B.M. Toner, C.G. Wheat, and K. Edwards. 2010. Colonization of subsurface microbial observatories deployed in young ocean crust. *The ISME Journal*, doi:10.1038/ismej.2010.1157.

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Integrated Ocean Drilling Program Management International
1001 Connecticut Avenue, NW, Suite #504
Washington, DC 20036 USA

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