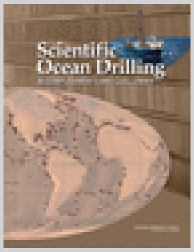

# Scientific Ocean Drilling: Accomplishments and Challenges

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Committee on the Review of the Scientific Accomplishments and Assessment of the Potential for Future Transformative Discoveries with U.S.-Supported Scientific Ocean Drilling

# Scientific Ocean Drilling

## ACCOMPLISHMENTS AND CHALLENGES

Committee on the Review of the Scientific Accomplishments and Assessment of the Potential for Future Transformative Discoveries with U.S.-Supported Scientific Ocean Drilling

Ocean Studies Board

Division on Earth and Life Studies

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*Cover*: Images of the *JOIDES Resolution* (front) and *Chikyu* (back left) are courtesy of the Integrated Ocean Drilling Program (IODP). Image of the *L/B Kayd* (back right) is courtesy of the European Consortium for Ocean Research Drilling, photograph by C. Cotterill. Global map of drill holes provided by Katerina Petronotis (IODP-U.S. Implementing Organization). Photos of cores provided by Rob McKay, Victoria University of Wellington, New Zealand (front) and IODP (back).

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# Preface

Scientific ocean drilling has been at the forefront of Earth science since it was first envisioned in the late 1950s. During the intervening 50 plus years, probably the most productive period in the history of studying Earth, we have seen remarkable progress in understanding the Earth system. New theories emerged that include the discovery of plate tectonics, elucidation of global climate, the discovery of submarine hot springs and the vent biological communities they support, and the even more remarkable realization that there is an extensive subseafloor biota that may well inhabit all of the world's oceanic sediments and much of the crystalline crust. The ability to retrieve drill cores from the ocean basins on a regular basis has been absolutely integral to all of these endeavors. Beginning in the late 1960s this work has been conducted in a highly organized, coordinated way via a variety of programs that grew increasingly complex and more international with time. Three different drillships have been commissioned expressly for scientific study of the oceans, and two are still in operation. The community has self-organized in such a way as to advance the most significant drilling projects, which stands as one of the most successful coordination efforts between an international scientific community and national funding agencies.

Our committee's report looks backward at significant scientific accomplishments enabled by scientific ocean drilling and also looks forward to the next phase of scientific ocean drilling. Those two foci comprise the two main parts of the report. In the first part (Chapters 1-5) we discuss the scientific accomplishments that have resulted from the first three scientific ocean drilling projects, the Deep Sea Drilling Project, the Ocean Drilling Program, and the Integrated Ocean Drilling Program, which span from 1968 to the present. This committee task was both challenging and rewarding because some of the most exciting science of the times resulted from these programs. In the second part of the report (Chapter 6), we examine the plans for future drilling, which was also stimulating because the potential for future accomplishments is significant.

The committee and its Co-chairs thank the Ocean Studies Board staff for their excellent support throughout committee deliberations. In particular we thank Dr. Deborah Glickson, Senior Program Officer, for her outstanding scientific insights, her willingness to put in long hours at any time of the day or night, her constant availability for discussions, her patience with a group of widely divergent personalities from around the world, and her constant good humor and positive attitude. We could not have asked for a better partner throughout this more than year-long effort. We thank Dr. Susan Roberts, Director of the Ocean Studies Board, for her leadership and insights. We also sincerely appreciate the valuable assistance and wise advice given to us on many occasions during our meetings and during the preparation of this report by Dr. Elizabeth Eide, Senior Program Officer with the Board on Earth Sciences and Resources. Mr. Jeremy Justice handled all of our logistical arrangements promptly and expertly and seemed to anticipate our many needs even before we did. One of us particularly appreciated his ability to find Dr. Pepper wherever our meetings took place.

During the committee deliberations we held several conference calls and participated in five meetings at various locations. These meeting were as follows: Washington, DC (June 21-23, 2010); College Station, Texas (July 24-28, 2010); Victoria, British Columbia, Canada (September 6-10, 2010); Denver, Colorado (October 28-30, 2010); Boston, Massachusetts (June 14-15, 2011).

Robert Duce, *Committee Co-chair*
Arthur Goldstein, *Committee Co-chair*

# Acknowledgments

This report was greatly enhanced by the participants of the meetings held as part of this study. The committee would like to acknowledge the efforts of the individuals who made presentations during committee meetings: Keir Becker (University of Miami), Michael Bickle (University of Cambridge), Robert DeConto (University of Massachusetts, Amherst), David Divins, Robert Gagosian, and Charna Meth (Consortium for Ocean Leadership), David Feary (National Research Council), and Christina Ravelo (University of California, Santa Cruz).

The committee is also grateful to the individuals who made presentations and provided white papers for the workshop: Keir Becker (University of Miami), Jim Channell (University of Florida), Hans Christian Larsen (Integrated Ocean Drilling Program Management International, Inc.), Millard Coffin (National Oceanography Centre), Henry Dick (Woods Hole Oceanographic Institution), Robert Duncan (Oregon State University), Katrina Edwards (University of Southern California), Susan Humphris (Woods Hole Oceanographic Institution), Dennis Kent (Rutgers University), Jerry McManus (Columbia University), Kenneth Miller (Rutgers University), Casey Moore (University of California, Santa Cruz), Theodore Moore (University of Michigan), Dick Norris (Scripps Institution of Oceanography), Carolyn Ruppel (U.S. Geological Survey), Dale Sawyer (Rice University), Doug Wilson (University of California, Santa Barbara), and James Zachos (University of California, Santa Cruz).

The committee also thanks Bradford Clement and Mitch Malone (Integrated Ocean Drilling Program-U.S. Implementing Organization) for providing background data on the previous and current scientific ocean drilling programs and for hosting the committee at the Texas A&M Gulf Coast Core Facility; Jeffrey R. Seemann, Vice-President for Research, and Kate C. Miller, Dean of the College of Geosciences (Texas A&M University) for hosting a reception for the committee and workshop guests; Katerina Petronotis (Integrated Ocean Drilling Program-U.S. Implementing Organization), for providing maps for this report; and Kristin Ludwig (formerly of the Consortium for Ocean Leadership) for facilitating continuous coordination between the Integrated Ocean Drilling Program and the committee and for arranging the committee's tour of the *JOIDES Resolution*.

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the NRC's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their participation in their review of this report:

**KEIR BECKER**, University of Miami, Florida
**EDWARD BOYLE**, Massachusetts Institute of Technology, Cambridge
**BARRY JAY KATZ**, Chevron Energy Technology Group, Houston, Texas
**PETER KELEMAN**, Lamont-Doherty Earth Observatory, Columbia University, Palisades, New York
**JOSEPH MEERT**, University of Florida, Gainesville
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**HEDI OBERHÄNSLI**, GFZ German Research Centre for Geosciences, Potsdam, Germany
**ANDREW ROBERTS**, Australian National University, Canberra
**WILLIAM RUDDIMAN**, University of Virginia, Charlottesville
**DAVID SCHOLL**, U.S. Geological Survey, Menlo Park, California

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations nor did they see the final draft of the report before its release. The review of this report was overseen by **Andrew R. Solow**, Woods Hole Oceanographic Institution, appointed by the Divison on Earth and Life Studies, who was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

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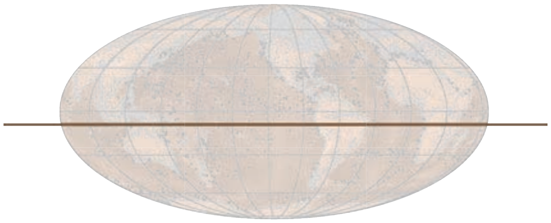

# Summary

U.S.-supported scientific ocean drilling has a long and illustrious history—from its earliest roles in the confirmation of plate tectonics to more recent contributions in paleoclimate and global sea level reconstructions. As the current phase of scientific ocean drilling draws to a close in 2013, the National Science Foundation (NSF) requested that an ad hoc National Research Council committee review the scientific accomplishments of U.S.-supported scientific ocean drilling over the past four decades. The committee evaluated how the programs (Deep Sea Drilling Project [DSDP], 1968-1983, Ocean Drilling Program [ODP], 1984-2003, and Integrated Ocean Drilling Program [IODP], 2003-2013) have shaped understanding of Earth systems and Earth history and assessed the role of scientific ocean drilling in enabling new fields of inquiry. The committee also assessed the potential for transformative discoveries[1] resulting from implementation of the science plan for the next proposed phase of scientific ocean drilling, which is scheduled to run from 2013 to 2023 if funding is approved by NSF.

## SCIENTIFIC ACCOMPLISHMENTS

**The committee found that the U.S.-supported scientific ocean drilling programs (DSDP, ODP, and IODP) have been very successful, contributing significantly to a broad range of scientific accomplishments in a number of Earth science disciplines. In addition, the programs' technological innovations have strongly influenced these scientific advances. To a large extent, the success of IODP and prior scientific ocean drilling programs has been a result of strong international collaboration.** Following the broad themes in the IODP Initial Science Plan (2001), the committee identified three general areas in which there have been significant accomplishments: solid Earth cycles; fluids, flow, and life in the subseafloor; and Earth's climate history. Several of the scientific achievements that could not have been accomplished without scientific ocean drilling are listed in Box S.1.

Scientific ocean drilling fundamentally advanced the fields of plate tectonics, paleomagnetism, geomagnetism, and geochronology. It has been critical to understanding connections between subseafloor fluid flow, microbial communities, and massive sulfide deposits. Technology pioneered by scientific ocean drilling enabled the recovery of intact gas hydrates, strongly influencing the understanding of gas hydrate distribution for economic and geohazard objectives. DSDP and ODP were integral to the study of continental breakup, in conjunction with onshore and offshore geophysical and geologic exploration and geodynamic modeling. Scientific ocean drilling has contributed to increased understanding of lithospheric formation and structure, and to connecting the occurrence of submarine large igneous provinces with volcanic eruption-related climate change. It also played a central role in deciphering the relationship between atmospheric carbon dioxide and global surface temperatures, glacial-interglacial cycles, global sea level change, ocean anoxia events, and the discovery of large climate excursions and abrupt climate change. In addition, scientific ocean drilling lent credence to the meteorite impact hypothesis as a paradigm for global extinction processes, a mainstay of modern Earth science education.

Since their earliest days, scientific ocean drilling programs have actively engaged in educating graduate students

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[1] NSF's definition of transformative research is: "Transformative research involves ideas, discoveries, or tools that radically change our understanding of an important existing scientific or engineering concept or educational practice or leads to the creation of a new paradigm or field of science, engineering, or education. Such research challenges current understanding or provides pathways to new frontiers." See http://www.nsf.gov/about/transformative_research/definition.jsp; accessed August 2011.

### Box S.1
### Scientific Accomplishments That Could Not Have Been Achieved Without Scientific Ocean Drilling

**Solid Earth Cycles**

- Verification of the seafloor spreading hypothesis and plate tectonic theory
- Development of an accurate geological time scale for the past 150 myr
- Confirmation that the structure of oceanic lithosphere is related to spreading rate
- Exploration of the emplacement history of submarine large igneous provinces
- Contribution to a new paradigm for continental breakup due to studies of rifted margins
- Definition of subduction zone inputs and confirmation of subduction erosion

**Fluids, Flow, and Life in the Subseafloor**

- In situ investigation of fluid flow processes, permeability, and porosity in ocean sediments and basement rocks
- Characterization of the sediment- and rock-hosted subseafloor microbial biosphere
- Study of subseafloor water-rock interactions and the formation of seafloor massive sulfide deposits in active hydrothermal systems
- Examination of the distribution and dynamics of gas hydrates in ocean sediments

**Earth's Climate History**

- Reconstruction of global climate history for the past 65 myr, based on ocean sediments
- Development and refinement of the Astronomical Geomagnetic Polarity Timescale
- Documentation of the pervasive nature of orbital forcing on global climate variability
- Recognition of past geological analogs (for example, the Paleocene-Eocene Thermal Maximum) for Earth's response to increases in atmospheric carbon dioxide
- Discovery of the history of polar ice sheet initiation, growth and variability, and their influence on fluctuations in global sea level

in the Earth sciences. During ODP, informal activities aimed at undergraduates, K-12, and community outreach were initiated. More structured and extensive programs during IODP included a vigorous education initiative aimed at K-12, undergraduate, graduate, and informal science educators. The education, outreach, and capacity-building programs are of significant value, but evaluations of each of them would enable a better understanding of the impacts of these activities on different groups and would demonstrate the broader impacts of scientific ocean drilling.

**RECOMMENDATION: Formal evaluation of education, outreach, and capacity-building activities should be implemented to demonstrate the broader impacts of scientific ocean drilling.**

## ASSESSMENT OF THE 2013-2023 SCIENCE PLAN

The committee also assessed the potential for future transformative scientific discoveries envisioned in *Illuminating Earth's Past, Present, and Future: The International Ocean Discovery Program Science Plan for 2013-2023*, which was released in June 2011 by Integrated Ocean Drilling Program Management International. The science plan is divided into four research themes: climate and ocean change, biosphere frontiers, Earth connections (deep Earth processes), and Earth in motion (direct time series observations on human scales). There are 14 scientific challenges within these four themes, which the committee evaluated individually for potential for transformative discovery, synergy between science plan challenges and themes, and linkages to NSF-supported and other research programs. **Each of the four themes within the science plan identifies compelling challenges with potential for transformative science that can only be addressed by scientific ocean drilling. Some challenges within these themes appear to have greater potential for transformative science than others.**

The committee was particularly positive about the potential for transformative discoveries resulting from subseafloor biosphere exploration and for continuing paleoclimate investigations to provide constraints on projected climate change. It also noted the need for data in underrepresented regions such as high latitudes and for deeper sampling into intact ocean crust. The themes and challenges identified in the science plan were well-justified and timely, although there was a lack of guidance as to which challenges were most important.

**RECOMMENDATION: The scientific ocean drilling community should establish a mechanism to prioritize the challenges outlined in the science plan in a manner that complements the existing peer-review process.**

The scientific ocean drilling programs have a history of making excellent use of legacy samples and data that have helped to quickly advance new areas of research. **Using legacy data and samples to their maximum capabilities will continue to increase the scientific value of the scientific ocean drilling programs. Expanded use of legacy materials could help, for example, with prioritization of drilling objectives in the next phase of scientific ocean drilling.**

There are several natural areas of synergy between the challenges and themes, and more detailed examination of potential integration would be valuable in lending strength to the overall program. Integration of scientific ocean drilling objectives is currently done in an ad hoc fashion during the expedition planning process.

**RECOMMENDATION: From the earliest stages of proposal development and evaluation, possibilities for increasing program efficiency through integration of multiple objectives into single expeditions should be considered by proponents and panels.**

Transformative discoveries are critically dependent on technological breakthroughs, and it is essential for future scientific ocean drilling programs to continue to advance a technological agenda. This is an area where prior programs have demonstrated great strength.

**RECOMMENDATION: Pathways for innovations in technology should be encouraged. In addition, setting aside some resources specifically to promote technological research and development could increase the potential for transformative science.**

# 1

# Introduction to U.S. Scientific Ocean Drilling

For more than 40 years, results from scientific ocean drilling have contributed to global understanding of Earth's biological, chemical, geological, and physical processes and feedback mechanisms. The majority of these internationally recognized results have been derived from scientific ocean drilling conducted through three programs—the Deep Sea Drilling Project (DSDP; 1968-1983), the Ocean Drilling Program (ODP; 1984-2003), and the Integrated Ocean Drilling Program (IODP; 2003-2013)—that can be traced back to the first scientific ocean drilling venture, Project Mohole, in 1961. Figure 1.1 illustrates the distribution of drilling and sampling sites for each of the programs, and Appendix A presents tables of DSDP, ODP, and IODP legs and expeditions. Although each program has benefited from broad, international partnerships and research support, the United States has taken a leading role in providing financial continuity and administrative coordination over the decades that these programs have existed. Currently, the United States and Japan are the lead international partners of IODP, while a consortium of 16 European countries and Canada participates in IODP under the auspices of the European Consortium for Ocean Research Drilling (ECORD). Other countries (including China, Korea, Australia, New Zealand, and India) are also involved.

As IODP draws to a close in 2013, a new process for defining the scope of the next phase of scientific ocean drilling has begun. *Illuminating Earth's Past, Present, and Future: The International Ocean Discovery Program Science Plan for 2013-2023*[1] (hereafter referred to as "the science plan"), which is focused on defining the scientific research goals of the next 10-year phase of scientific ocean drilling, was completed in June 2011 (IODP-MI, 2011). The science plan was based on a large, multidisciplinary international drilling community meeting held in September 2009.[2] A draft of the plan was released in June 2010 to allow for additional comments from the broader geoscience community prior to its finalization. As part of the planning process for future scientific ocean drilling, the National Science Foundation (NSF) requested that the National Research Council (NRC) appoint an ad hoc committee (Appendix B) to review the scientific accomplishments of U.S.-supported scientific ocean drilling (DSDP, ODP, and IODP) and assess the science plan's potential for stimulating future transformative scientific discoveries (see Box 1.1 for Statement of Task). According to NSF, "Transformative research involves ideas, discoveries, or tools that radically change our understanding of an important existing scientific or engineering concept or educational practice or leads to the creation of a new paradigm or field of science, engineering, or education. Such research challenges current understanding or provides pathways to new frontiers."[3] This report is the product of the committee deliberations on that review and assessment.

## HISTORY OF U.S.-SUPPORTED SCIENTIFIC OCEAN DRILLING, 1968-2011

The first scientific ocean drilling, Project Mohole, was conceived by U.S. scientists in 1957. It culminated in drilling 183 m beneath the seafloor using the *CUSS 1* drillship in 1961. During DSDP, Scripps Institution of Oceanography was responsible for drilling operations with the drillship *Glomar Challenger*. The Joint Oceanographic Institutions for Deep Earth Sampling (JOIDES), which initially consisted of four U.S. universities and research institutions, provided scientific advice. Among its numerous achievements, DSDP

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[1] See http://www.iodp.org/Science-Plan-for-2013-2023/.

[2] See http://www.marum.de/en/iodp-invest.html.

[3] See http://www.nsf.gov/about/transformative_research/definition.jsp.

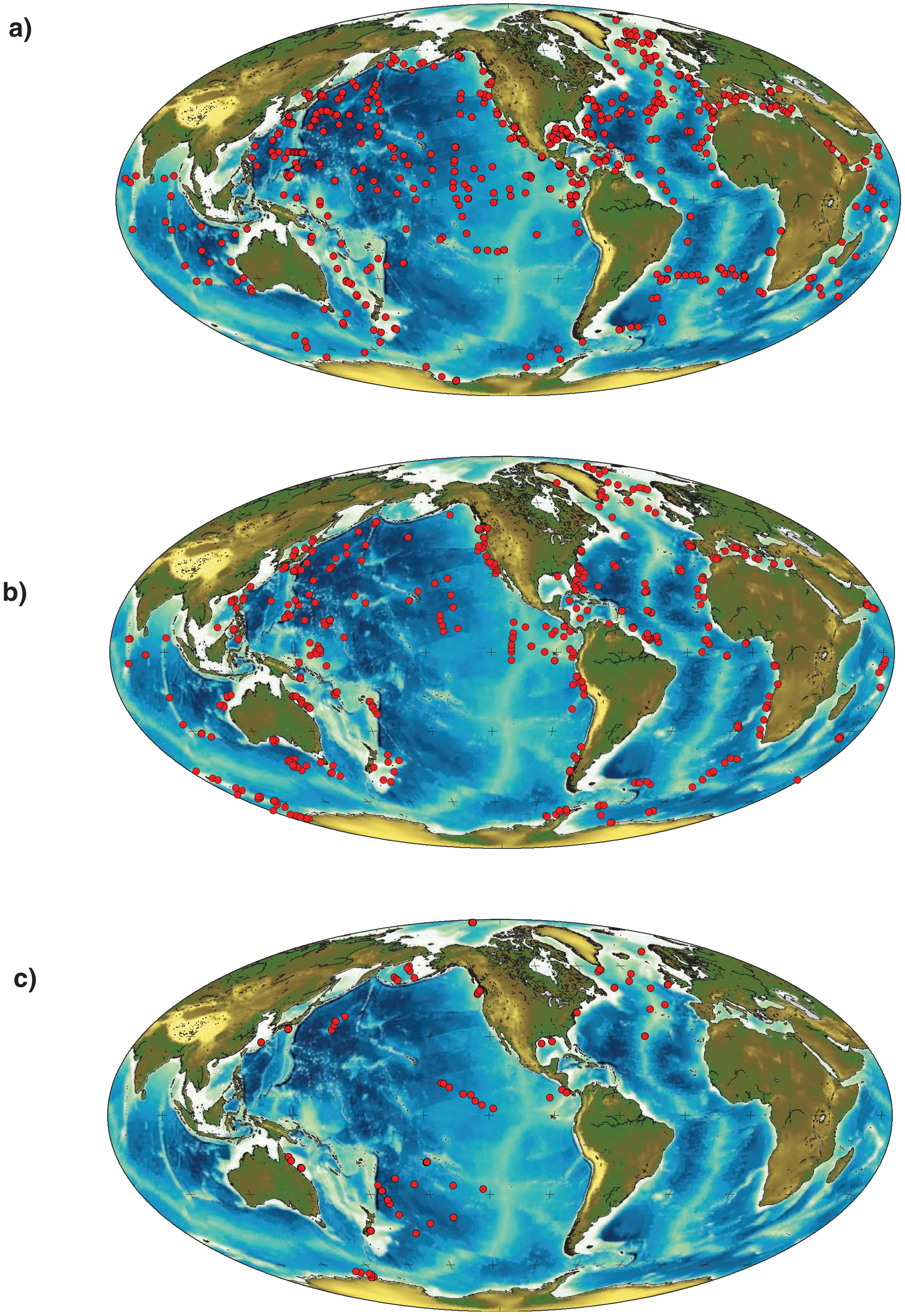

**FIGURE 1.1** Global distribution of drill holes and sampling sites from (a) DSDP, (b) ODP, and (c) IODP over four decades of scientific ocean drilling. Drill-hole symbols are greatly exaggerated in size. The depths of the drill holes also vary significantly, depending upon scientific objectives and technical and logistical considerations at each site. This is a Mollweide (equal area) projection with a color range of -9,000 to 9,000 m, with white marking the 0 m depth. SOURCE: IODP-USIO.

## Box 1.1
### Statement of Task

The National Science Foundation has requested that the National Research Council appoint an ad hoc committee to review the scientific accomplishments of U.S.-supported scientific ocean drilling (Deep Sea Drilling Project [DSDP], Ocean Drilling Program [ODP], and Integrated Ocean Drilling Program [IODP]) and assess the potential for future transformative scientific discoveries. The study committee will undertake two tasks:

1. Identification of DSDP, ODP, and IODP scientific accomplishments and analysis of their significance, with an emphasis on evaluating how scientific ocean drilling has shaped understanding of Earth systems and history. Additional emphasis will be placed on assessing the extent to which the availability of deep ocean drilling capabilities has enabled new fields of inquiry. The analysis will include consideration of the drilling programs' contributions to capacity building, science education, and outreach activities. The study will not consider organizational framework.
2. Assessment of the potential for transformative scientific discovery resulting from implementation of the draft science plan for the next proposed phase of international scientific ocean drilling (2013-2023). This assessment will include advice on opportunities resulting from stronger collaboration between ocean drilling and other NSF-supported science programs and research facilities.

provided conclusive evidence for the theory of seafloor spreading and added critical information that was the principal driver for the development of plate tectonic theory. DSDP also contributed significantly to the development of the fields of paleoceanography and paleoclimatology and developed piston coring technology that enabled better recovery of core samples. The International Phase of Ocean Drilling (DSDP IPOD) began in 1975, with the recognition that the most effective means of scientific ocean drilling was through a cooperative, international program whereby nations could share intellectual and financial resources. In many ways, the DSDP IPOD phase was a precursor for IODP, because it enacted a model for sharing financial resources between interested nations instead of having only U.S.-funded science and program management. The Shirshov Institute of Oceanology in Moscow was the first international partner, and by 1975 JOIDES included nine U.S. institutions and five international participants.

ODP continued international scientific ocean drilling through the 1980s and 1990s under the primary leadership of the United States, with 18 nations participating. The *JOIDES Resolution*, a new ocean drillship (Figure 1.2), was converted from use in the oil industry to use in scientific ocean drilling for this program. The *JOIDES Resolution*'s drilling facilities enabled more effective drilling in both deep and shallow water depths and had better shipboard laboratories than the *Glomar Challenger*. These technological improvements facilitated the understanding of continental rifting and Earth's climate history and the development of the global Geomagnetic Polarity Timescale. ODP also significantly moved forward the investigation and understanding of challenging oceanic environments, such as gas hydrates and hydrothermal vents. Throughout ODP, Texas A&M University (TAMU) was responsible for drilling operations, and Lamont-Doherty Earth Observatory of Columbia University (LDEO) was responsible for downhole logging activities. Core repositories were developed at several locations in the United States and Germany before the ODP phase of scientific ocean drilling concluded (Table 1.1). ODP also saw advancement in the use of boreholes for continued study of the subseafloor. While direct sampling through the acquisition of cores and downhole logging of data continued, new experimental approaches to seal drill holes and place in situ sensors led to the creation of long-term subseafloor observatories (see Box 3.2 in Chapter 3). Those dual uses of scientific ocean drilling continue to increase in importance.

The most recent program, IODP, has used a process-oriented approach to conduct research within three broadly defined, global scientific themes: (1) the deep biosphere and the subseafloor ocean; (2) environmental change, processes, and effects; and (3) solid Earth cycles and geodynamics (IODP, 2001). Japan and the United States have co-led the program of 24 countries and, together with a consortium of European countries and Canada, have provided multiple types of drilling platforms with new capabilities. These platforms have greatly expanded the scope of research addressed by scientific ocean drilling and have provided an example of best practices in international scientific cooperation (Box 1.2).

> **To a large extent, the success of IODP and prior scientific ocean drilling programs has been a result of strong international collaboration.**

During IODP, the core repository in Japan was established, and the Japanese riser drillship *Chikyu* (Figure 1.2) entered service. *Chikyu* is able to drill in water up to 2,500 m deep and can drill holes up to 7,000 m total.[4] *JOIDES Resolution* underwent a major refurbishment (2006-2009), increasing laboratory space by 34 percent, which led to greater efficiency in core handling, improved berthing arrangements, enhanced drilling capability, and better ship stability. The ship re-entered active service with the ability to drill more

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[4] See http://www.jamstec.go.jp/chikyu/eng/CHIKYU/data.html.

**FIGURE 1.2** Current scientific ocean drilling vessels: (left) *JOIDES Resolution* and (right) *Chikyu*. *JOIDES Resolution* was refurbished from 2006 to 2009. *Chikyu* began service in 2005. SOURCE: Used with permission from IODP.

**TABLE 1.1** Scientific Ocean Drilling Core Repository Data

| | Gulf Coast Repository (TAMU) | Bremen Core Repository (Germany) | Kochi Core Center (Japan) |
|---|---|---|---|
| Year established | 1985 | 1994 | 2005 |
| Geographic region covered | Pacific (east of western plate boundary), Caribbean Sea, Gulf of Mexico, Southern Ocean (south of 60°S except Kerguelan Plateau) | Atlantic and Arctic Oceans (north of Bering Strait), Mediterranean and Black Seas | Pacific (west of western plate boundary), Indian Ocean (north of 60°S), Kerguelan Plateau, Bering Sea |
| Total amount of core (km) | 125 | 141 | 93 |
| Total sample requests | 4,406 | 4,591 | 2,380 |
| Total samples taken | 1,138,799 | 1,249,652 | 342,715 |

SOURCE: Data from IODP-USIO, 2011, and http://www.iodp.org/repositories/2/.

than 2 km into the ocean floor, and in waters as deep as 6,000 m and as shallow as 75 m.[5] TAMU and LDEO, respectively, continue to be responsible for drilling and downhole logging operations. In addition, ECORD manages the use of mission-specific platforms for expeditions that require capabilities beyond those of the U.S. and Japanese drillships (e.g., drilling coral reefs, shallow waters, or high-latitude areas). IODP results have built upon previous program results to increase understanding of relationships between glaciation, sea level changes, ocean circulation, and atmospheric carbon dioxide; past climate change; the deep biosphere; evolution of large igneous provinces; occurrence of bolide impacts; and investigation of fluids and slope failure in the seafloor.

More than 26,000 publications have resulted from these four decades of scientific ocean drilling research, including program reports, maps, abstracts, and other peer- and non-peer-reviewed publications. About one-third of these publications have been in peer-reviewed journals, including more than 400 in *Science, Nature,* and *Nature Geoscience* (IODP-MI, 2011). In addition to contributing to research, scientific ocean drilling has fostered an integrated approach to the study of Earth's history. Drilling samples are collected in an integrated biological, geochemical, geophysical, sedimentological, and structural context that has been framed in a well-defined pre-drill site survey. Some samples are carriers of chemical proxies for the environment of deposition or formation, while others are part of a distinct biogeochemical community.

It is also important to note the impact that scientific volunteers brought to achieving the goals of scientific ocean drilling. Early, mid-career, and internationally established scientists recognized that scientific ocean drilling would open many new fields of inquiry, and they responded by volunteering substantial amounts of time and energy to initiate the overall program and to sustain it through the decades.

## TECHNICAL ACHIEVEMENTS OF U.S.-SUPPORTED SCIENTIFIC OCEAN DRILLING

In concert with the wide range of scientific successes that DSDP, ODP, and IODP have achieved across a wide

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[5] See http://www-odp.tamu.edu/publications/tnotes/tn31/jr/jr.htm.

### Box 1.2
### IODP as an International Best Practice

IODP is by far the largest Earth science effort to date. Twenty-four countries contribute, with the United States and Japan as the leading participants. The coordinated use of core samples, drillships, and mission-specific platforms has resulted in a community- and facility-oriented approach and a concentration of effort by a diverse group of scientists. Since the early days of scientific ocean drilling, priorities and technological developments have been driven by scientific needs, and this is still the case for IODP. An open application process and transparent, science-based peer reviews of proposals guarantee that scientists from all participating countries are given equal opportunities to set scientific and programmatic goals. The current IODP structure is designed to ensure that proposals are aligned with strategic priorities of an internationally agreed-upon science plan and evaluated on their scientific merits, but also takes feasibility and risk into account. The evaluation process is designed to counteract vested national interests that can plague large, international, scientific cooperative programs.

When a decision is made on a specific drilling target, IODP issues a second call to scientists from participating countries, asking them to take part on a drilling cruise by proposing add-on projects or by applying to participate as experts in already planned projects. The second call provides an important opportunity for young scientists and graduate students from many disciplines in Earth and environmental sciences to engage in scientific ocean drilling and work alongside leading geoscientists. The experience they gain builds capacity for a future career in the ocean sciences by providing access to a global, multidisciplinary scientific network, as well as by offering unique opportunities and facilities for original research.

span of fields, scientific ocean drilling has excelled in generating innovative technologies. Box 1.3 highlights some of the ground-breaking achievements of Project Mohole and follow-on scientific ocean drilling programs. Later boxes (in Chapters 2-4) provide further details of scientific ocean drilling technologies that have helped advance scientific discovery. These accomplishments occurred in concert with attempts by program scientists to answer questions of increasing complexity about processes affecting the Earth system, including the solid Earth, hydrosphere, and atmosphere. Some of these spin-off technologies have had an enormous impact on the evolution of commercial deepwater drilling and oceanographic research. Dynamic positioning (maintaining position through the use of propellers rather than an anchor; Box 1.3), deepwater coring equipment and practices (Boxes 2.2 and 4.3), taking measurements while coring (Box 3.1), long-term borehole monitoring (Box 3.2), and the ability to obtain drill cores in a variety of environmental conditions (Box 3.4) have all been spearheaded by scientific ocean drilling programs. Several of these technological developments, especially those that allow real-time borehole monitoring, have provided additional safety and hazard assessment tools that permit riserless drilling in difficult environments. The drilling statistics in Table 1.2 demonstrate the general increase in penetration depth of the drill cores as well as percentage core recovery as the programs have evolved (also see Figure 1.3).

## OVERARCHING CONCLUSIONS

In response to the first charge in the Statement of Task, the committee identified noteworthy scientific and technological advancements and new fields of inquiry spurred by results accomplished through four decades of scientific ocean drilling. Outstanding questions that have yet to be answered within each major field of study are also outlined. Although these achievements are explored in much more detail in following chapters, the committee felt that a conclusion describing the overall worth of the scientific ocean drilling enterprise was warranted.

> **The committee found that the U.S.-supported scientific ocean drilling programs (DSDP, ODP, and IODP) have been very successful, contributing significantly to a broad range of scientific accomplishments in a number of Earth science disciplines. In addition, their innovations in technology have strongly influenced these scientific advances.**

The second task focused on assessing the science plan, *Illuminating Earth's Past, Present, and Future: The International Ocean Discovery Program Science Plan for 2013-2023* (IODP-MI, 2011), that was produced for the next phase of scientific ocean drilling.

> **The committee found that each of the four themes within the science plan identifies compelling challenges with potential for transformative science that can only be addressed by scientific ocean drilling. Some challenges within these themes appear to have greater potential for transformative science than others.**

## REPORT ORGANIZATION

For the first task, numerous reports by ODP and IODP have summarized the major accomplishments during specific phases of the program's existence (e.g., JOI, 1990, 1996,

## Box 1.3
## Innovations in Riserless Drilling: Project Mohole and Beyond

In 1957, a number of prominent scientists suggested an ambitious project to drill to the Mohorovičić discontinuity (Moho), the sharp increase in seismic velocity 4 to 6 km below the seafloor in the ocean and 30 to 40 km below the surface of the continents. Such a project would require drilling in far deeper water than the routine depths of 20 to 50 m that commercial drilling attempted at the time. There were two major hurdles to accomplishing this feat: drilling in deep water without anchoring (the standard practice for drill ships at that time), and drilling or coring without a riser (a pipe with an outer casing, allowing drilling fluid to circulate between the ship and borehole while maintaining constant pressure within the borehole; see figure below). From 1958 to 1961, many engineering challenges associated with deep scientific ocean drilling were discussed and new approaches designed: a dynamic positioning (DP) system consisting of four shipboard propellers and a series of sonar buoys; a guide shoe to relieve stress on the drill string; a landing base for hole re-entry; and diamond drill bits for biting into hard rock (NRC, 2000; Winterer, 2000; Pete Johnson, PowerPoint presentation, 2011).

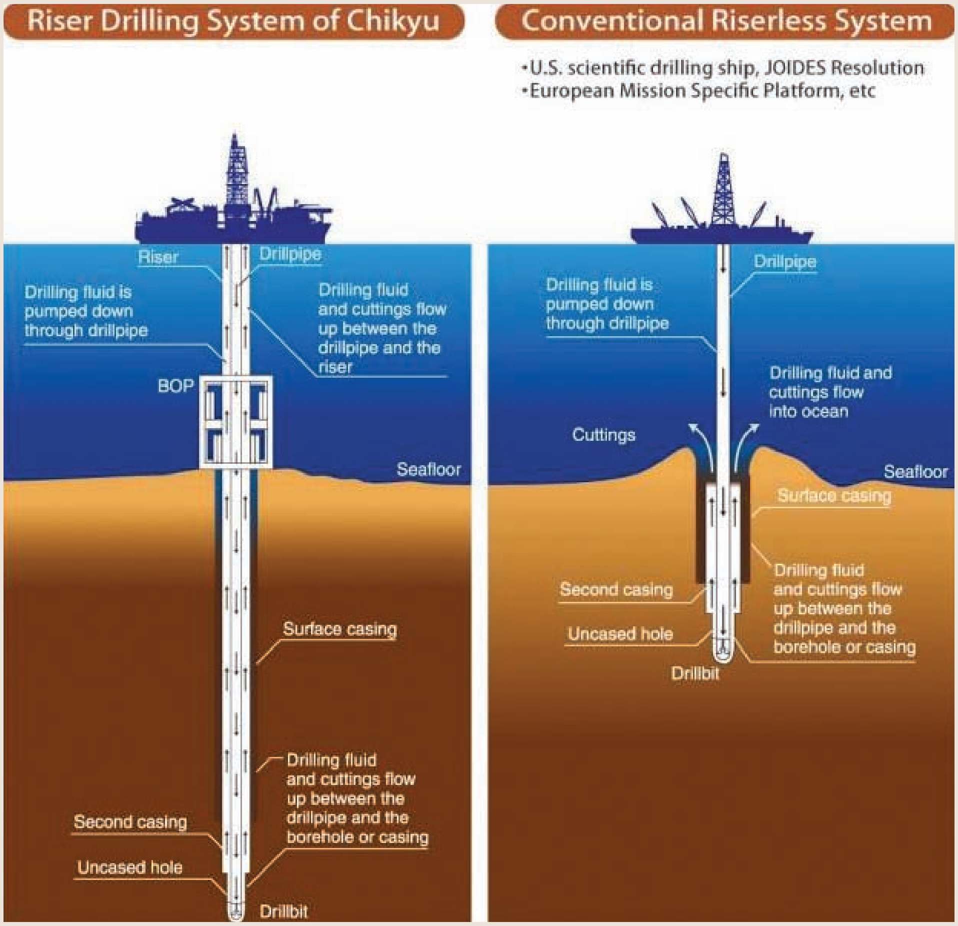
During the March 1961 Project Mohole cruise, the *CUSS 1* drillship used dynamic positioning to maintain its position over a small circle at a site in the Pacific Ocean offshore of Guadalupe Island, Mexico. The scientists and engineers aboard the ship managed to retrieve both soft sediment and basement rock, reaching a depth of 183 m beneath the seafloor while drilling in 3,570 m of water (NRC, 2000). This definitively proved that an unanchored drillship could maintain station in deep water and have continuous drilling or coring operations. Today, the majority of modern deepwater drillships and other self-contained floating drilling machines (also referred to as mobile offshore drilling units) have DP systems that can maintain a watch circle of 3 to 10 m under normal surface conditions (Ambrose et al., 2003). Without DP systems, many deepwater oil and gas discoveries worldwide would not have been economically viable. In some cases these sites could not have been drilled without DP, especially in water depths beyond 2,000 m (Smith and Parlas, 1979).

Conventional offshore drilling in the 1960s and 1970s with a mobile offshore drilling unit was limited by water depth because of the heavy riser pipe and blowout preventers required for well control purposes. Drilling for sediments and hard rock, while specifically avoiding hydrocarbon formations, could instead be done without a riser system and blowout preventers. The DSDP drillship *Glomar Challenger* was specially built to do non-riser drilling by circulating drilling fluids through the drill pipe and out the borehole to the ocean. This practice ultimately led to the now-common deepwater oil field practice of drilling a surface hole before the first long string of casing is installed and a riser employed. The next drillship for scientific ocean drilling, the *JOIDES Resolution*, was converted from a commercial oil drillship to a riserless scientific vessel. The *JOIDES Resolution* improved capability for scientific ocean drilling because it could drill in deeper and shallower water depths, had superior station-keeping capabilities, and better heave compensation (Cullen, 1994; NRC, 2000).

**TABLE 1.2** Scientific Ocean Drilling Technical Achievements

| Program | Distance Traveled (nmi) | Total Cored (km) | Total Core Recovered (km) | Number of Sites Visited | Deepest Core Penetration (m) | Deepest Water Depth (m) | Number of Cores Recovered |
|---|---|---|---|---|---|---|---|
| DSDP | 375,632 | 170 | 97 | 624 | 1,741 | 7,044 | 19,119 |
| ODP | 355,781 | 321 | 222 | 669 | 2,111 | 5,980 | 35,772 |
| IODP[a] | 81,008 | 40 | 33 | 91 | 1,928 | 5,708 | 4,840 |

[a] Through April 2011. There were commissioning delays with *Chiyku* and shipyard delays with *JOIDES Resolution* that led to fewer expeditions and core drilled than were otherwise expected. SOURCE: Data from IODP-USIO, 2011.



Riser drilling configuration (left) and riserless drilling configuration (right). SOURCE: JAMSTEC/IODP.

1997, 2004; IODP, 2001; Gröschel, 2002; ODP, 2007). Initial and technical reports related to specific DSDP,[6] ODP,[7] and IODP[8] legs also provided detailed information. The committee reviewed those reports as well as previous external assessments (e.g., NRC, 1992) and community-led activities. The information-gathering process also included presentations by and discussions with DSDP, ODP, and IODP scientists and engineers, program managers, and invited speakers in a variety of scientific disciplines during the June 2010 committee workshop in College Station, Texas. The committee commissioned white papers from the workshop speakers (see Appendix C); some of this report's contents build upon those materials.

Scientific ocean drilling accomplishments are organized into three chapters that follow the broad IODP themes: solid Earth cycles (Chapter 2); fluids, flow, and life in the subseafloor (Chapter 3); and Earth's climate history (Chapter 4). Those chapters present the analyses of significant accomplishments in 14 solid Earth and oceanographic areas, the accomplishments' impacts on understanding the Earth

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[6] See http://www.deepseadrilling.org/index.html.

[7] See http://www-odp.tamu.edu/publications/.

[8] See http://www.iodp.org/scientific-publications/.

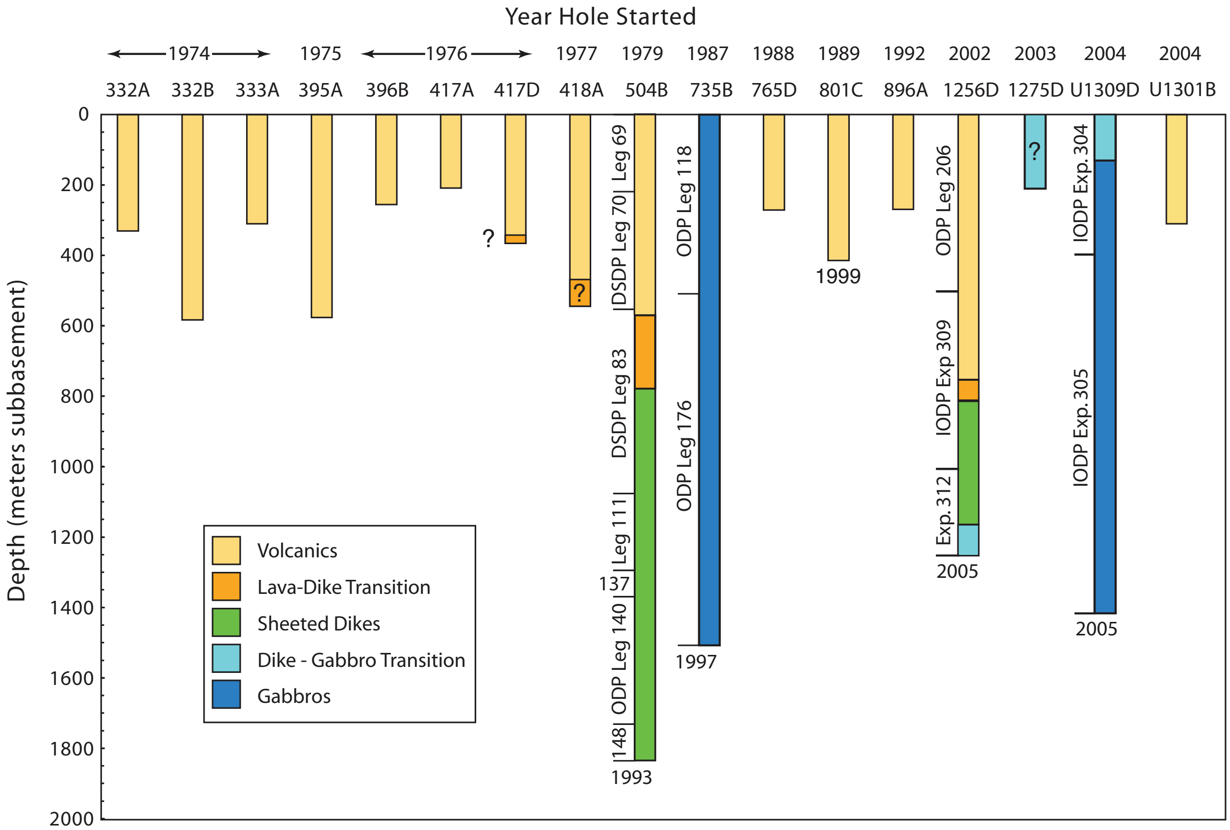


**FIGURE 1.3** Graphical representation of DSDP, ODP, and IODP holes drilled between 1974 and 2005 that extend more than 200 m into ocean crust. The most striking observation on this diagram is that most of the holes are shallower than 500 m and sample only the volcanic section (pillows and sheeted dikes) of the basement below the sedimentary cover. SOURCE: Modified from Dick et al., 2006.

system and their importance in developing new fields of inquiry, and identification of goals not yet accomplished. The report also examined capacity building, education, and outreach conducted through DSDP, ODP, and IODP (Chapter 5).

For the second task, the committee relied upon presentations by the science plan writing team, discussions with representatives from IODP and NSF, and review of the plan itself. The committee was presented with several versions of *Illuminating Earth's Past, Present, and Future: The International Ocean Discovery Program Science Plan for 2013-2023* (IODP-MI, 2011) during the course of the study. The draft plan was released in June 2010; the committee met with science plan writing team members during the September 2010 meeting. The committee also received some revised chapters in September and October 2010, which were significantly different in both content and style from the June 2010 version. Revisions continued throughout the rest of 2010, and the revised document was reviewed by an external panel of eight international scientists in early 2011 (IODP-MI, 2011). The final science plan was released in June 2011 and provides the basis for the committee's assessment of future opportunities for transformative science through scientific ocean drilling (Chapter 6). The committee also identified linkages between scientific ocean drilling, other NSF-supported programs, and non-NSF programs.

# 2

# Scientific Accomplishments: Solid Earth Cycles

Data from scientific ocean drilling have offered important insights through which we have begun to better understand solid Earth cycles, including the interaction and evolution of Earth's crust, mantle, and core. Changes in Earth's magnetic field, the processes of continental rifting, the subduction of oceanic lithosphere, and voluminous outpourings of magma onto the crust, for example, are significant manifestations of solid Earth cycles and are recorded in rocks on the ocean floor. The following sections review the scientific accomplishments and new fields of inquiry that scientific ocean drilling results have fostered in our knowledge of the solid Earth. Some of the remaining challenges about the solid Earth to which scientific ocean drilling can contribute are also discussed.

## GEOMAGNETISM

Earth's magnetic dipole field, generated in the liquid outer core, undergoes occasional reversals that are recorded in rocks containing iron-bearing magnetic (ferromagnetic, *sensu lato*) minerals. Because of the globally contemporaneous nature of Earth's magnetic field reversals, rocks preserving these magnetic signatures can be precisely dated and can serve as markers for the frequency and duration of magnetic reversals through geologic time. These kinds of magnetic minerals are typically abundant in basaltic rocks (such as ocean crust) and in some fine-grained sedimentary rocks overlying the ocean crust. Researchers involved in scientific ocean drilling have been able to take advantage of the magnetic properties of these rocks for more than four decades, spurring numerous fundamental discoveries, for example, about the age of the ocean crust, the way in which ocean crust is generated and destroyed, the timing of climatic oscillations, and the development of accurate geologic time scales.

### Scientific Accomplishments and Significance

The most widely known scientific accomplishment for which scientific ocean drilling was essential is the verification of the seafloor spreading hypothesis (Box 2.1), a lynchpin for establishing the paradigm of plate tectonics in the early 1970s. Scientific ocean drilling focused on obtaining ages of the seafloor magnetic reversal stratigraphy and corresponding biostratigraphic ages of sediments at successive distances from the Mid-Atlantic Ridge axis; these data confirmed the increasing age of ocean crust away from seafloor spreading centers. The landmark verification of the seafloor spreading hypothesis occurred as a result of the earliest Deep Sea Drilling Project (DSDP) cruises and particularly with data from DSDP Leg 3, which drilled to the top of the oceanic basement in the South Atlantic (e.g., Maxwell et al., 1970). Biostratigraphic, magnetostratigraphic, and isotope geochronologic analyses of seafloor samples from subsequent DSDP cruises (e.g., DSDP Legs 5, 6, 12) combined with similar data from continental sequences led to development of precise geologic time scales, specifically the Geomagnetic Polarity Time Scale (GPTS), which included astronomical, geomagnetic, and biostratigraphic calibrations (e.g., Berggren et al., 1985; Cande and Kent, 1995; Gradstein et al., 2004; Box 2.2). Another significant achieving of the scientific ocean drilling program was modeling the magnetic contributions of submarine source layers (basalt and gabbro), which matched the observed marine magnetic anomalies.

Beyond these first-order contributions, drill cores led to the discovery of variations in spreading rates between ocean basins and the age of the oldest ocean crust (e.g., DSDP Legs 9 and 69 and Ocean Drilling Program [ODP] Leg 138; Hayes et al., 1972; Wilson et al., 2003). A new way to confirm lateral seafloor spreading rates and the veracity of the GPTS came from analysis of vertical magnetic reversal stratigra-

## Box 2.1
## Confirmation of Seafloor Spreading

One of the earliest and most significant accomplishments of scientific ocean drilling was to provide data that confirmed seafloor spreading. Data and samples retrieved by the drillship *Glomar Challenger* in the early 1970s were used to confirm that new ocean crust was being generated at mid-ocean ridges, supporting the complete theory of plate tectonics, the paradigm for solid Earth science. Data from survey ships that provided geophysical evidence for the existence of symmetric, alternating patterns of magnetic polarity ("magnetic anomalies") on either side of the world's mid-ocean ridges led to suggestions by various scientists in the early 1960s that new ocean crust was being created there. However, these interpretations could not be conclusively substantiated in the absence of data directly obtained from the seafloor. In 1970, *Glomar Challenger* drilled a series of boreholes across the Mid-Atlantic Ridge in the South Atlantic and retrieved basal sediments that had been deposited on ocean crust. The biostratigraphic ages of those samples increased nearly linearly with distance from the ridge crest, in close agreement with the ages predicted by analysis of the magnetic anomalies on the seafloor. Confirmation of the theory of seafloor spreading had direct consequences for the development of new fields of scientific inquiry and cross-disciplinary geoscientific research.

SOURCES: Dietz, 1961; Hess, 1962; Vine and Matthews, 1963; Heirtzler et al., 1968; Maxwell et al., 1970.

phy recovered from ocean sediments at ODP Sites 677 and 846, where benthic and planktonic foraminiferal dates were correlated with Earth's orbital variations (e.g., Shackleton et al., 1990; also see Chapter 4). These results, in turn, have had implications for understanding of the composition and behavior of oceanic lithosphere, processes occurring at subduction zones, and the formation of large igneous provinces (LIPs) (see later sections of this chapter).

The development of hydraulic piston coring (HPC) and advanced piston coring (APC; see Box 2.2) allowed sampling of continuous undisturbed sediment cores from below the sediment-water interface to the crystalline bedrock (Prell et al., 1980; Ruddiman et al., 1986; also see Box 4.3). This unique achievement allowed the creation of a high-fidelity Cenozoic paleoceanographic/paleoclimatic time series by cross-validating magnetic dipole reversal stratigraphy from ocean core samples with higher resolution biostratigraphy and astronomically forced climate variations recorded in finely laminated ocean sediments (e.g., Hilgen, 1991). The basis for such an approach was first proposed by Shackleton and Opdyke (1973) when they dated high-resolution $\delta^{18}O$ stratigraphy with fixed-point magnetic reversal ages to yield multi-millennial-scale paleoclimate (i.e., global ice volume) records. When Hilgen (1991) extended his earlier cyclostratigraphic work to the Miocene-Pliocene boundary, it became possible to obtain three-way cross-validation of dated paleoclimate (biostratigraphy and lithostratigraphy based) records whose ultimate fixed-point dating scheme rested on the GPTS, synthesized from sediments of the world's oceans. A global approach to developing a precise astronomical time scale used many DSDP and ODP cores and enabled oxygen isotope excursions to be precisely dated (e.g., Lisiecki and Raymo, 2005; Box 2.2; also see Chapter 4).

Another method to correlate oxygen isotope changes with age and geomagnetic reversals or excursions uses the relative paleointensity of sediment cores (e.g., Channell et al., 2009; Figure 2.1). This method has provided independent age calibrations to which climate changes can be compared and is also valuable for understanding the behavior of Earth's magnetic field through time. Measurements of continuous relative geomagnetic paleointensity from long sediment cores have confirmed occurrence of intensity minima during dipole reversals and helped discover short-term dipole excursions.

Another accomplishment in the area of global plate motions and reconstructions came when cores collected on DSDP Leg 55 led to the initial recognition that the Hawaiian hotspot had not always been fixed at the latitude of Hawaii (Kono, 1980). In 1992, ODP Leg 145 cored a thickness of ocean floor basalt opposite Detroit Seamount, one of the oldest seamounts in the Hawaiian-Emperor chain, and determined that its paleomagnetic latitude of formation was well north of Hawaii (Tarduno et al., 2003). ODP Leg 197 provided compelling paleomagnetic evidence that from about 76 to 45 myr the Hawaiian hotspot was rapidly migrating southward to reach its present position, a finding that held implications for reconstructing past Pacific plate motions and also for the concepts of plume stability and mantle dynamics and circulation.

### Fields of Inquiry Enabled

Research derived from scientific ocean drilling has fundamentally influenced and advanced the fields of plate tectonics, paleomagnetism and geomagnetism, and geologic time scales. The combination of high-resolution magnetostratigraphy and relative paleointensity; oxygen isotope records as a proxy for changes in climate; and bio-, cyclo-, and lithostratigraphy have helped further the study of paleoclimate and paleoceanography (discussed in further detail in Chapter 4), which attests to the importance of cross-disciplinary approaches in advancing research of the ocean floor and Earth processes.

## Box 2.2
## The Development and Evolution of Geological Time Scales

Scientific ocean drilling has contributed significantly to the development of an accurate geological time scale for the past 150 million years (myr). The verification of seafloor spreading by dating basal age microfossils (Maxwell et al., 1970) tied together paleomagnetic reversal stratigraphy with seafloor magnetic anomalies and provided the first accurate time scales linking the age of ocean crust to the nannofossil and foraminiferal biostratigraphy of European uplifted marine sections (Berggren, 1969; Berggren et al., 1985). Building on this early success, the development of hydraulic and advanced piston corers (HPC and APC) in the late 1970s produced undisturbed marine sections that recorded paleomagnetic reversals, which allowed researchers to use changes in microfossil oxygen isotope chemistry controlled by long-term cycles in Earth's orbit (Milankovitch climate cycles) to date the paleomagnetic reversal stratigraphy. Previously these sections could only be recovered using traditional piston coring (Shackleton and Opdyke, 1973, 1976) in relatively recent marine sediments with slow sedimentation rates. The APC provided the first long, high-resolution records of oxygen isotope variations and paleomagnetic reversals, leading to the confirmation of the orbital theory of ice ages (Hays et al., 1976) and the observation of the pervasive fingerprint of orbital forcing on the marine record of climate change (further discussed in Chapter 4). Shackleton et al. (1990) extended the orbitally calibrated oxygen isotope chronology into the Pliocene in ODP Site 677 and noted that the dates of the magnetic reversals previously established by the radiometric dating of seafloor basalts were 5 to 7 percent younger than their predicted ages based on astronomical calibration, suggesting that the radiometric dates constraining the reversals were in error. Hilgen (1991) confirmed the Shackleton et al. (1990) observations through orbital tuning of uplifted Mediterranean marine sections and, in conjunction with the high-resolution oxygen isotope record from ODP Site 846 (Shackleton, 1995), further extended the time scale into the Miocene. The combined results of Shackleton et al. (1990, 1995) and Hilgen (1991) produced the first Astronomical Polarity Time Scale (Kent, 1999). Subsequent research showed that the K-Ar ages of the original time scales were indeed too young (Tauxe et al., 1992), and new $^{40}$Ar/$^{39}$Ar radiometric results showed the same ages as the orbitally tuned dates. Deeper and older recoveries with the APC and extended core barrel systems extended the orbital chronology continuously back to 5 myr: Lisiecki and Raymo (2005) combined 36 DSDP and ODP sites to produce an astronomical time scale for the marine oxygen isotope record of the past 5 myr. This work was subsequently extended back into the Cenozoic (Billups et al., 2004; Pälike et al., 2006; Westerhold et al., 2008) with an accuracy of several tens of thousands of years.

### Goals Not Yet Accomplished

As one of the earliest scientific ocean drilling fields, the field of geomagnetism has seen many of its goals accomplished. However, fundamental questions still remain in the mechanisms behind magnetic field reversals and extending temporal resolution of magnetic polarity stratigraphy. Continued work on paleomagnetism of deeper ocean crust (gabbros and ultramafic rocks) may address the sources of marine magnetic anomalies, providing observational benchmarks for geodynamo models of motions in Earth's liquid iron core. Unanswered questions related to high-resolution past climate change may also draw upon the combination of paleomagnetic, biostratigraphic, isotopic, and astronomical work on ocean cores for resolution.

## STRUCTURE, COMPOSITION, AND FORMATION OF OCEANIC LITHOSPHERE

Earth's lithosphere consists of the crust and the non-convecting portion of the upper mantle, formed by repeated magmatic activity at mid-ocean ridges. This magmatism is the dominant process helping to transfer mass and heat from Earth's interior. Approximately 62-75 percent of the global magma production rate of ~30 km$^3$/yr comes from mid-ocean ridge environments, with ~85 percent of this volume as plutonic rocks (predominantly gabbros) and the rest erupted on the ocean floor in the form of basaltic lava (Crisp, 1984). The oceanic lithosphere forms the outermost layer of the solid Earth and consists of this mafic crust (gabbros and basalts) and rigid ultramafic upper mantle (typically of peridotite composition); the crustal layer is about 5-10 km thick, and the upper mantle section can extend for another ~90 km below the crust.

Preliminary observations from results of scientific ocean drilling suggest that oceanic lithosphere compositions differ depending upon the spreading rate of the nearby ridge system (Box 2.3). The only way to obtain direct measurements of the properties of oceanic lithosphere to understand its composition, genesis, and structure, and the causes and consequences of different ridge spreading rates, is through the type of sampling enabled by scientific ocean drilling.

### Scientific Accomplishments and Significance

One motivation for early drilling into ocean crust was to assess whether oceanic lithosphere has a layered lithological structure from top to bottom of pillow basalts, sheeted dikes, gabbros, and ultramafic rocks (Box 2.3) in a manner similar

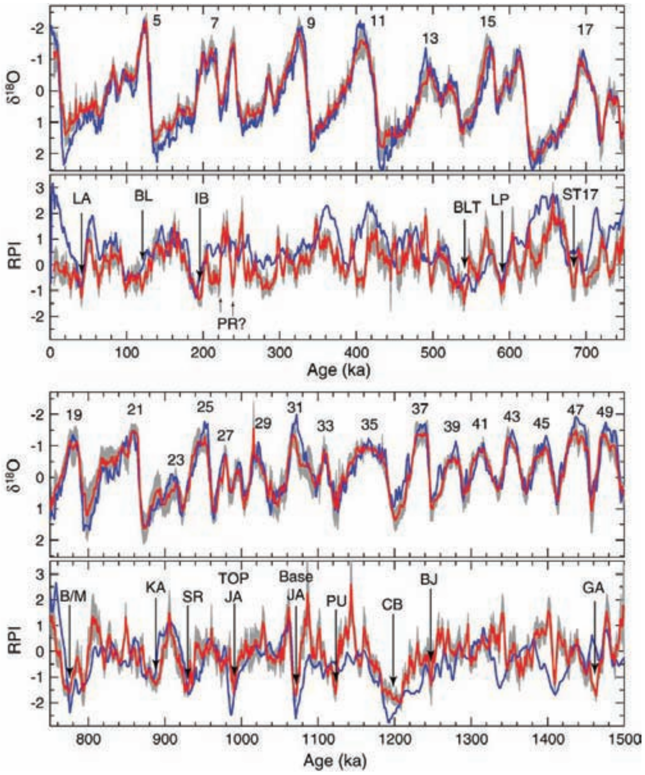


**FIGURE 2.1** Oxygen isotope ($\delta^{18}O$) and relative paleointensity (RPI). Half-width of the error envelope in both cases is $2\sigma$ (2 × standard error). The oxygen isotope stack (red) is compared with the LR04 benthic isotope stack (blue) (Lisiecki and Raymo, 2005). Paleointensity minima in the stack correspond to established ages of magnetic excursions and chron/subschron boundaries: LA-Laschamp, BL-Blake, IB-Iceland Basin, PR-Pringle Falls, BLT-Big Lost, LP-La Palma, ST17-Stage 17, B/M-Brunhes-Matuyama boundary, KA-Kamikatsutra, SR-Santa Rosa, JA-Jaramillo Subchron, PU-Punaruu, CB-Cobb Mountain Subchron, BJ-Bjorn, GA-Gardar. SOURCE: Channell et al., 2009.

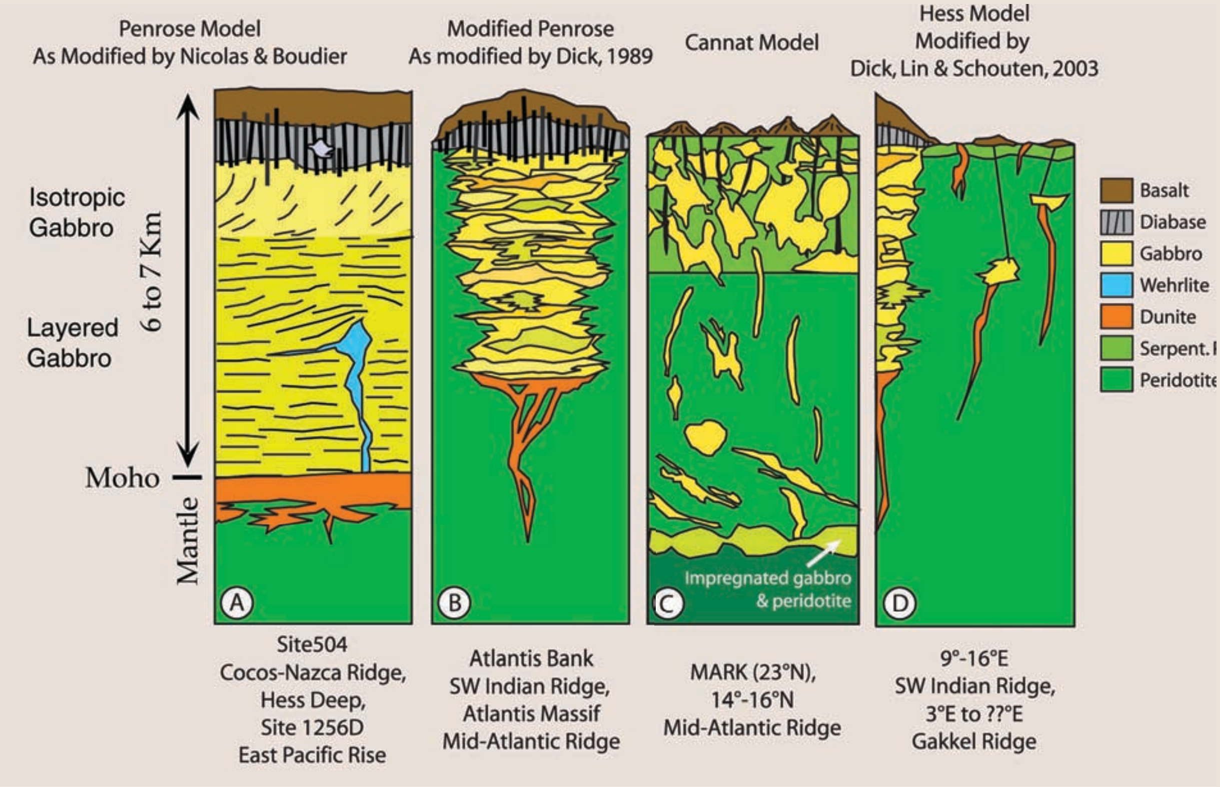
to the structure of ophiolites on land (called the "Penrose model" after a 1972 Penrose Field Conference consensus definition of ophiolite structure; Anonymous, 1972). Penetration into ocean crust was inaugurated by DSDP Leg 37 in 1974 at 37° N along the Mid-Atlantic Ridge. Although the total number of holes drilled into ocean crust between 1974 and the end of ODP in 2004 is about 50, these early efforts were hampered by technical difficulties in both penetrating the very dense crystalline rock and recovering samples. Only 17 of those 50 holes penetrated depths greater than 200 m into the crust, and only 7 holes reached depths greater than 500 m within crystalline rocks (Dick et al., 2006; Figure 1.3). One of these holes, 1256D, is notable for penetrating 1,507 m into superfast-spreading lithosphere produced at the East Pacific Rise. Not only did drilling reveal a classic, Penrose-type crust of pillow basalt, sheeted dikes, and gabbros, but it was also the first time a full, intact section was drilled, providing insight into oceanic crust formation (Teagle et al., 2006; Wilson et al., 2006).

These technological impediments to deeper drilling encouraged innovations: (1) improvements in drilling capabilities enabled by both ODP and IODP and (2) development of the concept of "tectonic windows," i.e., regions where strata that are usually deeply buried have been brought closer to or exposed on the seafloor through tectonic processes such as low-angle detachment faults (e.g., Ildefonse et al., 2007; Escartin et al., 2008). The innovation to sample these tectonic windows through scientific ocean drilling has made it possible to reach gabbroic and, in some cases, mantle sections of oceanic lithosphere (e.g., Cannat et al., 1997, 2006; Kelemen et al., 2004, 2007). ODP Hole 735B on Atlantis Bank in the Indian Ocean, for example, penetrated 1,508 m into gabbro (Dick et al., 1999); two Mid-Atlantic Ridge drill holes, 920D at 23° N and 1275 at 16° N, each penetrated ~200 m into mantle peridotite (Cannat et al., 1995; Kelemen et al., 2004); and ODP Hole 895D penetrated 94 m into peridotite exposed through rifted Pacific crust (Gillis et al., 1993). The presence of ultramafic rocks at or near the surface of the ocean floor at a number of slow and ultraslow spreading centers (e.g., Kelemen et al., 2004; Blackman et al., 2006) has resurrected the idea that the Hess model for oceanic lithosphere (i.e., serpentinized peridotite is overlain in igneous or tectonic contact by a thin layer of volcanic material; Hess, 1962) could apply to large sections of the oceanic lithosphere (Dick et al., 2003; Michael et al., 2003). Although most of the erupted lavas are focused on or are close to the ridge axial summit, mapping efforts combined with isotopic analyses of drilled samples and seismic surveys have shown that lateral magma transport may also occur through dikes in the shallow crust that erupt off-axis to form seamounts (Zou et al., 2002; Durant and Toomey, 2009).

Drilling innovations, such as the use of a re-entry cone guide to begin drilling hard rock formations and a drilling fluid-powered hammer to begin holes, have allowed re-entry to hard rock formations on the seafloor. Other innovations include testing of a mining-type continuous coring operation from a compensated platform, and mud motor-driven core barrels (Miller and Huey, 1992; Brewer et al., 2005). These improvements led to increases in the depths of holes drilled during IODP legs and in the amount of recovered core. For example, IODP Hole 1309D on the Atlantis Massif along the Mid-Atlantic Ridge penetrated to a depth of 1,415 m, and Hole 1256D in the equatorial east Pacific penetrated to 1,507 m (e.g., Blackman et al., 2006; Teagle et al., 2006; Wilson et al., 2006; Drouin et al., 2009).

Drilling on ODP Legs 147 and 209 confirmed the presence of abundant impregnated periodotites formed by partial crystallization of migrating mantle melt beneath the base of the crust and ODP Leg 209 and IODP Expeditions 304-305 substantiated that the lower crust was composed of many small sills rather than one large magma chamber (Mével

## Box 2.3
## Structure of Oceanic Lithosphere



The structure and thickness of oceanic lithosphere depend a great deal on spreading rates. An idealized ("Penrose model") structure of oceanic lithosphere includes pelagic sediments (layer 1), pillow basalts (layer 2A), sheeted dikes (layer 2B), isotropic gabbros (layer 3A), layered gabbros (layer 3B), and ultramafics (layer 4). However, the complete sequence is ubiquitous only in lithosphere produced at fast and intermediate spreading ridges, such as the Cocos-Nazca Ridge (Figure A above). Lithosphere produced at slow and ultraslow spreading centers may have ultramafic rocks exposed on the seafloor or ultramafic rocks in tectonic contact with a carapace of mafic materials, most likely pillow basalts without sheeted dikes or gabbros. This type of oceanic lithosphere has been observed at the slow Southwest Indian and Mid-Atlantic Ridges, respectively (Figures B and C), and in Arctic Ocean lithosphere produced at the ultraslow Gakkel Ridge (Figure D).

SOURCES: Perfit et al., 1994; figure from Dick et al., 2006.

et al., 1996; Kelemen et al., 2004; Blackman et al., 2006). These results have important implications for understanding the composition of the lower ocean crust.

### Fields of Inquiry Enabled

Rocks recovered by DSDP, ODP, and IODP have fueled studies and advancements in geochronology, experimental petrology, geochemistry, geodynamics, seismology, submersible-aided outcrop mapping and sampling, and structural geology, and have supplied a more complete picture of the formation and evolution of oceanic lithosphere in time and space. Petrologic samples collected by drilling have also contributed to growth in the study of different types of ocean basalts and have allowed for better connections between the study of intact ocean crust and opholites exposed on land.

### Goals Not Yet Accomplished

Although considerably more is now known about oceanic lithosphere than before scientific ocean drilling began, major questions remain because so few holes have penetrated more than 500 m into the lithosphere. Answering key questions requires more drilling of deeper sections of the lower crust and shallow mantle in a variety of tectonic settings, which will be dependent on technological advances to achieve high recovery of cores in deeper drill holes. Basic questions that have yet to be answered involve the structure of the oceanic lithosphere, including further testing of the Penrose and Hess models and the nature of the Mohorovičić discontinuity (Moho), a refracted arrival in seismic profiles that is thought to originate at the crust-mantle boundary. The nature of the boundary—whether an alteration front or a phase change—remains controversial because it has not been sampled in situ. There has yet to be a full penetration of the lower ocean crust to determine its vertical stratigraphy and composition with depth, the processes by which it forms, and how these shape the composition of mid-ocean ridge basalt, the most abundant magma type on Earth. Understanding the composition and evolution of oceanic lithosphere is also intimately linked with understanding the exchange of elements between the lithosphere and seawater during hydrothermal alteration, with implications for understanding the diversity of microbial life forms and their role in the global carbon cycle (discussed further in Chapter 3).

## CONTINENTAL BREAKUP AND SEDIMENTARY BASIN FORMATION

Early models for the evolution of rifted margins provided a simple, quantitative framework for predicting the subsidence of sedimentary basins (e.g., McKenzie, 1978; Wernicke, 1985). These models generally assumed single-phase rifting followed by instantaneous continental breakup, leading to the direct juxtaposition of continental and ocean crust (e.g., Figure 2.2a). Challenges to the models arose almost as soon as they were published (e.g., Royden and Keen, 1980), but the Galicia Margin discovery of mantle rocks by dredging in the late 1970s (Boillot et al., 1980) and drilling on ODP Leg 103 in 1985 (Boillot et al., 1987) prompted a 30-year effort to develop more realistic alternatives. The general outcome of this effort is a fundamentally new paradigm regarding the nature of continental breakup, in which polyphase deformation leads to a complex transition from continent to ocean crust (Figure 2.2b). The new model has significant implications for basic understanding of continental breakup processes, plate reconstructions, and prediction of hydrocarbon distributions. The paradigm shift was brought about by a combination of approaches, in which scientific ocean drilling played a significant part (DSDP Legs 38, 47, and 81; ODP Legs 103, 104, 149, 152, 163, 173, and 210; Figure 2.3). Equally important have been marine geophysical investigations and onshore studies, which have underscored the importance of several phases of lithosphere deformation (e.g., Karner et al., 2007).

### Scientific Accomplishments and Significance

The first rifted margin expeditions, DSDP Legs 38 (Vøring Margin), 47 (Galicia Bank), and 81 (Rockall Margin) examined the timing of initiation of seafloor spreading and the geometry of initial continental fragmentation (Figure 2.3). The Vøring and Rockall Margin drilling expeditions penetrated seaward dipping reflectors (SDRs) thought to mark the location of the continent-ocean boundary, revealing that the SDRs were associated with basaltic volcanic rocks erupted subaerially (on land) instead of under water. Drilling on the Galicia Bank demonstrated that the early sediment record was accessible and provided some of the first evidence for subsidence history (Sibuet and Ryan, 1979).

Nearly coincident with the initial DSDP rifted-margin legs, dredging on the flank of the Galicia Bank recovered mantle peridotites and set the stage for ODP Leg 103, which was designed to sample the early rift history and determine the nature of the underlying crust (Boillot et al., 1980). ODP Leg 103 yielded dates for sediments deposited during and after rifting and demonstrated that one of the prominent seismic reflectors was likely a low-angle extensional fault near the base of the crust and that peridotite exposed on the Galicia Bank ascended from a depth of 30 km (Boillot et al., 1988). Both observations suggested the need to re-evaluate prevailing models for continental rifting.

Subsequent recommendations for additional drilling related to continental rifting suggested that ODP focus on the Newfoundland-Iberia and southeast Greenland-Vøring margins as representatives of end-member margins (“magma-rich” and “magma-poor”). Eight drilling legs were recommended, and between 1994 and 2004 five of those drilling expeditions were conducted.

ODP Legs 149, 173, and 210 explored the geometries of magma-poor continental margins offshore Iberia and Newfoundland. ODP Leg 149 drilled a transect across the Iberia Abyssal Plain and sampled upper mantle rocks that separated extended continental crust from ocean crust (Whitmarsh and Sawyer, 1996). ODP Leg 173 demonstrated that continental crust was thinned to less than 5 km and that upper mantle peridotites were brought to within a few hundred meters of the seafloor (Whitmarsh and Wallace, 2001; Whitmarsh et al., 2001). ODP Leg 210 added information from the conjugate margin off Newfoundland (Tucholke et al., 2007).

As a complement to the drilling of the magma-poor margins, ODP Legs 104, 152, and 163 explored the geometries of the magma-rich continental margins off northeast Greenland and the northeast Atlantic (part of the North Atlantic Volcanic Province). These drilling legs established that SDRs were emplaced during initial development of the ocean basins, but well after the onset of rifting. ODP Leg 104 drilled 900 m of subaerial basaltic flows at the Vøring Margin and characterized the initial breakup of the margin (Eldholm et al., 1989). ODP Leg 152 located the seaward extent of rifted continental crust along the Southeast Greenland Margin (Larsen and Saunders, 1998), but a later leg (ODP Leg 163) intended to shed light on the tectonic development of southeast Greenland failed to achieve its objectives because of ship damage sustained during extreme storm conditions.

Other ODP expeditions that added to observations

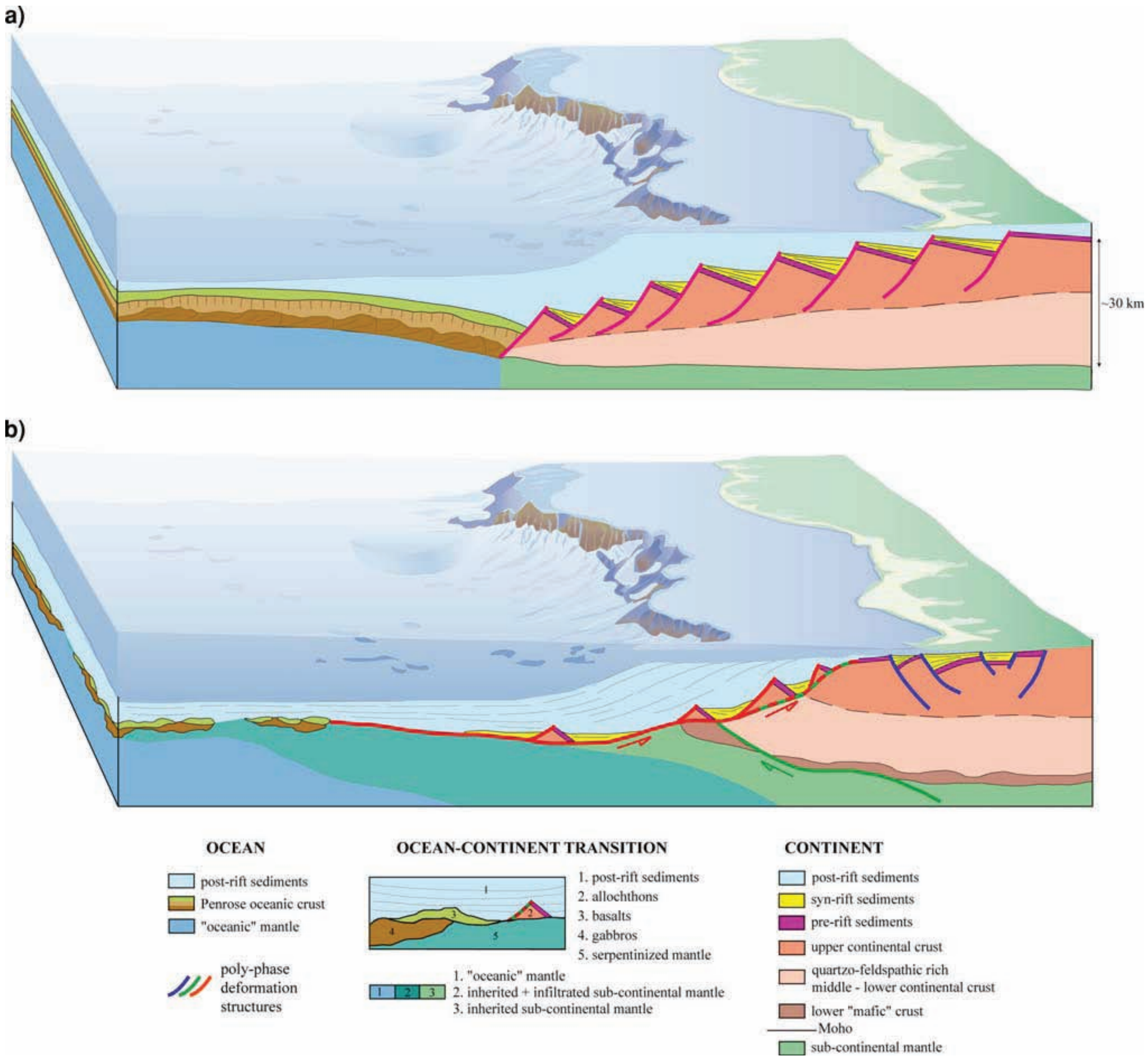


**FIGURE 2.2** Block diagram of magma-poor rifted margins. (a) The top diagram illustrates the classical representation of pre-, syn-, and postrift sediments over uniformly stretched continental crust, with high-angle normal faults in the upper crust and ductile deformation in the lower crust. Sedimentary basins formed during the deformation are all of the same age. (b) The bottom diagram illustrates a modern representation of the complex architecture at the ocean-continent transition. This architecture is acquired during multiple phases of deformation that begin with high-angle faulting, followed by extreme crustal thinning, mantle exhumation, and finally, seafloor spreading. Sedimentary basins formed during polyphase deformation are distinctly different in age. SOURCE: Modified from Péron-Pinvidic and Manatschal, 2009.

of continental breakup included single expeditions in the Tyrrhenian Sea (ODP Leg 107), Broken Ridge (ODP Leg 120), and Woodlark Basin (ODP Leg 180). Three of the seven sites drilled in ODP Leg 107 reached basalt-floored basins; varying age dates of those basalts supported the hypothesis that they were emplaced during extension (Kastens et al., 1987, 1988). One of the sites (ODP Site 651A) drilled mantle-derived, serpentinized peridotite (Kastens and Mascle, 1990). ODP Leg 180 sought to drill an active, low-angle normal fault thought to play a major role in the thinning of continental crust, the formation of the Moresby Seamount, and the formation of the Woodlark Basin (Taylor and Huchon, 2002). ODP Leg 120 was designed to study the origin and tectonic history of the Kerguelen Plateau, a large igneous province (Schlich et al., 1989). Preliminary drilling results reported no evidence for a continental origin of the plateau

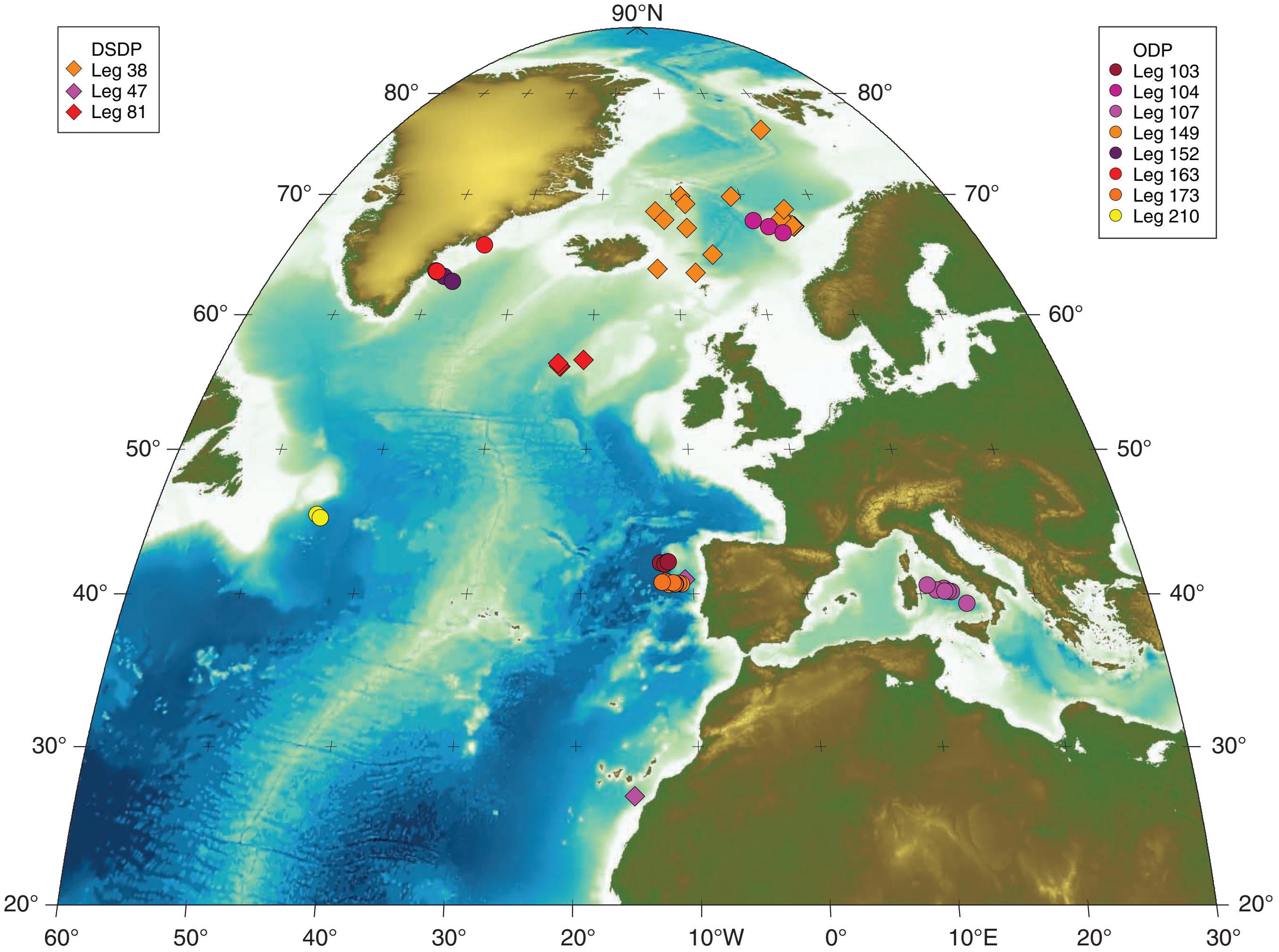


**FIGURE 2.3** Location map of DSDP and ODP legs related to rifting margins. This is a Mollweide (equal area) projection with a color range of -9,000 to 9,000 m, with white marking the 0 m depth. SOURCE: IODP-USIO.

(Schlich and Wise, 1992); however, subsequent geochemical and geophysical studies have suggested that the Kerguelen Plateau is indeed composed of remnants of Indian-Antarctic continental crust that interacted with the Kerguelen Plume (e.g., Bénard et al., 2010). The evolving interpretation of this feature is typical of the integrated, multidisciplinary studies that have allowed new paradigms for continental breakup to progress. In summary, all of these expeditions added elements to the evolving understanding of continental breakup processes, but none had sufficient coverage to fully illuminate the story at any single margin.

## Fields of Inquiry Enabled

The discovery of exhumed mantle during drilling expeditions along the Iberian Margin prompted extensive reinterpretation of existing seismic data and acquisition of several additional multichannel seismic profiles, designed to provide regional mapping context for the drilled horizons (Péron-Pinvidic et al., 2007). Those new interpretations were subsequently coupled with geodynamic models, shallow drilling by European research groups, and a synthesis of analogs from the Alps and relevant mid-ocean ridges to evolve the new paradigms for continental breakup (Lavier and Manatschal, 2006; Péron-Pinvidic and Manatschal, 2009; Unternehr et al., 2010). The integration of these multidisciplinary studies over several decades provides an excellent example of a case where scientific ocean drilling was part of an iterative process that also required both onshore and offshore geophysical and geologic calibration and validation, and geodynamic modeling.

The formation of magma-rich margins and associated LIPs has also recently been linked to biotic events and dipole reversal frequency, especially in the case of the North Atlantic and associated SDRs (Eldholm and Thomas, 1993) and the Paleocene-Eocene Thermal Maximum event (ODP Hole

690B; Kennett and Stott, 1991; Bains et al., 1999; Svensen et al., 2004). Though controversial, this example serves as a model for the initiation of other LIPs (see last section in this chapter for additional detail).

### Goals Not Yet Accomplished

The study of rifted margins is critical to understanding continental breakup processes, plate kinematic reconstructions, and prediction of hydrocarbon resource distribution. In addition, the formation of volcanic margins may be intimately related to climatic events, biotic events, and dipole reversal frequency. When the IODP Initial Science Plan (2001) was written, key elements of the new paradigm for continental rifting were in place, but the number of margins along which key sedimentary sequences were accessible by riserless drilling was limited. The Continental Breakup and Sedimentary Basin Formation initiative was aimed at answering remaining fundamental science questions via riser drilling using *Chikyu*. However, riser drilling of rifted margins was not accomplished in IODP for a variety of reasons. One of these was the two- to three-year delay in the delivery of *Chikyu*, which decreased the amount of time available for expeditions. IODP scientists cite this technical area as one where the objectives of the IODP Initial Science Plan were not achieved as planned (Keir Becker, PowerPoint presentation, June 2010).

Future improvements to the understanding of continental rifted margins will depend not only on scientific ocean drilling, but also on high-quality seismic reflection profiles and companion long-offset seismic surveys, which creates an opportunity for collaboration between academia and industry. U.S. scientists have recently finalized plans for a new initiative on rifted margins as part of the NSF-funded GeoPRISMS (Geodynamic Processes at Rifting and Subducting Margins) Program (GeoPRISMS, 2011).

## SUBDUCTION ZONE PROCESSES AND THE SEISMOGENIC ZONE

Subduction zones, where one tectonic plate plunges beneath another, are the source of some of Earth's greatest natural hazards. These areas are also where new continental crust is formed. Scientific ocean drilling plays a key role in a range of multidisciplinary studies of volcanic processes, particularly with regard to formation of new continental crust in volcanic arcs. The knowledge derived from these studies is essential for developing practical predictive models and warning systems to protect the inhabitants of volcanic regions from eruptions and associated hazards, such as mudflows and tsunamis. Past targets have included drill sites devoted to determining the composition of subducted material, the manner in which material is accreted to the overriding plate and incorporated into volcanic arcs, and the chemistry of material that is subducted and then extruded through forearc mud volcanoes. In 2008, a new IODP program (SEIsmogenic Zone Experiment [SEIZE]) was initiated to drill through the plate boundary at a seismogenic depth, thus contributing to the understanding of mechanisms that control whether a plate boundary fault slides slowly or becomes locked, episodically generating great earthquakes (magnitude 8.0 or larger).

### Scientific Accomplishments and Significance

Determining the nature of the crust, sediments, and pore water entering a subduction zone has been the primary objective at several DSDP, ODP, and IODP sites, because the distinctive composition of material that is subducted acts as a tracer of the processes at depth that lead to arc volcanism (Plank and Langmuir, 1993, 1998). Studies have evolved from identification of elements that can be used as tracers for modeling and constructing mass-balance budgets of inputs and outputs of material across a subduction zone.

Sampling from a number of different subduction zones revealed a correlation between the composition of sediments being subducted and the composition of the extruded basalts. Analysis of lithium isotopes from ODP Site 1039 suggests that half of the lithium in the down-going plate offshore Costa Rica is transferred to the arc, one-quarter returns to the ocean through fluid expulsion along the decollement, and one-quarter may be recycled into the mantle (Chan and Kastner, 2000). However, in other subduction zones (e.g., Kamchatka), a lack of correlation between sediment input to the subduction zone and the arc output in some regions implies that at least in some subduction zones none of the subducted sediment and crust reaches the deep interior to be reworked and incorporated in the zone of melt generation (Kersting and Arculus, 1995).

In some arcs, most notably in the Marianas, material extruded into the forearc through mud volcanoes provides a direct window into hidden processes that operate deep within the subduction zone. ODP Legs 125 and 195 provided samples of unusual minerals and freshened pore fluids derived from interaction of subducted sediments and crust with the overlying forearc mantle (Maekawa et al., 1993; Fryer et al., 1995, 1999). During ODP Leg 195, a long-term borehole observatory was installed in a serpentine seamount in order to examine mass transport, geochemical cycling, and physical, chemical, and microbial fluid characteristics.

Drilling also played a critical role in the realization that crustal erosion, as well as accretion, occurs in forearcs. Subduction erosion results in forearc subsidence and formation of large basins and deep terraces, subduction of crystalline forearc crust to depths at which arc magmas form, and trench retreat and arc migration. Although previous studies noted that a considerable amount of forearc material was missing from the Japan and Peru-Chile trenches and attributed it to the subduction of forearc crust (e.g., Miller, 1970a,b; Murauchi, 1971; Rutland, 1971), it was not until DSDP

Legs 56 and 57, when drilling results were combined with a network of site survey seismic reflection and refraction profiles, that a detailed model for tectonic erosion and its impact on forearc subsidence was developed (von Huene et al., 1980). Evidence of erosion of the upper plate has also been documented by scientific ocean drilling off Guatemala (DSDP Legs 67 and 84), Peru (ODP Leg 112), Tonga (ODP Leg 135), and Costa Rica (ODP Leg 170 and IODP Expedition 334). It is likely that most arcs experience episodes of subduction erosion as well as accretion (von Huene and Scholl, 1991), with implications for megathrust earthquake hazard and continental evolution (Stern, 2011).

Drilling has also provided some unique information on arc histories through recovery of well-preserved ash sequences (Figure 2.4). For example, cores from several DSDP and ODP legs (e.g., ODP Legs 125 and 126) yield a nearly complete 45 myr record of arc volcanism in the Mariana-Izu arc (e.g., Arculus et al., 1995). These studies demonstrated that the Mariana and Izu arc systems shared similar chemical behavior from 30 to 15 myr ago, diverging about 12 myr ago (Plank, 2002). Although the reason for the initial similarity and later change are not yet well known, the ash sequences provide an intriguing look at evolution of arc volcanism over time. Other ash studies from cores on the Caribbean Plate (ODP Leg 165) document the episodicity of explosive volcanism in Central America and indicate that some eruptions in this region rivaled the largest super-eruptions known in the geologic record.

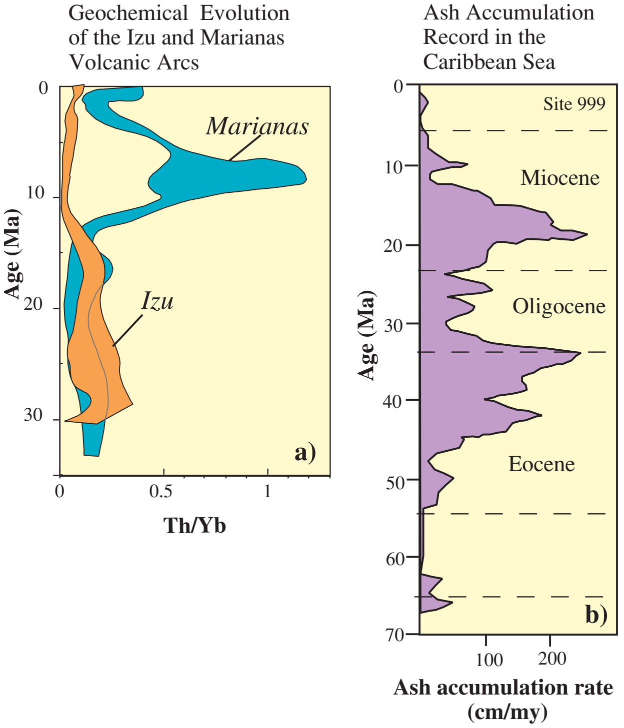


**FIGURE 2.4** Arc history in the Southwest Pacific (a) and Caribbean (b) as recorded by cored ash layers. Changes in isotopic ratios with time in the southwest Pacific provide fingerprints of changes in deep magmatic systems. In the Caribbean, changes in ash accumulation rate indicate temporal changes in volcanic vigor through the Cenozoic. SOURCE: Plank, 2002.

Recent accomplishments in understanding subduction zones have been under the aegis of the SEIZE program, which is designed to understand the processes that result in great earthquakes at subduction zones. IODP efforts to date have been focused on the Nankai Trough, offshore southeast Japan, which has a long history of earthquakes with magnitude 8.0 or larger.[1] Reaching NanTroSEIZE's ultimate objective of sampling the plate boundary at seismogenic depth (Box 2.4) requires the riser drilling capability of the *Chikyu* and has been the major component of the Japanese contribution to IODP in recent years. One important result thus far is the identification of a branching fault that reaches the seafloor at a steeper angle than the main thrust fault of the subduction zone system and may be responsible for the large, historic tsunamis that have affected this region (Moore et al., 2007; Bangs et al., 2009). Others include confirmation of recent activity on the fault from Pliocene sediments thrust over Pleistocene sediments, and indications of frictional heating from vitrinite (a component of coal) reflectance, related to high-velocity slip along a narrow fault plane (Sakaguchi et al., 2011).

## Fields of Inquiry Enabled

Documenting the materials that enter subduction zones is critical for a wide range of studies. Scientific ocean drilling is the only way to determine the composition of sediments and uppermost crust entering the trench and to calibrate seismically based estimates of upper plate erosion. Some of this sediment is accreted or underplated to the forearc, and some is subducted to great depth, providing volatiles that stimulate magmatic production in the arc, in proportions that are likely controlled by both sediment thickness and composition. Understanding this partitioning has implications for studies of arc magmatism, forearc structure and geohazards, and the formation of new continental crust. Documenting the occurrence of subduction erosion transformed estimates of crustal mass balance along active continental margins and provided a mechanism to explain marine observations of forearc basin subsidence and terrestrial observations of continent-ward migration of active volcanic arcs. Sediment subduction and subduction erosion may also affect the frictional properties of the plate boundary.

Although most knowledge about faulting processes is obtained from seismological and geodetic instruments and

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[1] The Nankai Trough NanTroSEIZE site is about 500 km away from the epicenter of the magnitude 9.0 Tōhoku earthquake of 2011, which was located on the Japan Trench.

modeling, scientific ocean drilling is required to sample fault plane materials at the depths at which earthquakes nucleate and to measure temporal changes in physical properties associated with a changing state of stress. Observatory installations at these depths (see Box 3.2), coupled with real-time data delivery systems, have the potential to support practical earthquake early-warning systems as well as to provide new scientific insights into earthquake processes. Such observatories can measure in situ temperature, pore pressure, and strain, and could include other parameters as new tools are developed.

### Goals Not Yet Accomplished

Some of the major unknowns about subduction zone earthquakes (and plate-bounding faults in general) are the characteristics controlling locked faults with infrequent large earthquakes vs. those with slow, aseismic slip. Deep drilling in forearc mud volcanoes promises to provide the most direct link to geochemical processes at depth in the forearc. Obtaining in situ, unaltered samples will provide scientists information on physical properties of the material, which is needed to test models of subduction zone processes and earthquake genesis. Installation of instruments to measure temperature, seismic waves, strain, pressure, fluid flow, and pore water chemistry at these depths are planned for the future.

Achieving the ambitious goals of SEIZE remains a challenge, with questions about the feasibility of deep drilling because of strong currents in the area, tool and instrument performances at high temperature, and the time and cost to drill to such great depth. The delay in being able to use the *Chikyu* also impacted the project timeline. The broad spectrum of onshore and offshore geophysical and geochemical observations required to further understand subduction zones and their associated geohazards, makes this area of research ideal for coordination between scientific ocean drilling and other programs (for example, GeoPRISMS, EarthScope, U.S. Geological Survey [USGS] hazards initiatives). Technological advances are also needed to improve sediment recovery in sandy sediments, and thus provide longer paleoseismic records. Deeper and more complete turbidite and ash records from additional arcs will increase understanding of arc histories, which will contribute to a predictive understanding of why some arcs are very explosive and generate mega-eruptions with global impact.

## LARGE IGNEOUS PROVINCES

Large igneous provinces are areas on Earth's surface that are covered with large volumes of volcanic and plutonic rocks, widely recognized as being related to mantle plumes or hotspots (see global distributions in Figure 2.5). In most places, they formed from large accumulations of mafic magma produced by large-volume melting over short time intervals (often no more than 2-3 myr; Coffin et al., 2006). Lava flows in oceanic LIPs encompass vast areas, reaching tens of thousands of square kilometers with thicknesses of a few to hundreds of meters. Oceanic LIPs are among the largest outpourings of materials from Earth's interior during a short-lived event (e.g., Tolan et al., 1989), with overall volumes that fall in the range of $10^3$ to $10^6$ km$^3$, yielding abnormally thick ocean crust of up to ~40 km (Gladczenko et al., 1997; Richardson et al., 2000; Miura et al., 2004; Kerr and Mahoney, 2007). They represent about 10 percent of the mass and energy flux from Earth's deep interior (e.g., Sleep, 1992) and have a large impact on ocean chemistry, climatic conditions, and even the trajectory of evolution and extinction of life forms. However, precisely how LIPs form remains a subject of great debate, with possibilities of origin including plume activity, bolide impacts, massive upwelling of eclogite, and lithospheric delamination.

### Scientific Accomplishments and Significance

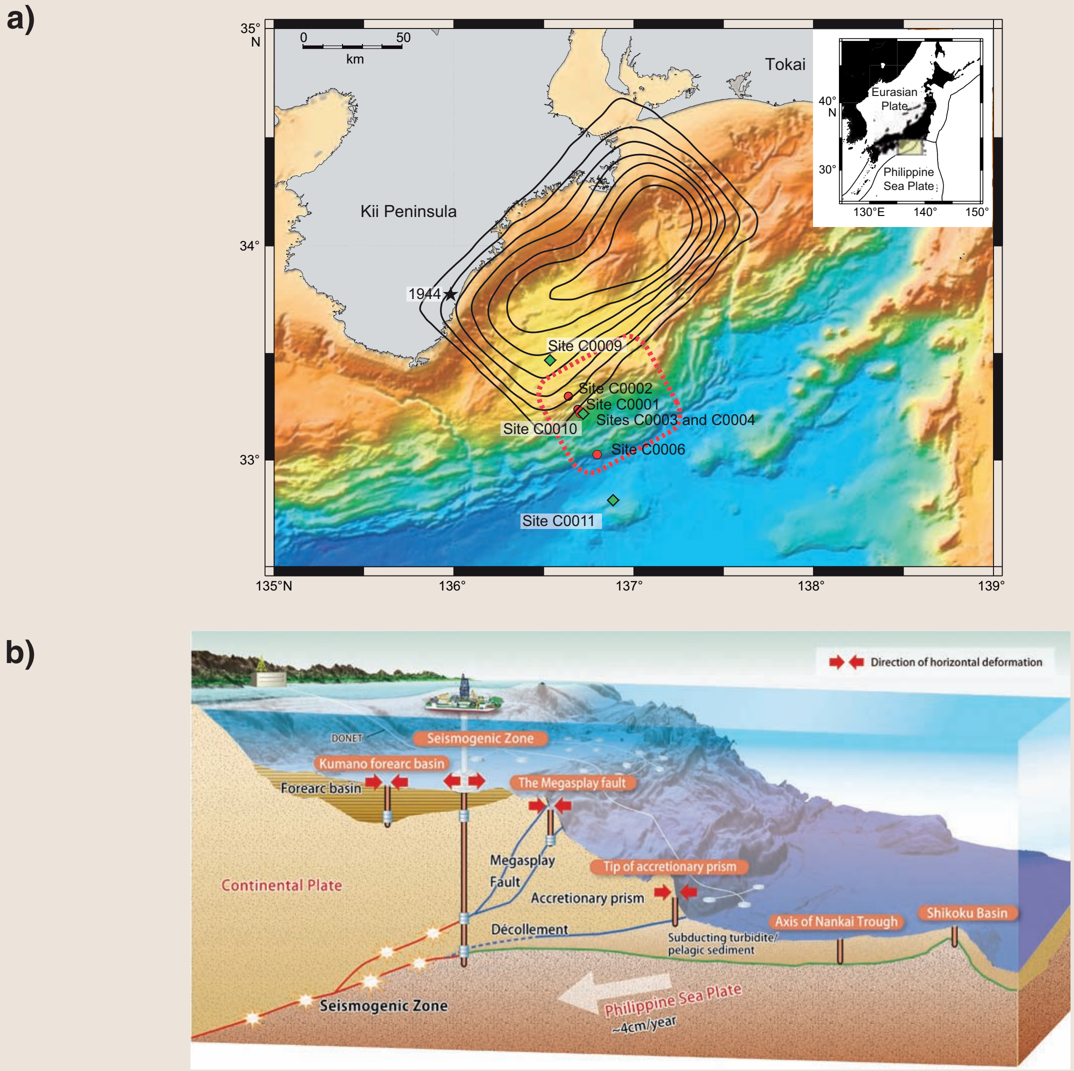
Sampling oceanic LIPs remains more difficult than accessing their continental counterparts, because of their inaccessibility and burial beneath marine sediments. Only four submarine LIPs have been drilled thus far: the 55 Ma North Atlantic Volcanic Province on ODP Leg 104 (e.g., Storey et al., 2007), the ~120 Ma Ontong Java Plateau on DSDP Leg 30 (e.g., Packham and Andrews, 1975) and ODP Leg 192 (e.g., Tejada et al., 2004), the 120-95 Ma Kerguelen Plateau/Broken Ridge on ODP Leg 183 (e.g., Frey et al., 2000), and the ~145-130 Ma Shatsky Rise on ODP Leg 198. In some cases where sediments completely blanket the underlying igneous rock, scientific ocean drilling has provided the only direct samples that have ever been collected (e.g., Neal et al., 2008). Although LIPs are tens of kilometers thick, the cores recovered thus far have been limited to only a few tens to hundreds of meters because of the difficulty of penetrating through thick sequences of crystalline rock.

DSDP drilling of the North Atlantic volcanic province for seaward-dipping reflectors (previously discussed in the continental breakup section) provided evidence that SDRs were subaerially erupted basalts that subsided below sea level. Dating of cores correlated the eruption of the North Atlantic Igneous Province with the Paleocene-Eocene Thermal Maximum (PETM), a period of rapid global climate warming. This led to hypotheses that the climatic and volcanic events are causally related and confirmed that submarine LIPs are formed in geologically short timespans.

ODP drill cores from the Kerguelen/Broken Ridge LIP revealed pieces of wood and sediment, confirming that some areas reached above the sea surface as islands before being submerged (Coffin et al., 2000). Drilling on ODP Leg 192 suggested that the Ontong Java Plateau was formed almost entirely beneath the sea surface, unlike the Kerguelan Plateau (Mahoney et al., 2001). Sampling 149 m into the basement at ODP Site 807 found basalt geochemistry indicative of high degrees of melting (Frey et al., 2000), with fairly uniform

## Box 2.4
## NanTroSEIZE

Eight NanTroSEIZE expeditions were completed between 2008 and 2010.[1] Stage 1, completed in February 2008, was a transect of eight sites that targeted the shallow part of the accretionary complex, providing information on stresses, pore water geochemistry, and sediment age, lithology, and physical properties (see white paper by Casey Moore, Appendix C). Results from the three Stage 1 expeditions were reviewed by Kinoshita et al. (2009). Stage 2, completed in October 2009, characterized the sediments on the subducted slab and prepared the stage for drilling a deep-riser hole through the megasplay fault and decollement. Stage 3 began in August 2010 and entails riser drilling to a depth of 6,000-7,000 m beneath the seafloor to penetrate several active fault zones and the crust of the subducting plate (see Figure below). Stage 4 is the planned installation of a long-term observatory to measure fluid pressure, seismicity, strain, tilt, and temperature within the ultra-deep boreholes drilled during Stage 3 and to transmit the data in real time.



(a) Map of the NanTroSEIZE transect. The epicenter and contours of seismic slip for the magnitude 8.1 tsunamigenic earthquake of 1944 are also shown (from McNeil et al., 2010). (b) Schematic illustration of the NanTroSEIZE transect (SOURCE: © JAMSTEC).

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[1] See http://www.jamstec.go.jp/chikyu/eng/Expedition/NantroSEIZE/.

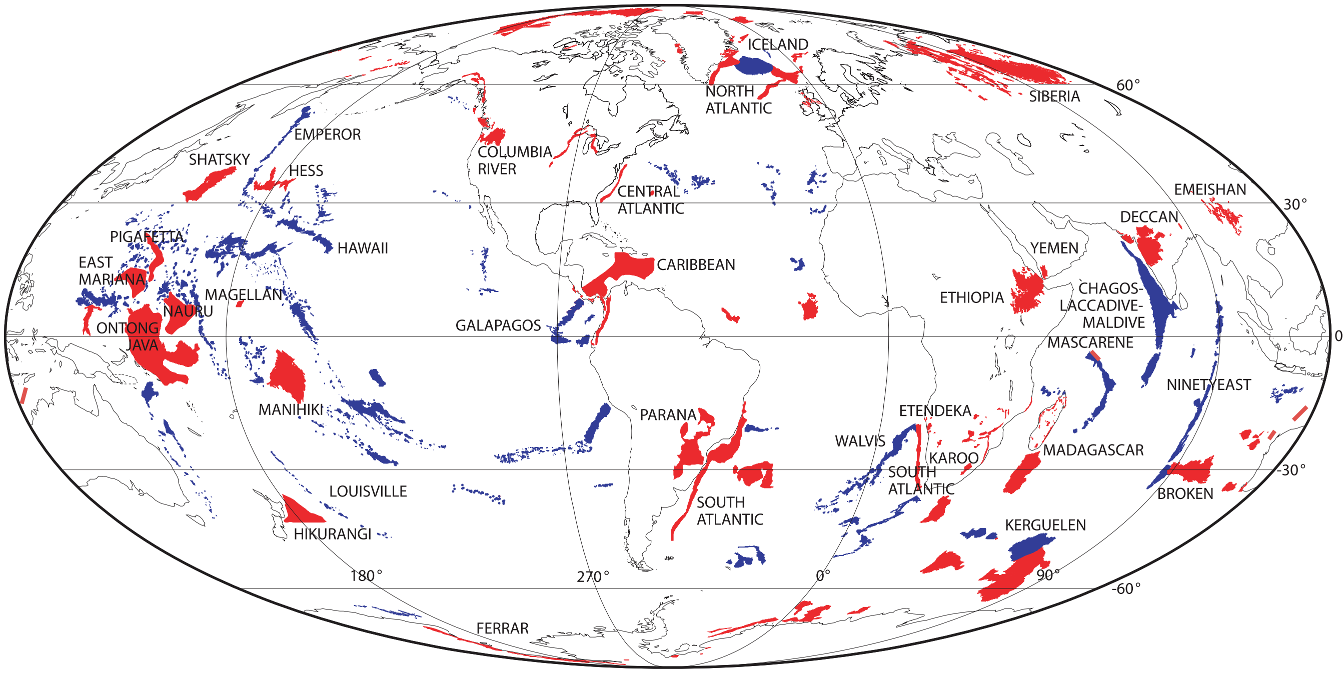


**FIGURE 2.5** Phanerozoic global LIP distribution. Red areas are LIPs (or portions thereof) generated by a transient "plume head"; blue areas are LIPs (or portions thereof) generated by a persistent "plume tail." SOURCE: Modified from Coffin et al., 2006.

compositions (Mahoney et al., 2001). Although oceanic LIPs are composed mainly of tholeiitic basalts similar to mid-ocean ridge basalts, they have higher concentrations of large ion lithophile elements, which likely reflect not only the compositional source of the basalt but also differentiation processes in the magma prior to eruption. Unlike other LIPs, the submarine emplacement of the Ontong Java Plateau may have lessened its impact on the climate.

The Shatsky Rise expedition (ODP Leg 198) recovered an excellent series of sedimentary cores, with evidence for ocean anoxic events, the PETM, and the K-T boundary, but was less successful penetrating the basement of the LIP itself (Bralower et al., 2002).

### Fields of Inquiry Enabled

LIPs provide a context to understand mantle variability and plume dynamics, the origin of mass extinction, and continental breakup events. Scientific ocean drilling provides opportunities to study how the geochemical composition of magmas changes over time, relationships to melting anomalies that cause LIPs, and the timing and rate of eruptions. However, it also provides an opportunity to understand the complex interplay between volcanic, climatic, and biotic processes.

Two other fields of inquiry that have benefited from the study of massive submarine LIPs are ocean anoxia events and volcanic eruption-related climate change. LIPs have been identified as potential triggers of oceanic anoxia, now recognized to be accompanied by the deposition of organic-rich black shales. LIP eruptions could also release massive amounts of aerosols and greenhouse gases, especially carbon dioxide, methane, and sulfur dioxide. Research into the cause and effect relationships between this type of massive volcanism and changes in climate has grown significantly with the emergence of data from both continental and oceanic LIPs. LIPs may have also played an important role in massive extinctions.

### Goals Not Yet Accomplished

Sampling LIPs by drilling has been likened to "pin-pricking an elephant," as LIPs are considerably thicker than the deepest cores recovered thus far. Those cores, in the 800-900 m range from the Kerguelen Plateau, only cover a fraction of the estimated 30 km thickness of the LIP (Operto and Charvis, 1995). Deeper drilling into the basement of these provinces would offer further opportunity to understand their emplacement, age, and geochemical variability.

More thorough drilling of submarine LIPs could improve understanding of LIP genesis and emplacement, because there is no single model that currently satisfies all observations. In addition, thorough dating could provide stronger evidence of potential linkages between LIP eruptions and mass extinctions. Other issues that scientific ocean drilling could address include the initiation and duration of oceanic LIP melting events, the impact on ocean chemistry and seafloor geochemistry, and the temporal and spatial relationships between LIPs and ocean anoxic events.

# 3

# Scientific Accomplishments: Fluids, Flow, and Life in the Subseafloor

The ability to drill deep into the seafloor has increased understanding of the role of fluid flow within ocean sediments and basement rock, especially the connectivity of hydrogeologic systems within the ocean crust. This knowledge has led to surprising achievements in the study of hydrothermal vent systems, especially in understanding vent compositions and subsurface extent, as well as in the research and recovery of gas hydrates. In addition, by providing the only direct access to the subseafloor biome, scientific ocean drilling has revolutionized understanding of subsurface microbial communities living at the limits of life, thus enabling a new field of scientific inquiry.

## HEAT FLOW, FLUID FLOW, AND GEOCHEMISTRY

Hydrogeologic systems are present beneath the seafloor in all geologic environments, and they influence a wide range of biological, chemical, and physical processes. These processes include the magnitude and distribution of fluid pressures and related hazards, formation of continental crust, hydration of plate boundary faults, initiation of explosive volcanism, generation of gas hydrates and other mineral resources, and distribution of subseafloor microbial communities. The complexity of interactions not only has challenged scientists attempting to understand the fundamentals of subseafloor processes, but also opened the door for exciting, interdisciplinary efforts in scientific ocean drilling.

### Scientific Accomplishments and Significance

From the time of Project Mohole (see Box 1.2), scientists recognized that scientific ocean drilling provided an opportunity to investigate fluid flow processes in oceanic sediments and crust (e.g., Von Herzen and Maxwell, 1964). Early Deep Sea Drilling Project (DSDP) studies focused on making measurements in sediments, including temperature and pressure (Box 3.1). However, the discovery of hydrothermal vents along mid-ocean ridges in the 1970s, and the subsequent recognition of robust hydrogeologic systems in nearly all subseafloor geologic environments, served as the catalyst for a multidecadal, multi-disciplinary effort to understand those systems. Beginning with the Conference on Scientific Ocean Drilling *(*COSOD) II in 1987, fluid flow became a major focus of study in the Ocean Drilling Program (ODP) and subsequent Integrated Ocean Drilling Program (IODP). The study of fluid flow included not only drilling, but also development of new technologies for sampling and long-term measurement, as well as tools for using thermal and geochemical anomalies to recognize fluid migration pathways (Moore et al., 1987; Kastner et al., 1991). Hydrogeology efforts have been concentrated in two distinct zones: seafloor basement and sediment. In both fields the emphasis has been on quantifying flow rates and patterns and understanding the links between chemical, biological, tectonic, geophysical, and hydrogeologic processes.

Basement hydrogeology studies initially focused on quantifying the circulation observed in hydrothermal vents. Early observations revealed that ocean bottom waters were being drawn down into the upper levels of the basement, implying that ocean crust was more permeable than the overlying sediments (e.g., Hyndman et al., 1976). The first direct measurements of basement permeability (DSDP Leg 83, DSDP Hole 504B) documented a stratified permeability structure, in which permeabilities decreased exponentially from very high values of $10^{-13}$ to $10^{-14}$ m$^2$ in the upper 150 m of oceanic basement to $10^{-17}$ m$^2$ and lower in sections deeper than 550 m (Anderson et al., 1985). Drill-string packer tests, like those used on DSDP Leg 83, were subsequently used successfully at many other sites. The resulting datasets were

## Box 3.1
## In Situ Measurement of Temperature and Pressure

Temperature is a major parameter controlling dynamic Earth processes. Borehole temperature measurements are important for understanding heat transfer from Earth's interior, lithospheric evolution, hotspot volcanism, gas hydrate stability, and fluid flow in marine sediments. Consequently, temperature was one of the initial downhole properties measured during DSDP (Von Herzen and Maxwell, 1964). Throughout DSDP, ODP, and IODP, new tools and analysis approaches have continuously been developed and improved (e.g., Uyeda and Horai, 1982; Horai, 1985; Fisher and Becker, 1993; Davis et al., 1997; Heeseman et al., 2006). A 2004 IODP workshop on downhole tools confirmed that precise downhole temperature measurements were critical to fulfillment of programmatic objectives in all primary research themes (Flemings et al., 2004).

The most efficient tool for measuring temperature in boreholes is the advanced piston corer temperature tool (APCT), which measures sediment temperatures as the core is being taken (Horai and Von Herzen, 1985). The APCT allows for the measurement of in situ temperatures in the undisturbed sediments that have not yet been reached by the drill bit. The APCT has undergone two major upgrades to improve sensor and data sampling accuracy and stability while retaining the same efficient physical format (Heeseman et al., 2006). For deeper sediments that are too stiff to be sampled with the APCT, the Davis-Villinger temperature tool (DVTP) was developed (Davis et al., 1997). The DVTP also measures in situ pore pressure, although obtaining reliable pressure measurements has been challenging because of the long time constant of the pressure response and fractures induced in the sediment when the probe is inserted (Villinger et al., 2010).

compiled into a regional summary (Figure 3.1), which illustrates that shallow basement permeabilities are consistently three to seven orders of magnitude higher than the overlying sediment column and supports the early observations of a stratified permeability structure controlled by depth within the basement (Fisher, 2005; Becker and Fisher, 2008). The widespread nature of large-scale basement fluid circulation has profound implications for the formation and continuation of subseafloor microbial communities, the creation of ore deposits and gas hydrates, and the overall chemical and heat budget of the oceans.

In some cases, borehole temperature measurements indicated down- or uphole fluid exchange between the ocean and basement formations that could be used to estimate formation permeability (Figure 3.1). However, such open flow also represented a perturbation to in situ conditions and revealed the need for tools with long-term in situ monitoring capabilities. The development of the CORK (Circulation Obviation Retrofit Kit) has led to widespread use for long-term measurement of temperatures, pressures, and fluid fluxes (Box 3.2). The first long-term observatories were established on the Juan de Fuca Ridge (ODP Leg 139). Pressure records from these observatories after 14 months showed high lateral fluid fluxes and short residence times in very permeable upper basement (Davis and Becker, 2002; Fisher, 2005). The first cross-hole experiment (ODP Leg 168), and the first three-dimensional CORK array (IDOP Leg 301), also along the Juan de Fuca Ridge, continued to add to the picture of large lateral fluid fluxes and high permeabilities, and recorded transient flow events associated with seismic activity and tides (e.g., Fisher et al., 2008).

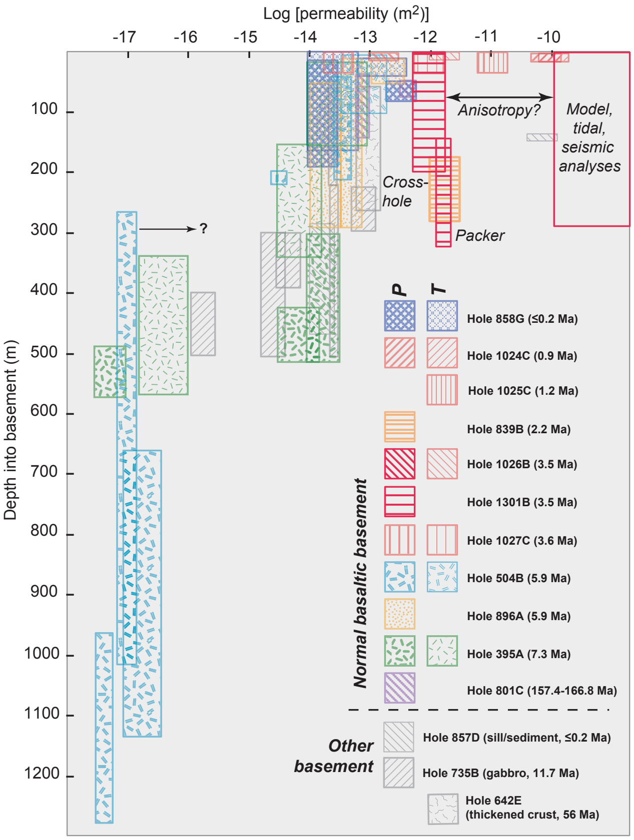
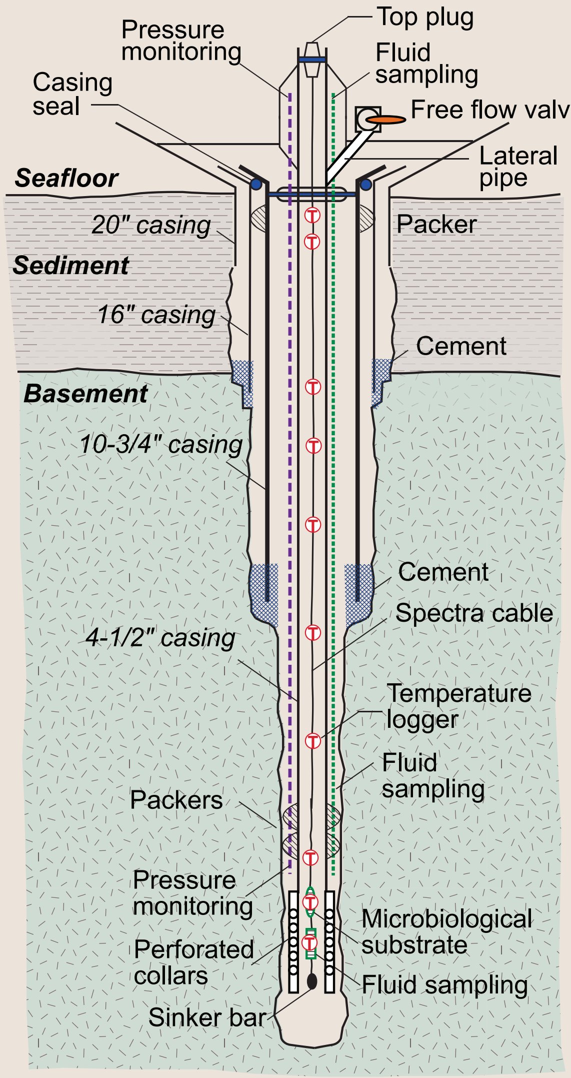


**FIGURE 3.1** Summary of borehole permeability determinations in oceanic basement rocks, based on packer and temperature (flowmeter) experiments. Vertical axis is depth into basement, accounting for differences in sediment thickness. Most seafloor measurements have been made in basaltic crust, but two sets of data (ODP Holes 857D and 735B) are from sediment/sill and gabbroic lithologies, respectively. Note range of values and relatively consistent depth trends. SOURCE: Fisher, 2005.

## Box 3.2
## CORKs: Subseafloor Borehole Observatories

Open drill holes allow significant exchange between bottom water and formation fluids following perturbations associated with drilling ocean crust. CORKs (Circulation Obviation Retrofit Kits) are designed to stop bottom water influx, thus allowing borehole conditions to return to a more natural hydrodynamic state (Davis et al., 1992; Becker and Davis, 2005). CORKs can be used for pressure, seismic, strain, and temperature monitoring; crustal fluid sampling; and microbiological and controlled perturbation experiments. CORKs were originally conceived to allow for estimates of in situ flow rates and permeability, and scientists have more recently begun using CORKs for a variety of chemical and biological experiments using both downhole and seafloor samplers (Fisher et al., 2005). Samples for geochemistry can be collected over long time periods (up to 5 years) using downhole basement fluid osmosamplers (Jannasch et al., 2004; Fisher et al., 2005, Wheat et al., 2010), as well as using seafloor samplers that can be accessed at the well-head (Cowen et al., 2003). Recent downhole experiments have been deployed with mineral colonization surfaces (Orcutt et al., 2010), and seafloor samplers are currently in use on the Juan de Fuca Ridge flank CORKs to allow for the sampling of multiple fluid horizons within the CORKed borehole, both from a submersible or as a stand-alone sampler (Fisher et al., 2005). CORKs as subseafloor borehole observatories offer unprecedented opportunities for integrating hydrogeological studies with microbial and chemical processes in basement fluids.



Schematic of casing and CORK systems deployed on the Juan de Fuca Ridge in 2004, idealized and not to scale. SOURCE: Modified from Fisher et al., 2011.

In the sedimentary realm, scientific ocean drilling focused on identification of flow pathways and fluxes in passive and active margins. Drilling in active accretionary margins resulted in development of new geochemical tracers for inferring fluid flow (ODP Legs 112, 125, 131, 134, 146, 156, 170, and 190; see Figure 3.2). Using pore water anomalies such as low chloride concentrations, negative chlorine isotope ratios, and carbon isotopic ratios of dissolved methane, scientists showed that fluids migrate tens of kilometers along focused pathways, with localized flow rates two to six orders of magnitude larger than steady-state models would suggest (e.g., Moore et al., 1987; Vrolijk et al., 1991; Ransom et al., 1995). The flow rates inferred from these data require transient, confined-aquifer flow, localized expulsion, and/or external fluid sources, but there is still much to be learned about specific flow pathways and magnitude, as well as the role that fluids play in seismicity, chemical alteration, and volcanism.

Hydrologic investigation of non-accretionary subduction zones proved to be more difficult because of limited geologic records. However, drilling on seamounts in the Mariana forearc and Costa Rica margins confirmed mass fluxes of fluids originating from several kilometers below the seafloor (see section on subduction zone processes in Chapter 2).

In passive margins, drilling along the New Jersey Mar-

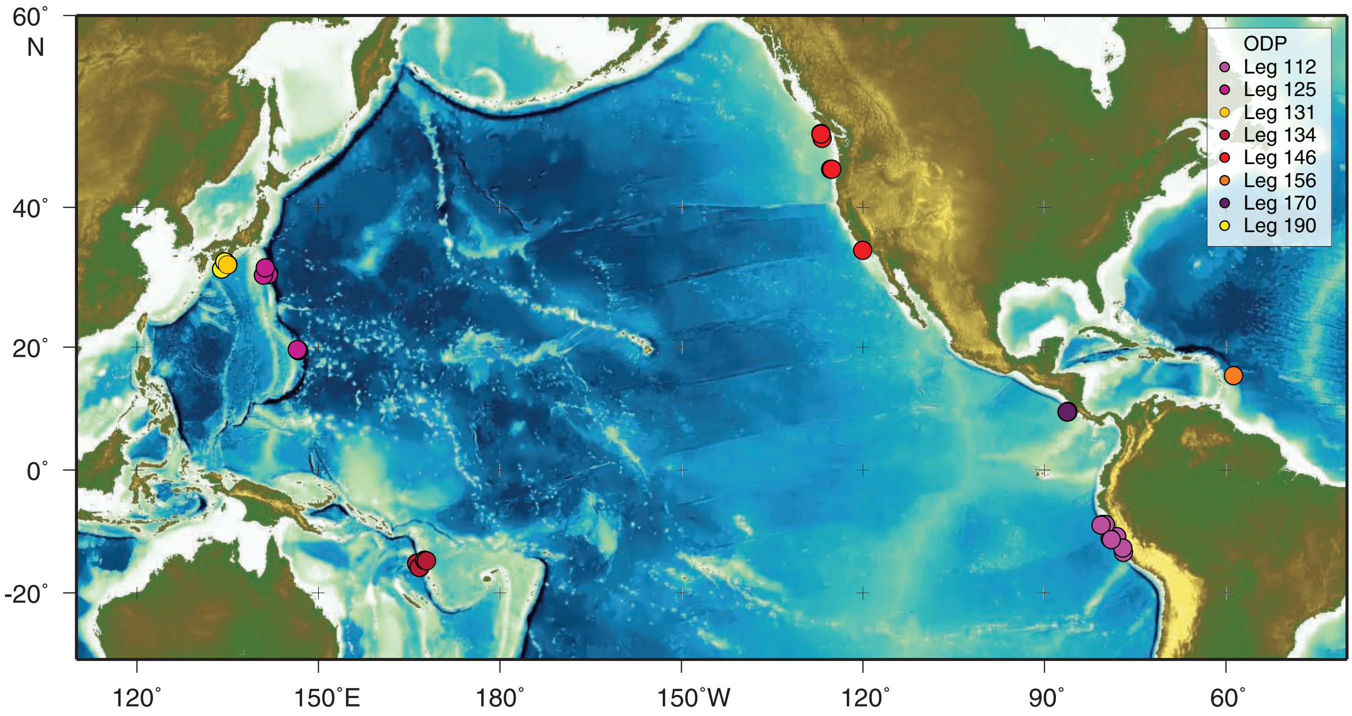


**FIGURE 3.2** Location map of ODP legs related to heat and fluid flow in subduction environments. This is a Mercator projection with a color range of –9,000 to 9,000 m, with white marking the 0 m depth. SOURCE: IODP-USIO.

gin (ODP Leg 174A) demonstrated coupling between excess fluid pressures and flow, but pressures could only be inferred from physical properties (Dugan and Flemings, 2000). Mudstone pressures were subsequently measured in the Gulf of Mexico (IODP Leg 308) in a rigorous demonstration of the coupling between flow and excess pressure (Flemings et al., 2006, 2008; Stigall and Dugan, 2010). Those concepts form the basis for new understanding of the relationship between overpressures and slope failures along passive margins.

### Fields of Inquiry Enabled

The recognition of the magnitude of fluid flow within sediments and beneath the seafloor has led to exciting new research to quantify the role that fluids play in controlling mechanical processes along both passive and active margins, including the occurrence and magnitude of large earthquakes along plate boundary faults and the distribution and timing of major slope failure events along passive margins. The body of literature on these topics is growing at a fast rate; Screaton (2010) provide a broad synthesis of other related studies.

The one-dimensional nature of fluid-flow measurements from boreholes has also led to the development and application of new, multidisciplinary tools designed to extend understanding to three dimensions. Notable accomplishments include the use of inexpensive heat probes to help resolve complex patterns of fluid flow (e.g., Fisher and Harris, 2010); modeling studies of fluid flow and fluid-rock interaction to quantify flow rates and pathways responsible for heat, pressure, and solute transfer (e.g., Spinelli and Saffer, 2004; Spinelli and Wang, 2008); and the emergence of three-dimensional (3D) seismic data as a routine tool for investigation of physical properties (e.g., Bangs et al., 2009).

### Goals Not Yet Accomplished

Tremendous progress has been made in the past 10 years in the understanding of subsurface flow systems. However, much is still unknown about the rates of transport and the shapes of pathways, and how they affect geologic hazards, mineral resources, and the distribution of subsurface microbe communities. Several first-order questions still need to be addressed in order to resolve the significance of these processes, including the nature of hydraulic communication between basement and sediments; the effect of diagenetic modification of sediments on geochemical and microbial processes in the underlying basement; changes in flow as the ocean crust ages; links between marine and continental hydrogeologic systems on passive margins; and determination of quantitative relationships between seismic activity, shallow faulting, and hydrologic processes in subduction zones.

Several marine science initiatives show promise for addressing these important questions, in particular the National Science Foundation's Ocean Observatories Initiative (OOI).[1] The combination of scientific ocean drilling, permanent observatory capabilities, and evolving drilling and sensor technologies has the opportunity to provide a powerful, new integrated approach to resolving key issues related to climate variability, changes in ocean ecosystems, plate tectonics, and subseafloor chemistry and biology.

## HYDROTHERMAL VENT PROCESSES

The seafloor expression of subseafloor hydrothermal vent processes is spectacular, with gushing high-temperature black smokers, fields of glassy new lava flows, and bushes of tube worms and other chemosynthetic life forms. With the confirmation of seafloor spreading and the discovery of deep-sea hydrothermal vents in 1977 (Corliss et al., 1979), there was a focused effort to delve beneath the seafloor to understand the underlying water-rock reactions that create spectacular deep-sea hydrothermal vents. Active hydrothermal circulation is driven by heat provided by magma chambers, where the circulating fluids react with the roof of the magma chamber, and convection in the crust is driven by the temperature gradient between the ocean and the magma. This allows for easy exchange of crustal fluids with the overlying ocean. Beneath the seafloor, hydrothermal fluids evolve when seawater is heated and a variety of water-rock chemical reactions take place, such as cation exchange, where elements such as magnesium are taken up into the rock and iron, zinc, manganese, and silica are released (Seyfried and Mottl, 1995). In addition, these chemical reactions create energy sources that support the chemosynthetic-fueled communities seen at vents, in which microorganisms use the huge amounts of volatiles and reduced compounds leached from rocks to grow, thus serving as the major food source and base of the vent ecosystem (e.g., Rau and Hedges, 1979). They also create subseafloor habitats that cross temperature and energy gradients, allowing for the growth of diverse microbial communities. These hydrothermally driven water-rock reactions are a fundamental component of global geochemical cycles and are critical for understanding exchanges and fluxes between the crust and the oceans. Scientific ocean drilling provides access to the subseafloor, which strengthens understanding of the processes responsible for the existence of seafloor hydrothermal systems and the role these chemical reactions play in influencing the composition of ocean crust and the regulation of ocean chemistry.

### Scientific Accomplishments and Significance

Four active hydrothermal systems were drilled as part of DSDP and ODP, representing different geological settings and highlighting diverse styles of water-rock reaction and crustal alteration. The first active site drilled was Guaymas Basin in the Gulf of California (DSDP Leg 64) in 1978 and 1979. Very few basement rocks were recovered, but analyses of hydrothermally altered sediments suggested the presence of two distinct hydrothermal systems: one of short duration and low temperatures, associated with shallow basaltic intrusions into sediments; the other of longer duration and higher temperatures, associated with large magmatic intrusions (Gieskes et al., 1982).

More than 10 years later, two more high-temperature hydrothermal vent sites were drilled: Middle Valley and the Trans-Atlantic Geotraverse (TAG) mound. TAG, located at 26° 08′ N on the eastern side of the Mid-Atlantic Ridge, is an area of known high-temperature (>360 °C) basalt-hosted venting that also supports diverse chemosynthetic life forms (Humphris et al., 1995). On ODP Leg 158 in 1994, 17 holes drilled at five locations on the active TAG sulfide mound (200 m in diameter and 50 m high) revealed a massive subseafloor sulfide zone in the upflow zone (Humphris et al., 1995). Combined with the seafloor sulfide deposits, geologists estimate almost 3 million tons of sulfide at this hydrothermal mound, raising the level of interest among economic geologists (Rona, 2003). In addition, drilling demonstrated that there is clear mineralogical zonation in the crust, with evidence for huge amounts of seawater intrusion in the subseafloor, as indicated by the presence of anhydrite, a highly soluble mineral that had not been seen in ancient mineral deposits and ophiolites (Moores and Vine, 1971). The formation and dissolution of anhydrite help to form the brecciated sulfide framework that allows the sulfide mound to grow over time (Humphris and Tivey, 2000).

Three years earlier, drilling began at Middle Valley (ODP Legs 139 and 169), located at the northern end of the Endeavour segment of the Juan de Fuca Ridge in the northeast Pacific Ocean (41° N, 127° 30′ W). Like TAG, Middle Valley is a basalt-hosted site with a massive sulfide deposit that is actively producing high-temperature hydrothermal fluids, but with the additional feature of being overlain by thick Pleistocene continental deposition (Zierenberg et al., 1998). In 1996, drilling at Middle Valley on ODP Leg 169 penetrated both the sulfide deposit and the feeder-zone, through which high-temperature metal-rich fluids reach the seafloor. This deep metal-rich zone contained almost 16 percent copper ore (Zierenberg et al., 1998) and had not previously been seen below seafloor mineral deposits, further raising the interest for mineral exploration both on land and in the ocean (Rona, 2003) (Figure 3.3). Cell counts and phospholipid profiles were also obtained from the sediment cores, spanning a range of temperatures, and it was found that even at high temperatures (up to 185 °C) microbial populations were still present, although at lower concentrations than at the cooler surface temperatures (Cragg and Parkes, 1994; Cragg et al., 2000; Summit et al., 2000).

The fourth hydrothermal system, PACMANUS (3° 43′ S, 151° 40′ E), was drilled on ODP Leg 193. PACMANUS is an active hydrothermal vent field within a back-arc basin hosted in felsic volcanic rocks at a convergent margin in

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[1] See http://www.oceanobservatories.org/.

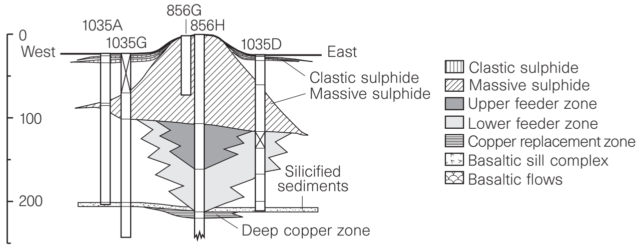


**FIGURE 3.3** A cross-section of mineralization at the Middle Valley hydrothermal site's Bent Hill massive sulfide deposit. SOURCE: Zierenberg et al., 1998.

the western Pacific near Papua New Guinea. Discovered in 1991, it hosts both high- and low-temperature venting, chemosynthetic communities, and extensive hydrothermal deposits (Binns et al., 2002). Four holes drilled in the field revealed that alteration is pervasive beneath the active sites and not, as in previous sites, narrowly confined to an upflow zone. Instead, permeability that controls hydrothermal venting and deposition to the seafloor is governed by fractures, not subseafloor high porosity (Binns et al., 2007). Data from fluid inclusions also demonstrated evidence for subsurface phase separation with deep-sourced hot hydrothermal fluids (Vanko et al., 2004). In addition, rocks from core interiors were collected from two of the holes to determine the distribution of microorganisms in the subseafloor, and microbial cells and ATP (adenosine triphosphate, a marker for biological activity) were detected down to 99.4 and 44.8 m below the seafloor, respectively (Kimura et al., 2003).

### Fields of Inquiry Enabled

Until scientific ocean drilling began, the only way to study the chemical reactions and physical stockwork beneath hydrothermal vents was via collection of exiting vent fluids and rocks at the seafloor or by examination of ophiolites. However, these approaches have the disadvantage of only inferring subseafloor hydrothermal processes. By providing access to samples beneath the seafloor, scientific ocean drilling has made a critical contribution to understanding active hydrothermal systems from a chemical, geological, and even a biological perspective. One of the more unexpected outcomes of drilling hydrothermal vents was the discovery of subseafloor massive mineral deposits, and together with previous interest in seafloor massive sulfide deposits, there is now considerable interest in mining seafloor hydrothermal systems, particularly in back-arc basins and arc volcanoes in water depths of less than 2,000 m (Hoagland et al., 2010). Because the scientific community's understanding of the formation and evolution of these deposits and associated ecosystems is incomplete, there is a strong desire to link industry and scientists to avoid potential environmental damage.

### Goals Not Yet Accomplished

There is a continued interest in drilling deep-sea hydrothermal vents, as exemplified by the August 2009 workshop, "Scientific Ocean Drilling of Mid-Ocean Ridge and Ridge-Flank Settings" (Christeson et al., 2009). Most recently, IODP Expedition 331 drilled hydrothermally active mounds in the Okinawa Trough to obtain more data on subseafloor microbial communities. A number of proposals have been put forward to expand the different geological settings and diverse styles of water-rock reaction and crustal formation drilled, with considerable attention paid to establishing borehole observatories and linking in with cabled ocean observatories. Special technological issues remain with drilling at active hydrothermal systems, and there is a strong need for improved core recovery in young (less than 3 myr) crustal environments. Ongoing developments include hard rock re-entry systems, remotely operated submersible drill rigs, advanced diamond core barrels, and engineered muds and instruments capable of withstanding high (>200 °C) temperatures (Christeson et al., 2009). Development and testing of these important tools will continue to be important for fulfilling scientific goals in these regions.

## SUBSEAFLOOR BIOSPHERE

Morita and Zobell (1955) first cultured bacteria from shallow marine sediment cores and concluded that the lower limit of Earth's biosphere was 7.5 m beneath the seafloor. It was not until almost 30 years later that scientists used sediment cores collected from DSDP Leg 96 in the Mississippi River delta to document microbial activity down to 167 m beneath the seafloor (Whelan et al., 1986). It took another 10 years for scientists to visualize and quantify these microbial cells at depths in excess of 500 m at five ODP sites around the Pacific Ocean (Parkes et al., 1994). These findings, coupled with the 1977 discovery of chemosynthetic-fueled life at deep-sea hydrothermal vents, sparked a new interest in microbiology of the subseafloor, with some estimates suggesting that more than one-third of Earth's carbon may be locked in microbial biomass within the subsurface (Gold, 1992; Whitman et al., 1998). Unlike much of the ocean, the subseafloor environment does not depend on photosynthesis; instead, the most abundant energy supply is from inorganic electron donors and acceptors (Bach and Edwards, 2003). The possibility of an extensive population of bacteria and archaea living in the subseafloor raises many important and intriguing questions about the limits of microbial life, the role of marine microbes in essential biogeochemical cycles, and the origin and evolution of life on Earth and its possibilities for other planets. Understanding the influence these microbes have on the chemistry of the ocean and any consequences for the global carbon and climate cycles is essential.

## Scientific Accomplishments and Significance

The marine subseafloor can be divided into two distinct biomes: sediments (derived from both terrigenous and volcanoclastic materials) and igneous rocks and their alteration products (Schrenk et al., 2010). The bulk of microbial data to date are derived from the sediment biome, primarily from coastal and shelf environments. In the mid-1980s, microbiologists began sailing on ODP legs to collect sediment cores for biological analysis. These expeditions focused on paleoceanography, gas hydrates, and other scientific themes rather than on microbiology. Parkes et al. (2000) summarized the findings of these first 15 years of study from 14 marine sediment sites and concluded that while microbial abundances generally decrease with increasing depth, cells are still present at depths in excess of 700 m; they can be stimulated by deep activity, such as subsurface seawater flow or gas hydrates; and they have a strategy of high biomass and low growth rate to guarantee survival (Figure 3.4). Parkes et al. (2000) estimated that microbial populations in the top 500 m of the sediment are equivalent to about 10 percent of the total surface biosphere, highlighting the potential planetary consequences of the subseafloor biosphere.

In 2002, the first dedicated microbiology leg sailed to core sediments from the Peru Margin (ODP Leg 201; see Box 3.3). An international group of multidisciplinary scientists examined the samples for microbial abundance, activity, genetic composition, and contribution to biogeochemical activity. Results indicated an active and abundant population of microbes in the subseafloor, with rates of activities and cell concentrations that varied from one environment to the other depending on electron donor and acceptor availability (D'Hondt et al., 2004). Molecular-based assessments of the sediment samples showed that microbes are indeed active at depth in the sediment column (Schippers et al., 2005), and they are composed of genetically and phylogenetically distinct microorganisms (Biddle et al., 2008; Fry et al., 2008). The findings from ODP Leg 201 were shortly followed by the discovery of active microbial cells in 111 myr sediments from >1,600 m below the seafloor collected on ODP Leg 210 from the Newfoundland Margin (Roussel et al., 2008), thus extending the depth of known microbial life in the sediment-hosted subseafloor biosphere.

Meanwhile, in the late 1990s there was growing interest in the other overlooked but important component of the subseafloor, the rocks. The crustal aquifer is potentially the largest habitat on Earth, with more than 60 percent of the ocean crust estimated to be hydrologically active (Stein and Stein, 1992). Current estimates suggest that the volume of ocean crust capable of sustaining life is comparable in magnitude to that of the oceans (Heberling et al., 2010). Although earlier examinations of surficial marine basalts had suggested a role of microbes in the transformation of basalt to palagonite (Thorseth et al., 1992), no subseafloor rocks had yet been studied for the presence and activity of microbes until scientists examined samples from DSDP Leg 70 and ODP Leg 148 (Furnes et al., 1996; Giovannoni et al., 1996). These studies (and others) employed various DNA stains to the rocks that suggested the presence of microbes in the alteration zones of the basalts. Fisk et al. (1998) examined more than 100 exposed and buried basalt samples, including many from DSDP/ODP archives that ranged from a few meters to 1,500 m below the seafloor, to record the breadth of weathering textures and conditions under which the basalts had formed. This research suggested that microbes may play an important role in the basalt alteration process, such as controlling rates of alteration or the composition of alteration products, and regulating the cycling of nutrients between seawater and ocean crust. However, definitive evidence of indigenous subseafloor microbes growing from or altering rock was not found.

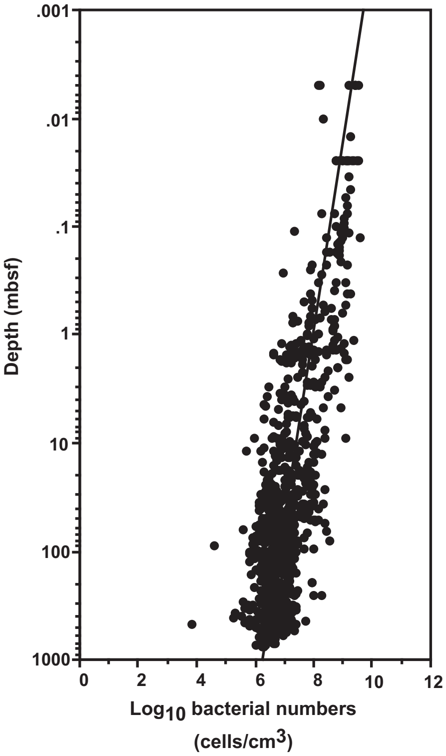


**FIGURE 3.4** Compilation of cell count data from recovered sediment cores from 1986 to1996, showing correlation of non-hydrothermal subseafloor bacterial populations with depth. SOURCE: Parkes et al., 2000.

The use of CORKs (Box 3.2) as subseafloor microbial observatories (Fisher et al., 2005) allows scientists to address the issue of in situ microbial-rock interactions in the subseafloor. In 2003, the first such microbiological study from ODP Hole 1026B on the Juan de Fuca Ridge flank was published, where warm crustal fluids were filtered from a CORK and examined for evidence of a unique thermophilic subseafloor microbial community (Cowen et al., 2003). More recently,

### Box 3.3
### "Core on Deck!"—Core Handling, Laboratory, and Rig-Floor Procedures

Critical to the success of ODP and IODP are major innovations in the fields of ship operations, downhole logging and instrumentation, and drilling technology and engineering development. However, these innovations do not stop at the drill bit. Increasingly, *JOIDES Resolution* core handling, laboratory, and rig-floor procedures have been modified as new science requirements become evident. Shipboard laboratories are constantly changing, as new techniques and expedition objectives demand new core-handling priorities. Highlighted below are a few areas where the need to support science objectives has driven innovation in the internal handling procedures of the *JOIDES Resolution*.

The use of non-magnetic core barrels, which reduce drilling-induced magnetic overprints, and non-magnetic bottom hole assemblies, which allow for core orientation, has resulted in much improved magnetostratigraphic dating of cored sequences. The need to obtain complete stratigraphic sections generally leads to drilling or coring multiple holes at one site, so that coring breaks overlap with one another. The need to quickly correlate these cores led to the development of a fast-track multi-sensor tool (Carter and Raymo, 1999; Moran, 2000) that can quickly scan core sections and document correlation between holes, without sacrificing the detailed measurements made on a regular multi-sensor track.

The need to preserve gas hydrate samples for further study drove several significant changes to rig-floor and core-handling procedures. On ODP Leg 164, cold spots indicative of gas hydrate dissociation were used to quickly identify samples. By ODP Leg 204, any cores collected in the gas hydrate stability zone were scanned immediately after recovery with a digital infrared camera, and samples were taken rapidly and preserved by a variety of means, including storage at in situ pressure or in liquid nitrogen. Procedures for scanning cores and processing the infrared scans were further developed during IODP Expedition 311. Gas hydrate studies also drove ODP to develop technology to retrieve cores at in situ pressure (see Box 3.4), priming further industry development (Schultheiss et al., 2006).

The emergence of subseafloor microbiology led to additional dramatic changes both in rig-floor and core-handling procedures onboard the *JOIDES Resolution*. Although interest in microbiological samples started as early as DSDP Leg 96, it was not until ODP Leg 185 (Izu-Mariana Margin) that contaminant testing demonstrated that uncontaminated material suitable for microbiological study could be obtained from drill cores. ODP Leg 201, a return to the Peru Margin, marked the first expedition dedicated primarily to microbiological objectives. During this expedition, IODP deployed a radioactive isotope van and modified the rig-floor protocol to ensure cores were available for sampling almost immediately, before they could warm significantly. Core-handling techniques were changed on the catwalk as well, allowing extensive whole-round sampling for microbiological studies (which in some cases completely consumed the cored interval). ODP Leg 201 also marked the first use of a thermal imaging tool on the catwalk.

During the 2006-2009 *JOIDES Resolution* refit, a dedicated space for the radioactive isotope van was added. This fully integrated the microbiology and chemistry laboratories. As part of the retrofit, a dedicated cold laboratory for sample processing was added to the microbiology laboratory.

geochemical fluid osmosamplers and downhole microbial samplers filled with mineral incubation material that encourage colonization and growth have been deployed and retrieved in the Juan de Fuca CORKs, with plans for future deployments in other CORK borehole observatories (Fisher et al., 2005; Orcutt et al., 2011). In concert with geochemical and pressure monitoring, these observatories allow for a comprehensive view of subseafloor microbial life over time and the interaction with the basement hydrogeology and chemistry.

Finally, a recent study examined microbial communities in gabbroic rocks for the first time as part of IODP Legs 304 and 305 to the Atlantis Massif. An extremely low diversity of bacteria was seen, dominated by putative hydrocarbon degraders that may be living completely independently of the surface biosphere (Mason et al., 2010).

## Fields of Inquiry Enabled

Until microbiologists began sailing on scientific ocean drilling legs, scientists had no way to access the deep and continuous cores needed to determine microbial abundance and activity in the marine subseafloor. The scientific ocean drilling program, therefore, uniquely enabled a new field of inquiry into life in the marine subseafloor. Rock-associated microbes are virtually unaccounted for in any census of subseafloor microbial life because of the inherent difficulties in collecting rock samples and using them in biological analysis (Santelli et al., 2010); therefore scientific ocean drilling is critical to success in understanding microbiology in the subseafloor. The ability to drill even deeper will continue to push our limits and understanding of microbial life in this unique biosphere.

### Goals Not Yet Accomplished

By the end of the next decade, the potentially huge and unaccounted for subseafloor habitat will become part of the census of Earth's microbial life, but only with the access and facilities allowed by scientific ocean drilling. Obviously, using scientific ocean drilling samples and holes for microbiological experiments demands special considerations with respect to drilling strategy, particularly when assessing contamination. The coring system is not designed for microbiology, and surface seawater, which is pumped through the drill string to remove tailings from the borehole, can contain on the order of 1 million microbes per liter. Techniques to monitor contamination using a chemical tracer (perfluoromethylcyclohexane) and a physical tracer (fluorescent spheres) have been tested to assess contamination in the cores (Smith et al., 2000; Lever et al., 2006). Results suggest that although the collection of mostly uncontaminated cores is possible, the type of coring, the nature of the formation, and various other factors influence the level of contamination seen. This type of variability requires increased vigilance for both drilling operators and scientists when deciding how best to drill holes and collect materials for microbiology. In addition, scientists are currently assessing best storage practice for cores needed in microbial analysis in conjunction with core repositories in the United States and abroad, and detailed notes on exactly how cores were retrieved and stored are essential in assessing potential contamination, even if tracers were not used onboard.

Although there was only one dedicated microbiology leg in all 60 years of scientific ocean drilling's history, there have been two recent IODP expeditions (South Pacific Gyre in 2010 [IODP Expedition 329] and Mid-Atlantic Ridge Microbiology in 2011 [IODP Expedition 336]), and many others have been proposed. The growing interest in the subseafloor biosphere will continue to be a driver of scientific ocean drilling in the next decade, and new developments in contamination assessment, storage practice, sample analysis, and subseafloor observatories will further enhance the ability of scientific ocean drilling to understand this essential and underexplored aspect of Earth's biosphere. Studies into this field of inquiry remain in their infancy, and scientific ocean drilling has been critical in advancing discovery and understanding of the deep marine biosphere and will continue to play a pivotal role in future discoveries.

## GAS HYDRATES

At high pressure and low temperature, some low molecular weight gases (e.g., methane, carbon dioxide) can combine with water to form gas hydrate, an ice-like substance. These seafloor conditions are found almost ubiquitously where the water depth exceeds 300-800 m (depending on regional seawater temperatures). Gas hydrate is most often found at continental margins and in enclosed seas, where organic matter builds up quickly enough to support microbial methane production or where existing gas is transported into the gas hydrate stability zone (Claypool and Kaplan, 1974). In the United States and elsewhere, methane hydrate occurs naturally in sediment beneath permafrost and along continental margins, and in some areas may be concentrated enough to augment conventional gas supplies and provide greater domestic energy security (NRC, 2010). Geohazards associated with gas hydrate include large-scale slope destabilization (e.g., Maslin et al., 2004) and release of methane, a potent greenhouse gas. Evidence collected from deep-sea sediments has been attributed to some massive releases from methane hydrate deposits and linked with major global warming episodes (e.g., Dickens et al., 1995; Kennett et al., 2003). Alternative hypotheses for the data are viable, and it is clear from ice core data that major global warming episodes in the past 100 thousand years (kyr) were not associated with atmospheric methane increases (e.g., Brook et al., 2000; Sowers, 2006). Box 4.2 contains more discussion on this topic.

### Scientific Accomplishments and Significance

Scientific ocean drilling has been a major factor in improving understanding of the distribution and dynamics of gas hydrate in marine sediments. The first gas hydrates collected in the deep ocean were sediments at the Middle America trench accretionary complex during DSDP Legs 66 and 67 in 1979, although hydrate-bearing sediments had previously been cored with no gas hydrate recovery during DSDP Leg 11 in 1970. ODP Leg 164 to the Blake Ridge, a passive margin sediment drift deposit, was the first expedition to focus primarily on gas hydrates. It was followed by ODP Leg 204 and IODP Expeditions 311 and 328 to the Cascadia accretionary complex offshore Oregon and Vancouver Island.

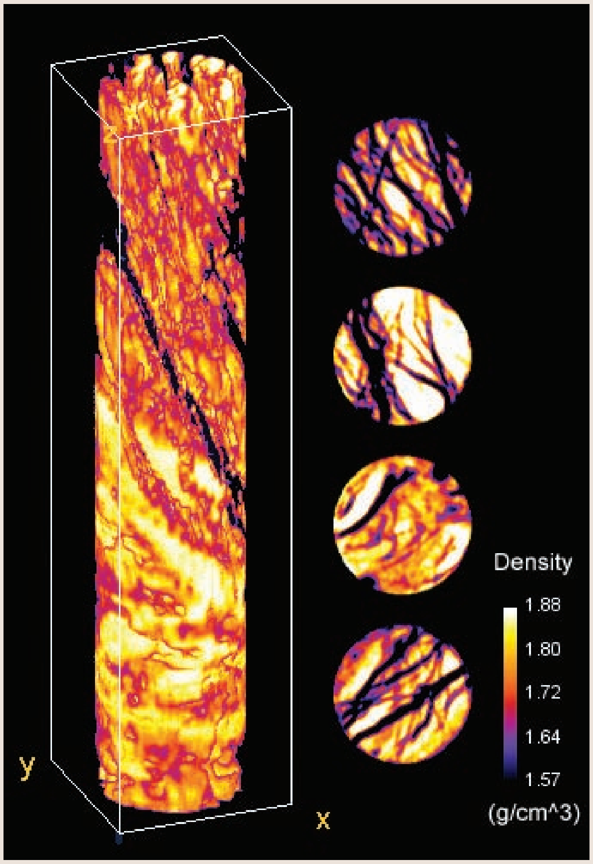
Drilling data are essential for calibrating and validating models of gas hydrate distribution, which are derived from remote sensing data. Because methane hydrate is stable at atmospheric pressure only at temperatures below about –80 $^{o}$C, much of the hydrate in deep ocean cores is probably lost because of decreases in pressure and increases in temperature during recovery. The unique challenges of sampling and preserving gas hydrates in cores and inferring the concentration and distribution of gas hydrate in situ have been addressed through development of new technologies to recover and analyze core at in situ conditions and through calibration of a variety of proxies for gas hydrate abundance and distribution of varying accuracy and resolution. The most accurate measurements are derived from pressure core samples (Box 3.4), which can only sample a very small subsurface volume. Geophysical logs are used to obtain high-resolution data at in situ conditions from the entire borehole, including the parts of the core where sediment is not recovered. Figure 3.5 presents data for several gas

## Box 3.4
## Retrieving Samples at In Situ Pressures

Pressure core samplers are key to gas hydrate investigations because they provide the only means of measuring the total amount of methane in sediments and of directly observing gas hydrate-sediment structures. During normal core recovery, the pressure decrease results in dissociation of gas hydrate and loss of methane. Development of pressure cores was initiated by ODP (Pettigrew, 1992) and provided critical data to "ground-truth" geochemical and geophysical proxies for gas hydrate during ODP Leg 204 and IODP Expedition 311. ODP pressure core samplers have primarily been used for depressurization experiments (Dickens et al., 1997a), in which gas is captured as pressure is released. Methane concentration can be calculated from collected gas volumes, given in situ pressure-temperature conditions and sediment porosity, allowing for calculation of equilibrium gas hydrate or free gas concentration.

Initial developments of wireline pressure coring technology were advanced by European Union funding of the HYACE (HYdrate Autoclave Coring Equipment) and HYACINTH (Deployment of HYACE tools In New Tests on Hydrates) programs (Schultheiss et al., 2006; Mount Albert Science Team, 2007) and by the U.S. Department of Energy (e.g., Yun et al., 2007), and include mechanisms to transfer core at full pressure into specialized pressure chambers for X-ray imaging (see Figure) and high-resolution geophysical measurements. Nondestructive geophysical measurements on pressure cores enable the nature, distribution, and morphology of gas hydrate structures to be related to the host sedimentology. Measurements on pressure cores show that thin, grain-displacing subvertical gas hydrate structures and nodules form in uniform clay lithology whereas distributed grains form in pore space in coarse-grained sediments.

Although gas hydrate investigations have primarily been the focus for development of pressure coring and analysis techniques, other scientists such as microbiologists (Parkes et al., 2010) have also found them to be of use.



X-ray computed tomography images of natural gas hydrates in clay-rich sediments collected by the *JOIDES Resolution* from the Krishna-Godovari Basin. SOURCE: U.S. Department of Energy National Energy Technology Laboratory, 2010.

hydrate proxies and illustrates the strong heterogeneity in vertical gas hydrate distribution (adapted from Tréhu et al., 2004). Analysis of pressure cores indicated the importance of lithology and fracture permeability in controlling where and how gas hydrate precipitates (e.g., Weinberger et al., 2005; Torres et al., 2008). Drilling combined with regional geologic characterization obtained from pre-drilling site surveys has also provided many new insights into the fluid flow regimes that control gas hydrate distribution.

### Fields of Inquiry Enabled

Until gas hydrates were drilled and sampled, geophysically based estimates of the gas hydrate content of sediments were very poorly constrained, and estimates of the amount of gas hydrate present on a global basis varied over many orders of magnitude (Milkov et al., 2003). Calibration of these estimates using drilling data resulted in a decrease in the range, although uncertainty remains large because of the very heterogeneous distribution of gas hydrate in nature. Perhaps more important are the insights into the factors that

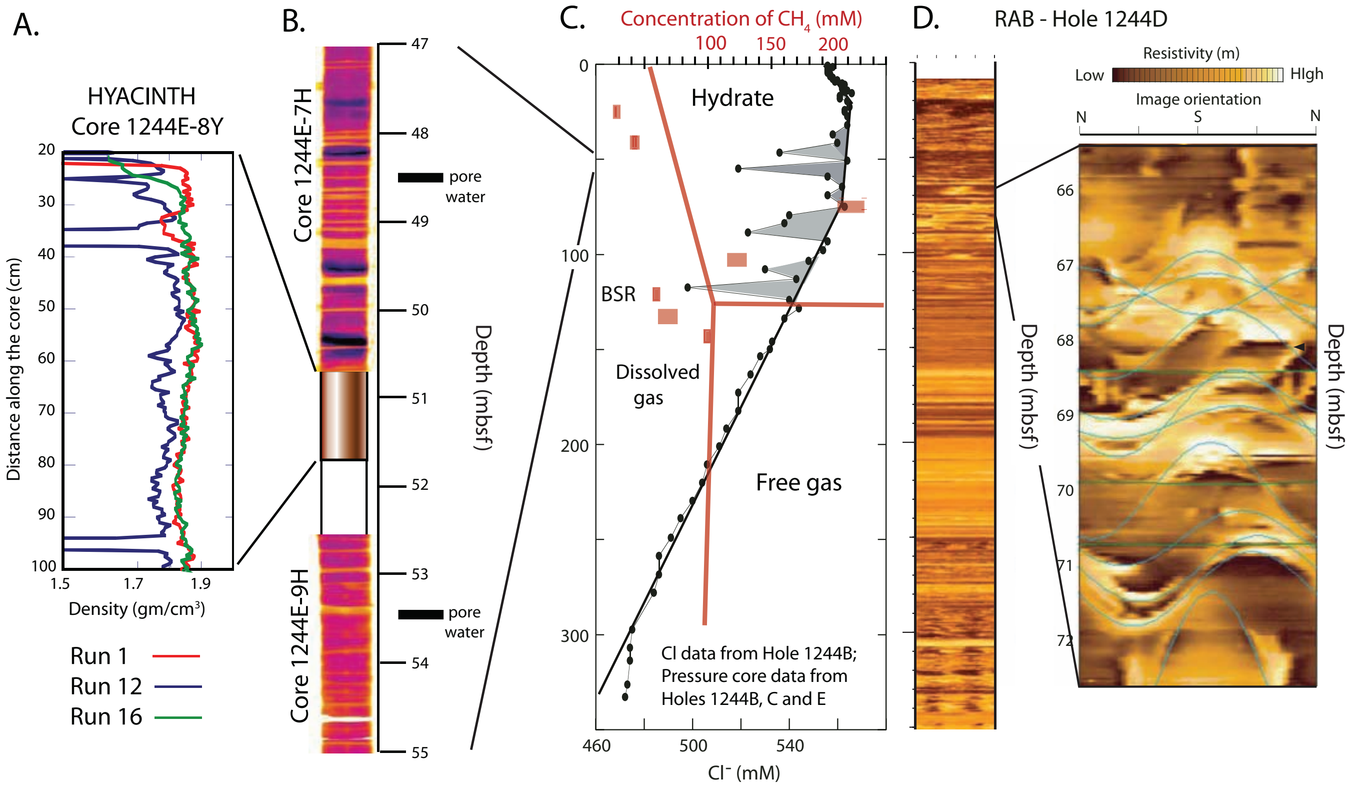


**FIGURE 3.5** (a) Gamma density profiles of a pressure core for ODP Leg 204 as pressure was released. Layers of very low density develop with time as gas hydrate lenses decompose in response to decreasing pressure. (b) Infrared image of the core on either side of the HYACINTH pressure core. Dark horizontal lines represent cold anomalies (6-8 °C) resulting from gas hydrate decomposition; yellow lines represent warm anomalies (12-14 °C) resulting from voids due to gas expansion. (c) Chlorine concentration measured in ODP Hole 1244C. Low chlorine anomalies imply that the pore space contained up to 9 percent gas hydrate in the anomalous samples. Methane concentration from pressure core data (red squares) are overlain on the chlorine data. (d) Resistivity-at-bit data (RAB) from logging-while-drilling operations in ODP Hole 1244D. A detail from 62 to 73 m below the seafloor is presented. Bright regions (high resistivity) are indicative of gas hydrate when they also correspond to low density zones. SOURCE: Tréhu et al., 2006.

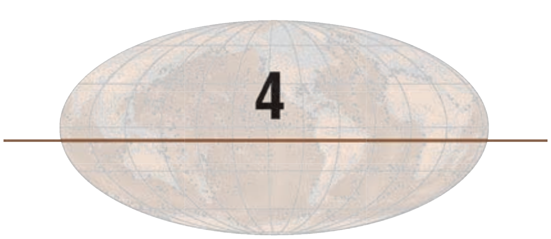
control gas hydrate distribution and dynamics that have been obtained from drilling. These insights can be extrapolated to the many regions where only remote sensing data are available.

Since 2006, much of the deep ocean drilling to characterize the distribution of gas hydrates has been undertaken by the Department of Energy Joint Industry Program in the Gulf of Mexico and international programs supported by Japan, India, Korea, and China on their continental margins, with the objective of evaluating fossil fuel potential or geohazards posed by gas hydrates for conventional oil drilling and recovery. Procedures and protocols for handling and archiving gas hydrate-bearing cores during these expeditions have been modeled on procedures pioneered during ODP and IODP expeditions (e.g., storage of samples in pressure vessels or liquid nitrogen; immediate routine scanning of all core with infra-digital infra-red cameras). Technologies for recovering and studying core at in situ pressure have been advanced by industry groups, following the initial efforts by ODP (see Box 3.4).

Drilling has also provided insights into the mechanisms that allow large amounts of free gas to migrate through the gas hydrate stability zone to form spectacular mounds of gas hydrate near the seafloor. Although seafloor gas hydrate deposits may constitute only a fraction of hydrate in marine sediments, they are the most easily accessible and, therefore, most well-studied.

## Goals Not Yet Accomplished

Studies of gas hydrate dynamics on decadal and shorter time scales, which require time series observations, will remain a main focus of the scientific ocean drilling community and will require close collaboration between scientific ocean drilling and ocean observatories (Torres et al., 2007). The recent advanced CORK installation and connection to the NEPTUNE Canada fiber optic cable (IODP Expedition 328) represents the first of what should be a new generation of methane hydrate studies. A challenge unique to gas hydrate studies is development of sensors that can record natural changes in temperature, pressure, electrical resistivity, pore fluid flow rate, and other parameters without getting fouled by gas hydrate formation initiated by the presence of the sensor itself. Several attempts are currently under way to develop probes that could be deployed through scientific ocean drilling to operate in this challenging environment.



# 4

# Scientific Accomplishments: Earth's Climate History

Scientific ocean drilling has revolutionized studies of Earth's climate system and has produced the most important geological archives of global climate history. Combining scientific ocean drilling results from a wide array of geological settings and geographical regions has transformed scientific understanding of the patterns and processes of past climate change, providing records of natural variability against which present and future climate change can be assessed. Deep Sea Drilling Project (DSDP), Ocean Drilling Program (ODP), and Integrated Ocean Drilling Program (IODP) expeditions have focused on many aspects of environmental processes and change, including global-scale orbital climate forcing; processes and thresholds of Northern Hemisphere and Antarctic glaciations and global sea level change; abrupt millennial-scale climate change; and past global warmth and extreme climate events.

Although paleoclimate data from scientific ocean drilling have lower resolution and sometimes lower precision than modern meteorological data, they extend over longer periods of time and provide information regarding various climate states, their stability, and impacts on other Earth systems. Innovations in piston coring technology during DSDP and ODP led to recovery of high-quality and high-resolution sediment cores. One of these innovations was double- and triple-coring sediments at the same site, which allowed for splicing cores together through biostratigraphy and matching physical properties, creating longer, continuous records. These composite records have created a more complete and detailed account of past changes in the ocean environment on annual to orbital (10 to 100 kyr) time scales, providing new insights into ocean-atmosphere, ocean-cryosphere, and ocean-biosphere interactions (ODP, 2007). Progressively higher resolution, better dated sediment records have led to reconstructions of atmospheric carbon dioxide ($CO_2$) concentrations for the past 60 myr (Royer, 2006); Cenozoic history of ice sheets (Zachos et al., 1992; Ehrmann, 1998; Backman and Moran, 2009); sea surface temperature (Huber, 2008; Bijl et al., 2009); and ocean bottom temperatures (Triapati and Elderfield, 2005). Cores from scientific ocean drilling have tied together marine and continental records, further constraining the timing of significant events in global climate history.

As their length and quality have improved, scientific ocean drilling records have strongly contributed to the understanding of dramatic and continuous change in Earth's climate system over the past ~100 myr, from extremes of expansive warmth with ice-free poles to massive continental ice sheets and polar ice caps. Significantly, these records of millions to tens of millions of years ago provide critical insights into environmental changes when atmospheric $CO_2$ levels were similar to or higher than today. The identification of orbital cycles that drive repeated cycles of polar ice sheet growth and collapse and global sea level fluctuations of up to 120 m (e.g., Chappell et al., 1996) remains one of the most fundamental discoveries of scientific ocean drilling.

The geological record below the seafloor extends beyond instrumental and ice core records for tens of millions of years, when Earth's climate was warmer than the present. Because of this, scientific ocean drilling records provide important context for assessing future climate change. Over the past decade, there have been moves toward the integration of ocean core proxy data that act as tracers of past climate (Box 4.1; Figure 4.1) and the use of numerical ice sheet and climate models to predict future climates. Past warm periods such as the Pliocene (5.3-2.6 Ma) and Eocene epochs (55-33.9 Ma) offer more realistic future climate analogs, which scientists can use to improve model performance, gaining better understanding of Earth system responses to elevated greenhouse gas levels.

### Box 4.1
### Proxy Records in Scientific Ocean Drilling

Over the past 40 years, a wide range of climate proxies that measure different components of marine sediments have been developed for use as tracers of past changes in climate and ocean circulation. These proxies include variations in plant and animal species abundances, which track past changes in environmental conditions at a specific location, as well as evolutionary distributions of fossils, which provide important age control and stratigraphic markers for correlation. Isotopic and geochemical measurements of fossil shell material provide information on past oceanographic conditions (e.g., temperature, salinity), past ocean chemistry (e.g., pH, carbonate ion concentration, deepwater mass circulation), and the concentration of paleo-atmospheric $CO_2$ (boron isotopes and boron-calcium ratios). More recently, chemical measurements of fossil organic compounds have been developed to reconstruct sea surface temperatures (e.g., alkenone saturation ratios, long-chain tetraethers), partial pressure of $CO_2$ ($pCO_2$; e.g., alkenone isotopic chemistry), and hydrology (e.g., leaf wax biomarkers such as compound specific deuterium measurements on alkanes).

A number of proxies are now well established and routinely applied (e.g., stable oxygen and carbon isotopic ratios of foraminiferal calcite), while others are still in a more developmental state. All proxies must deal with various levels of associated uncertainty due to a lack of knowledge regarding precise relationships between the proxy and the environmental characteristic being measured (e.g., some $pCO_2$ and sea surface temperature proxies), particularly when applied to older sediments. Nevertheless, as laboratory studies continue and calibrations improve, there has been significant convergence between different proxies used to estimate temperature and $pCO_2$ (e.g., Beerling and Royer, 2011). This explosive growth in the number, type, and utility of proxies has led to a significantly better understanding of past global environmental conditions. The combination of physical measurements of past temperatures with chemical measurements indicating past atmospheric $CO_2$ concentrations has been particularly valuable for understanding the sensitivity of the climate system to $CO_2$ forcing.

## PAST WARM CLIMATE EXTREMES AND THE GREENHOUSE WORLD

The reconstruction of Cenozoic surface temperature distributions and their relationship to changes in atmospheric $CO_2$ concentrations have been among the most important contributions of scientific ocean drilling to paleoclimate studies. Climates prior to 3 myr (particularly the past 65 myr) were generally warmer than today, and were associated with higher $pCO_2$ levels. Reconstructions show a long-term decrease in global average temperatures, from a maximum of about 26 °C in the early Eocene Epoch (~ 50 Ma) to a pre-industrial Holocene average value of 14 °C. This pattern of global cooling is associated with declining $pCO_2$ levels, from 2,000-4,000 ppm range in the Paleocene and Eocene to less than 400 ppm by ~24 myr (Pearson and Palmer, 2000; Pagani et al., 2005b; Beerling and Royer, 2011). Studying warm climate extremes recorded in ocean sediments enable new insights into Earth system responses to elevated greenhouse gas levels.

### Scientific Accomplishments and Significance

Scientific ocean drilling has significantly contributed to the recognition and quantification of latitudinal differences in temperature in response to $pCO_2$ (Figure 4.1) and other high-latitude Earth system feedbacks (e.g., sea ice albedo) that can lead to polar temperature amplification (e.g., Dowsett, 2007; Huber, 2008; Bijl, 2009). Sea surface temperatures reconstructed from globally distributed drill cores have demonstrated that the early Eocene (55-48 Ma) had the warmest climates of the past 65 myr, depicting a world that was ~10-12 °C warmer and with greatly reduced latitudinal temperature gradients compared with the present day (Bijl et al., 2009; see Figure 4.1).

Cores recovered from the Arctic (ODP Legs 151, 163; IODP Leg 302; Figure 4.2a) and the Antarctic (ODP Legs 113, 119, 120, 188, 189; IODP Leg 318; Figure 4.2b) indicate that polar regions of the greenhouse world could support only small terrestrial ice sheets, or had limited perennial sea ice (Moran et al., 2006; Stickley et al., 2009). This finding implies global sea levels more than 60 m higher than the present, when atmospheric $CO_2$ levels may have been as high as 2,000-4,000 ppm (Pagani et al., 2005b; also discussed in the following section).

Observations of past warm extremes are important for evaluating the performance of climate models in response to higher levels of $pCO_2$ (Huber and Caballero, 2011, and references therein). Although amplification of polar warming during the past warm periods appears to be underestimated by the current generation of climate models, the sensitivity of past tropical temperatures is generally overestimated relative to proxy-based temperatures from scientific ocean drilling. Comparisons between models and paleoenvironmental observations from drill cores play an important role in evaluating the performance of Intergovernmental Panel on Climate Change (IPCC) climate models that simulate warmer global climates.

A key discovery of the Paleocene-Eocene greenhouse world (55-50 myr) was the potential of the climate system

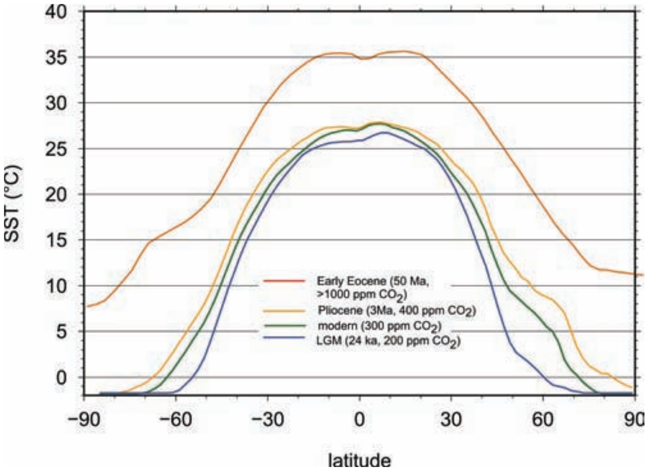


**FIGURE 4.1** Latitudinal variations in climate sensitivity, derived from scientific ocean drilling results. These variations consistently show that the effect of higher carbon dioxide on sea surface temperature, and thus air temperature, increases towards the poles. SOURCE: Adapted from Bijl et al. (2009), with additional data from Paul and Shafer-Neth (2003) and Dowsett (2007).

to experience abrupt and transient temperature excursions occurring within 1 to 10 kyr, termed "hyperthermals" (Bohaty and Zachos, 2003; Zachos et al., 2005). These hyperthermals had warming of several degrees C, indicated by changes in oxygen isotope ($\delta^{18}O$) and Mg/Ca records (Kennett and Stott, 1991; Zachos et al., 2003; Tripati and Elderfield, 2005). The first and largest of the hyperthermals was the Paleocene-Eocene Thermal Maximum (PETM; Box 4.2) at 55.8 Ma, which lasted for approximately 100 kyr.

One of the most important high $CO_2$ analogs studied in ocean sediment cores is the Early Pliocene Epoch (5.3 to 2.6 Ma), when continental and ocean configurations, ecosystems, and ice sheet extent were similar to today. Proxy estimates from sediment cores in a range of ocean basins indicate peak Pliocene values that are comparable to present day values of 379 ppm (IPCC, 2007). Although the high latitudes were significantly warmer, tropical sea surface and air temperatures were similar to the present (e.g., Dowsett, 2007). Drill core data (Raymo et al., 2006; Naish et al., 2009) and ice sheet simulations (Pollard and DeConto, 2009) show complete deglaciation of the Greenland and West Antarctic ice sheets and the low elevation margins of the East Antarctic ice sheet, with global sea levels up to 20 m higher than the present (Miller et al., 2011; Raymo et al., 2011).

Other regional phenomena, such as a permanent El Niño-like state in the tropical Pacific during the Pliocene, can be inferred from sediment core proxy data. In conjunction with climate models, they imply drought and a potential collapse of the Asian Monsoon, increased eastern Pacific precipitation, and increased cyclonic activity (e.g., Brierley and Fedorov, 2010; Fedorov et al., 2010; Ravelo et al., 2010). Observations such as these, from the last time global atmospheric $pCO_2$ levels approached ~400 ppm, may provide an analog for assessing the range of future equatorial climate changes due to anthropogenic warming.

## Fields of Inquiry Enabled

Scientific ocean drilling has enabled scientists to extend the relationship between atmospheric $pCO_2$ and global surface temperature by millions to tens of millions of years, confirming significantly warmer than present climate extremes that are increasingly relevant to future climate projections. The importance of past climate information was acknowledged in the IPCC's Fourth Assessment Report (IPCC, 2007), when it introduced a chapter on paleoclimate archives. As the quality and global coverage of $pCO_2$ and temperature proxies from ocean sediments steadily improve, the IPCC's Fifth Assessment Report (IPCC, in preparation) will place increased emphasis on these observations to verify the performance of climate models during warm extreme intervals.

Cores recovered from scientific ocean drilling have enabled improved estimates of Earth's climate sensitivity to sustained higher levels of greenhouse gases and to dramatic transient perturbations to the carbon cycle (including ocean acidification). These data have also determined the sensitivity of ice sheets to elevated greenhouse gas concentrations (discussed in more detail in the following section), including greater insight into the processes that lead to temperature amplification in polar regions. Finally, the integration of observations of physical and chemical processes elucidated by drilling records is critical for the next generation of climate models.

## Goals Not Yet Accomplished

In a prior review of ODP, the NRC (1992) recommended that the understanding of past climates, especially of rates and magnitudes of climate variability, should be improved. This recommendation was translated into a scientific priority for the IODP Initial Science Plan (IODP, 2001), and expectations in this field have largely been met. In some aspects, such as resolution of past climate extremes, the outcome has possibly exceeded the goals set forth by the plan. However, there is still progress to be made.

Spatial coverage of ocean records of past extreme warm intervals is biased toward the North Atlantic and East Pacific, leaving large swaths of the ocean floor to be sampled. Consequently, sea surface temperature datasets for these times (e.g., Pliocene, Eocene) are inadequate for the robust data-model comparison needed to better constrain future climate projections and understand regional climate variability. The polar regions presently experience temperature increases that are two to three times greater than the global average (Holland and Bitz, 2003; Bijl et al., 2009; Miller et al., 2010), yet the mechanisms and feedbacks are poorly understood, as

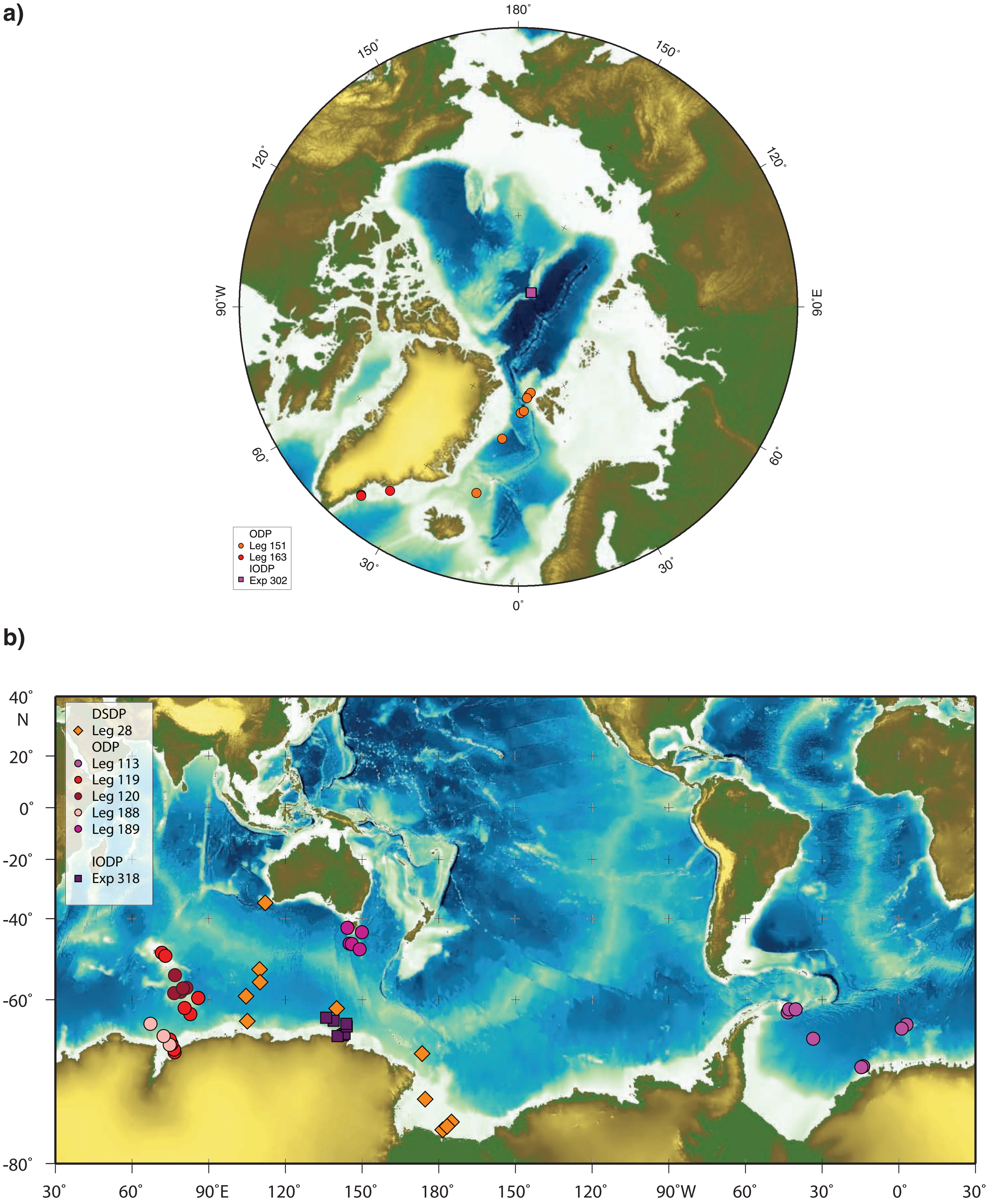
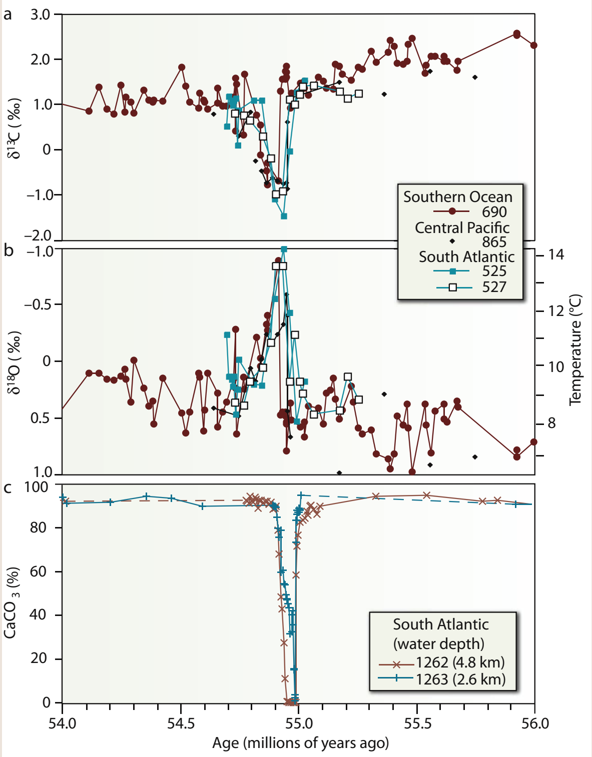


**FIGURE 4.2** Location maps of DSDP, ODP, and IODP expeditions in polar regions that were related to past climate extremes. (a) Illustrates the Arctic using a stereographic projection. (b) Illustrates the Antarctic using a Mercator projection. Both have a color range of –9,000 to 9,000 m, with white marking the 0 m depth. SOURCE: IODP-USIO.

## Box 4.2
## The Paleocene-Eocene Thermal Maximum

Observations of an extreme change in the carbon chemistry of fossils at 55.8 myr suggest that Earth experienced a sudden release of carbon into the atmosphere, followed by a rapid 4 to 8 °C increase in global temperature. This is the best past analog of rapid changes in atmospheric $CO_2$ so far observed in the geologic record. Kennett and Stott (1991) discovered a large Cenozic carbon isotopic ($\delta^{13}C$) excursion at the Paleocene-Eocene boundary, in core from ODP Hole 690B. A 35-50 percent species reduction of benthic foraminiferal taxa was associated with the enrichment of light carbon and a $\delta^{18}O$ excursion interpreted as reflecting a > 4-8 °C abrupt increase in surface water temperatures. This event was termed the Paleocene-Eocene Thermal Maximum (PETM). Study of these cores established the onset of the warming event as taking on the order of 1 kyr and lasting over ~130-190 kyr (Kelly et al., 1996; Bralower et al., 1997; Roehl et al., 2000).



Paleocene-Eocene Thermal Maximum, as recorded in oceanic benthic isotopic records from Antarctic, south Atlantic, and Pacific Ocean drill sites. The rapid decrease in carbon isotope ratios (top panel) indicates a large increase in atmospheric methane and carbon dioxide. This is coincident with 5 °C of global warming (middle panel, presented with oxygen isotope values). Subsequent ocean acidification is indicated by a rapid decrease in the abundance of calcium carbonate (lower panel). SOURCE: Zachos et al., 2008.

Analysis of other scientific ocean drilling cores, such as those from ODP Sites 525, 527, and 865, ODP Leg 208, and IODP Expedition 302 to the Arctic Ocean (Sluijs et al., 2006) showed these excursions were global. Arctic cores recovered by the IODP Arctic Coring Expedition (ACEX) in 2004 reveal that surface temperatures increased from 18 to 23 °C, synchronous with other PETM records. The sudden disruption in the carbon cycle—nearly equivalent to burning modern fossil fuel reserves—produced significant ocean acidification, disrupted the deep ocean ecosystem, and caused significant evolutionary turnover in benthic dwelling foraminifera. Advanced piston coring in 2003 at the Walvis Ridge in the South Atlantic recovered a set of cores that recorded the climate and chemistry changes associated with this event as well as the subsequent, several hundred thousand year recovery of ocean chemistry following the carbon disruption. For the first time it was possible to fully document the size of the carbon perturbation (an initial pulse of 3,000 GT in less than a few thousand years), the response of the surface warming, and the role of the oceans in removing the carbon from the atmosphere and neutralizing the increased pH of the deep sea.

One of the most striking possible explanations for the event is catastrophic and massive ocean floor methane hydrate dissociation triggered by otherwise incremental warming (Dickens et al., 1997b), which could produce abrupt global warming and then later oxidize $CH_4$ to $CO_2$. However, methane derived from heating of organic-rich shales by intrusions of the North Atlantic large igneous province (LIP) provides a plausible alternative (Svensen et al., 2004; see Chapter 2 for a discussion of LIPs).

are implications for ice sheet stability. Polar regions remain woefully undersampled, with only one drilling expedition in the high Arctic Ocean and only a few expeditions in the Antarctic, yet these sparse data points are the basis for many current models of climate responses in polar regions. Improved understanding of the role of the Southern Ocean in the carbon cycle is another priority. Recovering sediment cores from high latitudes presents one of the most important technological challenges for future scientific ocean drilling and will need the innovative use of both mission-specific platforms and the *JOIDES Resolution* to drill strategic transects. In addition to increased spatial coverage, continued advances in paleoclimatological observations from climate proxies will be needed to provide robust verification of climate models. Achieving this goal will entail close cooperation between the scientific ocean drilling and Earth system modeling communities.

## CENOZOIC ICE SHEET EVOLUTION AND GLOBAL SEA LEVEL CHANGE

Changes in global sea level over the past 40 myr reflect the evolution of polar ice sheets from ephemeral, small-medium Antarctic ice sheets (prior to 33.5 myr) to a large Antarctic ice sheet and variably sized Northern Hemisphere continental ice sheets for the past 2.7 myr. Marine sedimentary archives provided by scientific ocean drilling have revolutionized understanding of Earth's Cenozoic climate system and have imparted new insights into the pattern of behavior of polar ice sheets and their influence on global sea level (Figure 4.3). These studies also have important implications for assessing future sea level rise in a warming world, where uncertainties in sea level projections are large because ice sheet dynamics and climate system behavior during steadily warming conditions are still poorly understood.

### Scientific Accomplishments and Significance

Scientific ocean drilling has played an integral role in understanding the transition from a greenhouse to "icehouse" climate system with the onset of Antarctic glaciation 33 myr ago, at the Eocene-Oligocene boundary. In 1973, DSDP Leg 28 drilled on the Antarctic continental shelf in the Ross Sea, providing the first physical evidence of continental glaciation extending back into the Oligocene (Hayes et al., 1975) and dispelling the then-prevailing hypothesis that Antarctica had only been extensively glaciated since the beginning of the Quaternary (2.588 myr). Drilling of continental shelf sites in Prydz Bay (ODP Leg 119) provided the first direct evidence of continental-scale ice sheets calving at the Antarctic coastline (Hambrey et al., 1991), and ice-rafted debris collected at the Kerguelen Plateau (ODP Leg 120) offered further confirmation of glaciation at the Eocene-Oligocene boundary (Wise et al., 1991; Zachos et al., 1992). These same cores indicated that the Antarctic ice sheet grew quickly (within a few tens of thousands of years) and caused at least a 60 m global sea level fall (Zachos et al., 1996). Coring of thick, continuous Paleogene sediments in the Weddell Sea (ODP Leg 113) led to the idea that thermal isolation due to the separation of South America and Australia from Antarctica initiated ice sheet development. However, more recent numerical model simulations imply that a threshold in declining $p\mathrm{CO}_2$ was the first-order control on Antarctic glaciations (DeConto and Pollard, 2003; Huber et al., 2004).

High-resolution $\delta^{18}$O records from the Southern Ocean (ODP Site 1090) and the equatorial Pacific (ODP Site 1218) illustrate Antarctic ice sheet behavior during the Oligocene and early Miocene early icehouse world (33-15 Ma; e.g., Pälike et al., 2006). Glacial-interglacial ice volume changes equivalent to 10-40 m of global sea level change were driven by a pervasive 40,000-year orbital forcing, with major glacial events occurring every 1-2 million years. The first physical evidence for orbitally paced variability in the East Antarctic Ice Sheet during the Oligocene and Miocene came from sea ice–based drill cores (e.g., the Antarctic Geological Drilling program [ANDRILL][1]; Naish et al., 2001), which confirmed climatic patterns observed in global ice volume proxy records from scientific ocean drilling oxygen isotope records (e.g., ODP Leg 120, Zachos et al., 1996; ODP Leg 154, Zachos et al., 2001b; ODP Leg 199, Pälike et al., 2006). Integrating data from ice-based and ODP cores demonstrated that under warmer climates the Antarctic ice sheets were less stable than today.

Unlike the Antarctic, a detailed, relatively continuous ocean sediment record of the Arctic's glacial history was unavailable until the mid-2000s, when an astute strategy combining icebreakers and drillships succeeded in recovering the first direct evidence for Cenozoic climate change from this region (ACEX; e.g., Moran et al., 2006). The ACEX cores captured a 55 million year long history of the central Arctic Ocean, including the transition from a warm greenhouse world during the late Paleocene and early Eocene (Brinkhuis et al., 2006; Slujis et al., 2006) to a colder icehouse world influenced by sea ice (Stickley et al., 2009) and apparent sparse icebergs (Eldrett et al., 2007) from the middle Eocene to the present.

In the Northern Hemisphere, the interval from 3.0 to 2.5 myr ago is marked by the progressive expansion of continental ice and global cooling, which initiated a pattern of glacial-interglacial cycles controlled by long-term periodic variations in Earth's orbit. A major increase in understanding these variations came from DSDP Leg 81, which recovered an almost continuous sediment record from Site 552 in the high-latitude Atlantic Ocean using the newly employed hydraulic piston corer. At this site, Shackleton et al. (1984) were able to show that positive excursions in $\delta^{18}$O correlated with the influx of ice-rafted debris—indisputable evidence for nearby continental ice sheets. They established the first

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[1] See http://www.andrill.org.

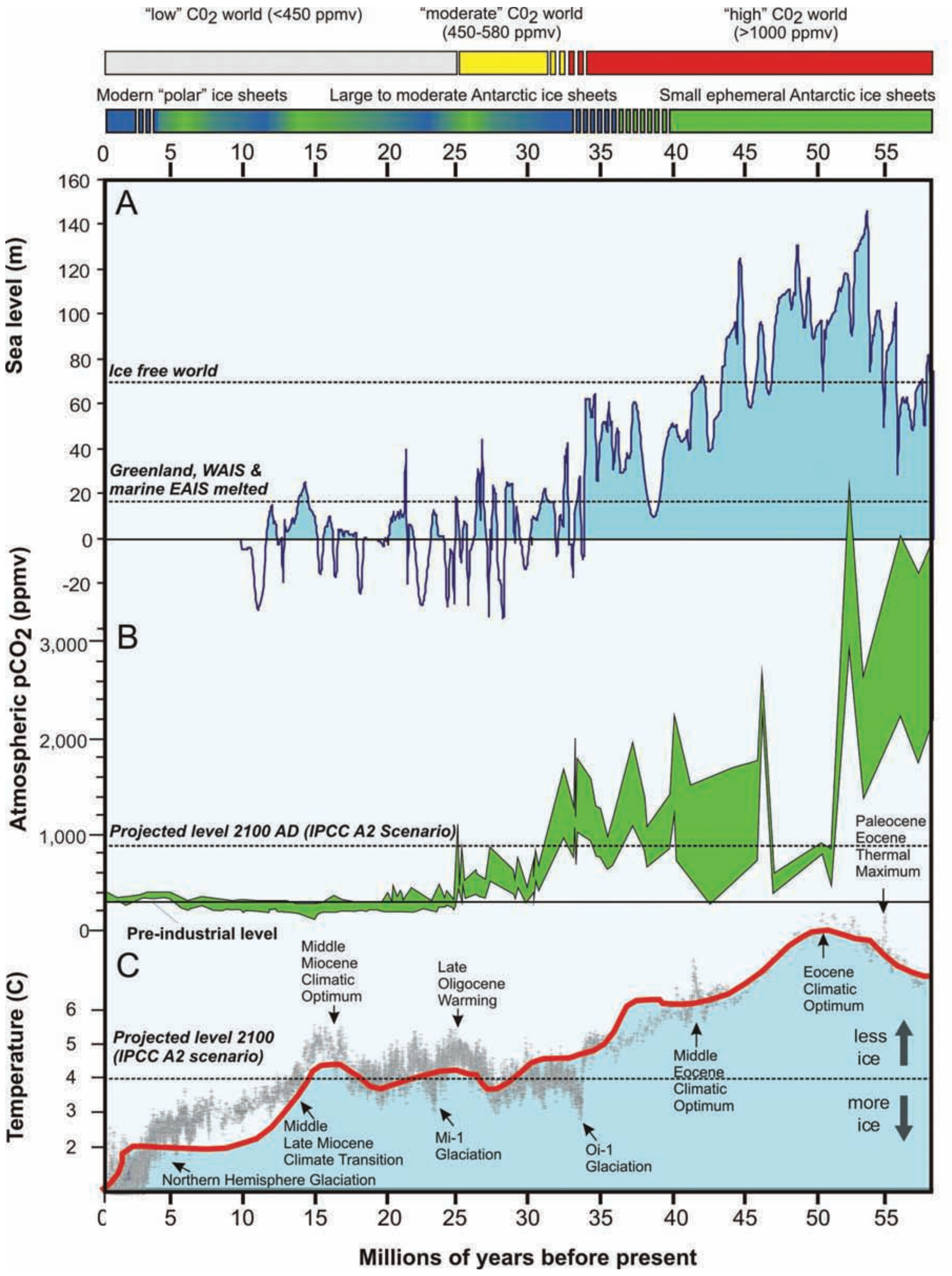

**FIGURE 4.3** Illustration of three major contributions to Cenozoic climate studies from scientific ocean drilling. The composite datasets used in the figure were generated from analysis of scientific ocean drilling sediment cores. (A) Global sea level curve from continental margin cores, which represent changes in sea level in response to polar ice volume fluctuation (e.g., Miller et al., 2005; Kominz et al., 2008). (B) Atmospheric $CO_2$ concentrations reconstructed from organic biomarkers and foraminifera preserved in ocean sediments (Pearson and Palmer, 2000; Pagani et al., 2005b). (C) Global atmospheric temperature curve (bold red line) adapted from Crowley and Kim (1995) overlaid on compiled benthic $\delta^{18}O$ data representing global ice volume and deep ocean temperature (Zachos et al., 2001a). Major periods of warmth and transitions to cooler climate are also presented. SOURCE: Modified from R. Levy, GNS Science.

age for onset of major continental glaciations (~2.5 myr ago), based on observations that only small amounts of ice-rafted debris were found in the cores before this time. Subsequently, drill cores from the equatorial Atlantic (DSDP Leg 94; ODP Leg 108) and North Pacific (ODP Leg 145) refined this date to 2.7 myr ago (Ruddiman et al., 1986; Haug et al., 1999, 2005).

Drilling of passive continental margins has provided a detailed 100 myr long history of global sea level change (e.g., Miller et al., 1996, 1998, 2005; Kominz et al., 2008). As part of an integrated study of the passive continental margin, ODP drilled a transect across New Jersey that extended from offshore to onshore. ODP Legs 150,174A, and 150X/174AX sampled the slope, outer shelf, and onshore, respectively; dated unconformities produced during sea level fall; and correlated them to increases in $\delta^{18}O$ values indicative of periods of polar ice volume growth. More than 30 oscillations in global sea level during the Oligocene and Miocene (33-6 Ma) were identified, proving the validity of the oxygen isotope curve as a proxy for changes in global ice volume (Miller et al., 1998). Stratigraphic patterns (e.g., unconformities, bedding geometries) in the New Jersey siliciclastic basins correspond to scientific ocean drilling cores recovered in carbonate platforms off the margins of Australia (ODP Legs 133, 182, and 194) and the Bahamas (ODP Leg 166), implying a global origin driven by sea level change.

Although early studies of Late Quaternary sea level changes using corals were not done under the auspices of scientific ocean drilling, IODP has recently successfully drilled reefs and shallow water carbonate sequences with mission-specific platforms in Tahiti (IODP Expedition 310; Camoin et al., 2007) and the Great Barrier Reef (IODP Expedition 325). Four transects of the Great Barrier Reef were drilled, with good core recovery of the last glacial cycle. The Tahiti expedition recovered excellent records of the last interglacial global sea level high stand (125 kyr ago) and of the rapid rise in sea level during deglaciation since the last ice age, providing critical constraints on past sea level high stands, the rate of sea level rise (up to 4 m per century; Deschamps et al., 2008), and the potential to fingerprint meltwater sources.

### Fields of Inquiry Enabled

Scientific ocean drilling has contributed significantly to understanding the growth of polar ice sheets and the timing of glacial and interglacial cycles in the Northern Hemisphere, as well as their influence on fluctuations in global sea level over the past 100 myr. Long-term projections of sea level rise remain highly uncertain, primarily because of poor understanding of the dynamic behavior of ice sheets during sustained warming. Physical records of past ice sheet behavior recovered through scientific ocean drilling have enabled scientists to evaluate the relationship between surface temperature and greenhouse gas concentrations over the full spectrum of climate states, leading to better understanding of thresholds for both Antarctic and Northern Hemisphere glaciation and deglaciation (e.g., DeConto et al., 2008). Consequently, the plausible range of changes in global sea level can be better constrained. In addition, well-dated reconstructions of global sea level rise following the last glaciation, derived from drilling corals, are increasing the ability to identify meltwater sources and rates of sea level rise.

### Goals Not Yet Accomplished

Extracting physical records of past polar ice sheet variability and sea level changes will remain a challenge, because it requires integrated onshore and offshore drilling transects on continental margins and core retrieval over multiple timeframes and depositional settings, including difficult drilling environments such as sea ice and unconsolidated sediments. Although IODP mission-specific platforms have begun to address recovery issues, challenges still remain and lead times are long. Increasing the use of logging-while-drilling technology could fill in some of the gaps related to poor core recovery.

Opportunities exist for scientific ocean drilling to build on cooperation with other programs that specialize in drilling on land and in shallow waters (e.g., the International Continental Scientific Drilling Program [ICDP]) and glaciated continental margins (e.g., ANDRILL), especially to address the role of high latitudes in Earth's climate system. For example, the evidence for ice-rafted debris in ACEX cores has sparked a debate about the existence of continental-scale ice sheets in the Northern Hemisphere prior to 2.7 myr ago (e.g., Eldrett et al., 2007; Tripati et al., 2008; Stickley et al., 2009). Although coupled ice sheet and climate models do not favor significant Northern Hemisphere ice at atmospheric $CO_2$ concentrations above pre-industrial levels (~300 ppm; DeConto et al., 2008), additional long paleoclimate records are critically needed to address these key questions and to provide a better understanding of the climate history of the Arctic.

Understanding the spatial heterogeneity of sea level rise in response to ice mass changes will also be critical for assessing potential regional impacts of rising sea level. Geodynamical models and overlapping sea level records recovered from a range of latitudes in different tectonic and sedimentary settings will be needed to identify the relative contributions of different processes that create a global pattern of sea level change. Scientific ocean drilling will play a critical role in further development of proxies for hydrologic cycles, sea ice coverage, and continental ice volumes.

## ORBITAL FORCING

The study of climate variability due to changes in Earth's orbit provides one of the best examples of an emerging field of scientific inquiry that blossomed because of scientific ocean drilling. The earliest observations that glacial-interglacial climate changes at 23, 42, and 100 kyr were paced by changes in Earth's orbital geometry related to precession, obliquity, and eccentricity ("Milankovitch cycles") (Shackleton and Opdyke, 1973; Hays et al., 1976) relied on the analysis of conventional short piston cores in relatively low sedimentation rate locations. The advent of hydraulic piston coring (DSDP Leg 64 in 1978) and its first deployment for paleoceanographic studies (DSDP Leg 68 in 1979) produced the first long, undisturbed records of marine sediment from which researchers were able to derive high-resolution records of oxygen isotopic chemistry in a well-dated, independent chronology based on paleomagnetic reversal stratigraphy (see also Chapter 2). The initial records from DSDP Sites 502 and 503 extended the history of marine oxygen isotope variations back to approximately 3.5 myr ago; previous records using traditional piston cores had been limited to observations of the past 1 myr or so. DSDP Leg 81 followed with the striking observation of a significant increase in glacial sediment delivery to the North Atlantic at about 2.5 myr, marking the initiation of Northern Hemisphere glaciation (Shackleton and Hall, 1984). DSDP Leg 94 coring in North Atlantic Sites 607 and 609 quantified the changing nature of the climate system response to orbital forcing, from the evolution of the obliquity-dominated response in the late Pliocene and early Pleistocene to the eccentricity-dominated response in the late Pleistocene. The nature of this change has been well documented elsewhere, but the reasons for the change remain an area of active research.

Based on these early successes, ODP embarked on a global-scale effort (Figure 4.4) to observe and study orbitally forced climate throughout tropical (ODP Leg 108 in the eastern equatorial Atlantic; ODP Leg 117 in the Arabian Sea; ODP Leg 130 in the western equatorial Pacific; ODP Leg 138 in the eastern equatorial Pacific; and ODP Leg 154 in the western equatorial Atlantic) and high-latitude locations of all ocean basins (ODP Leg 145 in the North Pacific; ODP Legs 151, 162, and 172 in the North Atlantic; ODP Leg 177 in the Southern Ocean; ODP Leg 181 in the western South Pacific; ODP Leg 188 in Prydz Bay; and ODP Leg 202 in the eastern South Pacific). This major effort and its successes are easily among the most significant for the scientific ocean drilling community.

## Scientific Accomplishments and Significance

The sediments collected by scientific ocean drilling have played a major role in advancing the understanding of orbitally forced climate changes. The very long and highly resolved records provided a means to document the changing effects of orbital forcing as ice sheets grew from modest sizes in the early Pliocene to large, continental-scale glaciers in the late Pliocene (~3 Ma). The response to forcing shifted from obliquity-dominated (41kyr period) to eccentricity-dominated (100-kyr period) about 800 kyr ago (Ruddiman et al., 1986), despite the fact that there were no changes in the characteristics of the orbital variability, and that eccentricity plays only a small role in the amount of energy Earth receives from the sun. Sediments collected by the drilling programs have been used to develop and test models of orbital forcing (Imbrie et al., 1992, 1993; Raymo, 1997; Huybers and Wunsch, 2004; Huybers, 2006) and how the growth of the large ice sheets may have changed the response to the forcing (Raymo and Huybers, 2008). On longer time scales, studies of orbital variability have linked eccentricity forcing at 400-kyr periods with changes in Antarctic ice sheet growth and decay, marine productivity, and carbon burial in the earlier Cenozoic (Pälike et al., 2006). As a result, all known periods of orbital forcing have been documented in the marine records, a feat which would not have been possible without scientific ocean drilling and the development of hydraulic piston coring (more information on piston coring can be found in Box 2.2).

The late Pleistocene records of climate change have also provided important constraints on climate sensitivity—the magnitude of climate change expected from a doubling of atmospheric $CO_2$ concentration (Hansen et al., 2006, 2007)—thus making these records among the most societally relevant accomplishments of scientific ocean drilling and conventional piston coring. Ice core $CO_2$ variations from Vostok and EPICA (European Project for Ice Coring in Antarctica) combined with sea surface temperature variability observed in marine and continental locations provide independent estimates of the sensitivity of climate to changes in atmospheric $CO_2$ concentration. Earlier Cenozoic reconstructions of climate have also been used to constrain climate sensitivity (the Paleocene-Eocene Thermal Maximum, for instance, described in Box 4.2). A low equilibrium sensitivity of warming to greenhouse gas increase is ruled out based on the relationship of glacial-interglacial changes in $CO_2$, the calculated changes in Earth's energy budget due to orbital variability and albedo changes, and the observed magnitude of climate and ice volume changes. This conclusion would not be possible without the ability to link marine, land-based, and ice core records of climate and $CO_2$.

The development of this understanding of orbital climate variability and its causes has provided a time scale and framework for interpreting scientific results from a wide range of research disciplines. Scientific ocean drilling played a significant role in producing the long time series of marine oxygen isotope variability that was used to modify and constrain the paleomagnetic reversal ages and to develop a revised Astronomical Polarity Time Scale for the Cenozoic (Kent, 1999), thus linking continental- and marine-based research on a common and accurate time scale (see Box 2.2). In the most recent example, Lisiecki and Raymo (2005) correlated a global set of long, marine oxygen isotope records, dominated by the set of advanced piston core sites recovered by ODP in the 1980s and 1990s, to develop a continuous, highly resolved record of oxygen isotope variability and

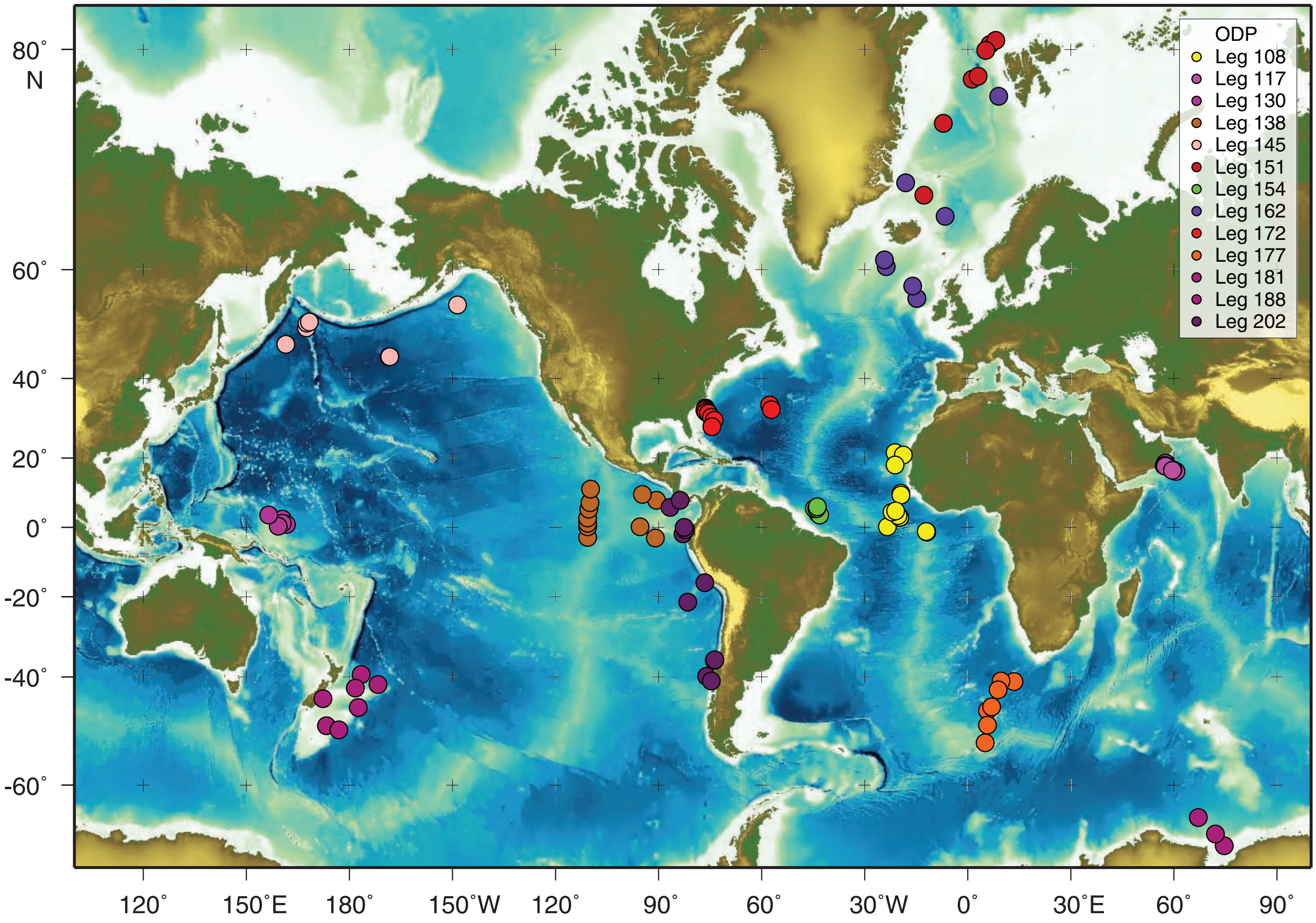

**FIGURE 4.4** Location map of ODP legs related to orbital forcing. This is a Mercator projection with a color range of –9,000 to 9,000 m, with white marking the 0 m depth. SOURCE: IODP-USIO.

paleomagnetic reversals (Box 4.3; Figure 4.5). On longer time scales, marine oxygen isotope records and magnetic reversals have been used to refine the Cenozoic chronology for at least the past 40 myr, with refinements to earlier stages still under way. The broad impact of the development of this chronology can be observed in terrestrial-based studies of archeology, anthropology, and climate, including the comparison of major human evolutionary events with changes in climate based on marine oxygen isotope records from ODP sites (e.g., deMenocal, 2011; see section on "Co-evolution of life and the planet" at the end of this chapter).

## Fields of Inquiry Enabled

The development of the Astronomical Polarity Time Scale for the Cenozoic has had widespread impact throughout the geosciences, influencing research in paleoclimate studies, archeology, anthropology, and astronomy. The combined sets of proxy records from terrestrial and marine sections of physical (temperature, rainfall) and biogeochemical (carbon isotopes, carbonate system proxies like barium and boron) properties have provided new target datasets for testing a variety of coupled climate and biogeochemistry models in ways that cannot be accomplished using the very short records of climate variability in the historical record. The fundamental understanding of how Cenozoic climate evolved has also provided a framework to evaluate the effects of changing climate on evolution, including hominins.

Scientific ocean drilling did not provide the first evidence for orbital forcing of climate, but without the development of long, continuous, undisturbed sedimentary sections, it is unlikely that the field would have progressed so far in such a short time. Since the late 1970s when orbital forcing was first being observed and quantified using a small number of conventional piston cores, the field has progressed to a much broader understanding and a high degree of confidence in the scale of the forcing and changes in the climate system response. The successes have largely been based on high-resolution data collected from long, continuous hydraulic piston cores. A major outcome of scientific ocean drilling is the understanding of the pervasiveness of orbital forcing on climate change. The study of orbitally forced changes in climate using marine sediments also provides a great example of what can occur when a field that is ready for explosive growth meets up with a tool (the hydraulic piston corer) that is nearly perfectly suited for the task.

### Goals Not Yet Accomplished

There are still unresolved issues about how small, orbitally controlled changes in the total amount of energy received from the sun are amplified by feedbacks within the climate system to cause the large Earth system responses seen during ice ages. In the most recent deglaciation, variations in Earth's orbit led to a rapid increase in global average temperature, a sharp rise in atmospheric $CO_2$, polar ice sheet collapse, and a rise in global sea level. A better understanding of how these systems interacted will provide important insight into coupling between the atmosphere, ocean, and ice sheets. Scientific ocean drilling will continue to play a major role in furthering these research activities. The progress during the past several decades in this field of inquiry has been remarkable and highly influential, with many major new insights still on the horizon.

## ABRUPT CLIMATE CHANGE

At ODP's advent in the early 1980s, the main focus of its climate research was orbital variability because so little was known about millennial-scale climate variability. In the mid-1980s, the observation that Greenland ice cores recorded rapid, abrupt changes in air temperature on millennial time scales, also known as Dansgaard-Oeschger events, led to interest in determining the causes of these changes and in finding similar records in marine sediments and continental climate archives. Because there was no known external forcing on these time scales, the principal hypothesis to explain the abrupt climate changes centered on coupled ocean-atmospheric interactions (Broecker et al., 1992), and rapid changes in North Atlantic overturning circulation became a major research focus for the paleoceanographic research community. Sampling of legacy cores from prior scientific ocean drilling expeditions greatly facilitated the understanding of changes in the North Atlantic region and associated far field climate effects. Although not included in earlier scientific ocean drilling planning documents, short period climate was listed as a research priority in the ODP Long Range Plan (ODP, 1990); the first legs dedicated to climate variability on millennial or shorter time scales began in 1995. Later expeditions included locations around the globe (e.g., ODP Leg 162: North Atlantic-Arctic Gateways; ODP Leg 167: California Margin; ODP Leg 169: Saanich Inlet; ODP Leg 172: Northwest Atlantic Sediment Drifts; ODP Leg 202: Southeast Pacific Paleoceanographic transects; IODP Legs 303 and 306: North Atlantic Climate I and II; and IODP Leg 323: Bering Sea Paleoceanography).

### Box 4.3
### Developments in Coring Technology and Core Recovery

The past four decades of scientific ocean drilling have led to great contributions in riserless deepwater drilling technology, which have significantly improved core quality and extended the amount of core that can be recovered during drilling. Early coring with the *Glomar Challenger* during DSDP mainly used a four cone commercial industry bit. With this bit, core recoveries were low to moderate, and many of the cores were highly disturbed. The more modern *JOIDES Resolution* helped to increase the overall core recovery and revolutionized deepwater coring practices (see white papers from Dennis Kent and Ted Moore, Appendix C). Innovations in piston coring technology during DSDP, later advanced by ODP, led to recovery of high-quality cores in soft to medium-soft formations (Larson et al., 1980; Gelfgat et al., 1994).

A major technological advance in core recovery occurred when DSDP Site 607 in the North Atlantic was double-cored with the newly developed hydraulic piston corer (see Box 2.2). The cores were then correlated to fill in gaps caused by loss of core material from ship heaving (Ruddiman et al., 1986). Piston cores are now routinely double- and triple-cored and spliced together on the basis of matching continuous logs of physical properties recorded on board the ship to produce a composite depth record. ODP, and later IODP, also evolved wireline coring techniques that permitted deeper penetrations into medium to hard formations (Storms, 1990). The scientific ocean drilling programs worked with industry to innovate better coring bits that would have longer life and provide less disturbed cores. One breakthrough was the extended core barrel for drilling harder sediments, which combined piston coring with a follow-up rotary coring bit (Brewer et al., 2005). In conjunction with Schlumberger, IODP also developed logging-while-coring systems that measure gamma rays, resistivity, and full bore resistivity images (Goldberg et al., 2004).

DSDP, ODP, and IODP achieved these technological advancements with limited development budgets, especially when compared to the research and development budgets of the commercial offshore drilling industry.

### Scientific Accomplishments and Significance

In a series of important contributions, Bond et al. (1992, 1993) used legacy cores from DSDP Site 609 to develop a comprehensive record of ice-rafted debris for the North Atlantic, identifying major ice-rafted debris events

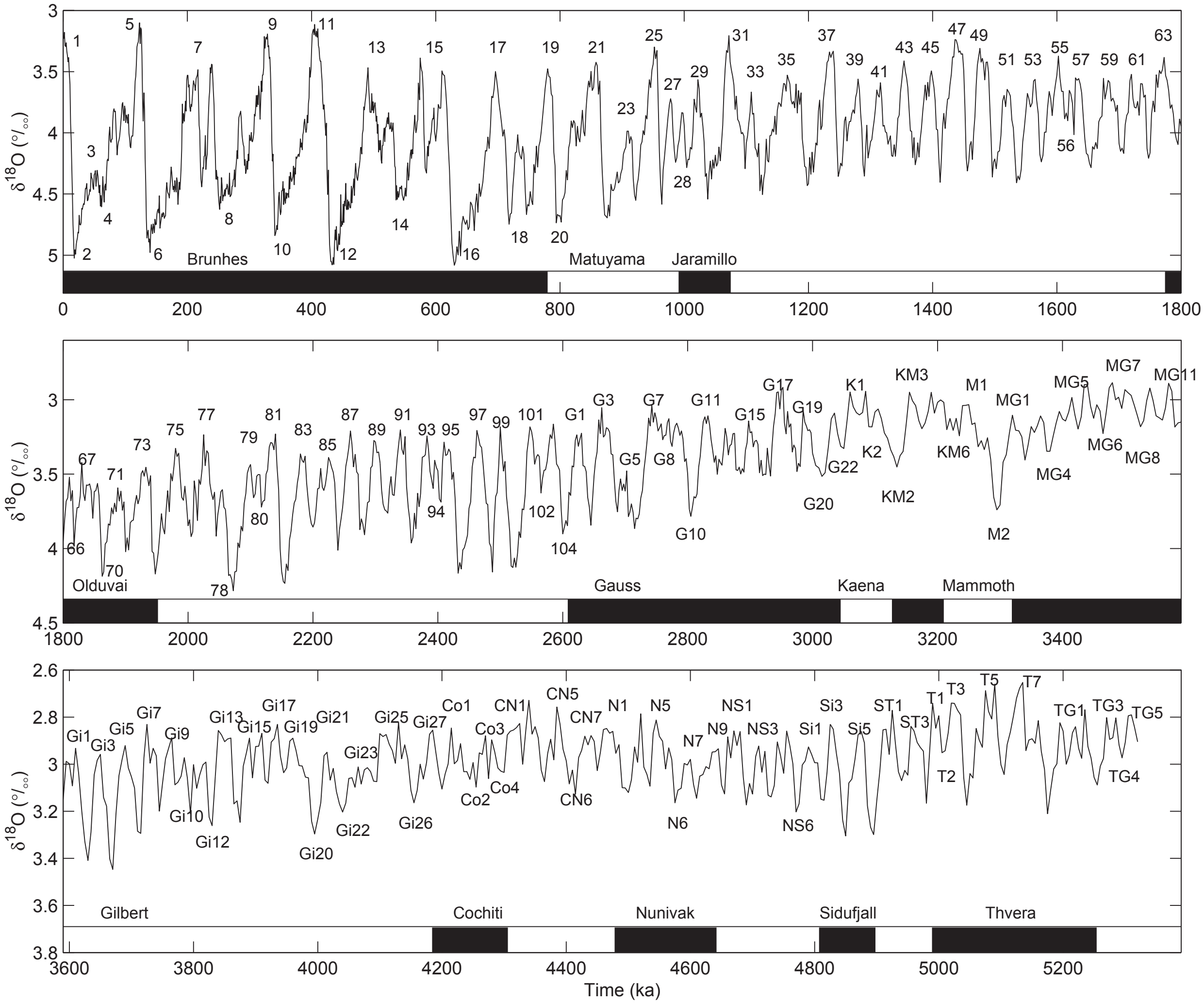

**FIGURE 4.5** The marine oxygen isotope and paleomagnetic record for the past 5 myr. SOURCE: Lisiecki and Raymo, 2005. Reproduced by permission of American Geophysical Union.

(Heinrich events) as well-higher frequency changes that correlated with the abrupt air temperature swings observed in Greenland. The close coupling between air temperature and ice-rafted debris strongly suggested that changes in North Atlantic Ocean overturning circulation were related to rapid changes in Greenland air temperatures. McManus et al. (1994) extended the ice-rafted debris record at the same site (DSDP Site 609) through the interglacial period 120 kyr ago, demonstrating that millennial variability was not limited to the glacial climate. At ODP Site 980, McManus et al. (1999) documented pervasive millennial-scale delivery of ice-rafted debris over the last 500 kyr, commencing when Northern Hemisphere continental glaciers reached approximately 50 percent of their maximum size. Raymo et al. (1998) observed millennial-scale fluctuations in the early Pleistocene at ODP Site 983, while McIntyre et al. (2001) found 2 to 5 kyr spacing of ice-rafted debris events in the late Pliocene at the same site, proving that millennial climate fluctuations are found not only in the eccentricity-dominated interval of the late Pleistocene but also in the obliquity-dominated interval of the Pliocene and early Pleistocene.

Scientific ocean drilling also played a major role in understanding the far-field effects of North Atlantic changes at this time by acquiring cores from sites with high sedimentation rates. The Santa Barbara Basin (ODP Site 893) provided evidence that interstadial-stadial fluctuations also occurred in the eastern Pacific (Hendy and Kennett, 1999), with colder intervals (stadials) associated with increased ventilation of the intermediate-depth eastern Pacific (Behl and Kennett, 1996). Cariaco Basin (Site 1002) cores recorded abrupt changes in sediment chemistry and lithology, which, in parallel with the Greenland air temperature record (Figure 4.6), reflected past changes in evaporation and precipitation over northern South America (Peterson et al., 2000a). These observed changes have been attributed to the migration of the Intertropical Convergence Zone. Combined with other observations of millennial-scale climate fluctuations in the Mediterranean region (ODP Site 977: Martrat et al., 2004) and other continental locations (e.g., Hulu Cave speleothem record [Wang et al., 2001]), the synchroneity of millennial-scale climate changes implies that ocean-atmosphere reorganizations happen quickly and have widespread impact on temperature and moisture patterns in and beyond much of the Northern Hemisphere.

## Fields of Inquiry Enabled

Rapid advances in understanding the coupled nature of atmosphere-ocean circulation occurred through comparison of the observational data of abrupt climate change patterns (many derived from scientific ocean drilling records) with the results of high-resolution numerical model simulations of the coupled ocean-atmosphere system. Observations of rapid climate changes in Greenland ice cores and in North Atlantic sediments were quickly confirmed in other continental records, and the patterns were reproduced by coupled ocean-atmosphere simulations of North Atlantic overturning and its response to variations in freshwater forcing. Marine and continental records from tropical locations documented latitudinal shifts in the position of the Intertropical Convergence Zone (Peterson et al., 2000b) forced by changes in North Atlantic surface temperature gradients (Vellinga and Wood, 2002).

Coupled ocean-atmosphere models demonstrate that abrupt reductions in the salinity of the North Atlantic reduce the meridional overturning circulation and cool North Atlantic air temperatures (Manabe and Stouffer, 1997). Temperature and ice rafting patterns in the North Atlantic exhibit this same variability. During periods of higher ice-rafted debris input and greater freshwater delivery into the North Atlantic, colder air temperatures prevailed over Greenland and colder sea surface temperatures were found in the high-latitude North Atlantic. Benthic foraminiferal records also showed that ventilation of the deep North Atlantic Ocean was significantly reduced (Oppo and Lehman, 1995), helping to establish strong coupling between ice sheets, atmospheric circulation, and ocean overturning.

These combined model-data investigations have been instrumental in showing strong coupling of freshwater input and reduced meridional overturning in the North Atlantic, widespread cooling in the circum-North Atlantic region, and perturbation of atmospheric circulation in the tropics and monsoonal regions of southern Asia. The close match between numerical simulations and observations from drill cores provide some of the best independent confirmation of climate model reliability.

## Goals Not Yet Accomplished

Although this area of inquiry has grown quickly, many unanswered research questions remain. The origin of climate variability on millennial scales remains elusive, and there is

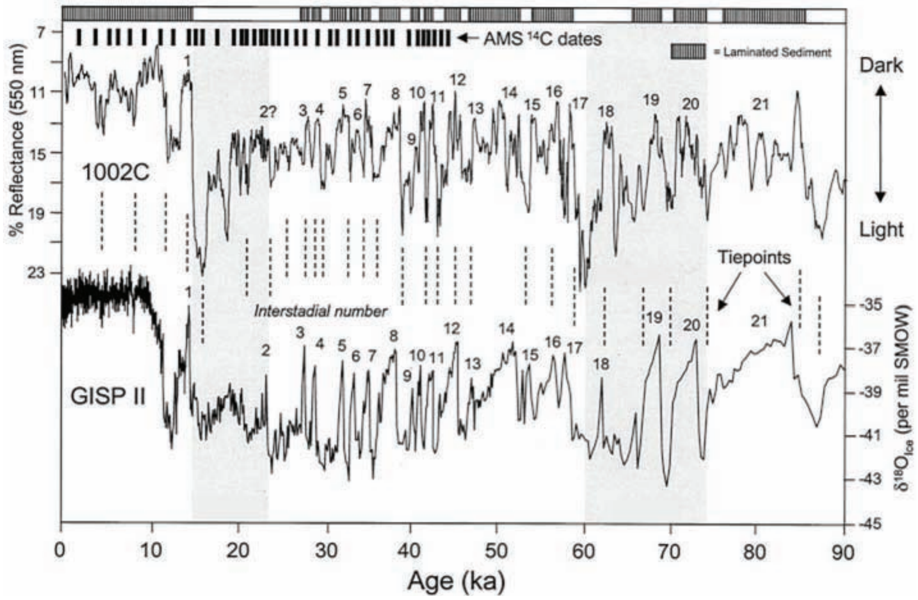

**FIGURE 4.6** Comparison of measured color reflectance (550 nm) of Cariaco Basin sediments from ODP Hole 1002C to oxygen isotope composition ($\delta^{18}O$) from the Greenland Ice Sheet Project (GISP) II ice core (Stuiver and Grootes, 2000). Laminated sediments with benthic microfauna (along top) indicate that deposition occurred under anoxic conditions. Deposition of dark sediments occured during warm interglacial/interstadial times, and deposition of light-colored bioturbated sediments occurred during colder stadial intervals. Visual tiepoints (denoted by a dashed line) show correlations between cores. SOURCE: Modified from Peterson et al., 2000b.

still significant debate about potential causes. Although there is a close correlation between rapid climate change and North Atlantic overturning, it is not yet known if the North Atlantic is the cause or a response to external drivers (Broecker et al., 1990; Kleiven et al., 2010; Billups et al., 2011).

The selection of sites with appropriate sedimentation rates has lacked geographic coverage and is strongly biased toward the North Atlantic. Many of the legacy cores are from locations that were originally chosen for study of orbital-scale climate variability and thus often have sedimentation rates that are too low for abrupt climate change studies. High-resolution studies of millennial-scale climate variability are likely to remain an important priority for scientific ocean drilling for another decade or more.

## CO-EVOLUTION OF LIFE AND THE PLANET

A fundamental distinguishing feature of Earth is the presence of life that modifies planetary processes, including the composition and properties of the atmosphere, hydrosphere, and lithosphere. The ~70 percent of the planet that is covered with oceans is both a living reactor of Earth system processes and a repository for the ocean floor sediments that record changes in oceanic life. Scientific ocean drilling is the best way to access this record in its most pristine form, where it is accessible with minimal alteration and provides the potential to obtain a full history of ocean sediments and the processes active in and on them.

Scientific ocean drilling results, integrated with onshore efforts, have led to radically new concepts of the relationships between evolution and extinction in the context of climate forcing (such as the PETM), many of which have direct societal relevance. Others are scientifically compelling, such as the Chixulub impact and its timing relative to the Cretaceous-Tertiary boundary. For the most part, the ocean floor record extends back well into the Jurassic, with progressively larger areas covered by younger sediments that have been proportionally more densely sampled. Scientific ocean drilling to advance the knowledge of co-evolution of life and the planet has been highlighted as a priority in ODP and IODP planning documents (e.g., IODP, 2001) and past achievements and future needs have been described in recent NRC reports such as *The Geological Record of Ecological Dynamics* (NRC, 2005) and *Understanding Climate's Influence on Human Evolution* (NRC, 2010).

### Scientific Accomplishments and Significance

A large proportion of scientific ocean drilling has involved biostratigraphy, as well as organisms that serve as ecological proxies or carriers of chemical proxies of environmental change, or as intrinsically important to basic understanding of life on the planet. Major scientific advancements have been realized in understanding co-evolution of phytoplankton, the atmosphere, and terrestrial ecosystems; the role of giant meteorite impacts on the extinction and evolution of life; the signature of stable isotopic anomalies in relation to global warming events and biological adaptation; and climate change and hominin evolution.

Photosynthesis by marine phytoplankton accounts for about one-half of global primary productivity. As shown in Late Triassic (228 myr ago) to recent records in marine sediments preserved on land and recovered in scientific ocean drilling cores, the nature of the phytoplankton has changed substantially, primarily with major evolutionary radiations and ecological expansions of dinoflagellates, diatoms, and coccolithophores. These changes have directly affected the composition of ocean floor sediments. In one specific example, diatoms alone account for ~40 percent of marine net primary productivity, ~50 percent of carbon export to marine sediment, and about ~20 percent of $CO_2$ drawdown; although their marine appearance has been documented in the Early Cretaceous record at ODP Site 693 (Gersonde and Harwood, 1990), their expansion as a major ecological and biogeochemical force occurred during the early to mid-Cenozoic as documented in ODP and DSDP cores[2] (Spencer-Cervato, 1999; Rabosky and Sorhannus, 2009). The temporally parallel rise in diatom productivity and the spread of grasslands have led to a controversial suggestion of a causal link via the silica cycle, which could lower global $CO_2$ as part of a positive feedback system (Johansson, 1996; Conley, 2002; Falkowski et al., 2004). The record of this is carried in marine organisms via alkenone and boron isotopes and other chemical proxies in scientific ocean drilling cores (DSDP Sites 511, 513, 516, 588, 608, 612, 730, and 803; ODP 865, 871, and 872 [e.g., Pearson and Palmer, 2000; Pagani et al., 2005b]).

The discovery of an iridium anomaly by Alvarez et al. (1980), shocked quartz and glass spherules (Bohor et al., 1984), and anomalous fern spore concentrations (Tschudy et al., 1984) in terrestrially exposed marine and continental deposits at the Cretaceous-Paleogene boundary (K-T boundary; 65.5 Ma) led to the meteorite impact hypothesis of mass extinction, the first testable hypothesis for that event. The Alvarez discovery led to a concerted effort in exploring ocean cores to document the global geographic anomaly distribution, temporal distribution of similar anomalies, effects on marine ecosystems, and location of the impact. By the 1990s, many scientific ocean drilling sites had been found with these phenomena clearly expressed (e.g., ODP Site 1049), not only demonstrating the global distribution of the anomalies (Smit, 1999) and the abrupt nature of the extinctions (e.g., DSDP Sites 356 and 384; Thierstein, 1981), but also hinting at the location of the impact site (e.g., Bohor, 1990). The impact site at Chicxulub was discovered by geophysics and coring by Pemex (Penfield and Camargo, 1981), but was not confirmed until 1991 through analysis of oil drill cores (Hildebrand et al., 1991), and later ocean and continental cor-

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[2] See http://services.chronos.org/databases/neptune/index.html.

ing by the IODP, ICDP, and DOSECC (Drilling, Observation and Sampling of the Earths Continental Crust) programs in the early 2000s (see review by Schulte et al., 2010).

Many additional processes involving the K-T boundary have been investigated by examination of scientific ocean drilling cores, notably the $\delta^{13}C$ anomaly (DSDP Site 524; ODP Leg 207; DSDP Sites 528 and 577; ODP Site 1001A; Hsü et al., 1982; Hsü and McKenzie, 1985; D'Hondt et al., 1998; D'Hondt, 2005; Schulte et al., 2010); impact-generated tsunamis (DSDP Sites 536 and 540, Alvarez et al., 1992; ODP Leg 174AX, Olsson, 1997), mass-flow deposits (DSDP Sites 387 and 386; ODP Site 1001; Smit, 1999; Norris et al., 2000), proximal ejecta (Claeys et al., 2002), and rhenium-osmium systems and their relation to the Deccan Traps (DSDP Sites 245, 525, 577, and 245; ODP Site 690; Ravizza and Peucker-Ehrenbrink, 2003; Robinson et al., 2009).

Stable carbon isotopic anomalies have proven to be associated with extinction and biotic turnover events. Studies of the PETM extreme warming event (Box 4.2) demonstrate that excursions and extinctions were coincident with a shallowing of the carbonate compensation depth due to ocean acidification (Zachos et al., 2005) and an intensification of the hydrological cycle involving shifts in the distribution and intensity of precipitation (Schmitz and Pujalte, 2007). Complementary work on the continents showed that there were latitudinal and intercontinental migrations for both terrestrial plants and mammals at the PETM, including the widespread dispersal of modern mammalian orders (see Bowen et al., 2002; Wing et al., 2003). Although not involving extinctions of the magnitude of the K-T boundary, the PETM event did involve a massive reorganization of marine and terrestrial biota with permanent effects and had an inferred forcing ($CO_2$) similar to that of anthropogenic global change (Zachos et al., 2008).

The continuous and detailed records of Cenozoic climatic and biotic change recorded in marine sediments and recovered by scientific ocean drilling have provided environmental context for explanations of biotic events on the continents, particularly the evolution of humans in Africa (NRC, 2010; Ravelo et al., 2010; deMenocal, 2011). While aspects of ocean records integrate global processes such as oxygen isotope anomalies due to ice volume, others capture more regional processes involving dust, freshwater diatoms, phytoliths, and sporomophs blown from adjacent continents. In particular, Indian and South Atlantic Ocean drill cores record processes occurring on the African continent, where humans evolved, within a global framework. ODP coring in the Mediterranean (e.g., at Site 967) has also given rise to excellent dust records that provide important evidence for African continental climate conditions (Larrasoaña et al., 2003). Marine sediment cores from ODP Sites 659, 661, 662, 663, and 664 record dust from plumes originating in West Africa, while DSDP Site 231 and ODP Sites 721 and 722 record dust derived from East Africa and Arabia, allowing for the construction of complete composite sequences for the two areas (deMenocal, 1995, 2004). These records show that North Africa's continental aridity tracked cold North Atlantic sea surface temperatures associated with Northern Hemisphere glaciations, while East Africa's aridity was influenced more by Indian Ocean sea surface temperature (NRC, 2010). Dust records also show similar changes in the frequency of climatic (ice) oscillations seen in the $\delta^{18}O$ record. Information from these cores suggests that prior to 2.8 myr ago, the African climate was regulated by low-latitude precessional (26 kyr) forcing of monsoonal climate. Evolutionary steps of African hominins and other vertebrates occurred with more arid, open conditions near 2.8, 1.7, and 1.0 myr; these times are coincident with the changes in the frequency modes and climate shifts.

In addition, freshwater diatom records from equatorial Atlantic core V30-40 (Pokras and Mix, 1987) suggested that hemi-precessional cycles (approximately 10- and 5-kyr cycles) were important to African tropical aridity, which was confirmed by cores in Lake Malawi (Cohen et al., 2007; Lyons et al., 2009) that suggest human migrations were tied to orbitally controlled megadroughts. The correlation of speciation events with the climate and vegetation shifts seen in ocean drilling cores has transformed thinking on the origins of humans. These hypotheses are guiding the selection of ocean and continental drilling cores, as well as methodologies to test the hypotheses themselves (e.g., Potts, 2006; Ravelo et al., 2010).

## Fields of Inquiry Enabled

More than perhaps any single achievement, the culture of scientific ocean drilling has changed the way the history of life has been studied. Organisms are examined fully integrated in their environmental and geochemical context, sometimes as carriers of chemical environmental proxies, sometimes as parts of communities, and always as part of an integrated stratigraphy in which superposition is unequivocal. Without scientific ocean drilling, the impact hypothesis likely would not have become as forceful a paradigm for extinction processes and certainly not a current mainstay of modern Earth science education (see Chapter 5).

Understanding the co-evolution of life and Earth was not an explicit goal in the DSDP and ODP eras but has come to the forefront with more recent IODP expeditions and recent community workshops (Ravelo et al., 2010), in which life plays a leading role. Another important outcome of this research has been the ability to combine the strength of data from new, specifically tailored drilling expeditions with the great value of the ocean drill core repository for comparative analysis and increased global coverage.

## Goals Not Yet Accomplished

The integrated approach to understanding the Earth-life system exemplified by scientific ocean drilling has resulted in a spectacular understanding of some of the largest biotic changes the planet has seen in the past 200 myr. Although some initial discoveries, such as the K-T impact, occurred on land, deeper understanding was achieved by the contextual approach provided by sediments preserved in the ocean basins. However, a number of scientific ocean drilling-related goals for the Earth-life system have yet to be realized. For example, very little new core-based progress has occurred in understanding the roles of LIPs in biotic change or the overall structure of the Chixulub crater. Scientific ocean drilling may also continue to contribute to understanding the processes that link climatic and evolutionary events in hominin evolution. Finally, the effects of the evolution of new life forms and new physiological modalities on biogeochemical cycles has not been examined in scientific ocean drilling studies; organisms and their physiology are a first-order control on processes such as oxygenation, terrestrialization, agronomic revolution, human culture, and technology.

# 5

# Education, Outreach, and Capacity Building

Education, outreach, and capacity building are so often interwoven that it is difficult to determine if a particular activity is one or the other. In this report, the committee considers education to comprise primary and secondary (K-12), undergraduate, and graduate activities in support of scientific ocean drilling; outreach includes all other non-research-related activities. However, much of what is meant by "education and outreach" is also clearly capacity building, because these activities are essential to create an ocean-literate society as well as the next generation of ocean scientists. Although each activity (education, outreach, capacity building) is discussed separately in this chapter, it should be kept in mind that there is considerable overlap among the topics.

The information included in this chapter resulted from conversations with Ocean Drilling Program (ODP) and Integrated Ocean Drilling Program (IODP) employees and scientists, a white paper drafted by the Consortium for Ocean Leadership (COL), and internet searches. The committee was unable to find evidence of assessments or evaluations of the various education, outreach, and capacity-building programs related to ODP and IODP. These programs are of significant value, but evaluations of each of them would enable a better understanding of their impacts on different groups (e.g., K-12, undergraduate and graduate, informal) and would demonstrate the broader impacts of scientific ocean drilling.

**RECOMMENDATION: Formal evaluation of education, outreach, and capacity-building activities should be implemented to demonstrate the broader impacts of scientific ocean drilling.**

## EDUCATION

Using scientific ocean drilling as an education tool does not appear to have been seriously considered in the Deep Sea Drilling Project (DSDP), although many graduate students went to sea and were involved in related research. There did not appear to be any explicit inclusion of K-12 or undergraduate educational activities despite the very significant contributions that the programs have made to understanding Earth systems (e.g., plate tectonic theory).

The committee found few instances of formal educational activities associated with ODP. During ODP, the Joint Oceanographic Institutions prepared a poster on the Cretaceous–Paleogene extinction event (*Blast from the Past* in 1997, in association with the Smithsonian National Museum of Natural History[1]) and CD-ROMs with associated teacher guides (*From Mountains to Monsoons* in 1997; *From Gateways to Glaciation* in 2000/2001[2]) for use in K-12 classrooms and in outreach. *From Gateways to Glaciation* and *Blast from the Past* were distributed to 25,000 teachers and students[3] (Robert Duncan, Oregon State University, personal communication, 2010). ODP also created the Schlanger Ocean Drilling Fellowships in 1995 (discussed in further detail later in this section). However, ODP science plans, workshop reports, or reviews of scientific accomplishments make very little mention of education (see NRC, 1992; JOI, 1990, 1996, 1997, 2004; Gröschel, 2002). For instance, the ODP Long-Range Plan devotes only one paragraph to education, which is focused on undergraduate and graduate opportunities (JOI, 1996). It is certainly understandable that the scientists involved in planning ODP were focused principally on defining scientific goals for the next phase of scientific ocean drilling, rather than on integrating their

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[1] See http://www.oceanleadership.org/education/deep-earth-academy/educators/classroom-activities/grades-5-8/blast-from-the-past/.

[2] See http://www-odp.tamu.edu/public/promomat.html.

[3] See http://www-odp.tamu.edu/public/pressrel_html/gateways.html.

efforts with Earth science education for K-12, undergraduates, or the public.

IODP's Initial Science Plan contained several paragraphs on education and outreach, including awareness of promotional activities to reach broader audiences (IODP, 2001), and IODP developed a more vigorous education initiative than did DSDP or ODP. Current (as of 2011) educational activities are coordinated through the COL's Deep Earth Academy,[4] which runs a variety of programs aimed at K-12, undergraduate, graduate, and informal science educators. COL staff includes a permanent director and assistant director for education, as well as a teaching fellow. Since 2004, the *JOIDES Resolution* has sailed 15 teachers as at-sea educators[5] (Leslie Peart, COL, personal communication, 2010). Given the limited berth space for scientists aboard the vessel, allotting one specifically for an education officer is an indication of IODP's commitment to its education initiatives. The Deep Earth Academy has also initiated a range of educational activities for students (e.g., games and activities, video clips, "ask a scientist," careers in oceanography) and teacher resources for grades K-12 and undergraduate education that include learning objectives, national science education standards, ocean literacy principles, classroom activities, and general oceanographic knowledge. Together, these indicate a significant, positive shift in the approach to education.

Additionally, since 2009 the expanded communications facilities of the *JOIDES Resolution* have broadcast video teleconferences between shipboard scientists and schools and museums worldwide. More than 10,000 students, teachers and members of the public have participated (COL, 2010). The Deep Earth Academy also hosts booths at national education conferences (e.g., the National Science Teachers Association National Conference, a venue widely attended by science teachers) and national geoscience conferences (e.g., Geological Society of America, a meeting that has become increasingly popular for undergraduate educators), where staff distribute educational materials and information about opportunities to become more engaged in scientific ocean drilling.

Although all of these activities are significant additions to IODP educational programming, the School of Rock[6] appears to have the greatest potential impact. This workshop, run either on the *JOIDES Resolution* (when drilling is not occurring) or at the Texas A&M University core repository, allows ~15 teachers each year to learn the scientific principles and techniques used to study the Earth system through core samples. Since 2005, 75 teachers have participated in the School of Rock and have taken their knowledge and understanding of scientific ocean drilling, and the research it enables, back to their schools (COL, 2010). They have also shared their experiences with others by conducting more than 150 workshops, with more than 3,000 participants from 30 states and 5 countries besides the United States (COL, 2010).

ODP and IODP have supported graduate education in scientific ocean drilling by awarding Schlanger Ocean Drilling Fellowships[7] and providing berths for students aboard the *JOIDES Resolution*. The Schlanger Fellowships are competitive grants that provide a generous stipend, to be used for activities including tuition, research activities, and travel. Since 1995, five fellows per year have been selected. Of these fellows, 75 percent have remained in academia (COL, 2010), many moving into leadership positions in the scientific ocean drilling community. This prestigious award has effectively contributed to the creation of the next generation of ocean scientists and, simultaneously, has enabled significant new scientific achievements. ODP and IODP have also been very successful at bringing graduate students aboard ship to participate directly in scientific ocean drilling; 28 percent of all ODP cruise participants and 22 percent of all IODP participants on the *JOIDES Resolution* have been undergraduate and graduate students (Brad Clement, IODP-USIO, personal communication, 2010). The U.S. Science Support Program's "Apply to Sail" website[8] specifically mentions graduate students, and approximately one-third of the U.S. berths are reserved for graduate students or postdoctoral fellows.

## OUTREACH

In the earliest precursor to DSDP, John Steinbeck fired the public interest by chronicling the Mohole drilling project for *Life Magazine* (Steinbeck, 1961). However, formal outreach attempts have only recently regained significance among the scientific ocean drilling community. The Deep Earth Academy presently partners with museums and other informal science institutions to initiate special programming ranging from exhibits and interactive displays to art competitions (COL, 2010). As an example, since 2008 a model of the *Chikyu*, three core samples representing different climate histories, and a series of scientific ocean drilling highlights videos have been part of the permanent exhibit in the Smithsonian National Museum of Natural History. The *JOIDES Resolution* also hosts a variety of outreach activities during its port calls in the United States and in other countries. Press conferences alert the local media to the presence of the ship and the nature of its activities, while ship tours allow up to 60 people per day to explore the vessel and learn more about scientific ocean drilling (COL, 2010). Speakers selected from the ship's current expedition have also given public lectures while in port. During and after expeditions, an IODP communications team works with local, national, and international press to inform them of current research.

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[4] See http://www.oceanleadership.org/education/deep-earth-academy/.

[5] See http://www.oceanleadership.org/education/deep-earth-academy/educators/teacher-at-sea/.

[6] See http://www.oceanleadership.org/education/deep-earth-academy/educators/school-of-rock/.

[7] See http://www.oceanleadership.org/programs-and-partnerships/usssp/schlanger-fellowship/.

[8] See http://www.oceanleadership.org/programs-and-partnerships/usssp/expedition-participation/apply-to-sail/.

Another essential aspect of IODP's outreach program is the Distinguished Lecturer Series. This program brings research results from scientific ocean drilling to undergraduates, graduate students, researchers, educators, and the broader Earth science community. Six or seven active ocean drilling scientists per year are selected as Distinguished Lecturers; each typically gives six research lectures to different institutions across the country. The host colleges and universities are selected with preference for those with high minority student populations or that have not previously hosted a Distinguished Lecturer. Since 1991, the program has provided 640 lecturers to universities, museums, and community colleges in all 50 states (Charna Meth, COL, personal communication, 2011). The series has served as a model outreach program for other IODP member countries, inspiring a similar program in Europe.

## CAPACITY BUILDING

In its report titled *Increasing Capacity for Stewardship of Oceans and Coasts: A Priority for the 21st Century*, the National Research Council (2008) defined capacity building as programs designed to:

- Strengthen the knowledge, abilities, relationships, and values that enable organizations, groups, and individuals to reach their goals
- Strengthen the institutions, processes, systems, and rules that influence collective and individual behavior and performance in all related endeavors.
- Enhance people's ability to make informed choices and fosters their willingness to play new developmental roles and adapt to new challenges.

Although the committee did not find specifically targeted capacity-building efforts within DSDP and ODP, these programs have used approaches that supported the above definition. Each of the scientific ocean drilling programs was designed so that organizations and individuals were best able to reach their goals, requiring strong collective and individual performance. This design resulted in stronger institutions and in the development of scientific processes and systems necessary for success. As an example, the need to develop novel instrumentation and equipment was a significant challenge that the programs met well.

A current exemplar of IODP's capacity building for a next generation of ocean drilling scientists is found in the European Consortium for Ocean Drilling Research (ECORD) summer school program[9] to "further the education of young scientists in marine-related sciences and to train a new generation to participate in scientific ocean drilling expeditions in the future." Two to three events, each hosting ~30 participants, are arranged each year around a specific scientific theme related to scientific ocean drilling. The program is open to postgraduate students and postdoctoral fellows from all around the world, and ECORD provides 10-15 scholarships every year to encourage participation of early career scientists. One example of this program is the Urbino Summer School in Paleoclimatology,[10] which is co-sponsored by a number of other international programs.

One feature of international capacity building includes developing the skills and competence of individuals and societies in developing countries. Although berthing commitments for ODP and IODP member countries preclude most such individuals from actually going to sea, modest efforts have been made to include them in the research enabled by scientific ocean drilling. There is no program in place that specifically targets support for students, staff, or faculty from developing countries, although they are able to make use of cores and other data collected by the programs, just as is the case for member countries' researchers.

IODP has also been actively engaged in strengthening diversity initiatives. Since 2004, the scientific ocean drilling community has partnered with a National Science Foundation program, Minorities Striving and Pursuing Higher Degrees of Success in Earth Systems Science,[11] which provides professional development for under-represented minorities. By 2010, IODP's U.S. Science Support Program supported 90 minority students in 17 different scientific ocean drilling-related activities, including scientific research and opportunities to interact with IODP scientists. In 2005, IODP's U.S. Implementing Organization (USIO) created a fellowship to encourage students at historically black colleges and universities to learn more about career opportunities related to scientific ocean drilling.[12] As of June 2011, nine fellowships have been awarded and the program has been expanded to include opportunities to sail with a *JOIDES Resolution* expedition. In July 2011, the Minorities in Scientific Ocean Drilling Fellowship[13] was initiated to embrace minority students majoring in Earth sciences and engineering beyond those represented by historically black colleges and universities. In addition, the IODP-USIO Diversity Internship[14] recently began. This 10-12 week program accepts full-time and recently graduated minority students from U.S. universities and colleges who have significant interest in the ocean sciences or geosciences. The first internship focused on science communications.

Approaches to attract minority students into the above programs have included advertising via geoscience, engi-

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[9] See http://www.essac.ecord.org/index.php?mod=education&page=summer-school.

[10] See http://www.urbinossp.it/.

[11] See http://www.msphds.org/.

[12] See http://www.oceanleadership.org/education/diversity/hbcu-fellowship/.

[13] See http://www.oceanleadership.org/education/diversity/minorities-in-scientific-ocean-drilling-fellowship.

[14] See http://www.oceanleadership.org/education/diversity/iodp-usio-diversity-internship/.

neering, education, and communications email distribution lists, especially those that target faculty members at minority-serving institutions; professional association websites, journals, and publications; professional society and education conferences and meetings; and targeted mailings. In addition, scientists and awardees have promoted the opportunities associated with these programs and have made recruiting trips to several institutions. These approaches can significantly aid in the recruitment of minorities to the geosciences in general as well as to the drilling programs.

# 6

# Assessment of *Illuminating Earth's Past, Present, and Future: The International Ocean Discovery Program Science Plan for 2013-2023*

One of the fundamental premises of *Illuminating Earth's Past, Present, and Future: The International Ocean Discovery Program Science Plan for 2013-2023* (referred to hereafter as the "science plan"; IODP-MI, 2011) is that scientific ocean drilling has the potential to enable essential advances in multiple fields of scientific inquiry, as it has done so significantly in the past (see Chapters 2-4 of this report for discussion of accomplishments in previous scientific ocean drilling programs). In this chapter, the committee assesses the potential for the scientific challenges described in the science plan to lead to transformative scientific discovery. Because the committee's intent was to provide guidance on how the plan could be most effectively implemented, recommendations are also offered on relevant areas of scientific ocean drilling inquiry that have the greatest potential for success.

The committee examined the potential for transformative discoveries that might result from research conducted within the framework of the science plan. The National Science Foundation (NSF) defines transformative research as research that "involves ideas, discoveries, or tools that radically change our understanding of an important existing scientific or engineering concept or educational practice or leads to the creation of a new paradigm or field of science, engineering, or education. Such research challenges current understanding or provides pathways to new frontiers."[1] Under this definition, the committee has considered those discoveries that might result from several different pathways, including: (1) new ways to interpret existing data, which lead to testable new theories or paradigms that can be assessed through the collection of new data (e.g., plate tectonics); (2) technological developments that enable previously impossible measurements (e.g., ability to date rocks with radiometric methods); (3) observations obtained in a frontier area (e.g., massive sulfide deposits beneath hydrothermal vents); and (4) novel integration of different data types or cross-disciplinary interchange (e.g., additional linkages between regional marine and on-land investigations of similar environments).

The first case of transformative discovery (new interpretations of existing data) is very difficult, if not impossible, to predict. Technological development will most directly lead to transformative discoveries through drilling to depths greater than have been reached previously or by coupling drilling with long-term time series measurements on scales not previously seen. Conventional drilling may lead to transformative science in regions that have not been previously drilled or sampled, while drilling transects of spatially related holes could lead to pathways for novel integration of data. Therefore, the committee focused on assessing the science plan through all of the pathways detailed above, except the first.

This chapter begins with a discussion of overarching comments regarding the science plan, including conclusions and recommendations. Following sections address each of the four research themes identified in the science plan. General comments on the theme are followed by a detailed analysis of each of the science plan challenges listed within the theme, assessment of other challenges or opportunities for transformative science beyond that in the science plan, synergies between the themes, and linkages between scientific ocean drilling, other NSF-supported science programs and facilities, and non-NSF programs. The wording of the themes and challenges after the overarching comments are taken directly from the science plan in order to easily map the science plan challenges to the committee's assessment.

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[1] See http://www.nsf.gov/about/transformative_research/definition.jsp.

## OVERARCHING COMMENTS

The science plan is divided into four research themes: climate and ocean change, biosphere frontiers, Earth connections (deep Earth processes), and Earth in motion (direct time series observations on human scales). Fourteen specific challenges, posed as questions, are included in these themes. In addition, chapters on education and outreach and on implementation are included. Although the document has no explicit vision statement, the science plan's focus is clearly on new discoveries and better understanding of Earth science topics to meet emerging societal challenges and enhance decision making. This overarching focus is considerably different from the Integrated Ocean Drilling Program (IODP) Initial Science Plan (IODP, 2001), which was based on further exploration of the ocean and new scientific understanding of Earth systems, with the assumption that recognition of how to apply that knowledge to relevant societal issues would be automatic. The committee supports linking scientific ocean drilling to issues of societal relevance and commends the writers of the science plan for taking this approach. The climate and ocean change (e.g., climate change, sea level rise, ocean acidification) and Earth in motion (e.g., earthquakes and other geohazards) themes identify challenges with the most direct societal relevance, but relevant topics also exist in the biosphere and Earth connections themes.

Overall, the science plan presents a strong case for the continuation of scientific ocean drilling, with its possible benefits for science and society. The committee was particularly positive about the potential for transformative science resulting from studies of the subseafloor biosphere and about the importance of continuing paleoclimate studies that will provide analogs and likely constraints on global and regional changes predicted with future climate. It also agreed that the emphasis on sampling deeper into the crystalline basement will lead to better understanding of deep earth processes, especially if high percentages of intact core are recovered and if active tectonic processes are monitored in situ.

> **Each of the four themes within the science plan identifies compelling challenges with potential for transformative science that can only be addressed by scientific ocean drilling. Some challenges within these themes appear to have greater potential for transformative science than others.**

The committee's assessments of each theme and specific challenge identified in the science plan are discussed in greater detail in the following sections. The themes and challenges are pertinent and well-justified, although the committee was concerned that the science plan reads like a wish list with little guidance as to which of the 14 challenges were considered most important. The committee is aware that the writers of the science plan may not have been asked to prioritize, but given the financial constraints that the next phase of scientific ocean drilling is likely to face, it may now be appropriate for the scientific ocean drilling community to provide additional guidance on prioritization of potential drilling objectives. Such a prioritization could include guidance on which drilling objectives might be dependent on platform capabilities and availability, innovations in technology, challenges in obtaining supporting data (such as in high latitudes), or global political or safety concerns.

**RECOMMENDATION: The scientific ocean drilling community should establish a mechanism to prioritize the challenges outlined in the science plan in a manner that complements the existing peer-review process.**

The scientific ocean drilling programs have a history of making excellent use of legacy samples and data that have helped to quickly advance new areas of research (see in particular the discussion of accomplishments in the section on Abrupt Climate Change in Chapter 4). On the other hand, the science plan is justifiably focused on the importance of future drilling challenges and thus spends little time discussing the use of legacy information and samples.

> **Using legacy data and samples to their maximum capabilities will continue to increase the scientific value of the scientific ocean drilling programs. Expanded use of legacy materials could help, for example, with prioritization of drilling objectives in the next phase of scientific ocean drilling.**

A more thorough future examination of the areas of natural integration among scientific ocean drilling objectives would also be valuable. Although several natural points of synergy between the challenges and themes are well described in the science plan, a more detailed examination of the areas where natural integration could occur between and among the science challenges would have further strengthened the science plan (see following sections for further discussion). An increase in efficiency and integration of multiple science objectives is one means by which resources can be most effectively used. For example, integrating multiple drilling objectives in the early planning stages of single expeditions would maximize scientific output in relation to costs. This approach is successfully used by the International Continental Scientific Drilling Program (ICDP)[2] and polar expeditions. Integrating multiple objectives into a single expedition requires compromises, but certain practices, such as bringing expedition leaders together beforehand to ensure agreement on expedition goals and providing adequate planning to create a viable work plan, will make success more likely. Other potential approaches to increasing efficiency include evolving efforts to optimize ship tracks,

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[2] See http://www.icdp-online.org.

which also has possible implications for prioritization of science objectives.

**RECOMMENDATION: From the earliest stages of proposal development and evaluation, possibilities for increasing program efficiency through integration of multiple objectives into single expeditions should be considered by proponents and panels.**

Chapters 2-4 extensively discuss the vital role played by technology in achieving many scientific advances in previous scientific ocean drilling programs (Deep Sea Drilling Project [DSDP], Ocean Drilling Program [ODP], and IODP). Although the committee's charge for this section was to assess the potential for transformative science in the science plan, it determined that transformative science is critically dependent on technological breakthroughs and could not be fully assessed without considering the need for continued technological development. Any future scientific ocean drilling program must continue to push the technological envelope. Previous scientific ocean drilling programs have shown great strength in this area, and the committee believes that the promise of continued innovation is high. Approaches such as dedicated engineering legs or establishment of sites with different lithologies to test and refine instruments could increase the potential for achievement of groundbreaking science.

**RECOMMENDATION: Pathways for innovations in technology should be encouraged. In addition, setting aside some resources specifically to promote technological research and development could increase the potential for transformative science.**

## THEME 1—CLIMATE AND OCEAN CHANGE: READING THE PAST, INFORMING THE FUTURE

This theme identifies four key challenges related to Earth responses to changes in atmospheric carbon dioxide ($CO_2$) concentration, sea level rise and diminishing ice sheets due to warming climate trends, regional precipitation pattern changes and potential impacts, and the ocean's sensitivity to changes in chemistry. All of these challenges are relevant to future Intergovernmental Panel on Climate Change (IPCC) projections and can help provide constraints on the range of possible future impacts. They map well to the IPCC Fifth Assessment Report, which is currently in preparation, and also represent issues of significant uncertainty and high importance that will remain relevant for the follow-up Sixth Assessment Report.

> **The science described in these challenges has potential to be transformative and, in most cases, can only be achieved through a continuation of scientific ocean drilling. The climate theme has a strong focus on achievements, specifically those within the past 10 years, and suggests that more related work is needed, especially on certain targeted topics (e.g., polar regions, permanent El Niño states, monsoon patterns).**

The science plan emphasizes the critical need to integrate proxy observations from paleoclimate data with numerical modeling of past climates to better understand climate system responses and feedbacks. In addition, there will be a need to develop new paleoclimate proxies and improve existing proxies. Both of these objectives will require strong linkages among the scientific ocean drilling, modeling, and climate proxy communities. The theme highlights the need for innovative thought and for collaboration with other drilling programs (e.g., Antarctic Geological Drilling program [ANDRILL], ICDP) to accomplish transects from the continental margin to the deep ocean, as well as the need for mission-specific platforms that have the flexibility to drill in difficult areas (e.g., shallow and ice covered regions) with increased core recovery. In many of these cases, the *JOIDES Resolution* may not be the optimum platform for future climate science needs. The next phase of scientific ocean drilling may need to consider new technology development or alignment with other programs that have common goals and appropriate technology.

The science plan also articulates well the case for the importance and societal relevance of these topics to decision makers. It acknowledges a number of international efforts (IPCC, International Geosphere-Biosphere Programme[3] and the Past Global Changes project,[4] European Project for Ice Coring in Antarctica, Scientific Committee on Antarctic Research[5]) that have developed strategies to address these challenges. One especially well-justified point is that of all paleoclimate drilling initiatives, only the next phase of scientific ocean drilling can consistently recover time-continuous, high-resolution records of warmer, high-$CO_2$ climates in the deep past.

### *Challenge 1: How Does Earth's Climate System Respond to Elevated Levels of Atmospheric $CO_2$?*

Sediment cores document the strong relationship between mean global atmospheric temperature and $CO_2$ over millions to tens of millions of years, and demonstrate the potential for using warmer-than-present pre-Quaternary climates as a rich venue for exploring the behavior of Earth system models that are used for future projections (provided that relevant proxies can be convincingly shown to be reliable). Quantifying this relationship has been assisted by dramatic improvements in

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[3] See http://igbp.sv.internetborder.se.

[4] See http://www.pages-igbp.org.

[5] See http://www.scar.org/.

the quality of proxy temperature and $pCO_2$ reconstructions from scientific ocean drilling records. This challenge has great potential for societally relevant outcomes, especially in quantifying and understanding the processes involved in amplified temperature changes at the poles. Polar amplification is strongly linked with responses of ice sheets and sea level, which are addressed in the discussion of Challenge 2. The continued focus on this topic places scientific ocean drilling at the forefront of transformative science.

This challenge also identifies climate system sensitivity and the performance of IPCC climate models under different $CO_2$ concentrations as areas where pre-Quaternary proxy temperature data are needed to increase understanding. Differences in climate sensitivity between data and models at low $CO_2$ levels (<400 ppm) raises the question of other underappreciated but important feedbacks.

### *Challenge 2: How Do Ice Sheets and Sea Level Respond to a Warming Climate?*

This challenge encompasses three areas of critical and transformative emphasis. The first area involves the need for more globally distributed atolls and coral reef records to constrain the rate, amplitude, and melt water source for sea level rise since the last glacial period, which is key to understanding the rate and pattern of future sea level rise. The second area pertains to spatially distributed sea level records for pre-Quaternary warm climate analogs such as the Pliocene (5-3 myr), which allow ice sheet-climate and proxy ice volume models to be verified. This issue is important, but difficulties exist with reconstructing sea level amplitudes by applying backstripping[6] methods to continental margin drill core records. Getting these types of spatially distributed cores requires mission-specific expeditions and the ability to drill transects in difficult drilling environments, which can be costly and often need long lead times to develop successful research strategies and the necessary pre-cruise site survey information. Finally, the ability to locate drill cores proximally to ice sheets, which is the subject of the third area, is critical to the success of this challenge, because these sites provide direct physical evidence of variability in sea ice behavior and past ice sheet extent. This challenge is very important in terms of societal relevance, has potential for transformative discovery, and can only be achieved by continued scientific ocean drilling. Drilling near ice sheets and improved sediment recovery in high-latitude regions are important technical challenges that need to be addressed by the next phase of the program.

### *Challenge 3: What Controls Regional Patterns of Precipitation, Such as Those Associated with Monsoons or El Niño?*

This challenge focuses on better understanding of regional climate variability, with specific focus on changes to the Pacific El Niño-Southern Oscillation (ENSO) due to warming and associated dramatic impacts on precipitation, drought, cyclonic activity, and the Asian monsoon. The aim of this topic is to quantify decadal and longer-term variability in regional climates and hydrological cycles, to support development of regional climate models on intermediate (10 yr-1 kyr) time scales, and to consider potential extreme events, such as floods and droughts. The challenge requires zonal and meridional transects of temperature gradients and their seasonal and longer-term variations, coupled with records of past intermediate and deepwater overturning. Sedimentary records from continental margins would need to be supported by synchronous continental records from lake sediments, ice cores, and speleothems.

Scientific ocean drilling in the equatorial Pacific identified weakening of the Pacific zonal temperature gradient and permanent El Niño-like conditions during the Pliocene. The reasons for these changes are unclear. The Pliocene is one of the best geological analogs for future warming, and, because El Niño has a major impact on global weather and moisture patterns, the study of this and similar past warmer climates has a high potential to improve understanding of the coupled ocean-atmosphere system. However, more data from scientific ocean drilling needs to be integrated with coupled ocean-atmospheric climate modeling. Although some progress can be made through the application of new temperature proxies to legacy cores, the large geographic scale of the problem requires that many new, strategically located drill cores be obtained to achieve the necessary high spatial and temporal resolutions. Because current numerical models cannot simulate permanent El Niño-like conditions without prescribing initial sea-surface temperatures, meeting this challenge requires close collaboration among groups working on model and proxy development. Developing hemispheric and regional temperature gradients for past climate states through targeted drilling is needed to achieve this and other theme challenges. The record of abrupt millennial-scale changes in ENSO above inter-annual variability, which has been identified in speleothems and corals, could also be explored through targeted high-resolution sediment cores. However, achieving the necessary resolution is generally difficult in oxygenated deep ocean regions, where bioturbation smoothes the records.

The prospect of achieving regional climate models on decadal time scales has lately been given considerable attention. Several European Union member states (e.g., France, the Netherlands, and Sweden) have invested in research funding and infrastructure and have launched a joint research program to look at modeling on this time scale. The U.S. sci-

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[6] "Backstripping" refers to a technique in which sediments are progressively removed from a basin in order to determine its subsidence and sedimentary history. In addition to sediment loading, corrections for changes in sea level, sediment compaction, and paleobathymetry are needed to separate out the sedimentary signal from thermal, crustal, and tectonic changes (Miall, 1997 and references therein).

entific community is aware of these climate modeling needs (e.g., Cane, 2010), and NSF supports the research through targeted calls within the context of climate, energy, and sustainability (e.g., decadal and regional climate prediction using Earth system models, water sustainability and climate change). A number of related programs exist within NSF's Directorate for Geosciences; better integration between those programs and scientific ocean drilling could support advances in this area.

Finally, this challenge focuses on improved understanding of the role of tectonics and uplift on atmospheric circulation and precipitation patterns, as well as the influence of mountains and high terrain on erosion, precipitation, weathering, and $CO_2$ drawdown through the silicate weathering cycle. Although having less immediate societal relevance, this much longer term process is important for understanding the Cenozoic evolution of atmospheric greenhouse gas concentrations, ocean nutrient production, and the carbon cycle.

### *Challenge 4: How Resilient Is the Ocean to Chemical Perturbation?*

This challenge focuses on the carbon and nitrogen cycles, has the potential for transformative science, and is among the most societally relevant challenges in the climate theme. This challenge involves developing a better understanding of ocean resilience to large perturbations in atmospheric $CO_2$ and ocean acidification, building on one of the major successes of IODP (see Box 4.2 on the Paleocene-Eocene Thermal Maximum [PETM]). The challenge identifies ocean eutrophication and oxygen depletion as key issues that can be addressed by scientific ocean drilling. In addition, the challenge poses a question about the length of time it takes for the ocean to neutralize carbonic acid following an abrupt increase in atmospheric $CO_2$. Continued development and application of $CO_2$ and carbonate system proxies (e.g., boron isotopes, boron/calcium ratios in carbonate fossils, carbon isotopic variations in alkenones, and other molecular organic compounds) will be required to address these issues. Although this challenge is of high importance, it is the most weakly justified within this theme. The science plan does not present a clear strategy for how future scientific ocean drilling will provide further insights on what is already known. Previous successful drilling of the PETM and the Eocene-Oligocene boundary (Coxall et al., 2005; DeConto et al., 2008), however, has demonstrated that the current scientific ocean drilling program has a strategy for and is capable of successfully addressing this challenge.

### Synergies Between This and Other Science Plan Themes

There are linkages between the challenges in this theme and Challenge 7 in Biosphere Frontiers regarding the sensitivity of ecosystems to environmental change. Increased understanding of evolutionary events that are recorded in high-resolution ocean sediment cores and of the relationship to environmental change at a range of time scales has clear synergy with time series of climate proxies (e.g., temperature, $pCO_2$) that document major environmental perturbations. Another area of connection is with Challenge 13 in Earth in Motion, which focuses on carbon flow and storage in the seafloor. Understanding carbon cycle perturbations in general and the Cenozoic evolution of atmospheric carbon dioxide in particular, especially their relationship to Earth's surface temperature during past warmer times, clearly links the climate objectives discussed in this theme with borehole observatory science discussed in the Earth in Motion theme.

### Linkages with NSF and Other Programs

The science plan attempts to acknowledge linkages with continental margin drilling programs such as ICDP, ANDRILL, and SHALDRIL (Shallow Drilling on the Antarctic Continental Margin). These programs are significant in the context of achieving transects from shallow marine to deep ocean settings, as well as in expeditions in seasonally ice-covered environments. However, the science plan provides little discussion of how these collaborative models could be advanced and implemented and how they could be balanced with mission-specific platforms. The science plan also identifies linkages that need to be developed between climate modeling programs and climate proxy development programs funded by NSF, including those at the National Center for Atmospheric Research, and other international partners and funding agencies. Finally, achievement of these challenges, especially Challenge 3, will require close integration with on-land climate and tectonics research communities that work on continental margins and mountain systems.

## THEME 2 —BIOSPHERE FRONTIERS: DEEP LIFE, BIODIVERSITY, AND ENVIRONMENTAL FORCING OF ECOSYSTEMS

This theme outlines three main challenges: the origins and importance of subseafloor microbial communities; limits to life in the deep biosphere; and the relationship between marine ecosystems and changes in the environment. Of all of the challenges in this theme, some are quite novel, while others represent the continuation of present scientific ocean drilling work. This area of research is new, exciting, and cutting-edge, particularly with respect to microbiology within igneous rocks and linkages between marine organism evolution and environmental changes.

The possibility of an extensive population of microbes living beneath the seafloor raises many important and intriguing questions about the limits of microbial life, the role of marine microbes in essential biogeochemical cycles, and the origin and evolution of life on Earth and other planets. Scientists are presently very much in the exploratory phase of some of these research areas, especially with regard to the application of next-generation "-omic" approaches (e.g., DNA and RNA metagenomic sequencing, proteomic analyses) that allow for detailed examination of the diversity, activity, and evolution of microbes in the subseafloor. However, exactly how to couple small-scale studies of subseafloor microbiology with large-scale biogeochemistry remains challenging. Because microbial biomass in marine rocks and sediments may have planetary-scale consequences, execution of these challenges is critical for success of the next phase of scientific ocean drilling.

Understanding the microbiology of the deep seafloor can only be accomplished through scientific ocean drilling. Given the large amount of data on sediment-hosted microbial communities that has already been collected by scientific ocean drilling, and the ability of microbiologists to now access "clean" crystalline rock, there is great potential for transformative science in this compelling area of research. This potential includes the interaction of microbial communities at the interface between sediments and crust, and the use of drill-hole observatories to advance understanding of subseafloor microbial communities.

> **Although not specifically identified in the science plan, identifying the synergies in understanding ecosystem dynamics in the deep sea— from microbes to viruses to eukaryotes, both living and fossil—is a fertile way to advance the science.**

### *Challenge 5: What Are the Origin, Composition, and Global Significance of Subseafloor Communities?*

The study of sediment microbiology has been an important aspect of both ODP and IODP, with scientists on numerous expeditions obtaining representative cores throughout the global ocean. Progress continues in the quantification and description of sediment-hosted microbial communities through a variety of microscopic and genetic tools, and the microbial community is poised to make significant strides in addressing some of the overarching questions related to the impact of microbial communities on geochemical transformations by moving beyond "who is there and how many" to "what is the activity, function, and contribution of sediment communities to carbon, sulfur, and iron cycling?" Specific missions and experiments to push our understanding of sediment communities to this next level have great potential for transformative science.

In contrast to sediment microbiology, the study of microbial life in igneous rocks is a relatively new facet of scientific ocean drilling, and there is yet to be a drilling expedition dedicated to igneous rock-hosted subseafloor microbiology. Although studies from the 1990s employed various DNA stains to drilling-recovered rocks and suggested the presence of microbes in basalt alteration zones, much less global sampling and detailed analyses of indigenous communities has been accomplished compared to the sedimentary microbial community. First-order questions concerning the origin and composition of igneous rock-hosted communities still need to be addressed, and the interactions between sediment and rock communities explored. As new observatory tools (CORKs; Circulation Obviation Retrofit Kits), instrumentation (in situ biosensors, tracer experiments), and hard-rock drilling techniques combine with microbiological and molecular techniques, exploration of the subseafloor habitat in oceanic rocks will advance considerably in the next phase of scientific ocean drilling.

### *Challenge 6: What Are the Limits of Life in the Subseafloor?*

Marine microbes thrive in diverse and extreme environments that push the known limits of life. Challenge 6 would extend understanding of the limits of microbial life on earth in a transformative way, and its aspects (e.g., collection of extremely deep microbes) can only be accomplished through scientific ocean drilling. The committee believed that this challenge would integrate well with Challenge 5, given that the study of microbial life in rocks and sediments will necessarily include determining where in temperature-energy-pressure space these organisms are surviving. Although cataloging the diversity of life in these different extremes is important, in situ technologies such as biosensors or downhole activity enrichments, for example, could also be used to examine the limits of life. Laboratory experiments will also assist in defining the limits of life and are critical for strengthening field collections and experiments. Finally, although the connections between life in the subseafloor and the origins of life on Earth are intriguing, the committee believed that stronger experimental linkages could be made between currently measurable limits to life, laboratory simulations of abiotic carbon and energy generation in the subseafloor, and the origins of life.

### *Challenge 7: How Sensitive Are Ecosystems and Biodiversity to Environmental Change?*

Understanding of abrupt environmental change and the role of $CO_2$ on marine ecosystems has important implications for current anthropogenic change and great potential for transformative science with strong societal relevance. In particular, past environmental perturbations potentially driven by $CO_2$ may have occurred at time scales similar to anthropogenically driven change, providing an opportunity to study biological consequences of rapid changes in atmospheric composition. Understanding the patterns and mechanisms of how marine ecosystems adapt to abrupt environmental change and longer-term orbitally forced environmental change also has great potential for transformative understanding of biological systems on Earth and is on the cutting edge of new science. This challenge provides justification for the need to study marine ecosystem response and organismal evolution at large scales, which requires samples obtained through scientific ocean drilling. Such studies would complement studies of ecosystem and biodiversity sensitivity in non-marine samples (e.g., outcrops, etc), which are at smaller spatial scales than those possible in the oceans for Jurassic and younger age strata.

This challenge has strong links to the climate challenges in the previous theme. For example, *Understanding Climate's Influence on Human Evolution* (NRC, 2010) highlights continent-ocean and climate-evolution linkages by proposing to drill not only lake strata spanning the time of human origin in the relevant geography, but also marine strata adjacent to Africa that received inputs from rivers with drainage areas covering the areas critical for human evolution. The goal is to link hominin evolutionary and ecological history with the high-resolution lacustrine record of environmental, particularly climatic, change within Africa and with the already developed global marine chronology.

### Other Challenges and Opportunities

The science plan misses the potential opportunity to study (living) eukaryotes (such as fungi and protists) and viruses in the subseafloor biosphere, information on which is essential to truly understand subseafloor ecology and the ecosystem that may exist there. Furthermore, understanding living eukaryotes could perhaps lead to clearer linkages to the fossil eukaryotic community, with stronger overlap between Challenges 5 and 7. The subseafloor may host life forms that are completely unknown; new life-detection tools that do not depend on DNA, for example, could be employed for studying this potentially novel biosphere (e.g., NRC, 2007). The study of life in the subseafloor will also require changing the way that cores are stored after collection. Unlike most of the other disciplines involved in scientific ocean drilling, microbiology core samples need to be frozen and/or preserved with a fixative when collected. Most of the current core repository is not useful for microbiologists studying subseafloor life, which needs to be addressed in the next phase of the program. As suggested by the large number of proposals submitted to IODP that focus on subseafloor life and the funding of new programs focused on the deep biosphere (e.g., the Sloan Foundation's Deep Carbon Observatory, the NSF-funded Center for Dark Energy Biosphere Investigations [C-DEBI][7]), there is a large and growing group of scientists interested in studying microbial life in the subseafloor. Finally, justification for continued research in this area could be strengthened by consideration of two issues. The first is potential biotechnological applications of novel organisms and genes recovered from the subseafloor, especially under extremes of temperature and pressure. This is a strong point of interest for microbiology, with societal implications in the United States and beyond. The second is the unique technological challenge presented by microbiology during drilling operations in terms of sampling, processing, and instrument construction.

### Synergies Between This and Other Science Plan Themes

There are natural synergies between Challenges 5 and 6 in this theme and Challenges 10 (Earth Connections; chemical exchanges between the ocean and the crust) and 14 (Earth in Motion; fluid flow in the crust), but they could have been better developed in the science plan. For example, the use of borehole CORK observatories to link hydrogeological, chemical, and microbiological observations is essential for integrating and understanding life within basaltic crust. Borehole observatories and the time series measurements they entail are discussed in great depth in Challenge 14, but they could have been more formally linked to the challenges in this theme. There are also obvious synergies between Challenge 7 and the climate theme regarding the sensitivity of ecosystems to environmental change, especially in understanding major climate perturbations that can impact the evolution of life.

### Linkages with NSF and Other Programs

The challenges in this theme have many strong linkages to NSF programs and initiatives. Some important links include the National Deep Submergence Facility and the UNOLS (University-National Oceanographic Laboratory System) fleet. Many subseafloor microbial studies, including those with CORK operations, require deep submergence assets to sample and service the CORK instrumentation, adding cost and scheduling complexity. In addition, changes in marine environments can be expressed in continental environments and thus links exist with continental dynamics, sedimentary geology and paleobiology, and other areas within NSF (such as Systematic Biology and Biodiversity Inventories). Opportunities also exist with cross-cutting programs such as Dimensions of Biodiversity, C-DEBI, and ICDP. Programs of interest outside of NSF include the Sloan Foundation's Deep Carbon Observatory and the Department of Energy's methane hydrate and bioremediation programs.

## THEME 3—EARTH CONNECTIONS: DEEP PROCESSES AND THEIR IMPACT ON EARTH'S SURFACE ENVIRONMENT

This theme has four key challenges related to the composition and structure of the upper mantle, architecture of the ocean crust, chemical cycling between ocean crust and seawater, and relationships between subduction zones and continental crust. These challenges deal with the chemical and energy exchanges between the solid Earth, ocean, and

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[7] See http://www.darkenergybiosphere.org/.

atmosphere, as well as their impact on the environment throughout geologic time.

This theme explores chemical and energy exchanges within Earth that lead to a distinctive layered internal structure, the tectonic activity that shapes the surface environment, and magmatic activity that builds the continents and ocean basins. The theme also deals with the importance of hydrothermal alteration in ocean crust, including how this process impacts seawater chemistry through time, as well as mantle rheology and magma generation in subduction zones. Finally, the theme also encompasses the importance of convection, both in the mantle where it may play a role in driving plate tectonics and in the outer core where it is responsible for generating Earth's magnetic field.

One of this theme's main messages is the great need to drill more deeply into and through intact ocean crust. Although the science plan emphasizes drilling to the Mohorovičić discontinuity (Moho), an ocean drilling objective with a long history (see Box 6.1), another aim could be to obtain good recovery of intact oceanic crust samples along the way. Some of the other objectives related to spatial variability in oceanic crustal structure and evolution could be better addressed with multiple, carefully chosen, shorter holes. Multiple, shorter holes could be very helpful in understanding ocean crust hydration (serpentinization), carbonation, and oxidation, where ultramafics that are out of equilibrium with their environment (usually through uplift processes) are altered through contact with water into serpentinite minerals.

> **Drilling intact ocean crust with high recovery rates would allow much to be learned, although a specific target of drilling to the Moho may not be technically viable and could be cost-prohibitive. Better understanding of oceanic mantle serpentinization is essential, and could be achieved through shorter holes drilled in disrupted ocean crust.**

### *Challenge 8: What Are the Composition, Structure, and Dynamics of Earth's Upper Mantle?*

The single longest-running goal of scientific ocean drilling has been recovering samples from the Moho, prompting the very first ocean drilling project (Project Mohole; Box 1.3). Despite more than 50 years of scientific discoveries, there has been little progress toward that goal. Few drill cores penetrate deeply into crystalline ocean crust, and none has remotely approached the Moho. The science plan states that the scientific ocean drilling community is working concertedly toward this goal, and that doing so is scientifically significant. Several community workshop reports on this topic discuss the scientific merits in greater detail than that found in the science plan. Clearly, it seems that a substantial part of the scientific ocean drilling community is ready to embrace this project. The committee discussed this topic at length and recognized technological challenges that would have to be overcome before such a deep hole could be drilled (Box 6.1). Opinions vary about the utility of recovering samples of oceanic crust and mantle at just one location, even if directional drilling could be achieved. Mantle heterogeneity may preclude broad generalizations about processes, especially when based on samples recovered at a single location.

Nonetheless, first-order petrologic and geochemical questions could definitely be addressed by materials recovered from a hole to the Moho (often referred to as the "Mohole"). In addition to the significant technical challenges involved in drilling to the Moho, recovering Moho samples might not be the biggest scientific contribution from the drilling attempt. The presence of exposed, serpentinized peridotite at slow spreading ridges suggests that in some places the Moho is the boundary between mafic oceanic crust and ultramafic upper mantle, while in other locations it is a serpentinization front separating altered from unaltered peridotite. It would be valuable to have good estimates of the relative abundance of those two different kinds of Moho. The importance of recovering intact samples of oceanic crust and mantle may lie less in reaching the destination of the Moho, and more in the recovery of materials drilled along the way. Having the ability to determine the nature of petrologic and geochemical processes in the mantle that lead to the building of oceanic crust would be a significant development, possibly leading to transformative science.

### *Challenge 9: How Are Seafloor Spreading and Mantle Melting Linked to Ocean Crustal Architecture?*

This challenge states that understanding linkages between seafloor spreading, mantle melting, and ocean crust architecture requires not only recovery of core material from intact crust from a single Moho location, but also shorter holes drilled through tectonically disrupted ocean crust. Fundamental differences between fast- and slow-spreading mid-ocean ridges and the processes that result in magmatic vs. amagmatic spreading are still poorly understood. These are first-order plate tectonic phenomena. The prevalence of detachment faulting at slow-spreading ridges is also a scientific topic of great significance. This challenge states that linking a series of shorter holes with geophysical investigations and seafloor mapping would add to the understanding of oceanic lithosphere structure that would be gained from drilling to the Moho. Because of the paucity of holes in crystalline basement, better understanding would almost certainly result. However, significant difficulties have been encountered when attempting to drill directly into crystalline ocean crust that lacks sediment cover, especially young volcanic crust, which could prevent progress on this front unless new technologies are developed.

The magnetic field is a shield that allows planets to maintain an atmosphere and is therefore a prerequisite for life on Earth. In addition, any major change in Earth's magnetic field will impact important infrastructure such as telecom-

## Box 6.1
## Technological Challenges in Drilling to the Moho

The first scientific ocean drilling was undertaken as a challenge to drill to the Moho (NRC, 2000). The science plan for the next proposed phase of scientific ocean drilling has renewed this goal. At the beginning of Project Mohole, deepwater technology was in its infancy, with only a few ships capable of drilling in water depths greater than 1,000 m. Although Project Mohole engineers created new methods and technology to achieve scientific ocean drilling goals (see Box 1.3), they were unable to reach the depths needed to drill to the Moho. Since that time, the deepwater drilling and production industry has consistently drilled in water depths greater than 2,500 m, and the *JOIDES Resolution* reached greater water depths using a riserless drilling system. Advances in materials science, new control systems, and better automation have all contributed to greater abilities in floating production platforms and riser drillships, allowing them to move into very deep water (3,000-4,000 m). This leads to a question: using existing deepwater technology, how can the Moho be drilled with the highest probability of success?

Moho drilling involves two major risks: subsea risk arises from drilling very deep water, with issues regarding currents and open water surface conditions, and drilling risk arises from drilling in more than 6,000 m of rock with poorly known properties and composition (e.g., high temperatures). The risk of drilling rock at high temperatures and unknown conditions is a topic that would need to be addressed thoroughly before deciding on a target for Moho drilling.

**A wide range of opinions exist regarding the viability of using existing scientific ocean drilling platforms to drill the Moho. The committee believes that the technical capabilities of the riser drillship *Chikyu* are insufficient to ensure success in this endeavor.**

Even though modern riser-equipped drill ships have achieved outstanding results, drilling on station for long periods of time is still challenging because of risks in handling the riser. Modern deepwater drill ships can drill to 6,000 m while maintaining station, even in severe weather conditions and strong currents. However, the long duration of a Moho project is significantly different than commercial deepwater drilling, and equipment failure over time could lead to operational delays and increased expenses associated with pulling the riser and the blowout preventers. By comparison, a fixed platform only needs to install the riser once, and blowout preventers are at the surface, mitigating subseafloor risk. Fixed platforms also have increased storage, better support facilities, and the ability to drill in extreme weather. Tethered deepwater platforms, for example spars or semi-submersibles, are types of fixed platforms that can be moored in water depths up 2,450[1] and 3,000 m, respectively. A fixed or tethered platform may be superior to a mobile drilling platform for the purposes of Moho drilling.

**If the goal of drilling to the Moho is to be achieved, additional resources for new technologies and perhaps alternate drilling platforms would need to be considered.**

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[1] See http://www.shell.com/home/content/aboutshell/our_strategy/major_projects_2/perdido/overview/.

munications and power grids. Geomagnetism, another area of scientific study that will benefit from continued scientific ocean drilling, encompasses three aspects with the potential for transformative change. First, continuous sediment records collected from a select number of sites could yield time series of geomagnetic dipole declination, inclination, and relative paleointensity. These data, best retrieved through scientific ocean drilling, could provide benchmarks for evaluating numerical models that have been proposed to describe the fluid core motions thought to be responsible for the magnetic dipole and its reversals and excursions. Better models and more data would lead to increased understanding of the ongoing changes in intensity and direction of the present geomagnetic field. Second, validation of true dipole excursions from dating continental and marine sediments could provide a new high temporal resolution magnetic time scale, in conjunction with currently available geomagnetic polarity reversal stratigraphy, for dating climatic and environmental events. Third, the collection of continuous, intact cores of fast-spreading ocean crust, when supplemented by opportunistic sampling of peridotite and serpentinite from tectonically exposed upper mantle, could provide essential ground-truthing opportunities for proposed sources of marine magnetic anomalies. These cores could provide valuable information for modeling some anomaly features that are currently not well understood, including skewness, amplitude variations, and other parameters that allow for reconstruction of oceanic plate formation and aging.

Another opportunity for significant scientific breakthrough lies in improved documentation of the emplacement history of oceanic large igneous provinces (LIPs). Currently, some researchers theorize that LIP emplacement occurred over short time intervals of no more than 800 kyr, which could explain pulses of $CO_2$ release into the atmosphere and possible relationships to mass extinction events. Very little scientific ocean drilling and core recovery has been done on submarine LIPs, and the paucity of materials has resulted in the inability to answer significant questions about their timing and origin. Increased activity on this topic, with significantly better core recovery, would lead to transformational understanding of oceanic LIPs and the implications of their emplacement.

### *Challenge 10: What Are the Mechanisms, Magnitude, and History of Chemical Exchanges Between the Oceanic Crust and Seawater?*

A broad misconception in the geological research community is that the existence of many scientific ocean drilling sites throughout the ocean basins is equivalent to significant sampling of the crystalline crust and underlying upper mantle. This challenge underscores the fact that little drilling has occurred in crystalline basement and that core recovery has not been good. Designing drilling objectives to increase the volume and spatial distribution of hard rock cores will result in significant advances that are likely to transform understanding of the structure and composition of oceanic lithosphere.

As stated under Challenge 8, quantifying the volume of altered mafic crust and serpentinized ultramafic mantle that results from chemical exchanges between the solid Earth and seawater are significant pursuits likely to provide transformative understanding of the carbon cycle. For example, studying the distribution of intact vs. tectonically disrupted crust would lead to better understanding of the long-term carbon cycle. However, water-rock interaction has been a topic of concerted research for at least two decades. It is uncertain if truly transformative science can be accomplished by continued scientific ocean drilling investigations aimed at such targets. Broad estimates of geochemical and thermal exchanges between various reservoirs can be made with current data; refining those estimates could be a priority within the scientific ocean drilling community. However, the ability to place reasonable constraints on the volume of serpentinized mantle requires additional drilling and could dramatically transform understanding of carbon uptake in mantle rocks and the long-term carbon cycle. This would be one of the more significant ocean drilling contributions for better understanding of water-rock interaction.

The science plan states that the best strategy to address this challenge would be a series of drilling transects across ocean basins, from youngest to oldest oceanic crust and in a variety of different regions. The committee believes that much could be learned with such a strategy, but has concerns about such an ambitious plan under the current uncertain funding climate. If such a strategy is to be employed, it would be best to plan drill holes that could contribute to multiple drilling objectives in addition to studying chemical exchanges between seawater and crust.

### *Challenge 11: How Do Subduction Zones Initiate, Cycle Volatiles, and Generate Continental Crust?*

Currently, most research focused on the area of subduction zone initiation, cycling, and generation of continental crust is based on observations and elemental analyses from ophiolites, which have mid-ocean ridge geochemical signatures overprinted by arc-like elemental distributions from younger magmatism. The proposed studies in the science plan invoke subduction initiation, at least in intra-oceanic settings, along fracture zones that are far from ridge systems and occur in significantly cooled lithosphere. Although this challenge's concept is indeed important, the science plan does not provide a clear approach on how it could be tackled. Information supporting this challenge is vague, with no identification of potential drill sites and a lack of clarity about whether any exist, which makes it difficult to assess whether scientific ocean drilling could contribute to greater understanding in this field. Because of this lack of clarity, transformative science is not a likely outcome.

Cycling of volatiles in subduction zones has also been a topic of considerable research since cold seeps and mud volcanoes were discovered close to or within accretionary prisms. Observational data have been collected, leading to some quantification of fluxes. Certainly, additional work could result in new discoveries and further refine flux estimates. Scientific ocean drilling in this area would likely contribute to the very significant work that has already been done. Additionally, the NSF-funded GeoPRISMS (Geodynamic Processes at Rifting and Subducting Margins) and predecessor MARGINS programs have led to much work on understanding the "subduction factory." As with subduction initiation, further work in the next phase of scientific ocean drilling would be useful but may not be transformative.

## Synergies Between This and Other Science Plan Themes

The challenges in this theme have a natural fit with all of the challenges in the Earth in Motion theme (discussed in the next section). These challenges focus on processes controlling geohazard occurrence, the flow and storage of carbon in the ocean crust, and the role of fluids in seafloor processes. Challenge 11, which includes understanding how subduction zones initiate, has natural synergy with the study of mechanisms that cause earthquakes (Challenge 12) and implications for cycling of crustal fluids (Challenge 14). Further study of the architecture of Earth's crust in Challenge 8 has links with Challenge 13, especially in the role of serpentinization.

### Linkages with NSF and Other Programs

There is considerable room for cooperation between activities that would occur under this challenge and the NSF GeoPRISMS Program, which in its earlier existence as MARGINS actively supported research on the topics covered under Challenge 11. Together, GeoPRISMS and the next phase of proposed scientific ocean drilling could make more concerted progress on significant topics if their objectives are tightly integrated. In addition, natural linkages exist between this theme and those of ICDP, the InterRidge Program, and the Deep Carbon Observatory. For example, further investigation of submarine LIPs will benefit from continued integration with terrestrially based studies.

## THEME 4—EARTH IN MOTION: PROCESSES AND HAZARDS ON HUMAN TIME SCALES

The fourth theme of the science plan concerns scientific objectives that require physical measurements or samples from boreholes as a function of time. Because physical and chemical properties of oceanic sediments and rocks change in response to fluid flow and subseafloor biological activity, the snapshots in time provided by conventional drilling and sampling are not adequate to answer many of the challenges presented in previous themes or explicitly discussed in the context of this theme. For example, temporal changes in fluid composition and flow rates must be measured to understand ecological changes beneath the seafloor, as in Challenge 7. Such measurements have been a part of past scientific ocean drilling programs since 1991, with the first CORK installation in Middle Valley on the Juan de Fuca Ridge (Becker and Davis, 2005). However, these measurements have been few and far between, mainly because of installation expenses and the need for extensive background studies to provide a geologic context for time series measurements. The relative importance of the information derived from the limited experiments to date suggests that demand will almost certainly grow in the next decade as new scientific questions develop from the information provided by DSDP, ODP, and IODP cores.

> **Recent developments in ocean observing systems that facilitate data communication to shore-based laboratories and in simpler, cheaper, specialized sensor packages are likely to enable further growth of borehole observatories.**

The research objectives that require time series measurements are grouped into three closely linked challenges: understanding mechanisms related to major earthquakes, tsunami, and landslides; subseafloor carbon sequestration and cycling; and subseafloor fluid flow processes.

### *Challenge 12: What Mechanisms Control the Occurrence of Destructive Earthquakes, Landslides, and Tsunami?*

The science plan notes that processes related to landslide, earthquake, and tsunami generation comprise "the only large-scale natural hazards for which no short-term prediction exists." Any significant increase in the short-term predictive capability for great earthquakes and tsunamis would be truly transformative. Acquisition of samples from the depths at which slip originates and the ability to monitor physical and chemical changes in the fault zone would provide critical new information on how frictional properties of faults change with time as a result of diagenesis, changes in fluid pressure, or other factors. Many of the largest and most destructive faults are located offshore, so sampling and in situ measurements of these faults can only be achieved by scientific ocean drilling. Because of the great depth and potentially corrosive conditions in these locations, these are difficult and expensive objectives that can only be achieved at a small number of sites.

This challenge does a good job of enumerating both the difficulties and societal benefits of addressing this challenge. The likely heterogeneity of fault slip surfaces suggests the need to collect a global range of seismological, geodetic, and geologic measurements from active faults and incipient landslides. Although scientific ocean drilling will be required to collect some of these measurements, well-established links with other initiatives (e.g., continental drilling) will also be required to obtain the complementary information that is needed to fully address the challenge. For example, the NSF/ICDP/EarthScope SAFOD (San Andreas Fault Observatory at Depth) effort to sample and instrument an active strand of the San Andreas Fault at seismogenic depth provides complementary information on the challenges of maintaining an observatory in a fault zone at several km depth as well as on alteration of fault zone rocks.

The past decade's discovery of episodic tremor and slip and of very low frequency (slow) earthquakes in subduction zones also provides a potential specific new target for drilling. The occurrence of this broad spectrum of fault slip behaviors at the down-dip edge of subduction megathrusts is currently being studied primarily by land-based networks and a recently proposed ocean bottom seismic network in Cascadia.[8] Similar processes may also occur at the up-dip edge of the megathrust, but remain poorly documented because of the lack of offshore seismic and geodetic stations everywhere except offshore Japan. The science plan does not clearly enunciate the contribution of scientific ocean drilling to understanding these phenomena. Another important aspect

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[8] See http://www.oceanleadership.org/wp-content/uploads/2010/05/Casc_Facil_Wkshp_Report.pdf.

of subduction zone geohazards that was not included in the science plan is the extension of paleoseismic histories further into the past. Although coring via less expensive platforms should remain the first approach to defining paleoseismic histories of large submarine faults, scientific ocean drilling will be needed to extend these records farther back in time. For example, short cores (less than 10 m long) have been successful at defining the earthquake history for the past ~12 kyr in Cascadia (Goldfinger et al., 2011). Longer time series are needed to develop robust models for earthquake recurrence patterns at major subduction megathrusts.

Scientific ocean drilling has the potential to improve forecasting and to provide early warnings of geohazards like earthquakes, tsunamis, and landslides. The science plan emphasizes installation of observatories at the base of landslides and at great depth in the seismogenic zone. However, conventional coring and logging that can be used to groundtruth seismic data, provide shallow holes for installation of arrays of buried geodetic and seismic instrumentation, and extend paleoseismic histories of major fault zones have equal, if not greater, potential for leading to transformative new insights. As the next phase of scientific ocean drilling moves forward, it would be helpful to consider a broader range of studies that could be designed in collaboration with other national and international geohazard programs (e.g., GeoPRISMS, U.S. Geological Survey).

### *Challenge 13: What Properties and Processes Govern the Flow and Storage of Carbon in the Seafloor?*

This challenge concerns better understanding of the role of the subseafloor environment in the global carbon cycle. Three specific aspects of this problem are highlighted: distribution and dynamics of gas hydrates in marine sediments; the fate of carbon dioxide when it is injected into the seafloor (carbon sequestration); and the impact of hydration (serpentinization), carbonation, and oxidation of ultramafic rocks by seawater and dissolved $CO_2$. All aspects of this challenge potentially have direct societal impacts. Gas hydrates have potential importance as an energy source, while their destabilization in response to environmental change may trigger underwater landslides with consequences for coastal communities. Ocean crust has been proposed as a possible repository for excess carbon dioxide, a growing concern due to global warming, and fluid-rock interactions may provide a way to trap excess carbon in deeply buried solids. Serpentinization, meanwhile, may drive or facilitate a number of tectonic processes because of the release of heat, increase in volume, and lowering of shear strength of serpentine minerals. Measuring rates at which fluids move through the subseafloor and at which rocks and sediments respond requires in situ time series observations, and can benefit from controlled perturbation experiments. This challenge emphasizes the flow and storage of $CO_2$, but the implications for understanding the flux of carbon dioxide and other volatiles through the seafloor are actually much broader and are encompassed to some extent within the next challenge. By quantifying the role of water-rock interactions in the carbon cycle, this challenge would lead to transformative discovery. The volume of seawater flowing in the subseafloor aquifer is unusually large, but it is unknown how that impacts carbon exchange between water and rock. Similarly, the science plan discusses the role of serpentinization of exposed peridotite at slow-spreading ridges. Quantifying the elemental exchange associated with that process would lead to more accurate modeling and would add significantly to understanding of the carbon cycle.

### *Challenge 14: How Do Fluids Link Subseafloor Tectonic, Thermal, and Biogeochemical Processes?*

This final challenge encompasses a wide range of topics that have already been partially discussed in the context of previous challenges. Recent studies have revealed that the amount of fluid being fluxed through the ocean crust is greater than previously thought and that changes in crustal fluid pressure and chemistry can change abruptly in response to distant earthquakes. The global implications of this apparently vigorous exchange between the crustal aquifer and the ocean remain to be explored, and there is little doubt that continued exploration will yield new surprises.

Calibration and verification of subsurface fluid flow requires direct measurement at more than one site so that more readily acquired proxies for fluid flow and chemical exchange in the subseafloor can be exploited, and results from local studies can be extended globally. Such calibration and verification requires direct sampling of the subseafloor fluid flow rates and compositional changes, information that cannot be obtained without scientific ocean drilling and the installation of long-term monitoring devices.

Significant potential exists for transformative scientific discovery related to studying subseafloor hydrology. Much will be gained from installation of monitoring networks related to seismic, geobiological, and other studies, but there is also a significant need for installations dedicated to long-term hydrological observations. Despite the availability of decades of data from terrestrial hydrology monitoring networks, significant aspects of the water cycle cannot be quantified. Developing such broadly based quantitative models of marine hydrogeology will take a significant investment of time, but the potential contribution to understanding a wide range of phenomena makes this long-term effort a high priority.

## Other Challenges and Opportunities

Submarine geodesy is an aspect of this theme that is not discussed in the science plan, but one where long-term observatories in the subseafloor could potentially have a transformative impact. With the advent of widespread acquisition of continuous GPS data on the continents, geodesy has transformed the understanding of the spectrum of fault slip behaviors, revealing a continuum of spatial and temporal scales. Development of marine geodetic networks on the seafloor would require stable baselines for measurement, which could perhaps be associated with borehole observatories to measure position and strain as a function of time. A focus on this type of interdisciplinary instrumentation could facilitate transformative understanding of active tectonics in the ocean.

### Synergies Between This and Other Science Plan Themes

As mentioned previously, Challenge 14 has natural synergy with topics discussed in all of the previous themes. This includes Challenges 1 and 4 (Climate and Ocean Change theme) on Earth's response to higher $CO_2$ concentrations and resilience to changes in ocean chemistry; Challenges 6 and 7 (Biosphere Frontiers theme) on the limits of life and ecosystem sensitivity in the subseafloor; and Challenges 10 and 11 (Earth Connection theme) on seawater-crust cycling and initiation of subduction zones. In addition, Challenge 13's focus on carbon sequestration in the seafloor is related to the Climate and Ocean Change theme, especially with regard to a potential role for geoengineering in mitigating climate change.

### Linkages with NSF and Other Programs

The scientific objectives of this theme dovetail with the objectives of many other national and international initiatives. There is a particularly strong symbiosis with the Ocean Observatories Initiative (OOI), which can enable high-resolution, real-time data flow from instruments that can be deployed in boreholes. It is essential that planning for these two programs be integrated so that boreholes and observing systems are collocated when appropriate. A comprehensive assessment of earthquake and tsunami hazards should take into account the full spectrum of observations from synergistic programs like EarthScope, GeoPRISMS, Ocean Bottom Seismography Instrument Pool Cascadia Initiative, NEPTUNE Canada, OOI, and the Dense Ocean Floor Network System for Earthquakes and Tsunamis.

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# DSDP, ODP, and IODP Legs and Expeditions

**TABLE A.1** Deep Sea Drilling Project (DSDP) Leg Start and End Dates, Sites Drilled on Each Leg, and the Region Where Drilling Occurred.

| Leg | Start Date | End Date | Sites | Region |
|---|---|---|---|---|
| 1 | 20-Jul-68 | 23-Sep-68 | 1-7 | Gulf of Mexico, western Atlantic, Bermuda Rise |
| 2 | 1-Oct-68 | 24-Nov-68 | 8-12 | North Atlantic Ocean |
| 3 | 4-Dec-68 | 20-Jan-69 | 13-22 | South Atlantic Ocean |
| 4 | 27-Jan-69 | 21-Mar-69 | 23-31 | Mid-Atlantic Ridge |
| 5 | 12-Apr-69 | 5-Jun-69 | 32-43 | Northeast Pacific Ocean |
| 6 | 14-Jun-69 | 5-Aug-69 | 44-60 | Mid-Oceanic Ridge |
| 7 | 8-Aug-69 | 2-Oct-69 | 61-67 | Western equatorial Pacific Ocean |
| 8 | 10-Oct-69 | 27-Nov-69 | 68-75 | East central equatorial Pacific Ocean |
| 9 | 6-Dec-69 | 27-Jan-70 | 76-84 | East Pacific Rise |
| 10 | 13-Feb-70 | 5-Apr-70 | 85-97 | Gulf of Mexico |
| 11 | 8-Apr-70 | 1-Jun-70 | 98-110 | Western North Atlantic Ocean |
| 12 | 19-Jun-70 | 11-Aug-70 | 111-119 | North Atlantic Ocean |
| 13 | 13-Aug-70 | 6-Oct-70 | 120-134 | The Mediterranean Ocean Basin |
| 14 | 10-Oct-70 | 1-Dec-70 | 135-144 | Continental margins off West Africa and South America |
| 15 | 5-Dec-70 | 2-Feb-71 | 146-154 | Caribbean Sea |
| 16 | 2-Feb-71 | 30-Mar-71 | 155-163 | Eastern equatorial Pacific Ocean |
| 17 | 30-Mar-71 | 25-May-71 | 164-171 | Central Pacific Ocean |
| 18 | 29-May-71 | 20-Jul-71 | 172-182 | Northeast Pacific Ocean, Gulf of Alaska |
| 19 | 25-Jul-71 | 7-Sep-71 | 183-193 | North Pacific Ocean, Bering Sea |
| 20 | 19-Sep-71 | 30-Oct-71 | 194-202 | Western Pacific Ocean |
| 21 | 9-Nov-71 | 11-Jan-72 | 203-210 | Pacific east of Tonga Trench |
| 22 | 21-Jan-72 | 4-Mar-72 | 211-218 | Ninetyeast Ridge and eastern Indian Ocean |
| 23 | 8-Mar-72 | 1-May-72 | 219-230 | Arabian Sea and Red Sea |
| 24 | 5-May-72 | 21-Jun-72 | 231-238 | Gulf of Aden, Somali Basin, Central Indian Ridge |

*continued*

**TABLE A.1** Continued

| Leg | Start Date | End Date | Sites | Region |
|---|---|---|---|---|
| 25 | 28-Jun-72 | 22-Aug-72 | 239-249 | Arabian Sea and Red Sea |
| 26 | 6-Sep-72 | 30-Oct-72 | 250-258 | Indian Ocean |
| 27 | 1-Nov-72 | 9-Dec-72 | 259-263 | Eastern Indian Ocean |
| 28 | 20-Dec-72 | 19-Feb-73 | 264-274 | South Pole/Antarctica, Ross Sea |
| 29 | 2-Mar-73 | 18-Apr-73 | 275-284 | Northern Antarctic, Subantarctic |
| 30 | 24-Apr-73 | 13-Jun-73 | 285-289 | Indian Ocean |
| 31 | 13-Jun-73 | 4-Aug-73 | 290-302 | West Philippine Basin and the Sea of Japan |
| 32 | 16-Aug-73 | 10-Oct-73 | 303-313 | Northwestern Pacific Ocean |
| 33 | 2-Nov-73 | 17-Dec-73 | 314-318 | Central Pacific Ocean |
| 34 | 20-Dec-73 | 2-Feb-74 | 319-321 | Nazca Plate |
| 35 | 13-Feb-74 | 30-Mar-74 | 322-325 | Antarctic waters, Southeast Pacific Basin |
| 36 | 4-Apr-74 | 22-May-74 | 326-331 | Antarctic water |
| 37 | May ‘74 | July ‘74 | 332-335 | Mid-Atlantic Ridge |
| 38 | 29-Jul-74 | 26-Sep-74 | 336-352 | Norwegian-Greenland Sea |
| 39 | 6-Oct-74 | 17-Dec-74 | 353-359 | Western South Atlantic Ocean |
| 40 | 17-Dec-74 | 15-Feb-75 | 360-365 | South Atlanic Ocean |
| 41 | 17-Feb-75 | 10-Apr-75 | 366-370 | Eastern central North Atlantic Ocean |
| 42- Pt 1 | 4-Apr-75 | 21-May-75 | 371-378 | Mediterranean Sea |
| 42- Pt 2 | 21-May-75 | 11-Jun-75 | 379-381 | Black Sea |
| 43 | 13-Jun-75 | 12-Aug-75 | 382-387 | Western North Atlantic Ocean |
| 44 | 5-Aug-75 | 30-Sep-75 | 388-394 | Western North Atlantic Ocean |
| 45 | 30-Nov-75 | 20-Jan-76 | 395-396 | Mid-Atlantic Ridge |
| 46 | 28-Jan-76 | 19-Mar-76 | 396A-396B | Mid-Atlantic Ridge |
| 47- Pt 1 | 20-Mar-76 | 12-Apr-76 | 397 | Eastern North Atlantic Ocean, Northwest African Margin |
| 47- Pt 2 | 13-Apr-76 | 9-May-76 | 398 | Western Iberian Continental Margin |
| 48 | 12-May-76 | 13-Jul-76 | 399-406 | Bay of Biscay, Rockall Plateau |
| 49 | 18-Jul-76 | 4-Sep-76 | 407-414 | North Atlantic Ocean |
| 50 | 13-Sep-76 | 8-Nov-76 | 415-416 | Central and North Atlantic Ocean |
| 51 | 20-Nov-76 | 17-Jan-77 | 417 | Western North Atlantic Ocean |
| 52 | 22-Jan-77 | 8-Mar-77 | 417-418 | Western North Atlantic Ocean |
| 53 | 12-Mar-77 | 21-Apr-77 | 418 | Western North Atlantic Ocean |
| 54 | 30-Apr-77 | 18-Jun-77 | 419-429 | East Pacific Rise |
| 55 | 18-Jun-77 | 6-Sep-77 | 430-433 | Hawaiian-Emperor chain |
| 56 | 12-Sep-77 | 6-Oct-77 | 434-436 | Japan Trench Transect |
| 57 | 19-Oct-77 | 2-Dec-77 | 438-441 | Japan Trench Transect |
| 58 | 4-Dec-77 | 30-Jan-78 | 442-446 | North Philippine Sea |
| 59 | 3-Feb-78 | 15-May-78 | 447-451 | West Philippine Sea and Mariana Trench |
| 60 | 15-Mar-78 | 15-May-78 | 452-461 | Philippine Sea, Mariana Trough |
| 61 | 22-May-78 | 29-Jul-78 | 462 | Nauru Basin, Western Equatorial Pacific |
| 62 | 29-Jul-78 | 7-Sep-78 | 463-466 | North central Pacific Ocean |
| 63 | 9-Oct-78 | 26-Nov-78 | 467-473 | Eastern North Pacific Ocean |
| 64 | 2-Dec-78 | 8-Jan-79 | 474-480 | Gulf of California |

**TABLE A.1** Continued

| Leg | Start Date | End Date | Sites | Region |
|---|---|---|---|---|
| 65 | 24-Jan-79 | 12-Mar-79 | 482-485 | Gulf of California, Esat Pacific Rise |
| 66 | 18-Mar-79 | 2-May-79 | 486-493 | Middle America Trench |
| 67 | 16-May-79 | 23-Jun-79 | 494-500 | Middle America Trench Transect |
| 68 | 13-Aug-79 | 13-Sep-79 | 502-503 | Western Caribbean Sea, Eastern equatorial Pacific Ocean |
| 69 | 20-Sep-79 | 25-Oct-79 | 501, 504-505 | Costa Rica Rift |
| 70 | 11-Nov-79 | 1-Dec-79 | 504b, 506-510 | Galapagos Spreading Center |
| 71 | 15-Jan-80 | 13-Feb-80 | 511-514 | South Atlantic Ocean, Falkland Plateau |
| 72 | 29-Feb-80 | 4-Apr-80 | 515-518 | Brazil Basin, Rio Grande Rise |
| 73 | 13-Apr-80 | 1-Jun-80 | 519-524 | South Atlantic Ocean |
| 74 | 10-Jun-80 | 20-Jul-80 | 525-529 | Walvis Ridge |
| 75 | 27-Jul-80 | 25-Aug-80 | 530-532 | Angola Basin, Walvis Ridge |
| 76 | 13-Oct-80 | 9-Dec-80 | 533-534 | Blake Outer Ridge, Blake-Bahama Basin |
| 77 | 29-Dec-80 | 25-Jan-81 | 535-540 | Southeastern Gulf of Mexico |
| 78A | 13-Feb-81 | 9-Mar-81 | 541-543 | Barbados Ridge complex |
| 78B | 14-Mar-81 | 8-Apr-81 | 395 | Mid-Atlantic Ridge |
| 79 | 17-Apr-81 | 22-May-81 | 544-547 | Mazagan Plateau |
| 80 | 30-May-81 | 22-Jul-81 | 548-551 | Goban Spur Region |
| 81 | 27-Jul-81 | 21-Sep-81 | 552-555 | Rockall Plateau |
| 82 | 22-Sep-81 | 1-Nov-81 | 556-564 | Central North Atlantic Ocean |
| 83 | 22-Nov-81 | 2-Jan-82 | 504B | Costa Rica Rift |
| 84 | 10-Jan-82 | 26-Feb-82 | 565-570 | Middle America Trench and Slope |
| 85 | 19-Mar-82 | 24-Apr-82 | 571-575 | Central Equatorial Pacific |
| 86 | 16-May-82 | 13-Jun-82 | 576-581 | Western North Pacific Ocean |
| 87 | 28-Jun-82 | 16-Aug-82 | 582-584 | Nankai Trough, Japan Trench |
| 88 | 24-Aug-82 | 3-Sep-82 | 581 | Northwest Pacific Basin |
| 89 | 18-Oct-82 | 23-Nov-82 | 585-586 | Western Pacific Ocean |
| 90 | 3-Dec-82 | 7-Jan-83 | 587-594 | Western Equatorial and Southwest Pacific Ocean |
| 91 | 21-Jan-83 | 6-Feb-83 | 595-596 | Southwest Pacific Basin |
| 92 | 23-Feb-83 | 18-Apr-83 | 504B, 597-602 | Southeast Pacific Ocean |
| 93 | 4-May-83 | 17-Jun-83 | 603-605 | Northwestern Atlantic Ocean |
| 94 | 2-Jul-83 | 12-Aug-83 | 606-611 | North Atlantic Ocean |
| 95 | 25-Aug-83 | 22-Sep-83 | 612-613 | New Jersey Transect, Continental slope and upper rise |
| 96 | 29-Sep-83 | 8-Nov-83 | 614-624 | Mississippi Fan, Gulf of Mexico |

SOURCE: Data from http://www.deepseadrilling.org/i_reports.htm.

**TABLE A.2** Ocean Drilling Program (ODP) Leg Start and End Dates, Sites Drilled on Each Leg, and the Region Where Drilling Occurred.

| Leg | Start Date | End Date | Sites | Region |
|---|---|---|---|---|
| 100 | 11-Jan-85 | 29-Jan-85 | 625 | Gulf of Mexico |
| 101 | 29-Jan-85 | 14-Mar-85 | 626-636 | Bahamas |
| 102 | 14-Mar-85 | 25-Apr-85 | 418 | Bermuda Rise |
| 103 | 25-Apr-85 | 19-Jun-85 | 637-641 | Galicia Margin |
| 104 | 19-Jun-85 | 23-Aug-85 | 642-644 | Norwegian Sea |
| 105 | 23-Aug-85 | 27-Oct-85 | 645-647 | Baffin Bay and Labrador Sea |
| 106 | 27-Oct-85 | 26-Dec-85 | 648-649 | Mid-Atlantic Ridge |
| 107 | 26-Dec-85 | 18-Feb-86 | 650-656 | Tyrrhenian Sea |
| 108 | 18-Feb-86 | 17-Apr-86 | 657-668 | Eastern Tropical Atlantic |
| 109 | 17-Apr-86 | 19-Jun-86 | 395, 648, 669-670 | Mid-Atlantic Ridge |
| 110 | 19-Jun-86 | 16-Aug-86 | 671-676 | Northern Barbados Ridge |
| 111 | 16-Aug-86 | 20-Oct-86 | 504, 677-678 | Costa Rica Rift |
| 112 | 20-Oct-86 | 25-Dec-86 | 679-688 | Peru Continental Margin |
| 113 | 25-Dec-86 | 11-Mar-87 | 689-697 | Weddell Sea, Antarctica |
| 114 | 11-Mar-87 | 13-May-87 | 698-704 | Subantarctic South Atlantic |
| 115 | 13-May-87 | 2-Jul-87 | 705-716 | Mascarene Plateau |
| 116 | 2-Jul-87 | 19-Aug-87 | 717-719 | Distal Bengal Fan |
| 117 | 19-Aug-87 | 18-Oct-87 | 720-731 | Oman Margin |
| 118 | 18-Oct-87 | 14-Dec-87 | 732-735 | Southwest Indian Ridge |
| 119 | 14-Dec-87 | 21-Feb-88 | 736-746 | Kerguelen Plateau and Prydz Bay |
| 120 | 21-Feb-88 | 30-Apr-88 | 747-751 | Central Kerguelen Plateau |
| 121 | 30-Apr-88 | 28-Jun-88 | 752-758 | Broken Ridge and Ninetyeast Ridge |
| 122 | 28-Jun-88 | 28-Aug-88 | 759-764 | Exmouth Plateau |
| 123 | 28-Aug-88 | 1-Nov-88 | 765-766 | Argo Abyssal Plain and Exmouth Plateau |
| 124 | 1-Nov-88 | 4-Jan-89 | 767-771 | Celebes and Sulu Seas |
| 124E | 4-Jan-89 | 16-Feb-89 | 772-777 | Philippine Sea/ Engineering Tests |
| 125 | 16-Feb-89 | 18-Apr-89 | 778-786 | Bonin/Mariana Region |
| 126 | 18-Apr-89 | 19-Jun-89 | 787-793 | Izu-Bonin Arc-Trench System |
| 127 | 19-Jun-89 | 21-Aug-89 | 794-797 | Japan Sea |
| 128 | 21-Aug-89 | 20-Nov-89 | 794, 798-799 | Japan Sea |
| 129 | 20-Nov-89 | 19-Jan-90 | 800-802 | Old Pacific Crust/ Pigafetta and Mariana Basins |
| 130 | 19-Jan-90 | 27-Mar-90 | 803-807 | Ontong Java Plateau |
| 131 | 27-Mar-90 | 1-Jun-90 | 808 | Nankai Trough |
| 132 | 1-Jun-90 | 4-Aug-90 | 808-810 | Western and central Pacific |
| 133 | 4-Aug-90 | 11-Oct-90 | 811-826 | Northeast Australian Margin |
| 134 | 11-Oct-90 | 17-Dec-90 | 827-833 | Vanuatu, New Hebrides |
| 135 | 17-Dec-90 | 28-Feb-91 | 834-841 | Lau Basin |
| 136 | 28-Feb-91 | 20-Mar-91 | 842-843 | Hawaiian Arch |
| 137 | 20-Mar-91 | 1-May-91 | 504 | Costa Rica Rift |
| 138 | 1-May-91 | 4-Jul-91 | 844-854 | Eastern equatorial Pacific |

**TABLE A.2** Continued

| Leg | Start Date | End Date | Sites | Region |
|---|---|---|---|---|
| 139 | 4-Jul-91 | 11-Sep-91 | 855-858 | Middle Valley, Juan de Fuca Ridge |
| 140 | 11-Sep-91 | 12-Nov-91 | 504 | Costa Rica Rift |
| 141 | 12-Nov-91 | 12-Jan-92 | 859-863 | Chile Triple Junction |
| 142 | 12-Jan-92 | 18-Mar-92 | 864 | East Pacific Rise/ Engineering Tests |
| 143 | 18-Mar-92 | 20-May-92 | 670, 865-870 | Northwest Pacific Atolls and Guyots |
| 144 | 20-May-92 | 20-Jul-92 | 800-801, 871-880 | Northwest Pacific Atolls and Guyots |
| 145 | 20-Jul-92 | 20-Sep-92 | 881-887 | North Pacific Transect |
| 146 | 20-Sep-92 | 22-Nov-92 | 888-893 | Cascadia Margin |
| 147 | 22-Nov-92 | 21-Jan-93 | 894-895 | Hess Deep Rift Valley |
| 148 | 21-Jan-93 | 10-Mar-93 | 504, 896 | Costa Rica Rift |
| 149 | 10-Mar-93 | 25-May-93 | 897-901 | Iberia Abyssal Plain |
| 150 | 25-May-93 | 24-Jul-93 | 902-906 | New Jersey Sea-Level Transect |
| 150X* | Mar-93 | Aug-93 | Island Beach, Atlantic City | New Jersey Coastal Plain |
| 150X Suppl.* | Mar-94 | Apr-94 | Cape May | New Jersey Coastal Plain |
| 151 | 24-Jul-93 | 24-Sep-93 | 907-913 | North Atlantic-Arctic Gateways I |
| 152 | 24-Sep-93 | 22-Nov-93 | 914-919 | East Greenland Margin |
| 153 | 22-Nov-93 | 24-Jan-94 | 920-924 | Mid-Atlantic Ridge/ Kane Fracture Zone |
| 154 | 24-Jan-94 | 25-Mar-94 | 925-929 | Ceara Rise |
| 155 | 25-Mar-94 | 25-May-94 | 930-946 | Amazon Deep-Sea Fan |
| 156 | 24-May-94 | 24-Jul-94 | 947-949 | Barbados Ridge Accretionary Prism |
| 157 | 24-Jul-94 | 23-Sep-94 | 950-956 | Gran Canaria and Madeira Abyssal Plain |
| 158 | 23-Sep-94 | 22-Nov-94 | 957 | TAG Hydrothermal Mound |
| 159T | 23-Dec-94 | 3-Jan-95 | 958 | Eastern Canary Basin |
| 159 | 3-Jan-95 | 2-Mar-95 | 959-962 | Côte D'Ivoire- Ghana Transform Margin |
| 160 | 7-Mar-95 | 3-May-95 | 963-973 | Mediterranean Sea I |
| 161 | 3-May-95 | 2-Jul-95 | 974-979 | Mediterranean Sea II |
| 162 | 7-Jul-95 | 3-Sep-95 | 907, 980-987 | North Atlantic-Arctic Gateways II |
| 163 | 3-Sep-95 | 7-Oct-95 | 988-990 | Southeast Greenland Margin |
| 163X* | Aug-99 | Sep-99 | EG64-66, 68 | Southeast Greenland Margin |
| 164 | 31-Oct-95 | 19-Dec-95 | 991-997 | Blake Ridge and Carolina Rise |
| 165 | 21-Dec-95 | 17-Feb-96 | 998-1002 | Caribbean Ocean History |
| 166 | 20-Feb-96 | 10-Apr-96 | 1003-1009 | Bahamas Transect |
| 167 | 20-Apr-96 | 16-Jun-96 | 1010-1022 | California Margin |
| 168 | 16-Jun-96 | 15-Aug-96 | 1023-1032 | Juan de Fuca Ridge |
| 169S | 15-Aug-96 | 20-Aug-96 | 1033-1034 | Saanitch Inlet |
| 169 | 21-Aug-96 | 16-Oct-96 | 856-858, 1035-1038 | Sedimented Ridges II (NE Pacific Ocean) |
| 170 | 16-Oct-96 | 17-Dec-96 | 1039-1043 | Costa Rica Accretionary Wedge |
| 171A | 17-Dec-96 | 8-Jan-97 | 1044-1048 | Northern Barbados Accretionary Prism LWD |
| 171B | 8-Jan-97 | 14-Feb-97 | 1049-1053 | Blake Nose Paleoceano- graphic Transect |
| 172 | 14-Feb-97 | 15-Apr-97 | 1054-1064 | Northwest Atlantic Sediment Drifts |

*continued*

**TABLE A.2** Continued

| Leg | Start Date | End Date | Sites | Region |
|---|---|---|---|---|
| 173 | 15-Apr-97 | 15-Jun-97 | 1065-1070 | Return to Iberia |
| 174A | 15-Jun-97 | 19-Jul-97 | 1071-1073 | Continuing the New Jersey Sea-Level Transect |
| 174AX* | Oct-96 | Nov-96 | Bass River | New Jersey Coastal Plain |
| 174AX Suppl.* | Jul-98 | Aug-98 | Ancora | New Jersey Coastal Plain |
| 174AX Suppl.* | Sep-99 | Oct-99 | Ocean View | New Jersey Coastal Plain |
| 174AX Suppl.* | May-00 | Jun-00 | Bethany Beach | New Jersey Coastal Plain |
| 174AX Suppl.* | Oct-01 | Oct-01 | Fort Mott | New Jersey Coastal Plain |
| 174AX Suppl.* | May-02 | Jun-02 | Millville | New Jersey Coastal Plain |
| 174AX Suppl.* | Sep-03 | Nov-03 | Sea Girt | New Jersey Coastal Plain |
| 174AX Suppl.* | Sep-04 | Oct-04 | Cape May Zoo | New Jersey Coastal Plain |
| 174B | 19-Jul-97 | 9-Aug-97 | 395, 1074 | CORK Hole 395A (N Atlantic Ocean) |
| 175 | 9-Aug-97 | 8-Oct-97 | 1075-1087 | Benguela Current |
| 176 | 8-Oct-97 | 9-Dec-97 | 735 | Return to Hole 735B (Indian Ocean) |
| 177 | 9-Dec-97 | 5-Feb-98 | 1088-1094 | Southern Ocean Paleoceanography |
| 178 | 5-Feb-98 | 9-Apr-98 | 1095-1103 | Antarctic Glacial History and Sea-Level Change |
| 179 | 9-Apr-98 | 7-Jun-98 | 1104-1107 | Hammer Drilling and NERO (Indian Ocean) |
| 180 | 7-Jun-98 | 11-Aug-98 | 1108-1118 | Woodlark Basin, Papua New Guinea |
| 181 | 11-Aug-98 | 8-Oct-98 | 1119-1125 | Southwest Pacific Gateways |
| 182 | 8-Oct-98 | 7-Dec-98 | 1126-1134 | Great Australian Bight Carbonates |
| 183 | 7-Dec-98 | 11-Feb-99 | 1135-1142 | Kerguelen Plateau-Broken Ridge |
| 184 | 11-Feb-99 | 12-Apr-99 | 1143-1148 | South China Sea |
| 185 | 12-Apr-99 | 14-Jun-99 | 801, 1149 | Izu-Mariana Margin |
| 186 | 14-Jun-99 | 14-Aug-99 | 1150-1151 | Western Pacific Geophysical Observatories |
| 187 | 16-Nov-99 | 10-Jan-00 | 1152-1164 | Australian- Antarctic Discordance |
| 188 | 10-Jan-00 | 11-Mar-00 | 1165-1167 | Prydz Bay-Cooperation Sea, Antarctica |
| 189 | 11-Mar-00 | 6-May-00 | 1168-1172 | Tasmanian Gateway |
| 190 | 6-May-00 | 16-Jul-00 | 1173-1178 | Nankai Trough Accretionary Prism |
| 191 | 16-Jul-00 | 8-Sep-00 | 1179-1182 | West Pacific ION Project/ Hammer Drill Engineering |
| 192 | 8-Sep-00 | 7-Nov-00 | 1183-1187 | Basement Drilling on the Ontong Java Plateau |
| 193 | 7-Nov-00 | 3-Jan-01 | 1188-1191 | Manus Basin Hydrothermal System |
| 194 | 3-Jan-01 | 2-Mar-01 | 1192-1199 | Marion Plateau, Northeast Australia |
| 195 | 2-Mar-01 | 2-May-01 | 1200-1202 | Seafloor Observatories and the Kuroshio Current |
| 196 | 2-May-01 | 1-Jul-01 | 808, 1173 | Nankai Trough Accretionary Prism: LWD and ACORK |
| 197 | 1-Jul-01 | 27-Aug-01 | 1203-1206 | Hawaiian Hotspot Motion |
| 198 | 27-Aug-01 | 23-Oct-01 | 1207-1214 | Cretaceous- Paleogene Climate, Shatsky Rise |
| 199 | 23-Oct-01 | 16-Dec-01 | 1215-1222 | Paleogene equatorial Transect (Pacific Ocean) |
| 200 | 16-Dec-01 | 27-Jan-02 | 1223-1224 | Hawaii-2 Observatory and Nuuanu Landslide |
| 201 | 27-Jan-02 | 29-Mar-02 | 1225-1231 | Microbial communities, Eastern equatorial Pacific and Peru Margin |
| 202 | 29-Mar-02 | 30-May-02 | 1232-1242 | Southeast Pacific Paleoceano- graphic Transects |

**TABLE A.2** Continued

| Leg | Start Date | End Date | Sites | Region |
|---|---|---|---|---|
| 203 | 30-May-02 | 7-Jul-02 | 1243 | Equatorial Pacific Ion Multidisciplinary Observatory |
| 204 | 7-Jul-02 | 2-Sep-02 | 1244-1252 | Gas Hydrates (Cascadia Margin) |
| 205 | 2-Sep-02 | 6-Nov-02 | 1253-1255 | Costa Rica Continental Margin CORK |
| 206 | 6-Nov-02 | 4-Jan-03 | 1256 | Fast Spreading Crust (Guatemala Basin) |
| 207 | 11-Jan-03 | 6-Mar-03 | 1257-1261 | Demerara Rise (Central Atlantic) |
| 208 | 6-Mar-03 | 6-May-03 | 1262-1267 | Walvis Ridge (Southern Atlantic) |
| 209 | 6-May-03 | 6-Jul-03 | 1268-1275 | Mid-Atlantic Ridge (Central Atlantic) |
| 210 | 6-Jul-03 | 6-Sep-03 | 1276-1277 | Newfoundland Margin |

NOTE: Sites marked with an asterisk (150X, 163X, and 174AX) were funded by organizations other than ODP.
SOURCE: Data from http://www.odplegacy.org/science_results/leg_summaries.html.

**TABLE A.3** Integrated Ocean Drilling Program (IODP) Expedition Start and End Dates, Sites Drilled on Each Expedition, and the Region Where Drilling Occurred.

| Exp # | Start Date | End Date | Sites | Region |
|---|---|---|---|---|
| 301 | 27-Jun-04 | 21-Aug-04 | U1301, 1026 | Juan de Fuca Ridge |
| 301T | 21-Aug-04 | 25-Sep-04 | 1253-1255 | Costa Rica Hydrogeology |
| 303 | 25-Sep-04 | 17-Nov-04 | U1302-U1308 | North Atlantic Ocean |
| 304 | 17-Nov-04 | 8-Jan-05 | U1309-U1311 | Atlantis Massif, Mid-Atlantic Ridge |
| 305 | 8-Jan-05 | 2-Mar-05 | U1309 | Atlantis Massif, Mid-Atlantic Ridge |
| 306 | 2-Mar-05 | 25-Apr-05 | U1312-U1315 | North Atlantic Ocean |
| 307 | 25-Apr-05 | 30-May-05 | U1316-U1318 | Southwest Irish continental margin |
| 308 | 30-May-05 | 8-Jul-05 | U1319-U1324 | Gulf of Mexico |
| 309 | 8-Jul-05 | 28-Aug-05 | 1256 | Eastern equatorial Pacific |
| 311 | 28-Aug-05 | 28-Oct-05 | U1325-U1329 | Cascadia Margin |
| 312 | 28-Oct-05 | 29-Dec-05 | 1256 | Eastern equatorial Pacific |
| 320 | 5-Mar-09 | 5-May-09 | U1331-U1336 | Equatorial Pacific Ocean |
| 321 | 5-May-09 | 23-Jun-09 | U1337-U1338 | Equatorial Pacific Ocean |
| 321T | 23-Jun-09 | 5-Jul-09 | U1301 | Juan de Fuca Ridge |
| 323 | 5-Jul-09 | 4-Sep-09 | U1339-U1345 | Bering Sea |
| 324 | 4-Sep-09 | 4-Nov-09 | U1346-U1350 | Shatsky Rise |
| 317 | 4-Nov-10 | 4-Jan-10 | U1351-U1354 | Canterbury Basin |
| 318 | 4-Jan-10 | 8-Mar-10 | U1355-U1361 | Antarctic Wilkes Land Margin |
| 327 | 5-Jul-10 | 5-Sep-10 | U1362-U1363, U1301, 1027 | Juan de Fuca Ridge |
| 328 | 5-Sep-10 | 19-Sep-10 | U1364 | Cascadia Margin |
| 329 | 9-Oct-10 | 13-Dec-10 | U1365-U1371 | South Pacific Gyre |
| 330 | 13-Dec-10 | 11-Feb-11 | U1372-U1377 | Louisville Seamounts, Southwest Pacific Ocean |
| 334 | 15-Mar-11 | 13-Apr-11 | U1378-U1381 | Costa Rica margin |
| 335 | 13-Apr-11 | 3-Jun-11 | 1256 | Eastern equatorial Pacific |
| 336 | 16-Sep-11 | 17-Nov-11 | 395, U1382 | Mid-Atlantic Ridge |

SOURCE: Data from http://www.iodp.org/expeditions.

# B

# Committee and Staff Biographies

## COMMITTEE

**Robert A. Duce** (*Co-Chair*) is presently Distinguished Professor Emeritus of Oceanography and Atmospheric Sciences at Texas A&M University. From 1991 to 1997 he was Dean of the College of Geosciences at Texas A&M. From 1987 to 1991 he was Dean of the Graduate School of Oceanography and Vice Provost for Marine Affairs at the University of Rhode Island. His research interests include the chemistry of the atmosphere and ocean, focusing on the chemical cycles of pollutant and natural substances in the global atmosphere, their transport from the continents, and their deposition to and impact on coastal and remote ocean regions. He is the past President of SCOR (ICSU Scientific Committee on Oceanic Research), the International Association of Meteorology and Atmospheric Sciences, and the Oceanography Society, and he is past Chair of the U.N. Group of Experts on the Scientific Aspects of Marine Environmental Protection. He has been a member of the National Research Council's (NRC) Ocean Studies Board and Board on Atmospheric Sciences and Climate. He is a Fellow of the American Geophysical Union, the Oceanography Society, the American Meteorological Society, and the American Association for the Advancement of Science (AAAS). Dr. Duce earned a B.A. in chemistry from Baylor University in 1957 and a Ph.D. in inorganic and nuclear chemistry from the Massachusetts Institute of Technology in 1964.

**Arthur Goldstein** (*Co-Chair*) has served as the Dean of the College of Science and Mathematics at Bridgewater State University, Massachusetts, since August 2010. As the founding Dean of this new college his responsibilities not only comprise the normal duties of a Dean, course scheduling, faculty workload, and promotion, tenure assessment, and hiring, but also include working with the faculty to craft a vision for the college and to develop strategic priorities. In addition, he has responsibilities for the completion of a new Science and Math Center, which will house the college in the future. Prior to joining Bridgewater State University he held appointments at the University of New England as Dean and at the National Science Foundation (NSF) in the Division of Earth Sciences as a Program Director, Section Head, and, eventually, Division Director. At NSF, Dr. Goldstein had responsibility for grants programs in excess of $150 million annually and had oversight responsibility for the construction of EarthScope, a $200 million project aimed at developing a comprehensive understanding of the plate boundary processes active in western North America and the structure and evolution of the North American continent. At NSF he was also involved in developing funding for geoinformatics projects and a variety of new initiatives including GeoTeach, a program that addresses development of pre-service and in-service secondary school teachers, and the Critical Zone Observatory Program that invested $8.5 million in integrated studies of Earth's near surface environments. Prior to his appointment at NSF he was a Professor of Geology at Colgate University and served as Department Chair for five years. Dr. Goldstein received his B.S. in geology from Kent State University and M.S. and Ph.D. degrees from University of Massachusetts, Amherst.

**Subir K. Banerjee** is Distinguished Professor Emeritus and Founding Director of the Institute for Rock Magnetism at the University of Minnesota, a national facility for state-of-the-art instrumentation and research in rock magnetism. Dr. Banerjee earned a Sc.D. in 1983 from Cambridge University. Dr. Banerjee, his students, and his postdoctoral colleagues have studied many drill cores from the ocean crust and ophiolite complexes on land. Their research led to models of very deep-seated crustal sources of marine magnetic anomalies. He is a Fellow of both the American Geophysical Union and the American Academy of Arts and Sciences. Dr. Banerjee has received many awards, including the 2006 John Adam Fleming Medal from the American Geophysical Union, the 2004 Louis Néel Medal from the European Geosciences Union, and the 2003 William Gilbert Award from the American Geophysical Union, Geomagnetism and Paleomagnetism. Dr. Banerjee was the President of American Geophysical Union's Geomagnetism and Paleomagnetism section and a member of the Council of Officers of the American Geophysical Union from 1984 to 1988. At the NSF, Dr. Banerjee has participated in many ad hoc panels to review research grant proposals and reseach programs and to help select Presidential Young Investigators.

**William B. Curr**y is a Senior Scientist at Woods Hole Oceanographic Institution (WHOI). He received a B.S. in geology from the University of Delaware in 1974 and a Ph.D. in geology from Brown University in 1980. Dr. Curry studies the history of Earth's climate and carbon cycle using geological records of ocean chemistry and physical properties. His detailed research interests are quantitative paleoclimatology and paleoceanography, sedimentation dynamics of marine particulates, and stable isotopic fractionation in carbonate-secreting organisms. Dr. Curry is actively involved with seagoing expeditions to collect deep-sea sediments and uses the chemistry of fossils in the sediments to determine how climate has changed on decadal to millennial time scales. He has been a member of the Scientific Staff at WHOI since 1981. He is a former Ocean Studies Board member and has served on three National Research Council Committees.

**Magnus Friberg** is a Research Officer at the Swedish Research Council with special responsibilities for large-scale infrastructures for earth and environmental research, polar research, and the Research Council's program for investments in research equipment in all areas of science. As such, he represents Sweden in international research cooperations in Earth and environmental sciences and polar research. He has a Ph.D. in applied geophysics from Uppsala University. His research involved geophysical exploration techniques and their combination with geological observations, focusing on the deep drilling site in the Middle Ural Mountains. It also included applying geophysics to archeology and environmental and geothermal exploration, as well as characterizing sites for nuclear waste repositories. Dr. Friberg also serves on several national and international organizations, including the EU Joint Programming Initiative on Climate Research and the European Strategy Forum for Research Infrastructures (EU Commission) Thematic Working Group on Environmental Research Infrastructures, and he chairs the Nordic Council of Ministers program on Cryosphere Research.

**Julie Huber** is a microbial oceanographer at the Marine Biological Laboratory, interested in the ecology of bacteria and archaea in the deep sea, especially at underwater volcanoes. Most of her research focuses on the oceanic crust as a microbial habitat and the distribution, diversity, and evolutionary and community dynamics of microbial groups in the subseafloor. Currently, Dr. Huber is using phylogenetic, metagenomic, cultivation-based, and geochemical measurements of deep-sea crustal fluids to link microbial groups with their metabolic and physiological functions in subseafloor habitats. She is broadly interested in marine microbial ecosystems of all types, from coral reefs to marine sediments, and the methods and approaches that unite microbial scientists. As a sea-going scientist, Dr. Huber is also interested in technology development for deep-sea exploration and in situ experimentation. Dr. Huber has a Ph.D. and M.S. in oceanography from the University of Washington, and she is a winner of the Loreal Women in Science award.

**Michael E. Jackson** is the Manager for Earth Sciences for Trimble Navigation. He was recently the Principal Investigator and Director of EarthScope Plate Boundary and SAFOD (San Andres Fault Obsevatory at Depth) Observatories, UNAVCO, Inc. Dr. Jackson specializes in the geodesy, paleoseismology, and physics of tectonically active parts of Earth with an emphasis on the installation, operations, and management of remote, geographically distributed instrumentation networks. As part of his duties as a National Science Foundation (NSF) Major Equipment and Facilities Construction Project Manager, Dr. Jackson provides advice to NSF on whether other large facility projects are well proposed and ready to begin construction/implementation, and he provides ongoing guidance to NSF during the construction and operations phases. Dr. Jackson was Chair of the Ocean Observatories Initiatives Preliminary Design Review panel and a member of the National Ecological Observatory Network (NEON) Conceptual Design and Preliminary Design review panels. Dr. Jackson has also served as a member of the U.S. Geological Survey's National Volcano Early Warning System (NVEWS) advisory panel. He has a B.S. in geology from the University of New Mexico and an M.S. in geological sciences and a Ph.D. in geophysics from the University of Colorado.

**Keith K. Millheim (NAE)** is President of Strategic Worldwide, LLC. Dr. Millheim received his Ph.D. in mining engineering from the University of Leoben in 1992. He also earned an M.Sc. in petroleum engineering from the University of Oklahoma in 1964 and a B.Sc. in petroleum science from Marietta College in 1963. Dr. Millheim is a member of many professional societies, including the Society of Petroleum Engineers (SPE) and the Society of Systems Thinking. He is also a member of many other organizations, including the Texas Academy of Science, Engineering and

Medicine and the National Academy of Engineering (NAE). He currently serves on NAE's Committee on the Analysis of Causes of the Deepwater Horizon Fire and Oil Spill to Identify Measures to Prevent Similar Accidents in the Future. His research interest focuses on the implementation of new technology in petroleum drilling. Dr. Millheim is currently serving on the NAE Committee on Membership.

**Samuel Mukasa** is Dean of the College of Engineering and Physical Sciences and Eric J. Essene Professor of Geochemistry at the University of New Hampshire (UNH). Dr. Mukasa earned a Ph.D. from the University of California, Santa Barbara in geochemistry in 1984, and spent 21 years on the faculty of the Department of Geological Sciences at the University of Michigan prior to moving to UNH in January 2011. His fields of study in petrology and geochemistry focus on integrated use of trace elements and lead, neodymium, strontium, hafnium, and osmium isotopes to model the petrogenesis of ultramafic xenoliths, arc lavas, layered mafic intrusions, and continental flood basalts, the application of uranium-lead and argon-argon ($^{40}$Ar-$^{39}$Ar) geochronology to provide constraints on the evolution of continental and oceanic arcs, the kinematic evolution of orogenic belts, and the chemical geodynamics of the mantle and lower crust. Dr. Mukasa recently served on the NRC's Polar Research Board and on the Committee on Principles of Environmental and Scientific Stewardship for the Exploration and Study of Subglacial Lake Environments.

**Tim Naish** is Professor and Director of the Antarctic Research Centre at Victoria University of Wellington in New Zealand. Dr. Naish's current research projects include understanding of how continental margin sedimentation responds to climate and sea level change over long (orbital time scales), specifically focusing on the role of ice sheets and Antarctica in the global climate system. Since 1990, his research has focused on documenting the physical evidence in shallow-marine sedimentary basins of climatic and sea-level variability inferred from deep ocean drill cores (e.g., oxygen isotope records). More recently his research has been concerned with documenting past variability of the Antarctic ice sheets and their contribution to global sea-level change and climate variability. During the past 10 years he participated on the Cape Roberts Drilling Project and led the recently completed ANDRILL McMurdo Ice Shelf Drilling Project. He is Chair of the International ANDRILL Science Planning Committee, and a member of the Executive Committee of the Scientific Committee on Antarctic Research's Antarctic Climate Evolution Project. He is also a member of the Royal Society of New Zealand Marsden Fund Council. Dr. Naish earned a B.Sc. in 1988, an M.Sc. (1st Class Hons.) in 1989, and a Ph.D. in 1996 from the University of Waikato, all in Earth sciences.

**Paul E. Olsen (NAS)** is the Arthur D. Storke Memorial Professor in the Department of Earth and Environmental Sciences at Columbia University. He earned his Ph.D. in biology from Yale University in 1984. Dr. Olsen's research interests include ecosystem evolution, especially aspects of external forcing and intrinsic biological innovations, and also Triassic and Jurassic continental ecosystems, paleobiology, climate, tectonics, and stratigraphy. Dr. Olsen's overall area of interest is the evolution of continental ecosystems, including their external and internal controls and their biological and physical components. Furthermore, he is especially interested in the pattern, causes, and effects of climate change on geological time scales, mass extinctions, and the effects of evolutionary innovations on global biogeochemical cycles. Dr. Olsen became a member of the National Academy of Sciences (NAS) in 2008.

**Lori Summa** is Senior Technical Consultant with the ExxonMobil Upstream Research Company. In this position, she advises corporate management on strategic geoscience issues to ensure appropriate research is performed in support of business objectives. Her background is in basin analysis and numerical modeling, and she has also done much applied research with exploration and drilling. She currently serves as a member of the TeXas Earth and Space Science (TXESS) Advisory Board and is a former member of the Integrated Ocean Drilling Program's U.S. Science Advisory Committee (IODP USSAC) Panel, which advises the U.S. Science Support Program on supporting drillship operations. Dr. Summa earned a B.S. in geology with honors from the University of Rochester in 1979 and a Ph.D. in geology from the University of California, Davis in 1985.

**Anne M. Tréhu** is a Professor of Geophysics in Oregon State University's College of Oceanic and Atmospheric Administration. She earned her Ph.D. from the Massachusetts Institute of Technology in 1982 and her B.A. from Princeton University in 1975. Dr. Tréhu's research interests focus on the influence of crustal structure on earthquake processes and on the distribution and dynamics of gas hydrates on continental margins. Dr. Tréhu is a current member of the Ocean Studies Board; she has also served on the NRC Committee to Review the Activities Authorized under the Methane Hydrate Research and Development Act of 2000 (2003-2004) and the Committee on Seismology (1990-1996). Dr. Tréhu is a Fellow of the American Geophysical Union.

## STAFF

**Deborah Glickson** is a Senior Program Officer with the Ocean Studies Board at the National Research Council (NRC). She received an M.S. in geology from Vanderbilt University in 1999 and a Ph.D. in oceanography from the University of Washington in 2007. Her doctoral research focused on magmatic and tectonic contributions to mid-ocean ridge evolution and hydrothermal activity at the Endeavour Segment of the Juan de Fuca Ridge. In 2008, she participated in the Dean John A. Knauss Marine Policy Fellowship and worked on coastal and ocean policy and legislation in the U.S. Senate. Prior to her Ph.D. work, she was a research associate in physical oceanography at Woods Hole Oceanographic Institution. Since joining the NRC staff in 2008, she has worked on a number of studies including *Critical Infrastructure for Ocean Research and Societal Needs in 2030* (2011), *Realizing the Energy Potential of Methane Hydrate for the United States* (2010), *Science at Sea: Meeting Future Oceanographic Goals with a Robust Academic Research Fleet* (2009), and *Oceanography in 2025: Proceedings of a Workshop* (2009).

**Elizabeth A. Eide** is a Senior Program Officer with the Board on Earth Sciences and Resources. Prior to joining the NRC in this capacity in 2005, she worked for 12 years as a researcher, team leader, and laboratory manager at the Geological Survey of Norway in Trondheim. Her research on large-scale crustal processes in many areas of the world included use of isotope geochronology, petrology, and field observations, and collaboration with academia and the private sector. She is author or coauthor of more than 40 research papers and 10 Geological Survey reports, and she has directed 10 studies at the NRC. She completed a Ph.D. in geology at Stanford University and received a B.A. in geology from Franklin and Marshall College.

**Jeremy Justice** was a Senior Program Assistant with the Ocean Studies Board from 2008 to 2011. He earned a B.A. in international and area studies from the University of Oklahoma in 2008. While at the NRC, Mr. Justice worked on *Science at Sea: Meeting Future Oceanographic Goals with a Robust Academic Research Fleet*, *Ecosystem Concepts for Sustainable Bivalve Mariculture*, *Assessment of Sea-Turtle Status and Trends*, and *Tsunami Warning and Preparedness: An Assessment of the U.S. Tsunami Program and the Nation's Preparedness Efforts* in addition to this report.

**Lauren Harding** joined the Ocean Studies Board as a program assistant in August 2011. In 2011, she graduated from High Point University majoring in biology and minoring in chemistry. As an undergraduate, she conducted an independent research project on cave ecosystems, which she presented at the 72nd Annual Meeting of the Association for Southeastern Biologists. Prior to her position at OSB, Lauren was a marketing and accounting assistant with Webco General Partnership, a company of the U.S. military resale market.

# C

# Workshop White Papers

## SCIENTIFIC OCEAN DRILLING: PAST, PRESENT AND FUTURE

Ted Moore
*University of Michigan*

U.S. oceanographic institutions banded together in 1968 to take the first steps toward exploring the sedimentary record and the crustal rocks of the deep ocean basins. It was auspicious timing. The new paradigms of seafloor spreading and plate tectonics had only recently been accepted by the broad scientific community. Based on the early results and technological developments of the Moho Project and on a careful consideration of all the potential scientific questions that might be addressed by drilling in the deep sea, a new effort was proposed that led to the development of the Deep Sea Drilling Project (DSDP). Unlike the Moho Project, DSDP would not involve large-scale technological development. Rather it would use "off the shelf" technology developed by the offshore oil drilling industry and placed on a single deep-water, dynamically positioned drillship. This did, of course, limit the scope of the problems addressed by the project. There would be no deep drilling down to the Mohorovičić discontinuity; drilling in ice-covered regions could not be undertaken; and drilling in very shallow water was not appropriate for the deep-water drill ship. But this still left a vast, unexplored region of the deep oceans open to investigation. In addition to limits on the range of operations, the technology of that day did not allow drilling with a riser in deep water. Seawater rather than drilling "mud" was usually used as the drilling fluid to clear debris from the hole and expel it onto the seafloor. This approach to deep-sea drilling has effectively limited the depth of section drilled and recovered to about 2 km.

The most important difference in how this "cutting edge" (for 1968) technology was used by DSDP scientists as opposed to how it was being used by the oil industry lay in the overall purpose of the drilling. The purpose of drilling for oil is to create a hole through which to extract hydrocarbons. The purpose of the scientific drilling is to recover the sedimentary and rock section in the deep sea and avoid encountering oil and gas at all costs. From the start, a safety advisory panel of oil company experts was set up to review required surveys and seismic data from every site drilled to assure there was no likelihood that reservoirs of oil and gas would be encountered in the drilling.

The desire by scientists to recover a complete, undisturbed section of the uppermost crustal material has required some technological development by the scientific community. The greatest advance in this regard for the recovery of sediments was the development of a hydraulic piston core that can be triggered to shoot out ahead of the drill bit and recover a virtually undisturbed 9 m section of sediment. When the sediment becomes too stiff to core in this way, an extended core barrel with a thin cutting face can be pushed ahead of the massive roller-cone drill bit and recover relatively undisturbed sections, until finally when the section becomes totally lithified, the standard roller-cone drill bit with an open center can core and recover the section.

In addition to the technical enhancements that were achieved during DSDP and the subsequent Ocean Drilling Program (ODP), there was a continued improvement in how these devices were used to achieve the recovery of a complete section and how the recovered section was described and documented. Initially in DSDP on-board core description was rather rudimentary: physical core/rock description, biostratigraphic age, smear slide description, core photographs, physical properties, and carbonate content. This could all be done on board with about 10 scientists and 6 technicians. By the end of the ODP program the greatly improved quality of the cores permitted the useful employment of core scanning devices that measure density, magnetic susceptibility, P-wave velocity, natural gamma radiation, color, and magnetic polarity. These digital measurements are in addition to pore water chemistry, physical properties, microbiological samples, biostratigraphy, and other measurements that were standard in the days of DSDP. In ODP the shipboard scientific party grew to as many as 30 scientists who operated the machines, did the descriptions, made the measurements, and carried out the scientific studies. Their efforts over 12-hour shifts, 7 days/week, on a 56-day expedition constitute an aggregate 9 to 10 man-years of work achieved during the at-sea time. These expeditions are very productive efforts.

The substantial improvements made in the recovery and documentation of the recovered section came in parallel to improvements in how we used the holes that were drilled. Logging of the holes has come very close to keeping pace with developments in the industry. Other measurements such as heat flow and vertical velocity profiles have also been commonly made. Perhaps one of the most elegant innovations in down-hole instrumentation has been the circulation obviation retrofit kit (CORK), a device that seals off one or more sections of the drill hole and allows measurements of the chemical and physical nature of the waters in that section to be made over time. Thus, the holes themselves can become deep-sea observatories or laboratories for chemistry, microbiology, and seismology.

As our knowledge of the deep-sea environment and the scientific questions we address expands, our technical capabilities continue to improve. Now with the Integrated Ocean Drilling Program (IODP) we have also been able to go beyond the limitations first accepted as necessary in the early days of DSDP. We have drilled in the ice-covered region of the high Arctic and brought back a startling record of climate change associated with the $CO_2$ rich atmosphere of the Eocene. We have drilled on the very shallow shelf off New Jersey and the reefs of Tahiti to delve into the history of sea level changes and its impact on the sedimentary architecture of shallow water environments. And we are beginning an ambitious program of exploring the tectonic, depositional, and hydrologic environment of convergent margins. We no longer have to drill lacking the well control provided by a riser and will hopefully extend the water depth in which we can operate in the riser (or “well control”) mode beyond the present 2,500 m.

The envisioned scope of the great exploration that awaited us in the beginning days of scientific ocean drilling has been exceeded. Not only have we applied crucial tests to the plate tectonic theory but also we have created a whole new scientific field—paleoceanography. Through the exploration of the deep-sea environment we have also expanded the science we address far beyond that envisioned in the early days of DSDP. The chemistry and hydrology of water in the sediments and the crust are now thought to play a key role in the chemistry of the oceans and the weathering of the basalt both near the ridge axes and far off the axes into the older crust. The structure of the oceanic crust itself is gradually being revealed as we penetrate deeper into the basaltic sections. And we are just beginning to realize the great importance of microbes in the ocean environment. These are just some of the aspects of scientific ocean drilling that continue to intrigue the scientific mind and expand both the science and the scientific community that use scientific ocean drilling to increase the scope of our knowledge.

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# THE RECORD OF HYDROTHERMAL PROCESSES IN THE OCEANIC CRUST

Susan E. Humphris
*Woods Hole Oceanographic Institution*

Hydrothermal chemical exchange between the crust and oceans is a fundamental component of global geochemical cycles, affecting the composition of the lithosphere, the oceans and, through subduction, the mantle and arc magmas. In addition, this process provides the energy and nutrients for chemosynthetic organisms. Understanding the processes that control chemical fluxes resulting from water-rock reactions requires direct sampling of *in situ* crust, and has been an overarching goal of the lithosphere community for more than 40 years. Scientific ocean drilling has played a critical role in (i) advancing our understanding of subsurface water-rock reactions and the mechanisms of formation of seafloor massive sulfide deposits in active hydrothermal systems at mid-ocean ridges, and (ii) the development of a conceptual model for the alteration reactions that occur in off-axis convection systems driven by lithospheric cooling.

## ACTIVE HYDROTHERMAL SYSTEMS AT OCEANIC SPREADING CENTERS

Scientific drilling at three active hydrothermal sites in different geotectonic settings has revolutionized our understanding of the formation and subsurface structure of seafloor massive sulfide deposits. Drilling at the basalt-hosted active TAG hydrothermal mound (~26°N, Mid-Atlantic Ridge) revealed abundant anhydrite ($CaSO_4$)—a mineral that is very uncommon in ancient deposits due to its retrograde solubility—attesting to considerable entrainment and heating of seawater into the subsurface. Although its formation provides a framework for construction of the deposit, the ultimate dissolution of anhydrite was recognized as an important mechanism for the formation of sulfide breccia—a lithology that had been previously interpreted in ancient ophiolite massive sulfide deposits to result from post-depositional weathering.

Drilling at the sediment-hosted Middle Valley hydrothermal sites (~48°N, Juan de Fuca Ridge) resulted in the first successful recovery of feeder zone mineralization underlying a seafloor massive sulfide deposit. Feeder zones in ancient deposits commonly account for a significant portion of the economic reserves of a deposit. An unexpected finding was the presence of a stratified zone of high-grade Cu-rich replacement mineralization (~16 wt.% Cu) at the base of the feeder zone formed by lateral flow of hydrothermal fluids beneath an impermeable silicified mudstone horizon. This type of mineralization had not been previously recognized below seafloor mineral deposits, and hence has implications for land-based mineral exploration.

The felsic-hosted PACMANUS hydrothermal system (~3°S, Manus Basin) provided the opportunity to investigate the characteristics of hydrothermalism in a back-arc basin. Drilling beneath active hydrothermal systems revealed a cap of unaltered dacites and rhyolites, below which the volcanics are pervasively and intensely altered rather than alteration being confined to a narrow upflow zone, with clay minerals dominating the alteration assemblage. In addition, fluid inclusion data provided clear evidence for a magmatic component to the hydrothermal fluid that played a fundamental role in the nature of alteration—a clear distinction from the TAG and Middle Valley hydrothermal sites.

Although drilling seafloor sulfide deposits has been technologically challenging, often with poor recovery, it has nevertheless revealed previously unrecognized shallow subseafloor processes—entrainment of seawater, mixing of hydrothermal fluids with seawater and magmatic components, deposition of secondary phases that play key roles in deposit construction but are not preserved in ancient deposits—that are now demonstrated to be critical in the formation of massive sulfide deposits.

## THE RECORD OF OFF-AXIS CONVECTION SYSTEMS

As the crust spreads, hydrothermal alteration continues in off-axis convection systems driven by lithospheric cooling. This process is believed to continue to an age of ~65 myr when the crust effectively becomes "sealed." Hence, the ocean crust provides a time-integrated record of water-rock reactions that occurred both on- and off-axis.

Scientific ocean drilling has provided many sections of the uppermost few hundred meters of ocean crust. These have predominantly been focused in young (< 20 Ma) and ancient (> 110 Ma) crust. Of particular note are two long sections of upper ocean crust formed at intermediate (Hole 504B on 6 Ma crust) and superfast spreading rates (Hole 1256D on 15 Ma crust) in the eastern Pacific. No holes penetrate greater than 50 m in 45-80 Ma basement, the interval in which the crust becomes sealed. Although details vary, the mineralogical and geochemical characteristics of all the upper crustal sections support a model whereby greenschist alteration of dikes at low water/rock ratios is overprinted by fracture-controlled alteration and mineralization by upwelling hydrothermal fluids, a conductive boundary layer above gabbroic intrusions, leaching of metals from dikes and gabbros in the deep "root zone," and stepped thermal and alteration gradients in the basement. The prediction that conductive boundary layers separate hydrothermal systems from the heat source that drives them has been confirmed by the identification of recrystallized sheeted dikes at the dike–gabbro transition at all locations. Incipient alteration of the uppermost gabbros occurs at high temperatures, with fluid flow along fracture networks occurring over very short timescales.

Drilling at oceanic core complexes on the more lithologically heterogeneous slow spreading ridges (e.g., the Atlantis Massif [30°N, Mid-Atlantic Ridge] and Atlantis Bank [Southwest Indian Ridge]) has provided access to lower ocean crust that has been tectonically exhumed at the seafloor. The combination of regional-scale geophysical and geological surveys with deep drill holes at these locations indicate that detachment zones act to focus fluids at high and low temperatures. Gabbroic rocks are variably altered at these two sites, and preserve complex, but different, records of metamorphism, brittle failure, and hydrothermal alteration. At the Atlantis Massif, greenschist facies alteration occurred at depths at least 1 km below seafloor, with variable degrees of interaction with seawater at temperatures generally >250 °C. In contrast, at Atlantis Bank, patchy high temperature alteration (up to 600 °C) by hydrothermal fluids over a wide range of temperatures likely occurred at or very near the spreading axis, while later, low temperature alteration is likely related to cooling during uplift.

In summary, drilling to date has highlighted the critical, but highly variable, interplay between fluid flow, lithology, and magmatism from the seafloor down to the axial magma chamber. Investigations of this interplay, and of the hydrological-geochemical-microbiological feedbacks in aging oceanic lithosphere—the largest fractured aquifer on Earth—require access to *in situ* oceanic crust and subsurface experimentation that can be provided only by drilling.

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## HEAT AND FLUID FLOW

Keir Becker
*University of Miami*

From the time of Project Mohole, researchers have recognized the opportunities that scientific ocean drilling presents to investigate heat and fluid flow processes in oceanic sediments and crust (e.g., Von Herzen and Maxwell, 1964). The early Deep Dea Drilling Project (DSDP) measurements were made primarily in sediments (see review by Erickson et al., 1975), before the discovery of hydrothermal circulation in the mid-1970s and the subsequent realization that fluid flow in subseafloor formations is a key process in nearly all subsea geological type settings from spreading centers to continental margins. Hence, the COSOD I (Conference on Scientific Ocean Drilling) report recognized the importance of subseafloor fluid flow, and understanding it fully became a focal point/major theme of DSDP/ODP (Ocean Drilling Program)/IODP (Integrated Ocean Drilling Program) scientific drilling starting with the 1987 COSOD II report. Since subseafloor fluid circulation occurs in most seafloor geological type settings, this summary overlaps several others from the workshop (e.g., S. Humphris on hydrothermal circulation, K. Edwards on deep biosphere, C. Ruppel on gas hydrates, and J.C. Moore on convergent margins). The table below summarizes in a historical context the main technical and scientific contributions of scientific ocean drilling in understanding subseafloor heat and fluid flow. This written summary touches on some of the themes covered by other speakers, but mainly features the off-axis, low-temperature, ridge-flank setting that for technical reasons has been the main setting to date for scientific ocean drilling into oceanic crust.

The early- to mid-1970s deduction of the likelihood of hydrothermal circulation in young oceanic crust was roughly coincident with the internationalization of DSDP (the IPOD or International Phase of Ocean Drilling) and a special IPOD focus on penetrating significantly into ocean basement. The last started with several important young Atlantic crustal holes, and borehole temperature measurements in some of them revealed a new phenomenon: that ocean bottom water was being drawn down the holes into the upper levels of basement beneath the sediment cover required to spud the holes (e.g., Hyndman et al., 1976). It was deduced that the upper oceanic basement in young crust is much more permeable than the overlying sediments. The first direct measurements of the upper basement permeability—the key parameter that controls fluid flow through the formation—were made in 1979 with a drillstring packer experiment in the famous crustal reference Hole 504B, located in thickly sedimented young crust on the south flank of the Costa Rica Rift (Anderson and Zoback, 1982). Thermal measurements in Hole 504B also indicated that ocean bottom water was flowing down the cased section into upper basement, and it was shown that these data could be interpreted to estimate both downhole flow rate and permeability of the formation into which the flow was directed (Becker et al., 1983). This method has been applied to numerous holes since then, including some less common examples that were drilled in sediment-covered basement highs and actually produced formation fluids up the hole (e.g., Fisher et al., 1997). Since 1979, drillstring packer experiments have been conducted deeper in Hole 504B and in the upper basement sections of several crustal holes. The combined datasets have documented a reduction over several orders of magnitude of permeability with depth in young oceanic crust and a reduction of permeability of uppermost crust with crustal age (e.g., Fisher, 1998; Fisher and Becker, 2000; Becker and Fisher, 2000, 2008) that are often used in current numerical models of hydrothermal circulation in oceanic crust. It is probably an oversimplification, but there seems to be a rough identity among the most permeable and porous upper few hundred m of young oceanic basement, seismic Layer 2A, and the zone of oxidative alteration.

While the down- or uphole flow in many crustal reentry holes can be interpreted to estimate permeability, it also represents a significant perturbation to the in situ subseafloor hydrological systems that we are trying to understand with scientific ocean drilling. This led to the development in 1989-1990 of a new experimental approach to seal these reentry holes, simultaneously emplacing long-term instrumentation to record in situ temperatures and pressures and to sample formation fluids. This concept was named the CORK (Circulation Obviation Retrofit Kit) hydrogeological observatory (Davis et al., 1992). CORKs have allowed for determination of in situ temperature and pore pressure state after the perturbation due to drilling has decayed (e.g., Davis and Becker, 2002). The subseafloor pressure data show an attenuated and phase-lagged seafloor tidal loading signal that can be interpreted to constrain hydraulic diffusivity and derived permeability at formation scales (Davis et al., 2000). In addition, once the tidal signals are filtered out, the subseafloor pressures also show formation responses to tectonic events, acting essentially as crustal strain meters (e.g., Davis et al., 2001). The combination of CORK and packer observations in ridge-flank sites indicates high lateral fluids fluxes and short residence times in very permeable upper basement under relatively small pressure differentials (e.g., Davis and Becker, 2002). This conclusion is supported by geochemical analyses of pore waters and long-term "OsmoSamplers" recovered from the CORKs (e.g., Elderfield et al., 1999; Wheat et al., 2000, 2003).

During the late 1990s, newer CORK concepts were developed to separately seal multiple zones in a single hole; these models include the "Advanced CORK," "CORK-II," and a "wireline CORK" that can be installed from oceanographic vessels. More than 20 CORKs of various models have been installed to date, primarily in ridge-flank settings

| Timeline/Program | Historical Context | Selected Program Highlights | Technical Contributions | Scientific Contributions |
|---|---|---|---|---|
| **Mohole 1961-1966** | Pre-plate tectonics<br>Pre-hydrothermal | Deep sediment temperatures measured at Mohole pilot site | First sediment temperature probe | Reconnaissance deep heat flow measurements and pore fluid sampling |
| **Early DSDP 1968-1974** | Pre-hydrothermal | Exploration scientific drilling around the world, primarily in sedimentary sections | | Deep heat flow measurements validated shallow oceanographic heat flow probe technique |
| **Later DSDP 1974-1983** | Hydrothermal circulation deduced/verified<br>JOIDES Hydrogeology Working Group | Deep Atlantic crustal holes<br>Guaymas Basin<br>Galapagos Mounds<br>Costa Rica Rift – 504B | Uyeda probe<br>Barnes probe<br>Water Sampler Temperature Probe (WSTP)<br>Hydraulic Piston Corer (HPC) T-tool<br>First packer experiments<br>First pore pressure probe | Interpretation of downhole flow in crustal holes<br>First recorded uphole flow<br>Vertical flow through sediments verified<br>Deep sedimentary pore fluids as proxy for basement fluids<br>First crustal permeability values<br>Permeable, oxidative upper basement ~ Layer 2A<br>First studies of fluids in prisms |
| **Early ODP 1985-1990** | | Reentries of deep crustal holes (418A, 395A, 504B)<br>Barbados + Nankai prism studies | ODP/IODP straddle packer<br>Borehole fluid samplers | Crustal permeability-depth profile through sheeted dikes<br>Direct evidence for fluid flow in subduction plate boundary faults |
| **Late ODP 1991-2003** | Boreholes as long-term observatories<br>Initiative in In-situ Monitoring of Geological Processes<br>Pilot Project in Deep Biosphere<br>Hydrogeology Program Planning Group (2001) | First- and second-generation CORK hydrogeological observatories deployed in sedimented ocean ridges, ridge flanks, and subduction settings<br>Targeted drilling of hi-T (270-365 °C) hydrothermnal systems<br>First targeted gas hydrates drilling in context of fluid flow | Original CORK<br>in-situ long-term OsmoSamplers<br>medium-T (up to 200 °C) sediment T and pore fluid probes<br>Hi-T borehole T-tool (up to 360 °C)<br>Multi-zone Advanced CORK, CORK-II, and wireline CORK | Expansion of crustal permeability-depth profile<br>Documentation of age variation of upper crustal k<br>In ridge flanks: huge lateral fluid fluxes with small pressure differentials and high permeabilities<br>First direct measurement of fluid pressure at subduction plate boundary fault<br>First in situ video in oceanic crust, showing microbiota |
| **IODP 2004-2011** | Initiatives in Deep Biosphere and Hydrates | Juan de Fuca 3-d CORK array<br>NanTroSEIZE seismic + fluid observatories<br>Gulf of Mexico margin overpressured zone<br>Three major biosphere/fluid programs to come | Addition of microbiological capabilities to CORKs + shipboard labs<br>Improvement of downhole tools | First crustal-scale cross-hole hydrogeological experiments<br>First in situ microbiological incubation experiments<br>First network cable-ready borehole observatories<br>Excess fluid pressures measured in Gulf of Mexico margin |

and in subduction zones. In the latter setting, a prime goal has been to document fluid pressures in plate boundary faults and the relationship between fluid processes and subduction earthquakes. To date, overpressures as high as 1 MPa have been documented in the monitored plate boundary faults, but this is significantly less than lithostatic pressure and thus not enough to enable slip along the faults. In the Hydrate Ridge subduction setting offshore Oregon, a CORK through a thrust fault apparently recorded the transient thermal signal of an up-fault fluid flow event. Even more ambitious observatories are planned for the IODP NanTroSEIZE program, combining seismic and strain instruments with the CORK hydrological concept.

In the process of installing wireline CORKs in Hole 504B and a companion Hole 896A ~1km away in 2001, it was determined that Hole 896A was producing crustal fluids and the first (only?) true video from within oceanic basement was collected (Becker et al., 2004). That video seems to show copious microbiota within the hole and images individual formations that are producing fluids into the hole and probably represent most of the bulk permeability of the formation. That serves to emphasize the fact that the permeability of oceanic crust—and probably most other subseafloor formations—is fracture-dominated and multi-scalar, so it cannot be accurately represented as a single-valued parameter (e.g., Fisher, 1998; Becker and Davis, 2003; Fisher et al., 2008). In summer 2010, IODP Expedition 327 to the Juan de Fuca Ridge flank featured the first attempt to resolve directional variation of crustal permeability and natural fluid flow via the first planned hole-to-hole pumping tests in an array of CORKs penetrating upper basement. (An unplanned hole-to-hole experiment in the same array is described by Fisher et al., 2008.) That array of CORKs has also involved the first in situ microbiological cultivation experiments in oceanic basement, and so represents an important new future direction for CORKs and scientific ocean drilling discussed in more detail by K. Edwards.

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# SUBSURFACE MICROBIAL OBSERVATORIES TO INVESTIGATE THE DEEP OCEAN CRUST BIOSPHERE: DEVELOPMENT, TESTING, AND FUTURE

Katrina J. Edwards
*University of Southern California*

Scientific ocean drilling has historically yielded some of the most transformative advances in the Earth sciences, cross-cutting many of its disciplines, and providing fundamental advances to our knowledge of how the Earth works. Today, ocean drilling is poised to offer these same transformative advances to disciplines within the life sciences, and provide insight into how life operates and interacts with Earth processes at and below the seafloor. To date, many exciting discoveries have been made about the nature of the deep microbial biosphere in marine sediments. In comparison, there is relatively little information about the nature, extent, and activity of microorganisms living in the volcanic oceanic crust. Because of the size and hydrodynamics of this potential biome, crustal life may have profound influence on global chemical cycles and, as a consequence, the physical and chemical evolution of the crust and ocean. Hence, it is imperative that the scientific community develops a more complete understanding of life in ocean crust. To do this, researchers must develop the appropriate tools for studying this unique habitat, and recent engineering and methodological advancements make now a particularly opportunistic time to do so. Subseafloor borehole observatories (Circulation Obviation Retrofit Kits or CORKs) can help to provide representative samples of crustal fluids and microbiological samples, reducing the extent of contamination associated with drilling, coring, and other operations.

## SUBSURFACE MICROBIAL OBSERVATORY TECHNOLOGY

Tools available for CORK-associated microbial observatory experiments can be broken down into two categories: those that are deployed down hole ("subsurface") within the CORK casing, and those that are deployed at the seafloor and connected to the horizon of interest via pumping of fluids through umbilicals. Redundancy between seafloor and subsurface sampling and experimental units allows for a higher confidence of capturing representative samples for targeted questions.

First-generation downhole observatory technology consisted of subsurface temperature and pressure loggers and osmotically driven fluid samplers ("OsmoSamplers"), which collect a continuous record of temperature, pressure, and composition of the fluid within CORKed boreholes. Second-generation downhole devices couple these to microbial colonization experiments. All downhole technology is limited by the lateral dimension of the experimental environment (i.e., all instruments must fit within the innermost borehole casing, which is typically on the order of 9 cm diameter). Downhole instruments also must provide necessary power for the duration of the deployment (4-5 years).

The continuing adaptation of technologies from other disciplines will advance capabilities to observe and sample the subseafloor crustal biosphere. Technologies that are suitable for long-term deployment, with ultra-low power consumptions and minimal impact by biofouling, are ideal for crustal biosphere observatories. Instrumentation for making remote measurements of downhole conditions is also required. This includes designing downhole electrochemical and mass spectrometer analyzers, for measuring changes in fluid and gas compositions, and also developing new ways to measure rates of chemical reactions *in situ*. For example, a protoype downhole sampler for manipulative experiments is nearly ready for field trials. Another promising adaptation would be instrumentation for measuring deep ultraviolet fluorescence downhole, permitting the detection of the native fluorescence of microbial cells without the use of stains or dyes or interference from auto-fluorescent mineral particles.

Future observatory experiments will also benefit from the utilization of components that are compatible with objectives in multiple disciplines (microbiology, hydrogeology, chemistry, etc.).

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## SCIENTIFIC OCEAN DRILLING AND GAS HYDRATES STUDIES

Carolyn Ruppel
*U.S. Geological Survey*

Gas hydrates and the huge quantities of methane that they sequester in marine sediments are typically linked to three broad scientific themes: carbon cycling and global climate change (e.g., Dickens et al., 1995, 1997a; Dickens, 2003; Kennett et al., 2003), submarine slope stability (e.g., Kvenvolden, 1999; Grozic, 2010; Maslin et al., 2010), and energy resources (e.g., Collett, 2002). The last element—the energy resource potential of gas hydrates—renders gas hydrates unique within the scientific ocean drilling (SOD) community: There has always been the expectation that routine gas hydrates drilling for resource issues would someday reach such maturity that SOD would no longer be appropriate. We are largely operating in this era now, with no gas hydrates drilling having been conducted by the Integrated Ocean Drilling Program (IODP) since 2005 (Expedition 311; Riedel et al., 2006). Over the past decade, government/private-sector operators in Japan, the United States, South Korea, India, China, and Malaysia (e.g., Collett et al., 2008a, b, 2009; Hadley et al., 2008; Jones et al., 2008; Park et al., 2008; Ruppel et al., 2008; Wu et al., 2008; Yang et al., 2008; Tsuji et al., 2009; National Energy Technology Laboratory, 2010) completed and/or have begun planning deepwater drilling operations to investigate the resource potential of gas hydrates and, in some cases, to assess geohazards related to drilling and eventual production. None of this government/private-sector activity would have been possible without the fundamental knowledge and technological developments provided by SOD activities during the Ocean Drilling Program (ODP) and IODP. In this brief, I review the contributions of ODP/IODP to gas hydrates science, highlight special technology developed by SOD for studying hydrates-bearing sediments (known as HBS), and make recommendations about the appropriate niche for SOD in future gas hydrates investigations.

Gas hydrates research has had a long history in the SOD community, even before its elevation to a focus area within the theme of "Subseafloor Ocean and Deep Biosphere" during IODP's formulation. Before the early 1990s, most of the direct knowledge about subseafloor gas hydrates had been acquired when gas hydrates were encountered, sometimes accidentally, during DSDP and ODP expeditions focused on other scientific goals. Leg 146 in 1992 (Westbrook et al., 1994) was an exception, having been designed to conduct limited gas hydrates investigations within the context of broader-scale fluids research on the Oregon and Vancouver parts of the Cascadian margin.

In 1995, ODP Leg 164 (Dillon et al., 1996) was the first expedition committed exclusively to gas hydrates objectives, focusing on the extensive gas hydrates province in the fine-grained sediments of the Blake Ridge. For the first time, ODP purposely cored and logged the entire hydrates stability zone and the underlying free gas zone, countering critics concerned about the safety of such activities. Many accomplishments of ODP Leg 164 have stood the test of time, with similar phenomena being rediscovered in other marine hydrates provinces even today. ODP Leg 164 proved that gas hydrates occurred even in the absence of the bottom simulating reflector (BSR) that sometimes marks the base of gas hydrates stability (Dillon et al., 1996) and provided strong evidence that small-scale permeability variations (e.g., slightly coarser-grained sediments or dual-porosity/diatomaceous layers) locally control preferential accumulation of gas hydrates in seemingly homogeneous sediments (Ginsburg et al., 2000; Kraemer et al., 2000). The expedition yielded a rich dataset for calibration of logging, vertical seismic profiles (VSP), and geochemical constraints on in situ hydrates concentrations (e.g., Holbrook et al., 1996; Collett and Ladd, 2000; Lorenson et al., 2000); demonstrated that gas hydrates filled only a small percentage of available pore space despite the widespread occurrence of a BSR; and marked a first attempt at shipboard microbiology within SOD (Wellsbury et al., 2000).

By the late 1990s, it was clear that ODP Leg 164, despite far exceeding initial expectations, had yielded a largely static picture of gas hydrates systems that are more properly considered dynamic and hydrologically driven. With the publication of studies that linked the evolution of gas hydrates provinces to fluxes of fluids, gas, and energy (Rempel and Buffett, 1998; Xu and Ruppel, 1999; Ruppel and Kinoshita, 2000) and with the increasing emphasis on gas hydrates "plumbing systems," the Gas Hydrates PPG, the Hydrogeology PPG (Ge et al., 2002), and subsequently the IODP science plan all alluded to a strategy of drilling in gas hydrates provinces characterized by different flux regimes. ODP Leg 204 (Tréhu et al., 2003) was the second SOD expedition fully committed to the exploration of gas hydrates, this time in the highly dynamic setting of Hydrate Ridge, an accretionary ridge offshore Oregon. Leg 204 yielded important constraints on processes and gas hydrates distributions in three dimensions (Tréhu et al., 2004a), sometimes with the additional fourth dimension of time. Leg 204 had unusually rich ancillary data-sets (e.g., 3D seismic [Tréhu et al., 2002] and CSEM [Weitemeyer et al., 2006]), included sophisticated microbiology (e.g., Colwell et al., 2008; Nunoura et al., 2008), and provided detailed insights into the nature of flux regimes and gas/hydrates dynamics at hydrates-bearing seeps (e.g., Torres et al., 2004; Tréhu et al., 2004b; Liu and Flemings, 2006). A few years later, Expedition 311 (Riedel et al., 2006) became the only IODP activity exclusively focused on gas hydrates, completing a drilling transect from the subducting plate onto the overriding plate on the northern Cascadia margin. The project highlighted lateral heterogeneity in gas hydrates distributions and discovered concentrations of gas hydrates in coarse-grained sediments well above the base of the gas hydrates stability zone, a finding that challenges simple models (e.g., Hyndman and Davis, 1992; Rempel and Buffett, 1998; Xu and Ruppel, 1999) for gas hydrates system dynamics (e.g., Malinverno, 2010). In September 2010, Site 889, which was drilled on Leg 146 and which lies close to IODP Expedition 311 Sites U1327/U1328, will be re-instrumented and prepared for eventual linkage of the borehole instrumentation to Canada's NEPTUNE cabled observatory (Davis et al., 2010). While the primary focus of this effort is not gas hydrates, it is noteworthy that SOD boreholes drilled originally for gas hydrates objectives will be the first on the North American Margin to be part of a cabled observatory.

Gas hydrates are unique among geologic materials studied by SOD: They are highly accessible to the drill (within the uppermost 10s to 100s of meters subseafloor), are stable over a specific pressure and temperature range, and rapidly dissociate to water and large volumes of gas. The dissociation process is strongly endothermic, which has led to reliance on routine thermal infrared imaging (e.g., Ford et al., 2003; Weinberger et al., 2005) to locate gas hydrates nodules in recovered conventional cores. Because the removal of hydrates-bearing cores from the gas hydrates stability field leads to rapid degassing, the destruction of sediment textures, and irreversible changes in bulk sediment properties (e.g., Francisca et al., 2005), pressure coring—coring that maintains in situ hydrostatic pressure—has long been viewed as a necessity for gas hydrates studies. Even in the mid-1980s, SOD was experimenting with pressure coring, but true success with the Pressure Core Sampler (PCS; Pettigrew, 1992) was not attained until ODP Leg 164 (Dickens et al., 1997b, 2000). The success of the PCS set the stage for larger, more sophisticated pressure corers (e.g., Hydrate Autoclave Coring Equipment (HYACE)/deployment of HYACE tools in new tests on hydrates (HYACINTH); Fugro corer) that are now routinely deployed to obtain high-quality, hydrates-bearing samples, particularly in relatively fine-grained sediments. Subsequent technical innovations made for sampling and testing of HBS at in situ hydrostatic pressure (e.g., Park et al., 2009) also owe a great deal to the initial work done within SOD. These outside-SOD developments include: (a) the pressure-temperature core sampler (PTCS), a chilled 3-m-long pressure corer developed for Nankai Trough drilling (Takahashi and Tsuji, 2005); (b) a chilled vessel to transfer pressure cores into imaging/measurement devices (PCATS) and an instrument to provide pressure core subsamples for microbiological and other studies (Schultheiss et al., 2006, 2010; Parkes et al., 2009); and (c) devices to measure the physical properties of pressure cores both at hydrostatic pressure (IPTC; Yun et al., 2006) and with effective stress restored (Ruppel et al., 2008). Other key technical contributions of SOD to the numerous international non-SOD gas hydrates drilling projects are the development of reliable borehole pressure-temperature tools (e.g., the Davis-Villinger Temperature Tool (DVTP) and DVTP-P; Graber et al., 2002), SOD's model of rapid, post-drilling publication of archival initial reports, and the shipboard deployment of imaging equipment capable of determining the distribution and character of gas hydrates in recovered cores (e.g., Abegg et al., 2006).

The international focus on developing deepwater hydrates as an energy resource means that SOD will not play a leading role in most future gas hydrates drilling. SOD's drilling platforms may on occasion be suitable for use for non-SOD projects that involve straightforward gas hydrates investigations, little advanced mud handling, and few special logging requirements.

SOD does have an important role to play in non-resource aspects of gas hydrates in a future program. First, marine gas hydrates at the upper feather edge of stability on the continental slopes (e.g., Westbrook et al., 2009) and those associated with subsea permafrost in shallow circum-Arctic areas (e.g., Rachold et al., 2007; Ruppel, 2009; Shakhova et al., 2010) are probably actively deteriorating now in response to climate change on relatively short timescales (contemporary to 20 ka). The dynamics of these gas hydrates systems represents a compelling, multidisciplinary problem that is well-suited for the future of SOD under the auspices of the "Earth in Motion" theme. Second, despite decades' worth of anecdotal studies exploring possible links between submarine slope stability and gas hydrates (e.g., Carpenter, 1981; Kayen and Lee, 1991; Paull et al., 1991), there remains no proof that gas hydrates and/or free gas play a causal role in triggering failures or exacerbate major failures once they are initiated (e.g., Bryn et al., 2005; Tappin, 2010). In light of (a) the tsunamogenic potential of major slope failures that occur in or near gas hydrates areas (e.g., Long et al., 1990; Hornbach et al., 2007), (b) advances in understanding the geomechanics of hydrate-bearing and gas-charged slope sediments (e.g., Sultan et al., 2004; Nixon and Grozic, 2007; Kwon et al., 2008; Liu and Flemings, 2009); and (c) inferred climate-induced dissociation of marine gas hydrates (e.g., Westbrook et al., 2009) under way now in areas near previously documented slope failures, the time is ripe for a fresh focus on the links between gas hydrates and slope stability issues within SOD.

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# THE DYNAMICS OF GREENHOUSE FORCING AND CLIMATE EXTREMES: PROGRESS AND PROMISE FROM OCEAN DRILLING

James C. Zachos
*University of California, Santa Cruz*

One of the more prominent accomplishments of earth sciences is the detailed depiction of the extreme, sometimes rapid, changes in climate that have occurred over the past 100 million years. This accomplishment, which is based largely on evidence gleaned from marine sediment cores recovered by the Deep Sea Drilling Project and Ocean Drilling Program (ODP), includes (1) the reconstruction of ocean temperatures, circulation, and $pCO_2$ during the well-known greenhouse periods (e.g., early Pliocene, early Eocene, and late Cretaceous), (2) the recent discovery and characterization of relatively rapid, but short-lived climatic excursions, or thermal maxima, and (3) the onset and scale of both Antarctic and Northern Hemisphere continental glaciation. These accomplishments were aided partly by innovations in drilling technologies and coring strategies that allowed for the recovery of high-quality marine sediment cores in older, more deeply buried sediments, and by a deliberate effort to focus on climatically sensitive regions, such as the Arctic, southern oceans, tropics, and on depth transects. Additional innovations such as the development of program planning groups (PPG) during ODP improved the organization of drilling strategies, identification of targets, and coordination of expeditions. Some of the key findings on greenhouse climates, particularly those involving extreme climatic events, have played a central role in the testing of greenhouse climate theory, and foretelling the potential long-term impacts of anthropogenic activity such as ocean acidification. To be sure, deep-sea based proxy records of the thermal maxima were included in the most recent IPCC report (Jansen et al., 2007).

The key contributions in characterizing the long-term greenhouse climates of the Pliocene, Eocene, and Cretaceous have come in two specific areas: (1) improving the spatial and temporal resolution and quality of the paleoclimate signals (i.e., temperature and circulation; Zachos et al., 2001; Wara et al., 2005; Cramer et al., 2009), and (2) in constraining past atmospheric $pCO_2$ (Pagani et al., 2005, 2010). ODP coring in the Southern Ocean (e.g., Legs 113, 119, 120), for example, provided the sediment archives that were essential for establishing the evolution of Atlantic and Indian Ocean sub-polar marine temperatures through the late Cretaceous and Cenozoic, and linking these changes to the appearance and evolution of the Antarctic ice-sheet (Ehrmann and Mackensen, 1992; Zachos et al., 1992). Similarly, successful expeditions in the Northern Hemisphere, particularly the Arctic (ACEX), provided the first constraints on marine polar climates of several intervals of the Eocene greenhouse (Sluijs et al., 2006; Stickley et al., 2009). With advanced piston coring and offset multi-hole strategies, most of the new paleoclimate records have been constructed at high-resolution with astronomically tuned age models, thereby aiding the correlation and development of high-fidelity climate reconstructions. Although the progress in building the Cenozoic atmospheric $pCO_2$ record has lagged that of the climate records, the recent development and integration of multiple marine organic- and inorganic-based proxies (i.e., alkenone $e_p$, B isotopes & B/Ca) has already produced more precise and detailed estimates of the $pCO_2$ for key intervals (Pagani et al., 2005; Pearson et al., 2009; Seki et al., 2010). Collectively, these records demonstrate that as $pCO_2$ levels have declined (by >1,000 ppm) since the early Eocene, surface temperatures have dropped accordingly and that the present-day levels of $pCO_2$ (~400 ppm) were last experienced during the early Pliocene and forecasted levels (~1,600 ppm) were last experienced in the Eocene.

The startling discovery of transient thermal maxima in ODP cores, coupled with massive carbon cycle perturbations, clearly represents one of the more transformative scientific achievements in the Geosciences Directorate in the past two decades. The most prominent, the Paleocene-Eocene thermal maximum (PETM; 56 Mya), first discovered in ODP Site 690 (Kennett and Stott, 1991), involved a global warming of 5 to 6 °C, with polar temperatures peaking at over 20 °C (Sluijs et al., 2006). A coeval negative carbon isotope excursion was viewed as evidence that the thermal maximum was driven by a relatively fast and massive release of carbon (Dickens et al., 1997). This hypothesis was tested with detailed reconstructions of depth-dependent changes in ocean carbonate saturation state (e.g., primarily with depth transects drilled during ODP Legs 198, 199, 207, 208; Zachos et al., 2005). With these observational constraints (C-isotopes and carbonate compensation depth [CCD]), it was possible to demonstrate that greater than 4500 Gt C were released in just a few thousands of years, while also computing the change in $pCO_2$ (800-1000 ppm $\Delta pCO_2$) and extent of ocean acidification (Panchuk et al., 2008; Zeebe et al., 2009). Although the exact source(s) of this carbon remains uncertain, given the input rates (>0.1 GtC/y) it is likely that a significant portion was supplied by exogenic (surface) reservoirs, of which only a few (i.e., soil peats, hydrates) would be of sufficient size to supply so much carbon so quickly. Regardless, the very existence of the hyperthermals has validated aspects of greenhouse climate theory, for example by revealing relatively uniform short-term warming from pole to pole (with the absence of an ice-albedo feedback). More importantly, along with the detailed records of the long-lived warm periods, hyperthermals serve as an additional means of assessing climate sensitivity (°C per doubling of $CO_2$) and testing numerical models. For example, the extreme polar temperatures of the Cretaceous, early Eocene, and PETM have proved difficult to replicate with general circulation models (GCMs), even under extreme greenhouse levels, thus motivating climatologists to reevaluate the processes that might amplify polar warming, for example ocean/atmosphere heat transport and clouds. Recent findings have implicated convective cloud activity as potentially significant amplifier of Arctic warmth (Abbot and Tziperman, 2008), a finding, if confirmed, that will have potentially serious implications for forecasts of future warming (Abbot and Tziperman, 2009).

The relatively rapid release of several thousand Gt C during the thermal maxima has also provided insight into the processes of acidification and carbon sequestration, as well as the impacts of such perturbations on ocean biogeochemistry. Similar to the modern, the rapid absorption of $CO_2$ lowered the ocean pH and carbonate saturation state. As a buffering response, the acidified waters were advected to the deep sea where dissolution of carbonate sediments resupplied carbonate. Because the latter scaled with the degree of acidification, by reconstructing the changes in carbonate sediment accumulation (~CCD), it was possible to estimate the total flux of carbon independent of other proxies, and estimate the change in $pCO_2$. The eventual sequestration of this carbon occurred via silicate weathering. In the case of the PETM, the rate of carbon release was slow relative to the mixing time of the ocean, so that severe lowering of surface ocean pH was avoided. Still, the rate was rapid enough relative to the residence time of carbon (~100 k.y.), so that the PETM serves as the best analog for assessing rates of carbon sequestration by natural processes (e.g., organic carbon burial, rock weathering/deposition). Indeed, the PETM has validated theory on the long-term fate of anthropogenic carbon emissions and potential biological impacts (Archer, 2005; Kump et al., 2009; Zeebe et al., 2009; Ridgwell and Schmidt, 2010).

The final key contribution to be highlighted by this paper is the role of ocean drilling in identifying the timing and hence the conditions under which the major ice-sheets originated. The high-latitude marine sediment archives have provided both the direct and indirect evidence required for assessing the evolution of the cryosphere (ice-sheets and sea ice). The direct evidence including glaciomarine sediments and ice-rafted debris point to a latest Eocene to earliest Oligocene onset to Antarctic continental ice-sheets and sea ice formation, with the mid-late Eocene initial appearance of sea-ice in the Arctic and mountain glaciers, pre-dating the appearance of full-scale Northern Hemisphere ice-sheets by a significant margin (Stickley et al., 2009). Indirect evidence, such as high-resolution oxygen isotope records, combined with independent proxies of temperature (e.g., Mg/Ca) have proved essential for establishing both the timing relative to forcing (i.e., $pCO_2$ and orbital), as well as the scale (volume) of continental ice-sheets on short and long time scales (Pälike et al., 2006; Lear at al., 2008).

It is evident that an opportunity now exists to test the sensitivity of climate models to the extreme range of greenhouse gas levels experienced in the Cenozoic. The observational dataset that is required includes, but is not limited to, reconstructions of pole to equator thermal gradients and $pCO_2$ during the transitions into extreme states. The drilling needs and challenges that remain for extreme climates are thus quite clear. First and foremost is simply the need to close critical gaps in the climatic reconstructions of the extreme warm intervals, particularly the polar regions and tropics. This includes the Arctic, where only a single, poorly recovered section is available to constrain the Cenozoic climatic evolution of this entire region. Coring in other parts of the basin are required at the very least to close the stratigraphic gaps, and to also verify the inferred extreme warmth in those intervals representing the thermal maxima, as well as the history of the arctic cryosphere. Another critical region is the sub-tropics to tropics, where sediment archives are required to establish zonal thermal gradients and circulation (Fedorov et al., 2006). Records from continental margins are needed to establish maximum sea surface temperatures, and to assess whether temperature exceeded key thresholds (e.g., for life) during the warmest intervals (Sherwood and Huber, 2010). The second critical data gap is the lack of suitable depth transects of multiple holes to constrain the changes in deep-sea carbonate chemistry and circulation, particularly during the abrupt events, in several regions (e.g., North Atlantic, South Pacific, Indian Oceans). The rapid changes in ocean carbonate chemistry have proved to be essential in constraining the carbon cycle fluxes and $pCO_2$ during the thermal maxima, as well as over the long-term. In this regard, the Pacific is key because of its contribution to the total carbon budget (Zeebe et al., 2009). New strategies devised to develop details reconstructions of the CCD, for example, appear to be successful for the middle Eocene and younger (IODP Expeditions 320/321) and should be extended further back in time to span the extreme greenhouse intervals/thermal maxima. Such observational constraints on ocean carbon chemistry combined with numerical models and proxies of $pCO_2$ offer the best hope of establishing both the long- and short-term variations in carbon dioxide levels that accompanied periods of ice-sheet formation/decay and extreme warmth, and impacts on sea level and the biosphere (see white papers by K. Miller, D. Norris).

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# OCEAN DRILLING TO EXPLORE PAST OCEAN CIRCULATION AND CLIMATE CHANGE

Jerry F. McManus
*Lamont-Doherty Earth Observatory of Columbia University*

Ocean drilling has provided opportunities and enabled important discoveries in a number of Earth science disciplines. Although they were not primary motivations for initial deep-sea drilling, the research disciplines of paleoceanography and paleoclimate are two of the outstanding successes of each of the international drilling programs, and they remain likely areas of future advances. This white paper will touch on some examples and highlights in these fields, as the number of significant contributions enabled by ocean drilling makes it impossible to be comprehensive in a short paper. The scientific progress associated with ocean drilling is made possible by logistical and technical advantages that can be broadly considered in two categories. One category is the active development and recovery of targeted sediment sequences from particular locations designed to address specific scientific questions. The other is the ready existence and expansion of high-quality sedimentary archives from globally distributed locations that may be utilized by any scientist seeking appropriate material to address newly arising questions about Earth's past. Uncovering changes in ocean circulation and regional and global climate requires accurate reconstruction of past oceanographic and environmental conditions using so-called sedimentary proxies as stand-ins for modern physical, chemical, or biological observations. These reconstructions typically demand relatively high spatial and/or temporal resolution, and are most often successful when utilizing long, continuous, high-quality sedimentary sequences such as best or even uniquely recovered through ocean drilling. The resolution of higher frequency variability and rapid changes requires, in addition, elevated rates of sediment accumulation resulting in thicker sequences representing shorter intervals of time. At a certain level, only ocean drilling provides the technology and logistical support to acquire such sequences successfully. Two examples of the unique opportunities presented by ocean drilling are the influence of tectonic gateways and the long-term evolution of the ocean-climate system. The global system of abyssal currents connects the ocean basins of the world and has a profound climatic influence because of the heat transport associated with the thermocline and shallow flows required to balance the deep transport. Particularly in the Atlantic, this system of currents has mean transports that are largely meridional, enhancing the climate impact at high latitudes. It was established in its present form only after the closure of Panama removed the low-latitude connection between the Atlantic and Pacific Oceans, thus potentially setting the stage for the dramatic warm-cold cycles of the Plio-Pleistocene ice ages (Raymo et al., 1992). The production of North Atlantic Deep Water (NADW), an important element of this global circulation, was enabled by the tectonic establishment of shallow sills defined by a series of ridges connecting Greenland, Iceland, and Scotland. Subsequently, salty northward surface flows could attain enhanced density at the high latitudes of the Nordic Seas before spilling over the ridges to form the core of the NADW (Wright and Miller, 1996). Investigation of the Cenozoic decline over tens of millions of years into the Plio-Pleistocene ice ages, as discussed in greater detail in a separate paper, has almost entirely been made possible by ocean drilling. Similarly, the discovery of an acceleration of Northern Hemisphere glaciation approximately 2.5 million years ago came directly from the pairing of evidence of iceberg debris and the oxygen isotope indicator of colder temperatures and more ice derived in a single long sequence drilled in the North Atlantic (Shackleton and Hall, 1984). On a similarly long time scale, it was discovered that the deep ocean stratification had changed markedly at high latitudes, an aspect strongly tied to ventilation of the deep ocean by the global ocean circulation (Haug et al., 1999). Far afield from these high-latitude processes, but no less important for the global climate, is the variable longitudinal asymmetry of sea surface temperatures (SSTs) produced by the interconnected dynamics of the atmosphere and shallow ocean in the tropical Pacific. This oscillating system, now known as El Niño-Southern Oscillation (ENSO), plays a fundamental role in the global climate, yet was only established as we know it since the Pliocene, evolving from a more persistent and symmetric pattern known as "El Padre" that could only have been uncovered and explored through a distributed array of long sediment sequences taken from sites across the equatorial Pacific recovered by multiple ocean drilling campaigns (Wara et al., 2005). The tropical Pacific was the focus of another breakthrough study, which applied a trace element geochemical proxy to microfossils preserved in long sediment sequences from the eastern and western equatorial Pacific to discover the pattern and magnitude of SST variations through the last several global ice age climate cycles (Lea et al., 2000). Although this study also utilized sediments that were recovered without ocean drilling, it was enabled by the existence of high-quality drilled sequences from Ontong Java, and could clearly only be extended further back in time through the use of cores from multiple ocean drilling sites. The discovery of ice-age cycles on so-called orbital or Milankovitch time scales constitutes a major contribution to our understanding of Earth's climate system. These cycles are associated with changes in the seasonal distribution of sunlight resulting from the varying tilt and orientation of Earth's axis of rotation, and changes in the ellipticity, or eccentricity, of its orbit. Although the cycles were first uncovered from continental and relatively thin marine sequences, they have best been established and explored through ocean drilling. Stacked microfossil oxygen isotope records from multiple drilling sites were used to establish the influence of Earth's varying tilt on the pacing of ice ages in a statistically robust way (Huybers and Wunsch, 2004). An even broader and far longer array of similar records from ocean drilling now stands as the gold standard of the entire sequence of Plio-Pleistocene glacial cycles, and a target to which any new paleoclimate record for this interval may be compared and matched (Lisiecki and Raymo, 2005). The recovery of long, continuous sequences allowed the exploration of the evolution of periodic behavior in the global glacial cycles. Drilling in moderate- to high-accumulation sites in the North Atlantic and elsewhere established that early Pleistocene ice ages were repeated every 40,000 years, whereas within the past million years these cycles slowed in pacing to approximately 100,000-year intervals and increased in magnitude to include some of the most extreme glaciations interspersed with enhanced warm interglacial intervals (Ruddiman et al., 1986; Shackleton, 2000). The shift from the "40K world" that shared timing with changes in the tilt of Earth's axis to the "100K world" pacing of changes in the eccentricity of Earth's orbit is a fundamental discovery, yet one that remains poorly understood in terms of climate physics. The large-scale ocean circulation has also varied, along with the global climate, and the two are inextricably coupled, although not in any simple, linear fashion. One valuable tool, perhaps the best, for reconstructing this circulation is the stable carbon isotopes of dissolved inorganic carbon in seawater, which is also recorded in microfossil shells. One now classic approach is the identification of approximately global geochemical end-members, because deep waters are formed at a limited number of locations, typically at the high latitudes in each hemisphere. Locations at the mid and low latitudes can then be examined to see which proportion of end-member signatures characterizes a given site through time. Such an approach, enabled by ocean drilling, was utilized to show that northern-sourced meridional overturning circulation (MOC), including the volumetric influence of NADW, was generally diminished during each Pleistocene glaciation (Raymo et al., 1990). The recovery of sediment sequences from depth transects has allowed the discovery of distinctly different patterns of variability in the intermediate and deep water masses and also in the deep waters influencing the various ocean basins (Hodell et al., 2003; Raymo et al., 2004). More recent discoveries of variability and the connection to climate have come from study of long records in the frequency domain as well as in the time domain (Lisiecki et al., 2008).

At higher frequencies, the MOC has varied persistently through successive glacial cycles, coupled strongly to millennial climate cycles (McManus et al., 1999), although the question of whether ocean or climate is the primary driver of the coupled changes remains an open one.

Combining the long continuous records of glacial cycles provided by ocean drilling with detailed analysis to explore abrupt changes reveals an apparent ice volume threshold in the ocean and climate response, such that an amount of ice equivalent to approximately 30 meters of sea level is enough to amplify rapid climate changes (McManus et al., 1999).

Following the discovery of dramatic oscillations in Greenland ice cores, an explosion of information has been uncovered about rapid changes in the regional and global climate, much of it made possible by ocean drilling. In a series of studies, it was found that the millennial climate cycles in ice cores had equivalents in deep-sea sediments, and that massive iceberg discharges had also left their episodic imprint (Broecker et al., 1992; Bond et al., 1992, 1993; McManus et al., 1994). These studies relied on the ready existence of high-quality ocean drilling sediments, and they have been followed by hundreds of globally distributed studies demonstrating the transformative power of discoveries resulting from ocean drilling. Some of these subsequent studies utilized ocean drilling material from unusual environments such as near-shore basins with limited ventilation and bioturbation (Hendy and Kennett, 1999; Peterson et al., 2000). Studies building upon these discoveries may now utilize ocean drilling sediments extending back in time (Oppo et al., 1998; Martrat et al., 2004), but also in the most recent climate cycle of the last ice age and even the Holocene (deMenocal et al., 2000; Haug et al., 2001; Oppo et al., 2003; Praetorius et al., 2008). The high quality of the sediments recovered, the ready availability of ancillary chemical and physical data, and the existence of a previous benchmark study only add to the value of existing ocean drilling sediments. In some cases the coverage is incomplete, so the choice of existing locations is a necessary compromise, and some of the oldest non-duplicated sediments are becoming depleted, or do not have the full suite of related data to optimize their use. There are also large, if not vast, stretches of the ocean floor that have not been explored and recovered by ocean drilling. So there are good reasons to expect that there are abundant opportunities for additional fundamental discoveries about the ocean-climate system based on continuing ocean drilling, even if it remains impossible to predict any one of them beforehand.

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# ROLE OF OCEAN DRILLING IN UNDERSTANDING CAUSES AND EFFECTS OF GLOBAL SEA-LEVEL CHANGE

Kenneth G. Miller
*Rutgers University*

Although the Intergovernmental Panel on Climate Change (IPCC) projected a 40 cm global sea-level rise in the 21st century (Intergovernmental Panel on Climate Change, 2007), we are tracking a minimal 80 cm rise and semi-empirical calibrations predict >1 m rise (Vemeer and Rahmstorf, 2009; Jevrejeva et al., 2010). Holocene reconstructions are needed to isolate anthropogenic influences on sea level determined from instruments (tide gauge, satellite, and temperature measurements) (Cazenave and Llovell, 2010). Evaluation of pre-Holocene records is required to understand the rates, amplitudes, and mechanisms controlling sea level, both global (eustatic) and relative (i.e., including subsidence and uplift). Calibration of sea level to temperature and $CO_2$ provides a sensitivity experiment that requires pre-Holocene records.

Sea level can be reconstructed by studying continental margin sequences, the $\delta^{18}O$ proxy of ice volume, and drilling coral reefs (“fossil sunshine”). Ocean drilling on passive continental margins has provided a detailed (±10m resolution) 100 myr history of sea-level change that yields insight into global climates and tectonics (Miller et al., 2005). A global array of ocean coreholes provides $\delta^{18}O$ proxy for glacioeustasy (Miller et al., 1991, 1996; Zachos et al., 2001; Cramer et al., 2009), although separating ice volume from temperature is progressively more uncertain prior to the Pleistocene. Coral drilling in Barbados (Fairbanks, 1988; Peltier and Fairbanks, 2006) and Tahiti (Bard et al., 2010) has shown a rise in excess of 40 mm/yr during the last deglaciation (MWP1a; ca. 14 ka) (Deschamps et al., 2009).

Extracting sea level from continental margin records is complicated by tectonism (subsidence and uplift), sediment compaction, and changes in sediment supply. Exxon Production Research (EPR) scientists (Vail et al., 1977) made a revolutionary breakthrough in using seismic reflection profiles to identify sequences (an assumption tested by Eberli et al., [2002]) by Legs 150, 166, 174, 313, and 317 and to estimate the magnitude and ages of past sea-level changes. The Deep Sea Drilling Project (DSDP) drilled the passive continental margins of Ireland (Leg 80) and New Jersey (Legs 93 and 95), but these deep-water (>1 km) sites provided little constraint on amplitudes. The Ocean Drilling Program (ODP) early on (COSODII [Conference on Scientific Ocean Drilling], 1987; JOI/USSAC [Joint Oceanographic Institutions’ U.S. Scientific Advisory Committee] Workshop, 1990; JOIDES [Joint Oceanographic Insitutions for Deep Earth Sampling] Sea-level Working Group, 1992) suggested drilling a global array of passive continental margin transects, deep-sea $\delta^{18}O$ records, and coral reefs to determine sea-level changes and identified four goals: (1) test the synchrony of events; (2) estimate amplitudes; (3) evaluate various models for the stratigraphic response to sea-level change; and (4) determine the controlling mechanism.

Recognizing the importance of margin transects, ODP endorsed drilling onshore and offshore New Jersey as an integrated study. ODP Legs 150 (slope), 174A (outer shelf), and Leg 150X/174AX (onshore) dated seismic sequence boundaries and tied them to $\delta^{18}O$ increases indicative of glacioeustatic falls (Miller et al., 1998; Eberli et al., 2002). ODP drilling on the margins of Australia (Legs 133, 182, and 194) and the Bahamas (Leg 166) provided sea-level records from carbonate settings, although atoll drilling suffered from core recovery problems (Legs 143 and 144). Drilling documented that similar Miocene unconformities, progradation, and stacking patterns occur in both carbonate and siliciclastic (New Jersey) basins. Drilling by Marion Plateau Leg 194 provided a eustatic estimate of 57±12 m for a major middle Miocene (ca. 13.9-13.8 Ma) lowering.

ODP accomplished the following: (1) validated the transect approach; (2) confirmed that the primary cause of impedance contrasts are unconformities; (3) demonstrated interregional correlation of unconformities, suggesting that they are global; (4) determined the ages of sequence boundaries better than ±0.5 Myr and provided a chronology of eustatic lowering for the past 100 Myr; (5) linked sequence boundaries directly to global $\delta^{18}O$ increases, demonstrating a causal relationship between sea level and ice volume; (6) provided evidence of small ice sheets during the Late Cretaceous-Eocene; and (7) showed that siliciclastic and carbonate margins yield comparable records of sea level (Miller, 2002).

Drilling onshore in New Jersey by ODP Legs 150X and 174AX resulted in the first testable Late Cretaceous to Cenozoic eustatic curve, derived with an inverse modeling technique termed backstripping that progressively removes the effects of sediment compaction, loading, and thermal subsidence. Backstripping showed that long-term sea-level changes were smaller than previously inferred, with a Cretaceous peak of 150±50 m, implying lower changes in ocean crust production rates than previously assumed. The New Jersey record has been criticized for its relatively low long-term peak due to epierogeny, but interregional correlations and ties to the $\delta^{18}O$ record demonstrate that is it untainted by tectonic overprints at higher frequencies. Comparison of eustatic estimates from New Jersey drilling mirrors $\delta^{18}O$ variations developed from global deep-sea cores, validating the link with ice-volume on the 104-106 yr scale. Finally, eustatic and $\delta^{18}O$-based temperature estimates allow calibration of sea level, global temperature, and atmospheric $CO_2$ estimates.

Initial coral sea-level studies were done outside of ODP (e.g., Barbados and Tahiti), but IODP has successfully drilled reefs and shallow water siliciclastic sequences with mission-specific platforms in Tahiti (Exp. 310), the New Jeresy shallow shelf (Exp. 313), and the Great Barrier Reef (Exp. 325), and with the *JOIDES Resolution* in New Zealand (Exp. 317). IODP Expedition 313 cored nearshore New Jersey lower to middle Miocene (24-14 Ma) sequences that are poorly represented onshore but seismically well-imaged nearshore; good recovery was obtained using jack-up platform at three strategically placed nearshore (35 m water depth) sites recording half a dozen early Miocene sea-level cycles. Expedition 317 cored upper Miocene to recent sequences in a transect of one slope and three shelf sites in the Canterbury Basin, New Zealand, providing a stratigraphic record of relative sea-level cycles that is complementary to New Jersey. Expedition 325 drilled 34 holes along four transects of the Great Barrier Reef with good recovery from key water depths (90-120 m) spanning the last glacial cycle. Tahiti (Exp. 310) recovered excellent records of the "stage" 5e interglacial and meltwater pulse (MWP) 1a, with critical constraints on maximum rates and fingerprinting meltwater sources.

Extracting a eustatic signal requires integrated onshore/offshore drilling transects involving global retrieval of cores representing multiple timeframes and depositional settings, including siliciclastic, carbonate and mixed systems (Fulthorpe et al., 2008). Opportunities exist for ocean drilling to build on cooperation with ICDP, which contributed funds to the New Jersey Expedition and a recent IODP-ICDP-DOSECC (Drilling, Observation and Sampling of the Earth's Continental Crust) sea-level workshop. Continuous coring is needed, although most sea-level drilling takes place in challenging environments with loose sands or coral debris. Although IODP mission-specific platforms have addressed recovery issues (e.g., Exp. 310 and 313 had >80 percent recovery), logging-while-drilling technology must be used to fill in the gaps despite its high costs.

Sea-level change captures the imagination of the public and scientists alike, with linkages to many fields, including climate change, geochemistry, biogeochemical cycles, sedimentology, stratigraphy, biologic evolution, tectonophysics, basin evolution, and resources (oil, gas, water, carbon sequestration [CCS]). The links to climate change are fundamental: sea-level studies have challenged conventional views of much of Earth history as an ice-free greenhouse. The evolution of eukaryotic phytoplankton appears directly related to long-term sea level (Katz et al., 2005). Facies models developed for sea-level cycles yield predictions about sand versus mud distribution directly applicable to reservoir/aquifer and cap rock/confining beds for hydrocarbon, groundwater, and CCS applications (Posamentier et al., 1988; Sugarman et al., 2006). Constraining eustatic history has important feedbacks into tectonophysics. Backstripping was developed to evaluate basin evolution, assuming sea level was known (e.g., the EPR record). ODP/IODP studies have demonstrated the inadequacy of the EPR curves and provided new eustatic estimates that can then be used to solve for tectonism. With recent and anticipated future accomplishments, sea-level studies are riding a high tide.

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## CO-EVOLUTION OF LIFE AND THE PLANET, MASS EXTINCTIONS, AND BOLIDE IMPACTS

Richard D. Norris
*Scripps Institution of Oceanography*

What would our understanding of Earth's past and future look like if there had been no deep ocean drilling? The deep marine fossil record gives us three vital tools—time, dynamics, and linkages—that become richly textured in the chronicle of oceanic fossils. Ocean drilling provides a highly resolved, near global, narrative of the rate and pacing of events in biological evolution that simply is unresolvable, with few exceptions, in erosion-prone strata preserved on land. Our knowledge of the dynamics of biotic evolution is brightly illuminated by the global correlation and incredibly detailed record of both marine and terrestrial fossils preserved in open ocean sediments. Finally, linkages can be resolved between the environment and the evolution of life far better than we ever could deduce from scattered exposures on land.

One of the most important legacies of ocean drilling has been the development of a highly resolved timescale for Earth processes and biotic evolution. The time scale is capable of identifying events at century to millennial resolution back into the Pliocene (~5 Ma). The network of orbitally tuned deep-sea cores also allows us to trace the timing of evolutionary events throughout the oceans. We can now demonstrate that some oceanic species can spread throughout the oceans in less than a few thousand years—an unexpected feat when faced with tectonic barriers like the Panama Isthmus. Much of modern evolutionary theory is based upon observations of living species, in which historical processes like speciation, extinction, and ecological assembly can only be inferred from modern patterns. The rich oceanic fossil record makes it possible, almost uniquely, to actually see history unfold, to trace the creation and destruction of communities, and to do so through many repeated "natural experiments" made possible by Milankovitch cycles and extreme climate change (deMenocal, 2004).

Drill cores also provide very high-quality time scales to examine evolutionary events in pre-Quaternary time such as major Antarctic glaciation (33 Ma), the Paleocene Eocene Thermal Maximum (PETM; 55 ma), a major impact event (65.5 Ma), and ocean stagnation events (~90-100 Ma). In many of these cases, marine coring has provided particularly highly resolved time scales of ecosystem change that can then be transferred to terrestrial exposures. Orbital chronologies for the marine record of the PETM, for instance, were used to show that global warming not only occurred with pacing broadly similar to anthropogenic warming, but also rapidly and profoundly disrupted marine ecosystems and precipitated a major extinction in the deep sea (Kump et al., 2009). The orbitally resolved time scale for the PETM was then used to date evolutionary events on land. These land-sea correlations allowed us to establish the rate of mammalian interchange between the continents during the PETM (Bains et al., 2003).

Such chronologies reveal an unexpected vulnerability of open ocean plankton to climate change. For example, plankton commonly display both rapid and massive changes in abundance tuned to orbital climate cycles. The dramatic changes in abundance (from near absence to 30 percent or more of a fauna) on century to millennial time scales demonstrate that marine ecosystems are much more dynamic than once thought (Norris, 2000). Studies of radiolarians and foraminifera show that both are subject to much higher rates of extinction (similar to that of large mammals) than was thought possible for the huge and widespread populations of most open ocean species. Indeed, the ocean fossil record shows parallels to the discovery of climate swings in ice cores in which the closer we look, the more rapid and frequent ecosystem change is seen.

The emerging picture is one of surprising sensitivity of oceanic and terrestrial ecosystems to small changes in climate forcing. The marine record of terrestrial pollen, wind-blown dust, and charcoal demonstrates the susceptibility of the land surface to small changes in precipitation or temperature (deMenocal, 2004). These same indicators of ecological change are also instrumental in demonstrating the vulnerability of human societies to drought and other ecological disruptions. Oceanic records are widely used to provide both a time scale to human evolution as well as to test theories of the collapse of highly structured human cultures (deMenocal, 2001).

A notable legacy of ocean drilling has been the ability to evaluate how impacts, large volcanic events, and abrupt climate events affect life on Earth. Most terrestrial records do not provide sufficient temporal resolution, or a sufficiently detailed fossil record, to produce the extremely detailed records of biotic change needed to test cause-and-effect models. For example, in the continuing debate over the causes of the Cretaceous-Paleogene mass extinction, the terrestrial vertebrate fossil record is simply too incomplete to do more than suggest that most species die out some time before the Chicxulub impact debris layer fell to Earth (Schulte et al., 2010). However, the impact precisely correlates with major turnover in many microfossil groups in the oceans as well as a host of geochemical and sedimentological indicators of marine and terrestrial ecosystem collapse. Ocean drilling has also shown that the extinction and impact were not presaged in the oceanic record as might be expected if the Deccan traps eruptions were an important source of ecological change. Remarkably, the deep-sea fossil record reveals that unusual "disaster" ecosystems last for nearly a million years after the impact in agreement with models of species evolution in disrupted ecosystems.

The deep-sea fossil record provides insight for how our world might react to major ecosystem changes today or in the future. Past extreme events represent analogs that show us how complex ecological systems respond to major shocks to our planet. Ecosystem changes are hard to model, so the fossil record has particular value in illustrating how Earth's biota has reacted to and recovered from hits to the biosphere. Drill cores show, for example, that ocean acidification during the PETM did not result in a major extinction of marine calcareous plankton even though current models suggest the total greenhouse gas release was on a similar scale to that expected from human fossil fuel consumption (Kump et al., 2009; Ridgwell and Schmidt, 2010).

What should ocean drilling do in the future to test evolutionary models? To date, the marine fossil record has mostly been used to explore long-term changes in marine and terrestrial ecosystems but there is much potential for incisive testing of current evolutionary theory. We have particular need to obtain astronomically tuned records of transects within the major oceanic ecosystems to be able to compare, at century to millennial time scales, changes in population size and distribution. Such comparisons are needed to test models of ecosystem stability developed for terrestrial environments. Most modern ecology and evolutionary biology does not deeply consider history, so ocean drilling can, almost uniquely, provide the long, temporally and spatially resolved records needed to test models of speciation that have been with us, unresolved, since Darwin. Finally, ocean drilling can examine questions that have not even occurred to ecologists such as whether the productivity and biodiversity of the Earth oscillates over time thanks to long-period orbital or tectonic cycles. Does Earth's biosphere have a "heartbeat" (Pälike et al., 2006)?

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# HOW HAS THE AVAILABILITY OF DEEP-OCEAN DRILLING CAPABILITIES ENABLED NEW FIELDS OF INQUIRY?

Dennis Kent
*Rutgers University & Lamont-Doherty Earth Observatory*

Earth is largely covered by water: two-thirds of the surface area with an average water depth of 3,700 m. The United States is essentially surrounded by oceans—Atlantic, Gulf of Mexico, Pacific, and Arctic. Deep-ocean research and drilling capabilities are important for a U.S. leadership role in global geosciences as well as for strategic, economic, and environmental reasons. This white paper attempts to outline some of the contributions of this technology.

Project Mohole (1958-1966) inaugurated deep-ocean drilling capability with a converted Navy barge fitted with experimental deep-water drilling equipment and a dynamic positioning system invented for the occasion. Phase 1 drilling was done off Guadalupe, Mexico, in March and April 1961 in 11,700 feet of water and penetrated more than 600 feet beneath seafloor to find that oceanic crust consisted of basalt. The project was discontinued before Phase II could be implemented.

Drillship *Glomar Challenger* operating under the National Science Foundation (NSF)-funded Deep Sea Drilling Project (DSDP; 1968-1985) almost immediately hit a grand slam by determining on Leg 3 (December 1968-January 1969) that the ages of sediment overlying oceanic crust at 8 sites in the South Atlantic increased systematically with distance from the ridge axis (Maxwell et al., 1970), as predicted by the new geomagnetic polarity time scale (Heirtzler et al., 1968). This landmark verification of seafloor spreading was decisive and only possible by deep-ocean drilling. Moreover, the discovery directly led to the paradigm of plate tectonics and heralded the development of integrated geologic time scales.

The recovery of undisturbed sediment with the hydraulic piston corer (HPC) starting on DSDP Leg 64 and especially Leg 68 (Prell et al., 1980), and subsequently the advanced piston corer (APC) beginning with Leg 94 (Ruddiman et al., 1986), revolutionized the study of Earth history and major events in deep time by providing long continuous sediment columns for high-resolution biostratigraphic, magnetostratigraphic, and isotopic studies. These records are the backbone of our understanding of Milankovitch cyclicity (e.g., Lisiecki and Raymo, 2005; Herbert et al., 2010) and the ongoing construction of high-precision astrochronologies further and further back in time (e.g., Pälike et al., 2006).

Examples of results from HPC coring include an oxygen isotope calibration of the onset of ice-rafting in the North Atlantic (Leg 81, Site 552A; Shackleton et al., 1984a) and broadly of environmental changes over the Cenozoic (Leg 74, Site 525-529; Shackleton et al., 1984b), as well as the construction of a composite isotope record (Miller et al., 1987) linked by more accurate geologic and geomagnetic polarity time scales (e.g., Berggren et al., 1985) for global sea-level and other studies including the overarching greenhouse-icehouse transition (Miller et al., 1991) in the Cenozoic.

Results from APC coring are ongoing (e.g., Channell et al., 2009), and examples include the discovery of episodes of extreme and rapid climate change, notably the Paleocene/Eocene thermal maximum and carbon isotope excursion at ODP Site 690 (Kennett and Stott, 1991), an event that has attracted huge research attention and has been widely verified and elaborated upon (e.g., Thomas et al., 2002; Zachos et al., 2005). The Paleocene Ecocene Thermal Maximum/Carbon Isotope Excursion (PETM/CIE) is often regarded as a geologic analog to anthropogenic production of $CO_2$ and global warming (e.g., Dickens, 2004). A net result of these studies is the development of a global picture of Cenozoic ocean circulation and climate change, including growth of Antarctic and Greenland ice sheets, and possible links to atmospheric $CO_2$ (Zachos et al., 2008; Cramer et al., 2009).

The Integrated Ocean Drilling Program (IODP) Arctic Coring Expedition in August 2004 produced a long continuous sedimentary record from this logistically difficult area that shows the transition from an exceptionally warm world during the late Paleocene and early Eocene to a progressively colder world increasingly influenced by ice (Moran et al., 2006).

Leg 130 drilling on Ontong Java Plateau (OJP) confirmed earlier drilling results that it formed by rapid volcanism during the Aptian (Tarduno et al., 1991). Emplacement of the OJP, which is likely to be the most voluminous oceanic large igneous province (LIP) known (Coffin and Eldholm, 1994), seems to be closely (causally?) associated with the beginning of the Cretaceous long normal superchron and may have contributed to generally warm mid-Cretaceous climates, a eustatic rise, and the formation of oceanic anoxia due to increased crust production and higher mantle outgassing (Larson, 1991; Tejada et al., 2009). However, there are still conflicting estimates of the precise relationship and age(s) of the OTP, Chron CM0 and OAE1 (oceanic anoxic event) (or Selli Event) (Larson and Erba, 1999; Gradstein et al., 2004) with major consequences for global systems such as seafloor production rates (Cogné and Humler, 2006) and associated geochemical cycles.

A volcanic origin for seaward dipping seismic reflectors that may be related to the North Atlantic igneous province was determined by drilling on Rockall Plateau on Leg 81 (Roberts et al., 1984; the same expedition that produced the seminal record of Northern Hemisphere glaciations; paragraph above). Seaward dipping reflectors elsewhere may also be associated with LIP magmatism, for example, in the southeastern margin of North America and Central Atlantic magmatic province (Austin et al., 1990).

With the exception of the highly speculative idea of the Ontong Java Plateau being due to a massive impact (Ingle and Coffin, 2004), impact structures on oceanic crust have yet to be found but must exist. Deep ocean drilling capability will be the only way to sample, verify, and better understand the dynamics of an oceanic impact crater when one is eventually identified, much like the strategy of the International Continental Scientific Drilling Program (ICDP) (and forthcoming Integrated Ocean Drilling Program/Mission Specific Platforms [IODP/MSP]) drilling on the Chicxulub impact crater in the Yucatan (Joanna Morgan, personal communication, 2010).

Direct estimates of paleolatitude by deep-ocean drilling of submerged edifices formed along the Hawaiian-Emperor hotspot track have challenged the fixed hotspot model (Tarduno et al., 2003) and provide dramatic support for predicted motion of mantle plumes wafting in the mantle wind (Tarduno et al., 2009). Results from scheduled drilling on the Louisville track will be essential toward resolving this issue.

Drilling that started on DSDP Leg 69 at Site 504B on the Nazca plate and continued on a half dozen subsequent expeditions penetrated through about 500 m of pillow lavas and about a 1,000 m section of dike rocks (Pariso et al., 1995; see compilation of magnetic data and discussion by Gee and Kent, 2007). The results provide the first in situ reference section for Seismic Layer 2 of the oceanic crust and documented the importance of the sheeted dike complex as a viable source of lineated magnetic anomalies.

Multi-leg drilling at ODP Site 1256 on the Cocos plate penetrated more than 1,250 m section of lavas, sheeted dikes and into gabbros of Seismic Layer 3, extending direct sampling of in situ ocean crust (Wilson et al., 2006). A 1,500 m section of tectonically exposed gabbros drilled at ODP Site 735B on the slow-spreading Southwest Indian Ridge provides evidence for a strongly heterogeneous lower ocean crust (Dick et al., 2003). It may be time to revisit a mission to the Moho.

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# CONFIRMATION OF SEA FLOOR SPREADING

Douglas S. Wilson
*University of California, Santa Barbara*

The first big success of scientific ocean drilling was the confirmation of the sea floor spreading theory with the results of the Deep Sea Drilling Project (DSDP) Leg 3. The sea floor spreading theory started to gain wide acceptance in 1966, with the publication of the Eltanin-19 profile from the southeast Pacific (Pitman and Heirtzler, 1966) showing highly symmetric magnetic anomalies and bathymetry, and the demonstration by both Pitman and Heirtzler (1966) and Vine (1966) that magnetic anomalies over multiple mid-ocean ridges could be explained by the Vine-Matthews mechanisms at different, nearly constant spreading rates according to the magnetic reversal time scale of Cox et al. (1964) and Doell and Dalyrmple (1966). These time scales were based on K-Ar dating and magnetic polarity stratigraphy of mostly basaltic lavas with ages 0-4 Ma. Heirtzler et al. (1968) took the bold step of calibrating a magnetic polarity time scale to ~80 Ma by assuming that magnetic anomalies mapped in the South Atlantic by Dickson et al. (1968) all formed at the same spreading rate of 19 mm/yr half rate, as deduced for 0-4 Ma.

DSDP Leg 3 drilled a transect across the South Atlantic in the 1968-1969 Austral summer with goals of testing both the general sea floor spreading theory and the specifics of the Heirtzler et al. age model. As reported by Maxwell et al. (1970a, b), the leg was a spectacular success. Basement age, as judged from overlying microfossils, was a nearly linear function of distance from the spreading ridge, with limited scatter, and agreed with a half spreading rate of about 20 mm/yr. The young ages near the ridge axis and the close agreement of the spreading rate determined from microfossil ages and the spreading rate determined from young magnetic anomalies both conferred the strongest possible confirmation of the revolutionary sea floor spreading theory.

Numerous later studies have continued to confirm the close correspondence of sea floor age inferred from magnetic anomalies and the age of overlying sediments sampled by scientific ocean drilling. This correspondence is so broadly accepted that it is rarely tabulated or reviewed, an exception being the time scale work of Berggren et al. (1995), which draws heavily on microfossil stratigraphy from DSDP and ODP (Ocean Drilling Program).

One interesting case involves the sea floor age of the tropical eastern Pacific, where the stratigraphic basement ages from DSDP Leg 9 (Hays et al., 1972) preceded confident magnetic anomaly identifications by many years. The wide spacing of Miocene Sites 79-82 on the Pacific plate led Hayes et al. to interpret a half spreading rate of 130 mm/yr, assuming the spreading history was simple, although they acknowledged that complex tectonic histories could mean that the full spreading rate was much less than twice the apparent half spreading rate. Subsequent work has overcome the challenges of low-latitude magnetic anomaly interpretation (Wilson, 1996; Barckhausen et al., 2001, 2008; Horner-Johnson and Gordon, 2003). The corridor of the first East Pacific Rise drilling transect of Leg 9 turns out to have been tectonically relatively simple, and the long-forgotten high spreading rate interpreted by Hays et al. (1972) has been confirmed.

An additional way scientific ocean drilling has confirmed sea floor spreading is by demonstrating that the same magnetic polarity record is recorded in both marine magnetic anomalies measured at the sea surface and in paleomagnetic records in drilled cores. Advances in dating the geologic record by recognizing the signature of predictable variations in Earth's orbit have revolutionized stratigraphic geochronology over the past 20 years. Although often the most useful records for such dating are from sections in outcrops (e.g., Hilgen, 1991), ocean drilling cores have also played a key role. Probably the best example of calibrating the ages of magnetic reversal from drilled cores is the calibration of Pälike et al. (2006), which provides a precise record of most of the Oligocene from the equatorial Pacific record of Site 1218 (ODP Leg 199). Spreading on the relatively steady Australia-Antarctica plate pair is very constant at about 70 mm/yr full rate (maximum rate) according to this calibration. According to the calibration, the Oligocene South Atlantic full spreading rate of about 50 mm/yr is slightly above the long-term average that figured so prominently in the Leg 3 results.

More recent research has focused much more on understanding processes of sea floor spreading rather than the long-acknowledged confirmation of the basic theory. As one example, Purdy et al. (1992) noted that the depth below active midocean ridges of seismic reflectors interpreted as melt bodies varies inversely with spreading rate at intermediate and fast spreading rates. Deep drilling at Hole 1256D in the Miocene equatorial Pacific allows this relationship to be tested at a superfast rate well outside the modern range of spreading rates. Drilling during IODP Exp. 312 encountered a gabbro body at 1,160-1,210 m below basement that would have originally had properties of the modern seismic reflectors. The depth fits perfectly within the range extrapolated from the results of Purdy et al. and subsequent workers. The fractionated composition of the gabbro allows us to begin to understand the magma-chamber processes that segregate the fractionated upper crust from the residual lower crust.

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## CHRONOSTRATIGRAPHY AND GEOMAGNETISM

James E.T. Channell
*University of Florida*

Early DSDP (Deep Sea Drilling Project) drilling contributed substantially to the revolution in the Earth sciences that took place in the late 1960s. Apart from documenting the age and nature of oceanic basement, DSDP opened up the deep-sea sediment archive of Earth history to lithological, micropaleontological, geochemical, and magnetostratigraphic studies. Prior to that time, conventional piston cores limited investigations to the top ~20 m of the sediment sequence. The development of the hydraulic piston corer (HPC), first used in 1979 during DSDP Leg 64, improved sediment core quality and allowed recovery of long (~300 m) sequences of undisturbed sediments. The field of paleoceanography was born, and research in micropaleontology, and isotope and magnetic stratigraphy, blossomed.

Traditional magnetic polarity stratigraphy has become the backbone of geologic timescales because polarity reversal is attributable to the main dipole field, and therefore provides global timelines for precise correlation at the time of reversal. In modern Cenozoic and Mesozoic timescales, the GPTS (geomagnetic polarity timescale) is the central thread to which the other facets of geologic time (bio- and chemostratigraphic and radiometric) are correlated. The Late Cretaceous-Cenozoic GPTS of Cande and Kent (1992, 1995) was temporally calibrated by interpolation among available radiometric ages using a uniformly varying spreading-rate assumption, with astrochronological calibration for the last ~4 Myr (Cande and Kent, 1995). Astrochronological calibration of the GPTS has now been extended further back into the Cenozoic.

The correlation of the Cenozoic polarity record to biostratigraphies and chemostratigraphies, and to the cyclostratigraphies that provide the astrochronologies, has been largely achieved through DSDP, ODP (Ocean Drilling Program), and IODP (Integrated Ocean Drilling Program). The timescales with which we calibrate Earth history, and the paleontological and isotopic data that are the building blocks of paleoceanography, would not have progressed to anything like the same level in the absence of DSDP/ODP/IODP. We would have relied on sequences exposed on land and on conventional piston cores. The task of GPTS calibration has yet to be satisfactorily accomplished, even for the late Cenozoic; however, cyclostratigraphies tuned to orbital solutions (astrochronologies) provide the way forward, and these calibrations are likely to be accomplished largely through IODP and its successor program.

For obvious societal reasons, the study of rapid climate change is of paramount importance. The marine sediment archive has become increasingly important for understanding the climate system because historical direct measurements are woefully inadequate in detail, distribution, and duration (~100 yrs), and ice cores, although providing wonderful detail, are also restricted in distribution and duration. Marine "drift" sequences, characterized by elevated mean sedimentation rates, have become targets for documenting the record of climate change on millennial timescales.

The study of rapid change requires stratigraphic correlation at an appropriate resolution. In spite of the considerable progress made in the past 40 years, the quest for improved stratigraphic correlation remains one of the great challenges in paleoceanography. Benthic $\delta^{18}O$ is the hallmark of Quaternary marine stratigraphy; however, $\delta^{18}O$ changes in seawater are not globally synchronous on millennial timescales (see Skinner and Shackleton, 2005), and the rate of change of global ice volume (the basis for $\delta^{18}O$ stratigraphy) is gradual other than at Terminations, limiting the correlation potential of the records.

There would be great advantage in coupling oxygen isotopes with an independent stratigraphic tool that is global in nature and devoid of environmental influences. The accumulation of relative paleointensity (RPI) data in the past 10 years holds the promise of stratigraphic correlation within polarity chrons, possibly at millennial scale. A first step in the utilization of RPI records in stratigraphy has been the development of RPI stacks (e.g., Valet et al., 2005) and an RPI stack based on the tandem correlation of RPI and $\delta^{18}O$ data (Channell et al., 2009).

An objective in the next phase of IODP should be the coring of sediment drifts, not only to exploit the high-resolution environmental/climate records associated with them, but also to utilize stratigraphic tools ($\delta^{18}O$ and RPI) to place these records in a stratigraphic framework appropriate for the study of rapid climate change. When these tandem correlations ($\delta^{18}O$ and RPI) have been satisfactorily established, RPI can be used with confidence in locations where $\delta^{18}O$ is unavailable due to lack of foraminifera, such as the Antarctic Margins where sediment drifts document the history of Antarctic ice sheets and related sea-level change.

Magnetic excursions are brief directional excursions that usually, when adequately recorded, constitute paired polarity reversals. Knowledge of magnetic excursions has been greatly enhanced by ODP and IODP expeditions in the past 15 years. The best-recorded excursions have durations of ~1 kyr, and apparently not exceeding a few kyr. The brief duration of excursions is such that they are rarely recorded except in sediments with accumulation rates exceeding 10 cm/kyr. Excursions occupy minima in RPI records, and RPI minima are more readily recorded than excursions because troughs in RPI records are longer lasting than directional excursions. There are ~6 excursions that are adequately recorded in the Brunhes Chron, and ~8 in the Matuyama Chron (see review by Laj and Channell, 2007). Excursions are believed to be manifest globally and are therefore important for stratigraphy, although they are too brief to be recorded at typical pelagic sedimentation rates.

RPI and magnetic excursions are geomagnetic phenomena that could not have been studied in the absence of HPC technology, developed by DSDP, for recovering long sediment sequences. Additionally, the shipboard procedure for real-time control of drilling strategy, developed by ODP and first utilized in 1991, for construction of complete composite sections from multiple holes drilled at a single site, has been critical to modern high-resolution stratigraphy, not just to magnetic stratigraphy but also to bio- and chemostratigraphy, and hence to paleoceanography.

Finally, the new magnetic stratigraphies described above are an important means of testing numerical simulations of the geodynamo. Such simulations can now mimic a wide range of geomagnetic field behavior depending on input parameters. Records (from sediment drifts) are needed to compare with numerical simulations, and in so doing refine the simulations and obtain important mechanistic information for the geodynamo.

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## GEOCHRONOLOGY OF THE OCEAN FLOOR

Robert A. Duncan
*Oregon State University*

The principal goal of the initial phase (1968) of scientific ocean drilling was to test the plate tectonics model. Namely, the ocean floor is generated by a process of seafloor spreading, and so is progressively older with distance away from spreading ridges. The ocean basins, as a consequence, are relatively young features developed as a result of divergence and convergence of more permanent continental lithosphere. Hence, the ability to accurately and precisely estimate the ages of the ocean floor has been an ongoing critical need in scientific ocean drilling. In the first decade, ages of the ocean floor were provided predominantly by biostratigraphic data (microfossils) obtained from the lowermost (oldest) sediments deposited on the volcanic crust because of the lack of a reliable radiometric method. Such indirect dating provides a minimum age.

Potassium-argon (K-Ar) dating is the most readily applicable radiometric method because (1) the decay constant for $^{40}K \rightarrow ^{40}Ar$ is appropriate for dating volcanic rocks and minerals over a wide age range (~$10^4$ to $10^9$ years), and (2) K is a minor but ubiquitous element in ocean crustal rocks. Several issues make K-Ar dating of ocean floor rocks problematic, however. The most serious of these are (1) seafloor weathering with post-crystallization addition of K (from seawater) and loss of Ar (during breakdown of primary igneous minerals to clays)—both of which violate the closed chemical system assumption of the K-Ar method and lead to measured ages younger than the crystallization age, and (2) quenching of magmas in seawater under high hydrostatic pressures, that causes glassy, poorly crystallized material to retain a mantle-derived Ar isotopic composition different from the atmospheric composition of Ar, leading to an erroneously old calculated age. The $^{40}Ar$-$^{39}Ar$ incremental heating variation of the K-Ar method has been successful in providing reliable crystallization ages for ocean floor rocks. In this technique, developed from the mid-1960s to 1970s, whole rocks or minerals are heated under vacuum in progressive temperature increments, to separate Ar released from low-temperature (alteration, e.g., clay) minerals from high-temperature (primary igneous) minerals, or altered margins from fresh cores of minerals. The isotopic composition of Ar released from the range of temperature steps can also be used to calculate an isochron and an initial composition of Ar in the sample at the time of crystallization. Recently, improvements in instrument sensitivity and sample preparation methods have meant that more precise ages can be measured on smaller masses of less altered phases (e.g., plagioclase feldspar, biotite, groundmass).

The following significant achievements have followed the success in reliable dating of crystallization ages for ocean floor rocks obtained by scientific ocean drilling:

(1) Confirmation of the age-distance relationship for ocean floor predicted by plate tectonics. Initially substantiated by biostratigraphic dating of lowermost marine sediments overlying the volcanic ocean crust, basement rocks at many drilling sites have now been dated by the $^{40}Ar$-$^{39}Ar$ method. Because the ocean floor also records a continuous record of the alternating polarity of the geomagnetic field, these radiometric ages have led to calibration of the Geomagnetic Polarity Time Scale.

(2) Age-progressive trends of "primary" hotspot tracks. Linear arrays of ocean islands and seamounts that occur within plates and crossing plate boundaries have been related to deep-seated, upwelling plumes of warmer than ambient mantle. Because of thermal subsidence of aging ocean plates, volcanoes initially constructed as islands eventually sink below sea level and are covered with marine sediments (including coral and carbonate banks in tropical latitudes). In many important cases, volcanic samples of these older parts of hotspot tracks can be obtained only through drilling through the sedimentary cover. Radiometric dating has provided ages that confirm the motion of plates over quasi-stationary hotspots (e.g., Hawaiian-Emperor chain and Hawaii; Walvis Ridge and Tristan da Cunha; Mascarene-Maldive chain and Reunion). This has resulted in a reference frame for plate motions that is tied to the pattern of deep convection—independent of the relative motion reference frame provided by seafloor spreading magnetic anomalies and fracture zones, and the geomagnetic field reference frame. Recently, comparison of hotspot and geomagnetic reference frames derived from drilling in the Emperor seamounts (ODP Leg 197) has shown trans-latitude (N to S) motion of the Hawaii hotspot of 4-5cm/yr in the period 80-50 Ma.

(3) Hotspots begin with catastrophic volcanic events. Prominent hotspots are now linked, through age-progressions and chemical tracers, to vast outpourings of basaltic lavas constructed in geologically brief periods, called large igneous provinces (LIPs). Examples are Iceland-North Atlantic Igneous Province (East Greenland Margin and Faeroes-British Tertiary); Tristan da Cunha-Parana/Etendeka basalts; Reunion-Deccan basalts; and Kerguelen-Rajmahal basalts/Kerguelen plateau. This has led to a geodynamic model for mantle plume behavior (large impact "head" and continuous but smaller volume "tail") and a recognition that the enormous eruption rates during LIP formation should have important environmental impacts, such as mass extinctions and ocean anoxic events. Ocean plateaus (e.g., Ontong Java, Manihiki, Caribbean) are now recognized as LIPs erupted in ocean basins, equivalent to the more accessible subaerial versions. These developments would not have been possible without precise dating of hotspot tracks and submarine portions of LIPs sampled by ocean drilling.

(4) Time scale of seafloor hydrothermal systems. The dramatic "black smokers" discovered at many seafloor spreading systems are driven by the intense thermal gradient at ocean ridges, a highly permeable ocean crust, and ubiquitous seawater. How long do these systems last, and how far off-ridge is hydrothermal circulation an important process in chemical exchange and removing heat from the seafloor? With cooling to fluid temperatures of 50-60 °C, zeolites, clays, and micas (celadonite) with relatively high %K contents precipitate in voids and fractures in the ocean crustal rocks. This is the end stage of sealing the permeability of the crust, and dating celadonite provides an age estimate for the end of fluid circulation. 3D sampling and K-Ar dating of celadonite at the Troodos ocean crust section (Cyprus) reveal a pattern of progressive filling of small to large fractures over ~30 m.y. A similar large age range has been found for celadonites from ocean crust drillsites, and confirms evidence from seismic imaging and heat flow measurements that off-ridge hydrothermal circulation ends about this time.

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# THE SEISMOGENIC ZONE OF SUBDUCTION THRUSTS

J. Casey Moore
*University of California, Santa Cruz*

The current seismogenic zone drilling program is based on the National Science Foundation (NSF) MARGINS Seismogenic Zone Experiment concept (SEIZE). This program examines the movement of sediments, rocks, and fluids from the surface to the seismogenic zone and intends to understand how these materials produce the world's largest earthquakes. The program's goals are to (1) determine the nature of the material incoming to the subduction zone, (2) predict its changes at depth through experiments, (3) image the seismogenic zone through active and passive source seismology, (4) drill into the upper extent of the seismogenic zone, and (5) monitor the behavior of the seismogenic zone with seafloor and borehole instrumentation. Focus areas are currently southwest Japan and Costa Rica. Under the renewed MARGINS program the focus will move to Cascadia and perhaps other convergent margins.

Scientific ocean drilling has concentrated on the seismogenic zone of subduction thrusts off southwest Japan recently. This program has completed an extensive transect across a subduction zone that produced an 8.1 magnitude earthquake in 1944 (Ando, 1975; Park et al., 2002). This effort has involved drilling 12 sites to depths of 1,600 m, extending from the incoming oceanic crust landward to the center of the forearc basin (Saffer et al., 2009; Tobin and Kinoshita, 2009; Underwood et al., 2009). Penetrations include one riser hole and the emplacement of a pressure-monitoring device in a tsunamigenic thrust fault. The 2010 program involves installing the initial casing string for the deep riser hole, installing a riserless observatory near the accretionary prism-forearc basin boundary, and completing the subduction input drilling. In 2011 and beyond the program intends to extend a deep riser hole into one of the thrust faults responsible for the 1944 earthquake. During 2011, in the broader SEIZE context, a 3D seismic survey and riserless drilling will occur off Costa Rica.

Currently, the transect off southwest Japan has virtually completed goal 1 of SEIZE, made excellent progress on goal 2, is continuing to complete goal 3, plans to initiate goal 4 this summer, and has begun to work on goal 5. Deep riser drilling has been slowed by high current problems; however, the *Chikyu* engineering group has added fairings to the riser, tested their performance, and are ready to drill in the high current environment.

## SOME KEY SCIENTIFIC RESULTS OF SEISMOGENIC ZONE DRILLING

Drilling on the main transect off southwest Japan began in September 2007 (Tobin and Kinoshita, 2009), and imaging somewhat before. The capstone achievements are yet to come; nevertheless, what are some of the exciting results?

(1) The seismogenic zone is not so far away: Seismic activity, tremor, and very low frequency earthquakes occur at very shallow depths (1-2 km) along thrust faults in the accretionary prism (Ito and Obara, 2006; Obana and Kodaira, 2009). The shallow seismic activity means that some current holes may have drilled into the zone of conditional stability of earthquakes; instruments placed into this zone can provide meaningful understanding of earthquake cycles in the near term. The full 7 km borehole depth may not be required to achieve the SEIZE goals.

(2) Earthquake slip propagates through the accretionary prism to the surface: People have questioned whether the soft sediments of accretionary prisms absorb high-velocity slip through distributed deformation or not. Major candidates for transfer of seismic slip to the surface are the frontal thrust and megasplay faults (Plafker, 1972; Moore et al., 2007; Strasser et al., 2009). Inversions of tsunami waves (Cummins et al., 2001; Baba and Cummins, 2006) suggest displacement of the splay fault during the 1944 great earthquake, as does extension of the thrust interface directly to the surface (Moore et al., 2007). Finally the drilling recovered the splay fault interface, within which a mm-thick gouge zone at 400 mbsf shows anomalously high vitrinite reflectance and other geochemical anomalies, suggesting high temperatures and high-velocity slip (Sakaguchi et al., 2009, 2011; Yamaguchi et al., 2009). These authors have also found a similar result on the frontal thrust at the base of the slope. Apparently, high-velocity slip has propagated to the surface or near surface during the recent earthquakes, explaining the devastating tsunamis that characterize this margin. This result is consistent with the extension of the conditional stability zone of earthquakes to very shallow depths (see 1 above).

(3) Stress magnitudes and strain responses vary during the earthquake cycle: Apparently the interseismic stress regime, now observed, contrasts to the coseismic stress and strain regime of the great earthquakes. Complete borehole imaging and caliper data across the margin indicate maximum horizontal stresses nearly perpendicular to the margin across the trench slope with a 90-degree rotation at the transition into the forearc basin (Tobin and Kinoshita, 2009). Farther landward in the forearc basin the maximum horizontal stress again becomes nearly perpendicular to the margin (Lin et al., 2010). The outer forearc basin is characterized by normal faulting (Martin et al., 2010). Stress magnitude estimates and core observations suggest the accretionary prism has currently active strike-slip and normal faulting at the depths drilled (Byrne et al., 2009; Chang et al., 2010).

This suggests that the major thrust faulting both drilled and observed on the seismic data must be coseismic, as inferred from temperature anomalies along slip surfaces (Sakaguchi et al., 2011) and the earthquake focal mechanisms (Ando, 1975). The variable types of strains observed at shallow depths, in the 100 year plus interseismic interval, are probably caused by small differences in magnitude of principal stresses; these minor variations in stress can "flip" the strain response (Tobin et al., 2009). Conversely the few minutes of coseismic activity every 100 plus years imprint the margin with its dominantly thrust faulted architecture.

## LEGACY OF DSDP/ODP CONVERGENT MARGIN DRILLING

Although the seismogenic zone is the focus of the current convergent margin drilling, it stands on a foundation developed during the preceding three decades. For example, the community has become very skilled at using 3D seismic imaging to extend core-log observations away from the 1D borehole realm (Bangs et al., 1999). In the absence of pressure measurements, both thermal and geochemical anomalies have been developed as tools to recognize fluid migration along faults (Moore et al., 1987; Kastner et al., 1991). The techniques for long-term pressure and geochemical monitoring were developed during ODP (e.g., Solomon et al., 2009). The earliest efforts of convergent margin drilling in the 1970s and early 1980s were focused on unraveling the margin tectonics including documentation of accretionary versus erosional subduction zones (von Huene and Scholl, 1991). This concept has been used to frame the contrast between the two main focus sites of the SEIZE experiment—southwest Japan (accretionary margin) and Costa Rica (erosional margin).

## PROGNOSIS

The current seismogenic zone drilling activity has produced the best convergent margin transect ever. Numerous ground-breaking results stem from this recent activity. But, fully transformative achievements await the completion of the deep riser boreholes and associated instrumentation. Lessons from this focused effort will be clearly applicable to ongoing programs at U.S. convergent margins in Cascadia and Alaska.

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## WHAT MAJOR TECHNOLOGICAL ADVANCES AND INNOVATIONS HAVE DEVELOPED FROM THE DRILLING PROGRAM?

Hans Christian Larsen
*IODP Management International, Inc.*

This white paper summarizes some major technological advances and innovations made over the 40+ years since the inception of scientific ocean drilling by the Deep Sea Drilling Project (DSDP) in 1966. The focus is on the more recent developments from the later part of the Ocean Drilling Program (ODP) and from the Integrated Ocean Drilling Program (IODP). Limits on report length only allow highlights to be included. Funding of many of the technical developments is from outside the program, which traditionally deploy most of its funds for operations. According to AGI (American Geosciences Institute), scientific publications underpinned by these technologies now exceed 26,000 (>1,500 in *Science* or *Nature*).

Scientific ocean drilling (SOD) deployed the first ever deepwater drill-ship, the *CUSS* 1 for project Mohole in 1961 in a water depth of 3,500 m. The thruster-supported positioning system laid the groundwork for modern dynamic positioning (DP) systems. The offshore hydrocarbon industry that subsequently developed is now a top global industry with development budgets many orders of magnitude higher than within SOD. SOD therefore piggy-backs on industry developments, such as coring, sampling from boreholes, core description, core-log integration, borehole observatories, and development of new research tools and environmental proxies. SOD set the benchmark in these fields using a truly unique set of tools and expertise, and is at the forefront of coring within extreme environments. Four key topics of technology developments and spin-offs are reviewed.

## PLATFORMS, DRILLING, AND CORING TECHNOLOGY

The DSDP *R/V Glomar Challenger* was a purpose-built, first-generation deepwater drillship, globally breaking new ground drilling in water as deep as 7,044 m (open hole, non-riser). ODP was served by the *R/V JOIDES Resolution* (JR), an oil exploration platform converted to a non-riser scientific drilling vessel. Superior to *Glomar Challenger* in all aspects (e.g., tonnage, drill string capabilities, DP performance, heave compensation), JR drilled deeper, in shallower waters, in higher latitudes, and with improved core recovery. *JR* underwent major refurbishment during IODP years 2006-2008, extending vessel lifetime, improving accommodations and laboratory space, further improving heave compensation, and adding newly developed, state-of-the-art coring analytical facilities.

Innovations and improvement of drilling and coring systems on *JR* over time include: unique bare-rock, spud-in guide-base allowing use of rotary coring bit (RCB); extended core barrel (XCB) for improved recovery in formations too hard for piston coring; motor-driven core barrel for environments of highly alternating formation strength; and advanced piston coring (APC) system (developed from the previous hydraulic piston coring [HPC]) for ultra-high recovery (~100 percent) within soft sediments. Recent "drill over" technology has pushed the limit of APC to 458 m below seafloor (HPC: ~100 m). True orientation of cores can also be achieved. Information systems for in-situ monitoring of drill bit conditions are being developed to further enhance recovery.

In addition, IODP saw two major new inventions: the deepwater, riser drilling vessel *D/V Chikyu*, purpose-built for SOD by Japan; and application of the mission-specific platform (MSP) approach to coring within uniquely challenging environments.

*Chikyu* is one of the most capable drillships worldwide. Her current riser capability is 2,500 m water depth, amongst the deepest at time of ship design. A 4,000+ m deepwater, benchmark-setting riser is currently being explored through optimization of conventional riser technology (material standards, downsizing of blowout preventors [BOPs]) and a riserless (or dual gravity) mud recovery system (RMR). *Chikyu*'s double rig design is uniquely well suited for RMR, but RMR could also be applied on *JR* and may be considered for a new SOD vessel planned by China. Another ongoing riser innovation is a monitoring and vibration mitigation system for operation under strong currents (a condition offshore Japan), pushing the envelope of current industry standards.

The innovative application of the MSP concept to the high Arctic (2004) resulted in a transformative technical achievement of the first ever deep coring within the central Arctic Ocean. This was achieved through sophisticated ice management in conjunction with two powerful ice breakers and a purpose fitted, ice-breaking drilling vessel (a concept now adapted by industry). Application of a piggy-back, narrow kerf coring system to a DP positioned vessel for high-recovery drilling of carbonate reef material is another noteworthy innovation that increased core recovery with one order (+) of magnitude.

Developments by SOD partners (e.g., BGS and MARUM) are pushing the shallow (0-100 m) coring from seabed frames (e.g., MeBo of MARUM), which can provide high-recovery cores from young oceanic crust, otherwise proven impossible to effectively core. SOD is also developing high-temperature core barrels for such environments.

Because of these many incremental innovations in drilling technology, SOD can effectively core in almost any environment, and maintains leadership in deepwater coring, despite being the David compared to the Goliath in the global drilling industry.

## SHIPBOARD AND LAB-BASED TECHNOLOGIES AND MEASUREMENTS

Core splitting and processing tools and protocols still in use by IODP were developed by DSDP and laid the foundation for an unparalleled collection of legacy data from below the oceans. Of course, major advances in both discrete and continuous core measurements have been made over time. In this field, SOD can claim credit per se for innovations within continuous core descriptions and measurements, laying the groundwork for development of different physical/chemical proxies for environmental change and temporal constraints: (1) A core cryogenic magnetometer, which contributed to the commercial product now in use, provides onboard rapid paleomagnetic stratigraphy; (2) Multi-Sensor Track (MST), which is applied pre-core splitting to provide density, magnetic susceptibility, p-wave velocity, and resistivity; (3) rapid measurement color spectrophotometry; (4) spectral natural gamma ray analysis rapidly measuring cores at comparable resolution to downhole logging tools (unique for core-log integration); (5) rapid, high-resolution, high dynamic range linescan split core imager; (6) continuous XRF high-resolution core scanning (split core); (7) ultra-clean sample and curation protocols for microbiological sampling; (8) infrared cameras to identify gas hydrate horizons in core before sublimation; and (9) non-destructive rhizon porewater sampler. Ocean drilling has adapted a number of other advanced facilities for use. Of these, the continuous core computed tomography (CT) scanning stands out and has opened a new world of 3D imaging before core splitting.

The opportunities offered by these advanced core scanning and analytical tools are vastly supplemented by a large number of (non-program) state-of-the-art analytical facilities for mainly discrete samples (e.g., isotopes, magnetic properties including paleo-intensity, microbiology, and DNA sequencing). More than 13,000 scientists are using SOD samples. Approximately 2.2 million ODP samples have been taken; this number is increasing, with a recent record of 53,000 samples provided by a SOD core repository.

## DOWNHOLE MEASUREMENTS/LOGGING AND ADVANCED SAMPLING

Because of its unique expertise in core-log integration, SOD is a respected partner of world-leading geophysical logging companies. Downhole logging has grown in SOD drilling, with logged drill sites increasing from 14 percent during DSDP to 64 percent during IODP. Most technology used in scientific drilling originates from the hydrocarbon industry, from wireline logs to logging-while-drilling measurements. However, SOD likely has the globally best core-log integration data, and specialty tools developed by SOD include magnetic properties, high-resolution natural gamma ray radioactivity, borehole temperature, pressure-measuring penetrometers, and laser imaging for microbiology. Through academic-industry collaboration, IODP supported a logging-while-coring system that measures an electrical image of the borehole while taking a core sample, thereby enhancing core log integration. SOD also developed formation temperatures tools and is the global source of deep temperature data for the sub-seafloor. Large-diameter drill pipe (6-5/8") will in the future allow for development of better pore fluid sampling and formation testing, geochemical logging, nuclear magnetic resonance for pore size distribution, and high-coverage electrical imaging.

Gas hydrates and associated logging and sampling tools is an area where SOD has led the initial research and development. Hydrates are unstable at surface conditions. Through core-log integration an estimate of gas hydrate content that is continuous at depth can be made. An SOD-developed pressure core sampler (PCS) paved the way for recovery of gas hydrate to the surface without sublimation of the hydrate. SOD partners (including Geotek Ltd) then developed the PCS into the HYACINTH for in situ pressure and temperature-preserving sampling tool for gas hydrates. This tool is pivotal in the many governmental and commercial investigations of gas hydrates as a possible new hydrocarbon energy source.

In 2009 SOD took borehole-hosted vertical seismic profiling (VSP) to a new level by conducting a wide-angle, semi-3D walk-away experiment over the drill site location offshore Japan that is targeted for ultra-deep (7 km) riser drilling and instrumentation of a seismic plate boundary. In this location SOD activities eventually will enable surface 3D seismic data, advanced VSP data, borehole logging, sampling, and long-term borehole observatory data to be integrated in a unique collage of plate-boundary data.

## DEEP EARTH OBSERVATORY SCIENCE

Following successful advances in downhole sampling and logging, the concept of actually installing downhole observatories that could sample time series (e.g., fluids, pressure, and temperature) was introduced during the ODP by the CORK (Circulation Obviation Retrofit Kit) concept. IODP is making big strides toward establishing a permanent presence of subseafloor observatories within critical ocean floor locations, and with a vastly expanded set of observations. These include time-series of pore water geochemistry from osmosamplers (resolution of ~a few days) and geochemical tracer flow-meter allowing estimates of lateral fluid flow rates; microbiological observatory elements into hydrological observatories via use of substrates; vastly improved pressure resolution (order of 1 ppb full scale) as a sensitive proxy for strain, and with sampling frequency <1Hz linking deformation to seismological data; and tilt meter and seismic broadband sensors. Implementation protocols to co-locate multiple sensors for hydrological-geodetic-seismological purposes or hydrological-thermal-microbiological purposes are being developed and planned for upcoming experiments.

Extending these subseafloor observatories to the high-pressure and -temperature regimes at 6-7 km depth (seismogenic zones) is currently under development, and links to land by fiberoptical networks for real-time monitoring are being implemented offshore Japan and Northwest America in two seismically active zones. This SOD development is in cooperation with and co-funded by other entities and programs. These novel technologies, combined with the experience gained to implement them via drillships, submersibles, and remotely operated vehicles (ROVs), underpins a new scientific paradigm of observing processes as they happen (as opposed to simply studying the lasting imprint of processes in the geological record). Naturally, the new science plan (in preparation) for SOD beyond 2013 makes this emerging field of "Earth in Motion" science one of its four grand challenges.

## SOD STUDY OF ACTIVE LIFE BELOW THE SEAFLOOR

Rapid and ongoing technology development underpins another emerging field of science: the study of active microbial life, below, in part deeply below (~1,600 m), the seafloor (a second grand challenge of the new science plan). Technology development in this field takes place globally, and with many different entities and constituencies involved. Special contributions by SOD, apart from making sampling possible, are laboratories (on platforms and at core repositories), protocols for clean sampling, curation processes and storage (long-term and legacy), computer-automated cell counts (living cells), and DNA replication from limited amount of material. Initial findings and technology developments by SOD have generated very significant spin-off activities by other groups.

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## DRILLING THE OCEAN CRUST

Henry J. B. Dick
*Woods Hole Oceanographic Institution*

Formation of the ocean lithosphere is the principle magmatic process on the planet, generating some three-fifths of the Earth's crust by surface area and representing the major transfer of heat, mass, and volatiles between the Earth's interior, crust oceans, and atmospheres. At the present time we do not have direct knowledge of the composition of the ocean crust or a full understanding of how it forms. What we do know is largely the result of ocean drilling both in intact sections of the ocean crust and in tectonic windows where the lower ocean crust and mantle have been unroofed to the seafloor. The initial stimulus for drilling was to test two competing models for the ocean crust, which at the time was assumed to be a relatively simple layered sequence some 6-7 km thick. Harry Hess, in his landmark paper, *History of the Ocean Basins* (Hess, 1962), proposed that the ocean crust largely consisted of mantle peridotite hydrothermally altered to serpentine with the Mohorovičić discontinuity (Moho) representing the upper temperature limit for the stability of this mineral. The opposing model, which had gained general acceptance from the Earth sciences community, was a layer cake consisting of pillow lavas overlying sheeted dikes and gabbro, with the Moho representing the igneous crust-mantle boundary. In the latter, known as the Penrose ophiolite model (Conference Participants, 1972) the lower ocean crust represented the remains of a large magma chamber in which mantle melts pooled and underwent fractional crystallization, while the dikes represented the conduits through which differentiated magmas erupted to the seafloor to form a layer of pillow lavas. Obvious differences in the morphology of the seafloor between relatively low relief smooth seafloor formed at the fast spreading East Pacific Rise (EPR) and slower spreading ridges were largely ignored in this model.

The ultimate goal of ocean drilling initially was to achieve a full penetration of the crust from pillow lavas to mantle. Given the presumed simplicity of the ocean crust, a single core would answer all questions. A total penetration of "intact" crust has not been achieved, although we now know that it is technically feasible given the will. Thirty-five years of ocean drilling, in combination with seafloor mapping, however, has radically transformed our view of the ocean crust, which is now viewed as highly varied in composition and architecture, with radically different models for fast and slow spread crust. Ironically, both the Hess and the Penrose models have proved to describe the ocean crust as it forms under different tectonic conditions. The mechanisms of accretion of the lower crust now believed to exist are also radically different from the simple closed-system magma chamber that was the widely accepted paradigm at the start of ocean drilling, with direct intrusion of numerous small magma bodies, an absence of large magma chambers, melt-rock reaction, mass transfer by upward percolation of melts through the lower crust, and vertical rafting of intrusions and altered mantle peridotite all having been recognized as major accretionary processes.

Ocean crust drilling began in earnest in 1974 with Leg 37 of DSDP (Deep Sea Drilling Project), which drilled a four hole transect at 37°N on the Mid-Atlantic Ridge (MAR) in shallow ocean crust from 3.5 to 13 myr. The sites included a planned deep hole at Site 332 that penetrated 583 m before abandoned. At Site 334, a tectonically emplaced layer of serpentinized peridotite and gabbro was recovered beneath 50 m of pillow basalts. Ironically, this first in situ section of lower crustal rocks proved to be atypical of what was later drilled on seven legs in the Pacific, Atlantic, and Indian Oceans. In all, about 50 holes were drilled into "intact" sections of oceanic crust up to the start of the Integrated Ocean Drilling Program (IODP) in 2004, when it was believed that layered crust, such as described in the Penrose model, existed in the Atlantic and Pacific Oceans. At Hole 504B south of the Costa Rica Rift, and possibly at Hole 418A in the 108-million-year-old MAR crust, seismic layer 2B was penetrated, with only Hole 504B possibly reaching the very top of seismic layer 3 (Dick et al., 1992; Alt et al., 1993; Detrick et al., 1994). Drilling in young Pacific crust was particularly difficult, with 10 holes in crust less than 30 million years old reaching a maximum penetration of only 178 m—a result attributed to the difficulty of drilling abundant glassy sheet flows. Success was better at slower-spreading ridges, with 11 holes penetrating greater than 200 m, and 7 reaching greater than 500 m. This drilling showed that seismic layer 2A was composed of basalt lavas and rubble, and that at an intermediate spreading ridge, seismic layer 2B at Hole 504B was sheeted dikes as in the Penrose model. Unexpectedly, however, the layer 2B-layer 3 seismic boundary there corresponded to an alteration front in dikes, rather than the dike-gabbro transition. Surprisingly, short sections of often brecciated serpentinized peridotite and gabbro, exhibiting high-temperature alteration and crystal-plastic deformation, were found in six Atlantic holes drilled in supposedly "intact" crust. Drilling at slow spreading ridges demonstrated unexpected tectonic complexity that did not fit the Penrose model and proved a harbinger of things to come.

The early failure to drill deeply into intact oceanic crust was a huge disappointment. Recoveries were low, averaging ~20 percent. Other than sporadic drilling at Hole 504B, no serious attempt to drill ocean crust was made for many years after DSDP Leg 53 in 1977. Drilling difficulties were attributed to highly fractured basalt and diabase and possibly thermal problems deep in Hole 504B, although these were likely due as much to not properly designing holes for deep penetration. Thus, a new strategy was adopted during the Ocean Drilling Program (ODP), using "tectonic windows" to drill lower crust and mantle (Dick, 1989; Dick and Mével, 1996). This drilling strategy targeted peridotite and gabbro exposed at topographic highs at oceanic core complexes: Atlantis Bank on the Southwest Indian Ridge; the MARK area at 23°N; the MAR Atlantis Massif and tectonic blocks in the rift mountains near the 15°20′ fracture zone; and Hess Deep in the Pacific, where the amagmatic tip of the Cocos-Nazca rift propagates into young (1.5–2 million-year-old) EPR crust.

Drilling at Hess Deep recovered important sections of tectonically disturbed lower crust and mantle that was consistent with the Penrose model. These sections included the important Hole 894G 154-m section of fine-grained gabbros with a few diabase dikes, which are believed to represent a section of lower crust formed in the melt lens beneath the EPR and resembled part of the Oman Ophiolite section. They are believed to be the precursor to a similar thick underlying gabbro section. The gabbros are too evolved, however, to represent crystallization products of the relatively primitive pillow basalts that characterize the East Pacific Rise, in conflict with the generally accepted hypothesis that the melt lens is their primary source. A second result was a series of holes at Site 895 that represent a transect across a melt transport conduit through a mantle section. The host peridotites were highly depleted residues of partial melting, consistent with a fractional melting model, while the dunite conduits contained gabbroic segregations that demonstrated for the first time that the mid-ocean ridge basalt (MORB) is formed within the mantle itself, rather than representing mixing of diverse magmas in a lower crustal magma chamber. The segregations also showed that basaltic melts can crystallize at near constant temperature by reaction with the host mantle—a result whose importance was not fully appreciated until analysis of the Hole 1309D gabbro section in the Atlantic. One of the great successes of IODP has been the penetration of an intact section of EPR crust down to the dike-gabbro transition at Hole 1256 penetrating 1257.1 m of the upper crust, including a 345.7 m sheeted dike complex and 100.5 m into gabbro near the depth predicted by seismologists for the layer 12-3 boundary. Besides affirming the results from Hess Deep, Hole 1256D proved the hypothesis that the shallow ocean crust (dikes and lavas) thins at the fastest spreading rates, confirming the utility of seismology in shallow Pacific crust.

Drilling lower crustal rocks in tectonic windows at slow and ultraslow spreading ridges is one of the dramatic successes of ODP and IODP. Hole 735B penetrated 1,508 m of gabbro at the Atlantis Bank core complex on the southwest Indian Ridge, while Hole 1309D penetrated 1,415 m at the Atlantis Massif on the MAR. Recovery was ~87 percent of both sites. These successes show unequivocally for the first time that thick gabbro sequences do exist at slower spreading ridges, but that they are the remains of numerous small intrusive swarms, not of large magma chambers. Moreover, the sections are riddled with microgabbro dikes and solution channels representing melt transport from depth through preexisting gabbro. Equally startling is a superimposed igneous stratigraphy produced by upward compaction of interstitial melt to produced numerous high-level Fe-Ti rich oxide gabbro layers. In addition, olivine-rich troctolites occur in the mid-section at Hole 1309D. These rocks form by reaction between basalt melt and mantle peridotite at the base of the crust, and are subsequently mechanically rafted up through the section (Drouin et al., 2007a, b, 2009; Suhr et al., 2008). Overall, the large majority of gabbros drilled at these sites and by Leg 153 at MARK are far too evolved to crystallize directly from MORB. Thus, to date, we have not recovered anything like the full lower crustal suite at either slow or fast spreading ridges, which is critical, because until we do we will have only indirect knowledge of the processes that shape MORB—the most abundant magma on earth.

Leg 209 examined what was once thought to be atypical ocean crust. It is drilled 19 holes at eight sites from 14°43′N to 15°39’N on the MAR where dredging found extensive mantle outcrops intruded by small gabbro bodies. This finding led to the hypothesis that the crust was largely serpentinized peridotite with local small magmatic centers cut by small dike swarms and local eruptive sequences (Cannat et al., 1997, 2006). This was what Leg 209 drilled, confirming the existence of crustal sections that form by direct intrusion and hydrothermal alteration of mantle rock along a significant portion of slower spreading ridges. Moreover, the crust consisted of one tectonic block cutting another with alternate fault capture, leading to spreading of blocks in opposite directions from the rift valley (Schroeder et al., 2007)—a new form of seafloor spreading, which morphological analysis of the seafloor suggests makes up a substantial portion (~40 percent) of the crust at slower spreading ridges (e.g., Escartin et al., 2008).

Drilling in lower crust at slower spreading ridges shows that its accretion occurs by mechanisms previously not considered: direct intrusion of small batches of melts at all levels, upward compaction of interstitial melts by permeable flow, and rafting of deeper intrusions and material formed by reaction between melts and mantle at the base of the crust. Moreover, it has also shown that both Penrose- and Hess-type sections exist along slow and ultraslow spreading ridges.

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## LARGE IGNEOUS PROVINCES

Millard F. Coffin
*University of Tasmania, Australia*

Large igneous provinces (LIPs)—oceanic plateaus, volcanic rifted margins, and continental flood basalts—result from fundamental processes in Earth's interior and have been implicated as a cause of major worldwide environmental changes. Although the plate tectonics paradigm successfully explains volcanic activity on Earth's surface associated with seafloor spreading and plate subduction, it does not elucidate the massive "hotspot" volcanism that produces LIPs, which dominates the record of volcanism on all other terrestrial planets and satellites in our solar system and the cause of which is debated vigorously. Temporal correlations between LIP emplacements and environmental phenomena such as mass extinctions and oceanic anoxic events (OAEs) are well documented, yet the underlying mechanisms causing these global catastrophes are only beginning to be grasped. Scientific ocean drilling has played a central and critical role in illuminating solid Earth processes causing LIPs and in comprehending the effects of LIP formation on Earth's environment.

Reconnaissance drilling of oceanic plateaus and volcanic rifted margins began soon after scientific ocean drilling started in 1968, but the first targeted LIP investigations involving drilling, focusing on the ~55 Ma North Atlantic volcanic rifted margins, commenced in the 1980s. Drilling on the UK margin confirmed a hypothesis that submarine "seaward-dipping reflectors" (SDRs) observed on seismic reflection data were stacks of originally subaerial lava flows that subsequently cooled and subsided beneath sea level, where they were buried by sediment—a nearly ubiquitous characteristic of submarine LIPs that precludes their volcanic and plutonic rocks from being sampled by any means other than drilling. Further focused drilling of the North Atlantic LIP, on the Norwegian Margin in the 1980s and the conjugate East Greenland Margin in the 1990s, documented extreme magmatic productivity over a distance of at least 2,000 km during continental rifting and breakup, provided the first age data from an oceanic LIP showing that construction of these margins was geologically "instantaneous" (ca. 1 million years), and yielded geochemical evidence that landward SDRs were contaminated during ascent through continental crust and that oceanward SDRs formed at a seafloor spreading center resembling Iceland. A proposed mechanism for these ~55 Ma magmas triggering the Paleocene-Eocene Thermal Maximum is intrusion of voluminous mantle-derived melts into carbon-rich sedimentary strata in the northeast Atlantic that caused explosive release of methane into the ocean and atmosphere via hydrothermal vent complexes. More than 50 percent of passive margins globally are "volcanic," but to date scientific ocean drilling has only sampled the North Atlantic LIP at one site.

Focused investigations of oceanic plateaus have targeted the two largest features globally, the ~120 Ma Ontong Java Plateau (Pacific Ocean) and ~120-95 Ma Kerguelen Plateau/Broken Ridge (Indian Ocean), each encompassing an area approximately one-fourth the size of the contiguous United States. Several expeditions have drilled multiple holes penetrating the igneous basement of each. In late 2009, igneous basement of a third oceanic plateau, the ~145-130 Ma Shatsky Rise (Pacific Ocean), was drilled in various locations. These three features constitute the only oceanic plateaus where igneous basement has been drilled at more than one site.

Drilling results from Ontong Java Plateau basement rocks are complemented by studies of obducted plateau rocks exposed in the Solomon Islands. All basement rocks recovered to date are remarkably homogeneous—submarine tholeiitic basalts with minor variations in elemental and isotopic composition. Partial batch melting (≥30 percent) generated the basalts, with melting and fractional crystallization at depths of <6 km. The lavas and their overlying sediment indicate relatively minor uplift accompanying emplacement and relatively minor subsidence since emplacement. Primarily on the basis of drilling results, multiple models—plume, bolide impact, and upwelling eclogite—have been proposed for the feature's origin. The Ontong Java Plateau correlates temporally with oceanic anoxic event (OAE-1a), and interpretation of strontium, osmium, and lead isotopic systems during the time of OAE-1a points to a close linkage between the two, with $CO_2$, Fe, and trace metal emissions from the massive magmatism potentially triggering the event.

Uppermost igneous basement of the Kerguelen Plateau/Broken Ridge is dominantly subaerial tholeiitic basalt, and it shows two apparent peaks in magmatism at 119-110 Ma and 105-95 Ma. Geochemical differences among these basalts are attributable to varying proportions of components from the primary mantle source (plume?), depleted mid-ocean ridge basalt (MORB)-related asthenosphere, and continental lithosphere. Proterozoic-age zircon and monazite in clasts of garnet-biotite gneiss in a conglomerate intercalated with basalt at one drill site demonstrate the presence of fragments of continental crust in the Kerguelen Plateau, inferred previously from geophysical and geochemical data. For the first time from an intra-oceanic LIP, alkalic lavas, rhyolite, and pyroclastic deposits were sampled. Flora and fauna preserved in sediment overlying igneous basement record long-term plateau subsidence, beginning with terrestrial and shallow marine deposition and continuing to deep water deposition. The first results of 2009 basement drilling on the Shatsky Rise include evidence for initial shallow water or subaerial eruption of predominantly massive lava flows, subsequent deeper water eruption of mainly pillow lava flows, and post-emplacement subsidence resembling that of normal oceanic crust.

Future LIP drilling has the potential to transform our understanding of the Earth system through investigating:

(1) magma (and hence mantle source) variability through time, through drilling deep sections in multiple LIPs; (2) the nature of melting anomalies, i.e., compositional vs. thermal, that produce LIPs; (3) the precise durations of oceanic LIP events; (4) modes of eruption, i.e., constant effusion over one to several million years, or several discrete pulses over the same time interval; and (5) relationships among oceanic LIPs, OAEs, extinction events, and other major environmental changes (e.g., ocean acidification and fertilization). The 2010 Eyjafjallajökull eruption underscores the nascent state of and need for knowledge of the first four pathways of investigation above, and results from the last will contribute to understanding and forecasting regional and global environmental changes during the Anthropocene.

Advancing knowledge of LIPs and the Earth system requires integrated multidisciplinary and cross-disciplinary approaches involving mantle geodynamics, plume modeling, petrology, geochemistry, environmental impacts, paleoceanography, micropaleontology, physical volcanology, geophysics, and tectonics. Drilling and logging are critical tools for most of these disciplines. Oceanic LIPs must be studied in concert with continental counterparts to better understand emplacement mechanisms and environmental effects of their formation. Needed technology developments include better recovery of syn-sedimentary sections, sidewall coring, oriented cores, and controlled circulation drilling in water depths >2,500 m. The oceanic and continental drilling communities should merge efforts for seamless thematic and onshore/offshore investigations, and LIP-focused IODP-industry collaborations should be enhanced.

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# CONTINENTAL BREAKUP AND SEDIMENTARY BASIN FORMATION

Dale S. Sawyer
*Rice University*

In the study of continental breakup (and other large-scale tectonic systems), scientific ocean drilling is not a capstone activity, but rather is part of an iterative process comprising drilling, improved geophysical (primarily controlled source seismology) and geological (including onshore exposures where available) characterization, ongoing geodynamic modeling, and drilling again. Continental breakup and ensuing seafloor spreading inherently separate the "field area" for a study into a pair of conjugate rifted margins. Typically both margins must be studied comprehensively to learn about the whole. Every rifted margin is a blend of end-member types: (1) magma-dominated or magma-poor, (2) actively rifting or no longer rifting, (3) normal spreading, obliquely spreading, and transform, and (4) sediment-dominated or sediment starved. Examination of any single rifting system cannot reveal details of all the important breakup processes. Successful drilling studies will include geodynamic modeling efforts before, during, and after each coordinated drilling activity

In 1991, the Ocean Drilling Program (ODP) Planning Committee formed a North Atlantic Rifted Margins Detailed Planning Group (NARM-DPG) with a charge to explore options and make recommendations for conducting drilling on volcanic and non-volcanic conjugate rifted margins. The NARM-DPG recommended that ODP efforts focus on the Newfoundland-Iberia conjugate pair for studies of magma-poor rifting and the southeast Greenland–northeast Atlantic for studies of magma-dominated rifting.

Drilling on the magma-poor Newfoundland and Iberia rifted margins comprises DSDP (Deep Sea Drilling Project) Leg 47 and ODP Legs 103, 149, 173, and 210. DSDP Leg 47B (Sibuet and Ryan, 1979) drilled a deep sedimentary hole that provided stratigraphic information about the breakup of Newfoundland and Iberia. ODP Leg 103 (Boillot and Winterer, 1988) drilled a transect across the Deep Galicia Basin and demonstrated that (1) a prominent seismic reflector "S," later to be characterized as a detachment fault, is within or overlain by rotated, fault-bounded blocks of continental crust, (2) peridotite, which ascended from 30 km depth and shows a history of partial melting, stretching, serpentinization, and fracturing, is exposed in a margin parallel ridge at the foot of the margin, and (3) obtained dates for the syn- and post-rift sediments reflect the last stage of breakup. ODP Leg 149 (Whitmarsh and Sawyer, 1996) drilled a transect across the Iberia Abyssal Plain margin segment. Peridotite was again sampled at the top of a ridge, providing additional information about its exhumation history. However, serpentinized peridotite was also sampled 20 km to the east of the peridotite ridge, indicating that there is a wide zone of upper mantle rocks exhumed to the seafloor and presumably separating extended continental crust from oceanic crust. Some of the sampled peridotite contained strong remnant magnetization, explaining the presence of apparent seafloor spreading anomalies over crust that is not oceanic. ODP Leg 173 (Whitmarsh and Wallace, 2001) showed that the continental crust was thinned to nearly zero thickness by low-angle detachment faulting, which in some places brought upper mantle peridotite to within a few hundred meters of the seafloor at the time of breakup. The peridotites are most likely to be subcontinental mantle. Mafic cores were shown to have been emplaced in or just below the thinned lower continental crust. Surprisingly no samples of upper continental crust or synrift melt were obtained, which is attributed to gradual breakup and transition to seafloor spreading. During Leg 173 shipboard scientists noted strong similarities between cores obtained from the Iberia Abyssal Plain and the character and history of rifted margins and transition zones exposed in the modern Alps (Manatschal and Bernoulli, 1998). This line of research has been very fruitful in expanding our understanding of both systems. ODP Leg 210 (Tucholke and Sibuet, 2007) drilled off Newfoundland in a position conjugate to the Legs 149/173 transect. The primary site bottomed in a pair of diabase sills dated at 98 and 105 Ma. The upper sill is intruded at the level of the prominent and widespread "U" reflection, suggesting that sills may be pervasive at this stratigraphic level. No equivalent to these sills was observed on the Iberia Margin. A second site off Newfoundland sampled exhumed peridotite in a shallow basement high that is similar to peridotites sampled off Iberia. As in Iberia, these peridotites showed little evidence of melting even though they were coincident with apparently normal lineated magnetic anomalies.

Extensive reinterpretation of seismic profiles after Legs 173 and 210, synthesis of Alps analogs (Peron-Pinvidic et al., 2007), comparison to drilling results, comparison to slow spreading midocean ridge analogs (Cannat et al., 2009), and geodynamic modeling (Lavier and Manatschal, 2006) has led to a new understanding of the Newfoundland–Iberia breakup (Peron-Pinvidic and Manatschal, 2009). This understanding moves past thinking of continental breakup as mono-phase and laterally uniform rifting followed by an abrupt breakup and formation of a sharp continent-ocean boundary. The new model describes rifting as a process of progressive strain localization, stacking different modes of extension in temporally and spatially varying domains. It defines the end of rifting and onset of seafloor spreading neither as a moment in time, nor a mappable boundary, but as a transition zone in which a series of processes interact and overlap in complex ways. Features that we could not explain are now comprehensible. Furthermore, this new understanding is revolutionizing the way academic and petroleum industry scientists interpret other magma-poor rifted margins around the world (Reston, 2009).

Drilling on the magma-dominated southeast Greenland and northeast Atlantic volcanic margins comprises DSDP Legs 38 and 81 and ODP Legs 104, 152, and 163. DSDP Leg 38 (Talwani and Udintsev, 1976) found that acoustic basement of Vøring Plateau was composed of basaltic volcanics. DSDP Leg 81 (Roberts et al., 1984) drilled Rockall Margin, suggesting that seaward dipping reflectors (SDRs) were subaerial volcanic constructions. ODP Leg 104 (Eldholm et al., 1989) drilled 900 m of subaerial flows of the SDR at the Vøring Margin and was able to characterize events during the initial opening of a volcanic margin. ODP Leg 152 (Larsen and Saunders, 1998) drilled a transect of holes across the southeast Greenland SDR from the middle shelf to deep water. They distinguished continental and oceanic flow sequences and located the seaward extent of rifted continental crust. They showed that the SDR overlies fully oceanic crust and that it formed in the manner of the present-day Iceland rift zone. They were able to infer features of the plume associated with the formation of the margin. ODP Leg 163 (Larsen and Duncan, 1996) was not able to achieve its primary tectonic objectives because of "a drilling accident and damage to the ship sustained during extreme storm conditions" (Initial reports 163). During this period of drilling, 1976 to 1995, and complementary seismic, geological, and modeling studies, the understanding of magma-dominated continental breakup moved forward, as did our conception about the global extent and importance of these margins and large igneous provinces, their counterpart in the oceans.

Future opportunities in the study of continental breakup will depend not just on access to ocean drilling, but also on coordinated high-quality, two- and three-dimensional multichannel seismic reflection profiling and companion long-offset seismic surveys. The INVEST report mentions several times the need for increased collaboration with industry. The study of continental breakup is one of the most obvious and important touch points between academic and industry science.

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# Acronyms

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| ACEX | IODP Arctic Coring Expedition |
| APC | Advance Piston Corers |
| ANDRILL | ANtarctic Geological DRILLing Program |
| BOP | Blowout Preventers |
| C-DEBI | Center for Dark Energy Bioshpere Investigations |
| COL | Consortium for Ocean Leadership |
| CORK | Circulation Obviation Retrofit Kit |
| COSOD | Conference on Scientific Ocean Drilling |
| DSDP | Deep Sea Drilling Project |
| DSDP IPOD | DSDP International Phase of Ocean Drilling |
| DVTP | Davis-Villinger Temperature Tool |
| ECORD | European Consortium for Ocean Research Drilling |
| ENSO | El Niño-Southern Oscillation |
| GPTS | Geomagnetic Polarity Timescale |
| GeoPRISMS | Geodynamic Processes at RIfting and Subducting MarginS Program |
| HYACE | HYdrate Autoclave Coring Equipment |
| HYACINTH | (Deployment of HYACE tools) In New Tests on Hydrates |
| HPC | Hydraulic Piston Coring |
| ICDP | International Continental Scientific Drilling Program |
| IODP | Integrated Ocean Drilling Program |
| IPCC | Intergovernmental Panel on Climate Change |
| JOI | Joint Oceanographic Institution |
| JOIDES | Joint Oceanographic Institutions for Deep Earth Sampling |
| K-T | Cretaceous-Paleogene boundary |

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|---|---|
| LIP | Large Igneous Province |
| Moho | Mohorovičić discontinuity |
| NanTroSEIZE | Nankai Trough SEIsmogenic Zone Experiment |
| NOAA | National Oceanic and Atmospheric Administration |
| NRC | National Research Council |
| NSF | National Science Foundation |
| ODP | Ocean Drilling Program |
| OOI | Ocean Observatories Initiative |
| PETM | Paleocene Eocene Thermal Maximum |
| RPI | Relative PaleoIntensity |
| SEIZE | SEIsmogenic Zone Experiment |
| SDR | Seaward Dipping Reflectors |
| TAG | Trans-Atlantic Geotraverse |
| TAMU | Texas A&M University |
| USIO | IODP-U.S. Implementing Organization |