Illuminating Earth’s Past, Present, and Future

THE INTERNATIONAL OCEAN DISCOVERY PROGRAM
EXPLORING THE EARTH UNDER THE SEA

SCIENCE PLAN FOR 2013–2023
Science Plan Writing Committee

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

Liaisons

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

INVEST Steering Committee

Wolfgang Bach (Co-Chair), University of Bremen
Christina Ravelo (Co-Chair), University of California, Santa Cruz
Jan Berrman, IFM-GEOMAR
Gilbert Camoin, Centre Européen de Recherche et d’Enseignement des Géosciences de l’Environnement
Robert Duncan, Oregon State University
Katrina Edwards, University of Southern California
Sean Gulick, The University of Texas at Austin
Fumio Inagaki, Japan Agency for Marine-Earth Science and Technology
Heiko Pälike, University of Southampton
Ryuji Tada, University of Tokyo

Additional Contributors, continued

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

External Reviewers

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

Editing and Design

Ellen Kappel and Johanna Adams, Geosciences Professional Services, Inc.
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SCIENCE PLAN FOR 2013–2023
Development of this Science Plan

Planning for the International Ocean Discovery Program began in early 2009 with the solicitation of input from the international community on scientific topics that could be addressed by a new ocean drilling program. In September 2009, approximately 600 scientists from 21 nations gathered at the INVEST conference in Bremen, Germany, to discuss and refine a set of scientific questions that require drilling and associated capabilities deep below the ocean floor (go to http://www.marum.de/Page7894.html to download a full copy of the INVEST report). Subsequent to this meeting, a science plan writing team was assembled, consisting of scientific leaders from Integrated Ocean Drilling Program member countries or consortia having expertise in geology, geophysics, geobiology, paleoclimatology, climate modeling, and geochemistry. This writing committee circulated an early draft of the science plan for community review and comment in late 2010. In early 2011, an external panel reviewed a revised draft, and additional comments and discussions contributed to substantive revision as the final document was prepared. This process demonstrates the foundational strength of scientific ocean drilling: the community’s ability to think big, challenge itself, and incorporate diverse ideas through a rigorous process of peer review and prioritization.
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All parts of the Earth system—the solid Earth, hydrosphere, atmosphere, cryosphere, and biosphere—are linked through flows of mass, energy, and life. Interactions between these realms have affected the development and evolution of our planet, and ultimately determined its habitability through time. Buried beneath the ocean floor are records of millions of years of Earth’s climatic, biological, chemical, and geological history. Scientific ocean drilling permits researchers to access these records and explore, analyze, theorize, and test models that describe how Earth works. Scientific ocean drilling also enables collection of subseafloor fluids, microbes, and geophysical and geochemical data by instrumenting boreholes, and using networks of boreholes for active experiments to resolve important properties and processes. As a growing global population demands more resources and a better understanding of geological hazards and ongoing and future climate change, access to data and samples acquired through scientific ocean drilling is essential.

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

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

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

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

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

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

**Biosphere Frontiers** includes exploration of deep life within the subseafloor, where microbes isolated from the photosynthetic world live at the limits of habitability. Subseafloor biosphere studies have evolved from early exploratory work to systematic broad-based research on genomics, habitats, ecological niches, and metabolic pathways. These studies are being facilitated by rapid developments in DNA technology, complex lipid analysis, and other techniques. Scientific ocean drilling will also investigate ecosystem response to environmental forcing. Samples and data will be recovered.
from periods when climate and ocean chemistry changed dramatically on relatively short time scales. Drilling will address the impacts of such events on individual microorganisms to whole ecosystems, including hominid evolution.

**Earth Connections** examines the links between surface, lithospheric, and deep Earth processes. Enhanced drilling capabilities are essential for extending the vertical dimension of subseafloor studies, permitting recovery of pristine samples of Earth’s upper mantle. Reactions between seawater and the ocean floor depend on crustal structure that, in turn, depends on geodynamic processes that are poorly understood. For instance, the oceanic crust takes up CO₂ during reaction with seawater, but at rates and in locations that are weakly constrained by observations. These processes determine how much CO₂ and water are fed into subduction zones, where their return to the surface influences volcanic and hydrothermal processes. Volcanic outputs, in turn, can be used to test models of subduction initiation and the transformation of ocean island arcs into continental crust. Drilling is an essential tool for unraveling and understanding the geologic, geochemical, magmatic, and hydrological processes responsible for development and evolution of these solid Earth systems.

**Earth in Motion** addresses dynamic processes that occur on human time scales, including those leading to and resulting from earthquakes, landslides, and tsunami. Scientific ocean drilling will resolve the frequency, magnitude, mechanisms, and impacts of these events, including changes of in situ properties during the earthquake cycle related to fault rupture. This theme also explores fluid flow in seafloor sediments and volcanic crust, formation and stability of gas hydrates, and the potential for sequestering large quantities of CO₂ in deep-sea reservoirs. Earth in Motion studies will use real-time observations from individual and linked networks of long-term, subseafloor observatories installed in boreholes. These systems provide the only means to collect pristine fluid and microbial samples from the volcanic oceanic crust. They can also yield critical information on the accumulation of stress and resulting strain, large-scale crustal movements, and links between these processes and fluid transport at scales of seconds to decades. Observatory networks will be linked to land using cables for real-time monitoring and experimental response to active Earth processes.

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

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

**Training the Next Generation of Scientists**

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

**Fostering Stewards of the Planet**

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

**Informing and Inspiring the Public**

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

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

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

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

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

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Table 1.1. List of publications

<table>
<thead>
<tr>
<th>Publication Dates</th>
<th>All Peer-Reviewed Publications</th>
</tr>
</thead>
<tbody>
<tr>
<td>1968–1974</td>
<td>18 14 1582</td>
</tr>
<tr>
<td>1975–1981</td>
<td>69 124 3616</td>
</tr>
<tr>
<td>1982–1988</td>
<td>95 163 4474</td>
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<tr>
<td>1989–1995</td>
<td>63 415 5835</td>
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<tr>
<td>1996–2002</td>
<td>75 568 5840</td>
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<tr>
<td>2003–2010</td>
<td>117 840 5464</td>
</tr>
<tr>
<td><strong>Totals</strong></td>
<td><strong>437 2124 26,811</strong></td>
</tr>
</tbody>
</table>

*Began publication in 2008

From 2003 to 2010, a total of 2,638 sample requests were made for IODP materials with 617,535 samples provided to the scientific community.
Ocean drilling has permitted shallow sampling of large igneous provinces, vast outpourings of lava that may have had a catastrophic influence on Earth’s climate, and that serve as windows into deep Earth processes.

Drilling has revolutionized understanding of continental breakup, faulting, rifting, and associated magmatism.

Scientific ocean drilling researchers and engineers have developed the first sub-seafloor borehole observatory systems, generating long-term samples and data records used to explore remote environments and processes.

Drilling allowed an initial assessment of what materials are recycled by subducting plates at convergent margins.

Drilling has begun to illuminate fault zone behavior and related tectonic processes at active plate boundaries where Earth’s largest earthquakes and tsunami are generated.

Scientific ocean drilling revealed large flows of fluids through virtually all parts of the seafloor, from mid-ocean ridges to deep-sea trenches.

Drilling demonstrated that a previously unknown biosphere exists within sediments as deep as 1.6 km below the seafloor, and within the volcanic carapace of the oceanic crust.

With its array of platforms, proven drilling, sampling, and long-term observational techniques, as well as the diverse range of science that can be addressed by studying Earth beneath the sea, the International Ocean Discovery Program will build on this legacy and accelerate the pace of discovery and understanding. The following four chapters of this plan describe 14 scientific challenges that the scientific ocean drilling community has identified as the most important to pursue during 2013 to 2023. Topics range broadly from how a changing climate impacts ocean ecosystems, sea level, and monsoons; to understanding the role that deep microbial ecosystems play in the global carbon cycle; to how mineral resources form and fluids move between the mantle, crust, and Earth’s surface; to resolving active processes at continental margins where earthquakes and other geohazards threaten the safety and livelihood of coastal communities. The chapters discussing these scientific challenges are followed by chapters describing education, outreach, and communications efforts, as well as the implementation strategy that will be used to make progress on the scientific goals, including required infrastructure and partnerships.
Population growth and the rising standard of living in our global society has led to vast increases in the need for food, water, energy, metals, novel biochemical compounds, and waste storage (e.g., CO$_2$, nuclear waste), among other resources. Energy security and strategic mineral supplies are major concerns of governments and industry worldwide. Covering over 70% of our planet, the seafloor is a potentially significant source of resources as well as a location for waste storage, if development is carried out responsibly.

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

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

Gas hydrates are one of the largest hydrocarbon reservoirs but their potential as an energy resource, or geohazard, requires improved understanding of their formation mechanisms, extent, and stability (Figure 5.4). Similarly, subseafloor environments of shale-hosted gas or coal-bed methane provide opportunities to understand the nature and role of microbial communities in generating and biodegrading hydrocarbons, as well as potentially providing environments for CO$_2$ storage. Ongoing and ancient reactions between the ocean and subseafloor basalt and peridotite may lead to alternative approaches for storing CO$_2$. Ocean drilling can undertake “proof of concept” experimentation that will be an essential precursor to industrial-scale testing.

Seafloor spreading centers host, albeit challenging-to-harness, geothermal reserves. Seawater reacts with mantle rocks, leading to the formation of H$_2$, and these abiotic hydrocarbons are targets for alternative energy research. Seawater-rock interactions can lead to the formation of major base (Cu, Zn, Pb) and precious metal (Au, Ag) and metalloid deposits, some of which have already been studied by ocean drilling. The extreme conditions (e.g., high temperatures, high/low pH, high salinity) in these and many other seafloor environments (e.g., deep sedimentary basins, mud volcanoes) have led to the evolution of highly adapted microbial communities with the potential to reveal novel chemical compounds of medical and industrial value. Photo courtesy of C. Yeats, Commonwealth Scientific and Industrial Research Organisation.
2. Climate and Ocean Change
Reading the Past, Informing the Future

CHALLENGES

1. How does Earth’s climate system respond to elevated levels of atmospheric CO₂?
2. How do ice sheets and sea level respond to a warming climate?
3. What controls regional patterns of precipitation, such as those associated with monsoons or El Niño?
4. How resilient is the ocean to chemical perturbations?

INTRODUCTION

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

Scientists are working to predict the response of the climate system to human-induced perturbations against this backdrop of natural climate variability. By integrating and assimilating data from ocean drilling cores with numerical models used to predict future climates, scientists are able to conduct “back-casting” experiments, allowing them to evaluate and improve model performance. Drilling data are particularly useful for understanding climate sensitivity and the nature and strength of climate feedbacks, helping to identify potential thresholds that could trigger rapid climate change. Development of ever more sophisticated analytical techniques is revolutionizing our ability to reconstruct past environmental conditions and allowing us to reduce uncertainties associated with these reconstructions (Box 2.1). Drilling strategies that include latitudinal, ocean floor sediment cores provide records of past environmental and climatic conditions that are essential for understanding Earth system processes.
longitudinal, and depth transects, combined with longer and more-detailed temporal records, will allow increasingly detailed reconstructions of the spatial and temporal patterns of past climate change.

Gaining a long-term perspective on the climate system’s response to greenhouse gases and other forcings is a goal shared with the Intergovernmental Panel on Climate Change (IPCC), the NSF Paleo Perspectives on Climate Change (P2C2) program, the International Geosphere-Biosphere Programme (IGBP), Past Global Changes (PAGES) project, EPOCA (European Project on Ocean Acidification), as well as numerous other observational ocean and atmosphere monitoring programs. In addition, collaborative polar paleoclimate programs include international ice coring efforts (such as the European Project for Ice Coring in Antarctica [EPICA]), integrated data-modeling initiatives like the Scientific Committee on Antarctic Research-Antarctic Climate Evolution (SCAR-ACE), and offshore efforts using alternative drill platforms including SHALDRIL (drilling along the Antarctic continental margin) and Antarctic Geological Drilling (ANDRILL). On land, synergistic paleoclimate efforts include the International Continental Scientific Drilling Program (ICDP), among others. Of all these programs, it is only through deep ocean drilling that we are able to recover time-continuous, high-resolution records of the warmer, higher-CO$_2$ climates of the deep past.
Warming in the high northern latitudes has accelerated in recent decades as atmospheric CO₂ concentrations have risen, resulting in substantially diminished summer sea ice cover in the Arctic Ocean and increasing loss of the polar ice sheets over Greenland and western Antarctica. These changes are occurring at a faster pace than previously predicted, suggesting that parts of the Earth system are more sensitive and dynamic than indicated by the current generation of climate models. The potential exists for climate thresholds to be exceeded, especially at high latitudes where snow and ice albedo feedbacks are strongest.

Understanding the risks of rapid climate change requires taking a long view of Earth’s response to increasing atmospheric greenhouse gases. The geologic record below the seafloor extends beyond the instrumental and ice core records of the recent ice ages, to more distant time periods when atmospheric CO₂ was comparable to today’s level (Figures 2.1 and 2.2) and to the much higher levels that are expected in the coming decades.

**Drilling and Research Strategy**

Scientific ocean drilling will allow us to explore conditions during past warm climate states at nearly all latitudes. Using new proxy methods that reveal a wealth of paleoenvironmental information (e.g., Figure 2.1), these studies will permit reconstruction of surface and deep ocean temperatures, ocean circulation, nutrient distribution, and ocean productivity. Importantly, multiple proxy methods can help us reconstruct ancient CO₂ levels beyond the age of the oldest ice cores, allowing us to study times characterized by the CO₂ levels predicted in the near future. These records of the ocean’s physical, chemical, and biological response to past changes in greenhouse gases will enable us to: (1) improve estimates of global climate sensitivity to both sustained higher levels of greenhouse gases and to dramatic transient perturbations to the carbon cycle; (2) determine the magnitude of ice sheet and sea ice loss due to elevated greenhouse gas concentrations, including the underlying mechanisms that amplify polar warming; (3) understand how tropical temperatures, upwelling regimes, and El Niño variability behave in a high-CO₂ world; and (4) identify key physical and chemical processes that need to be better represented in predictive climate system models (Box 2.1).

Providing mechanistic explanations for observations derived from ocean drilling has long been a challenge for the climate modeling community. While exciting advances have been made in recent years, a number of fundamental data-model conundrums remain. Foremost among them is that most IPCC-class climate models underestimate climate sensitivity (defined here as the equilibrated global temperature response to a doubling of CO₂) relative to paleoclimatic indicators from the last 160 million years. Differences between observations and simulations of past warmer climates are most profound in the polar regions, where the models tend to severely underestimate the warming inferred from paleoproxies. This potential for dramatic amplification of polar temperatures under elevated CO₂ conditions is important for predictions of sea ice and permafrost melting, and the future stability of ice sheets.

The differences between north and south polar geography (a polar ocean versus a polar continent) offer an opportunity for ocean drilling to help resolve the complex linkages among the polar ocean, atmosphere, and high-latitude land surface processes. Achieving this goal requires high-resolution sampling from carefully selected, temporally overlapping pole-to-pole drilling transects.
With such data we can better ground-truth Earth system models and quantify the strength of polar feedbacks. To date, a limited number of sites around Antarctica have been drilled, and only three deep-sea sites have been cored (to relatively shallow depths) in the central Arctic basin.

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

Some climate trends and events, including the extreme warmth 61–45 million years ago, gradual late Eocene cooling, and the sudden appearance of a continental-scale Antarctic ice sheet around 34 million years ago, are correlative with inferred trends in atmospheric CO₂, in keeping with fundamental climate theory and model-derived cooling-glaciation thresholds (Figure 2.2). Climate trends and events, including the extreme warmth 61–45 million years ago, gradual late Eocene cooling, and the sudden appearance of a continental-scale Antarctic ice sheet around 34 million years ago, are correlative with inferred trends in atmospheric CO₂, in keeping with fundamental climate theory and model-derived cooling-glaciation thresholds (Figure 2.2). Climate

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**BOX 2.1 | MODEL-DATA INTEGRATION**

Numerical climate, ocean, ice sheet, and Earth system modeling is becoming an increasingly important partner in ocean drilling research. Models can test data-driven hypotheses, provide physics-based explanations for observed phenomena, and fill spatial and temporal data gaps. They can also help guide the location of drilling targets, maximizing the potential for successful expeditions. In turn, data provided by drilling are needed to help reconstruct model boundary conditions and to evaluate model performance through comparison and testing. The goal is to iteratively improve both the models and the model/data calibrations. Ultimately, advancing models beyond basic climate scenario projections and toward prediction of our future climate change requires sufficient knowledge of Earth’s prior responses to natural fluctuations in greenhouse gases and other climate forcings. Ocean drilling provides the only true capability to explore Earth’s prior climate response to increases in atmospheric CO₂ levels that are on par with the increases occurring today.
change over the last 25 million years is more difficult to explain as a simple function of reconstructed CO₂ concentrations. For example, some Miocene CO₂ reconstructions (23–5.3 million years ago), derived from different proxy methods, show continually low concentrations (much like the last 2.6 million years). These low CO₂ concentrations make the relative warmth and presumed absence of orbitally paced Northern Hemispheric ice sheets during this time period enigmatic. However, other lines of evidence suggest that CO₂ levels during the Miocene were higher. This possible decoupling between CO₂ concentrations and climate variability over the last 25 million years may suggest an increased sensitivity to other climate forcings (e.g., tectonic or orbital) when background greenhouse gas concentrations are low and climate is relatively cool. For example, some climate feedback mechanisms, such as the strong positive snow/ice-albedo feedback, only operate in a climate cold enough to allow expansive continental snow cover, ice caps, and sea ice to exist, dramatically increasing the sensitivity of the poles to relatively modest forcings. Other greenhouse gases such as CH₄ and N₂O may also be important, perhaps varying in concert with CO₂. We know the relationship between CO₂ concentration and radiative forcing is logarithmic, so small changes in CO₂ may have a greater impact when initial concentrations are low. Improved confidence in CO₂ reconstructions for the pre-ice core era, when levels were comparable to where they will be in coming decades, will be critical for better constraining climate sensitivity.

Finally, during some intervals, like the mid-Pliocene warm period (3.3–3.0 million years ago), current proxy reconstructions suggest that atmospheric CO₂ levels were comparable to today (~30% higher than pre-industrial levels) (Figure 2.1). Yet, global mean sea
surface temperatures were measurably higher than at present (Figure 2.3). Ocean drilling has shown that warm tropical Pacific surface waters expanded both poleward and eastward, with average conditions in the eastern Pacific resembling a persistent El Niño-like state (see Challenge 3). At high latitudes, sea surface temperatures were also warmer than today, especially in the area of the North Atlantic and Norwegian-Greenland Sea that is critical for deepwater formation (Figure 2.3). A drilling strategy targeting locations ranging from polar seas to low-latitude upwelling zones is needed to explain the behavior of the climate system during past episodes of global warmth. This strategy must be combined with continued development of ever more reliable proxies. Ocean drilling data will test the capabilities of models to simulate warm climates, help identify latitudinal and regional model biases, and determine if underlying mechanisms responsible for climate states like the Pliocene are likely to occur in the future.
Mean sea level is expected to rise between 0.5 and 1.5 m by the year 2100, affecting coastal ecosystems and water supplies, and flooding densely populated coastal communities. In the last decade, most of the measured global mean sea level rise has been caused by thermal expansion of the ocean in response to global warming. In the future, melting of the Greenland and Antarctic ice sheets, containing the equivalent of ~64 m of sea level, pose a far greater threat. Satellite-based measurements show that the ice sheets have recently begun to lose mass at an accelerating pace (Figure 2.4). This melting is contributing about half of the current sea level rise, but ice sheets will become the largest contributor if the rate of mass loss continues to increase.

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

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

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

Through scientific ocean drilling we can reduce the uncertainties in our understanding of the magnitude and rate of past sea level change. Did large sections of the East Antarctic Ice Sheet collapse the last time atmospheric CO₂ levels reached 400 ppm? What are the time spans over which past ice sheet collapses occurred, and how much warming was required to push them past their “tipping points”? To answer these questions, we need cores from high-latitude shelf and slope sites where sediment accumulates rapidly (Figure 2.6). Recovered cores will resolve the timing and amount of sea level rise and, in conjunction with glacio-isostatic
modeling, the sources of the melting ice. This information is needed, along with land-based records, to constrain numerical ice sheet models that attempt to predict how ice sheets melt under warmer conditions. Such models, coupled with ocean and atmosphere general circulation models, will be crucial for projections of future sea level, with direct application toward planning for climate change impacts.

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

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

Figure 2.6. Proposed drilling strategy from pole to pole using International Ocean Discovery Program drilling platforms to collect records linking climate, ice sheet, and sea level histories on geologic time scales. The climate history derived from these records is used to ground-truth and test the performance of numerical ice-atmosphere-ocean models, thus improving their ability to project future sea level rise. Ice and coral records are best preserved over the last 100,000 years, Antarctic ice cores go back 850,000 years, and sediment records extend back tens of millions of years. Red arrows represent warm water flow beneath floating ice, recently recognized as a key factor in accelerating ice loss from West Antarctica. Elements of this figure were adapted from Schoof (2010).
overlapping sea level records recovered from a range of latitudes, in different tectonic and sedimentary settings and at varying distances from formerly glaciated regions. For example, samples from ancient coral reefs at a number of sites distant from former ice sheets will be necessary to constrain the total volume changes in land ice and the geographic partitioning of this volume between different ice sheets on different continents. Complementary drilling of open-ocean sediments at sites close to past ice sheets will provide more direct information regarding regional ice melt history and the timing of ice advance-retreat. Ultimately, the combination of these data with modeling techniques can be used to “fingerprint” the relative contributions of different ice sheets to past sea level change, providing more realistic scenarios for testing predictive models and a better understanding of ice sheet behavior in a changing world.
Episodes of warming in the eastern tropical Pacific Ocean, called El Niño events, bring devastating floods to some regions and drought to other regions around the globe. These events exemplify the vulnerability of water resources to small changes in ocean temperatures and highlight a pressing societal need to understand what factors control the global hydrologic cycle. Four billion people in Asia, India, and Africa rely on the regular return of the monsoon, yet it is unclear how increasing greenhouse gas concentrations and global temperatures will disrupt, or amplify, this cycle.

Drilling and Research Strategy

When Earth’s global average temperature shifts, temperature changes are not uniform. These changes have a regional complexity that result in changes in equator-to-pole and land-to-sea temperature gradients, as well as alterations in atmospheric and oceanic circulation, absolute humidity, and rainfall patterns. Scientific ocean drilling has yielded samples showing climate change during past warm periods such as the early to mid Pliocene (5–3 million years ago) when atmospheric CO₂ levels may have been about the same as today. At that time, warm tropical Pacific surface waters extended much further poleward and a permanent El Niño-like state existed in the equatorial region (characterized by the expansion of warm water southward over the upwelling zones off of Peru; compare top and bottom panels in Figure 2.8). If such a change were to occur again, it would have dramatic global hydrologic, economic, and social consequences (Figure 2.9).

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

Using ocean sediment cores (Figure 2.11), ice cores, and speleothems (cave stalagmites and stalactites), scientists have also identified...
rapid and extreme millennial-scale variations in regional sea surface temperature and precipitation. These climate shifts are often large relative to the interannual variability of the background state and occur quickly, on the order of years to centuries. Scientific ocean drilling will obtain paleoclimatic records that can be used to determine whether these climate shifts are triggered by small perturbations in radiative forcing (e.g., solar cycles, greenhouse gases) or whether they are tied to the intrinsic variability of an ocean-climate system whose behavior depends on its mean state. This drilling strategy has three components. First, by drilling continental margin sediments that contain terrestrial material transported by rivers mixed with marine sediment, it is possible to obtain continuous, well-dated records of both continental and oceanic change. New continental proxies offer great potential for obtaining detailed information regarding changes in terrestrial precipitation patterns and vegetation. By drilling ancient corals and sediments with annual layering, even seasonal to interannual climate variability will be examined within the context of long-term global climate change.

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

Third, ocean drilling will investigate the character of regional climate change across a range of time periods with different mean climatic states, solar forcing, and greenhouse gas concentrations. In this way, a mechanistic understanding of hydrographic...
Climate, in turn, can have a reciprocal impact on mountains, as cooling can lead to expansion of mountain glaciers, which further increases erosion and weathering, leading to additional exhumation and isostatic adjustment. Feedbacks also result from chemical weathering through its influence on the availability of dissolved nutrients and, therefore, enhanced biological productivity. Over multimillion-year time scales, variations in regional monsoon systems are inextricably coupled to tectonic processes. Study of the history of Asian or Indian monsoons will require recovery of physical and chemical weathering records contained in nearshore margin and fan sediments.

Finally, scientific ocean drilling will also explore the role that tectonic-climate interactions played in Earth system history. Tectonic uplift of mountains can influence atmospheric circulation and continental climate by altering the position of the jet stream, by enhancing land-sea temperature gradients, by increasing monsoon strength and seasonality in some areas, and by increasing aridity through the development of rain-shadow effects in other areas. Steeper topography also leads naturally to greatly increased rates of mechanical erosion that, when combined with enhanced orographic precipitation, result in greater rates of chemical weathering that consume atmospheric CO$_2$ and lead to global cooling.

change can be derived from data representing a large dynamic range of climate conditions and forcings, providing valuable insight into the possible future behavior of the hydrologic cycle.
Challenge 4 | How resilient is the ocean to chemical perturbations?

Human activity has led to dramatically increased fluxes of fossil fuel carbon and fertilizers into the atmosphere and ocean, resulting in profound and easily measurable chemical perturbations to the environment. CO₂ absorption by the ocean has led to surface water acidification, which is a threat to the health of numerous economically important marine ecosystems, including coral reefs and coastal upwelling zones. Neutralization of this geologically instantaneous CO₂ input to the ocean carbon system will take tens of thousands of years but, in the shorter term, ocean acidification could take a devastating toll on calcifying marine organisms. Likewise, increased riverine fluxes of nitrogen into the ocean have caused eutrophication and oxygen-deprived dead zones, or hypoxia. Fish and crustaceans appear to be particularly sensitive to low O₂ levels, and even episodic expansion or recurrence of hypoxic zones can devastate fisheries. Marine biological responses to these perturbations can themselves influence both atmospheric greenhouse gas concentrations and climate, resulting in additional biological and climate perturbations (feedbacks). While instrumental data and real-time observations can characterize the short-term transient behavior of ocean chemistry and associated ecosystems, sediment cores are needed to understand the long-term behavior of these Earth systems, especially during intervals warmer than today.

Drilling and Research Strategy

The geologic record contains numerous intervals when abrupt increases in atmospheric CO₂ coincided with ocean acidification and warming (Figure 2.12). Study of this history can elucidate how individual species and entire marine ecosystems were perturbed by events too long and geochemically complex to mimic in the laboratory. Long-term biological responses to ocean acidification and hypoxia likely include both ecological adjustments (such as changes in organismal distributions) and loss of biodiversity through extinctions. Furthermore, using the geologic record we can look for the presence, during past events, of the physiological and ecological changes predicted by modern experiments (such as widespread...
skeletal malformation and changes in ecosystem structure). In this manner, the history embedded in marine sediment complements laboratory experiments, documenting how the marine realm adjusts to global change.

Of central importance to ocean carbon chemistry research is quantifying how fast the ocean neutralizes excess CO$_2$ from the atmosphere. Rates of atmospheric CO$_2$ increase, oceanic pH changes, and Earth system recovery during past global warming and acidification events differ depending on the source, magnitude, and location of CO$_2$ injection (e.g., extreme volcanism, changes in size of the terrestrial biosphere, ocean overturning, or methane hydrate disintegration). For example, the Paleocene-Eocene boundary event 55 million years ago included a massive carbon release (3–6 trillion tons) that caused global warming and ocean acidification that lasted over 100,000 years. Remarkably, the rate of global change at the onset of the Paleocene-Eocene Thermal Maximum might have been comparable to the modern rate. While the ocean-climate system was different than today, valuable lessons can be learned about the impact of such a rapid perturbation on ocean geochemistry and ecosystems. Due to the extremely short time period over which anthropogenic carbon is being released, the impacts could be greater for many ecosystems than observed for similar systems in the fossil record.

Scientific ocean drilling will also be used to understand the connection between ocean chemistry and extreme internal and external forcings to Earth’s surface, including catastrophic volcanic events and bolide impacts. Large igneous provinces, or LIPs, are huge accumulations of mafic igneous rocks that were erupted or emplaced within a few million years or less (see also Challenge 9). They released large amounts of trace metals and gases, including CO$_2$, H$_2$S, and SO$_2$, to the ocean-atmosphere system, triggering a chain of biogeochemical-climate feedbacks. These gigantic events in the geological past provide excellent case studies for understanding how ocean chemistry responds to major environmental perturbations.
REFERENCES AND RECOMMENDED READING


