NATIONAL ACADEMY OF SCIENCES
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REPORT IN BRIEF

Scientific Ocean Drilling: Accomplishments and Challenges

Through direct exploration of the subseafloor, U.S.-supported scientific ocean drilling programs have significantly contributed to a broad range of scientific accomplishments in Earth science disciplines, shaping understanding of Earth systems and enabling new fields of inquiry. The programs' technological innovations have played a strong role in these accomplishments. The science plan for the proposed 2013-2023 program presents a strong case for the continuation of scientific ocean drilling. Each of the plan's four themes identifies compelling challenges with potential for transformative science that could only be addressed through scientific ocean drilling, although some challenges appear to have greater potential than others. Prioritizing science plan challenges and integrating multiple objectives into single expeditions would help use resources more effectively, while encouraging technological innovations would continue to increase the potential for ground-breaking science.

A rich history of Earth's past lies within the sediment and rock of the ocean floor. These formations contain records of biological, chemical, and geological processes within Earth's crust and mantle, as well as past climate conditions. Over the past forty years, scientists have explored this trove of information through scientific ocean drilling— the process of coring or drilling into ocean crust (the outer layer of Earth's crust beneath the ocean) to extract samples, collect data on the fluid and microbes beneath the seafloor, and monitor subseafloor processes.

Figure 1. The scientific ocean drilling vessel *JOIDES Resolution.*
Credit: Integrated Ocean Drilling Program

Past programs, including the Deep Sea Drilling Project [DSDP, 1968–1983], Ocean Drilling Program [ODP, 1984–2003], and Integrated Ocean Drilling Program [IODP, 2003–2013]), have spurred remarkable progress in understanding the Earth system. Accomplishments such as verification of seafloor spreading and plate tectonics, insights into the past 65 million years of global climate history, and direct exploration of the subseafloor microbial biosphere would not have been possible without U.S.-supported scientific ocean drilling programs.

In preparation for the next proposed phase of scientific ocean drilling, *Illuminating Earth's Past, Present, and Future: The International Ocean Discovery Program Science Plan for 2013–2023* (hereafter called the science plan) was released in June 2011. This science plan defines research themes and challenges for the next ten year program.

As part of the planning process, the National Science Foundation requested the National Research Council convene a committee of experts to review the scientific accomplishments of U.S.-supported scientific ocean drilling, and assess the science plan's potential for stimulating future transformative scientific discoveries.

What is Scientific Ocean Drilling?

Scientific ocean drilling is the process of drilling cores of rock and/or sediment from below the seafloor and bringing them to the surface for study. Scientists can analyze these cores and install sensors in the boreholes left after drilling to learn about the geology, chemistry, and biology of Earth. Scientific ocean drilling expeditions are not linked to efforts to find or extract fossil fuels and actively avoid areas where hydrocarbons are known to occur.

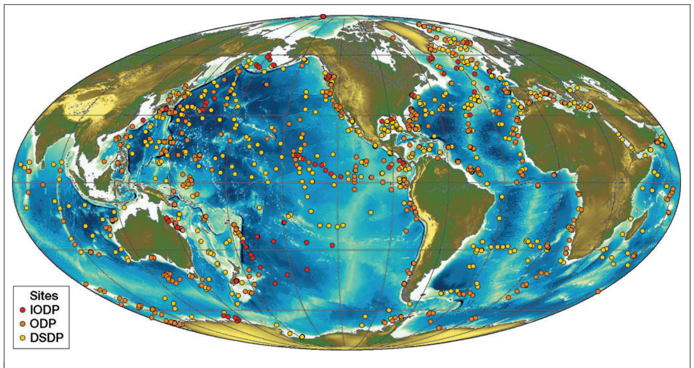

Figure 2. Global distribution of drill holes and sampling sites from the Deep Sea Drilling Project (yellow), Ocean Drilling Program (orange), and Integrated Ocean Drilling Program (red).
Credit: Integrated Ocean Drilling Program–U.S. Implementing Organization

Major Scientific Accomplishments

U.S.-supported scientific ocean drilling programs have been very successful, contributing significantly to a broad range of scientific accomplishments in a number of earth science disciplines. Scientific ocean drilling has advanced understanding of solid Earth cycles, revealed the flow of fluid and microbe ecosystems within the seafloor, and gathered extensive information on Earth's climate history. In addition, scientific ocean drilling has spurred technological innovations that have strongly influenced further advancements in both the research community and the private sector.

Solid Earth Cycles

Solid Earth cycles are geologic processes driven by the heat of Earth's core and mantle. Through scientific ocean drilling, researchers can directly explore intact ocean crust, and have developed innovative technologies to sample and collect ocean cores. Discoveries made over the last four decades have provided important insights into plate tectonics, changes in the Earth's magnetic field, the structure and function of oceanic crust and upper mantle, and the processes that generate major earthquakes and tsunamis. Drilling provides unique information on the timing of tectonic events and on the chemistry and physical properties of subseafloor materials, providing critical information for modeling solid Earth processes.

Fluid, Flow, and Life in the Subseafloor

A massive natural plumbing system carries fluids, heat, chemicals, and microbes through the ocean's subseafloor. Seawater enters the seafloor through permeable sediments and through exposed rock, which is fractured enough to allow fluid to infiltrate. As the water percolates through the subseafloor, it helps vent heat from Earth's interior and distributes microbes through the deep ecosystem. Under high heat and pressure, the seawater reacts with rock, undergoing chemical changes and forming deposits of mineral ores. At the end of its journey, the fluid exits the ocean crust at hydrothermal vents, cold seeps, and diffusely through fractures.

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 subseafloor. This has led to achievements in the study of hydrothermal vent systems, in understanding how rock and fluids interact, and of the mineral composition and subsurface extent of vents. It has also provided new insight into the development of gas hydrates. By providing the only direct access to microbes beneath the seafloor, scientific ocean drilling has revolutionized understanding of subsurface microbial communities living near the known limits of life.

Earth's Climate History

The seafloor holds a geological archive of Earth's climate history that extends for tens of millions of years, beyond the timeframe that can be captured using instruments or ice cores. This record provides critical insights into conditions in Earth's past, including when atmospheric carbon dioxide levels were similar to or higher than they are today—information that could help scientists understand how the Earth system will respond to elevated greenhouse gas levels in the future.

Scientific ocean drilling provides the only means of accessing this history. Combining scientific ocean drilling results from a wide array of regions and geological settings has transformed 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.

As the length and quality of scientific ocean drilling records have improved, they have contributed to the

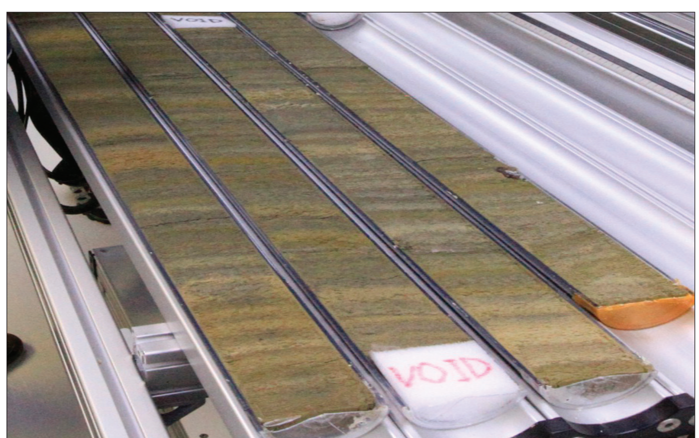

Figure 3. Sediment cores collected off the margin of Wilkes Land, Antarctica. These cores, ready for sampling, will help scientists understand the evolution of the East Antarctic Ice Sheet during the Cenozoic Era.
Credit: Rob McKay, Victoria University of Wellington, New Zealand

Scientific Accomplishments Achieved Only Through 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 million years
- Confirmation that the structure of oceanic lithosphere is related to spreading rate
- Exploration of the emplacement history of submarine large igneous provinces
- Contributed to a new paradigm for continental breakup due to studies of rifted margins
- Confirmation that subduction erosion as well as accretion occurs in subduction zone forearcs

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 million years, 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 analogues (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

understanding of dramatic and continuous change in Earth's climate history over the past 65 million years, from times of warmth to periods when massive continental ice sheets covered the planet. Confirmation that orbital cycles drive repeated polar ice sheet growth and collapse remains one of the most fundamental discoveries of scientific ocean drilling.

Assessment of the Science Plan

The science plan sets out four research themes—climate and ocean change, biosphere frontiers, Earth connections, and Earth in motion—and presents 14 scientific challenges within these themes. The committee examined the potential for transformative discoveries that might result from research conducted within this framework. In addition, the committee identified synergies among the challenges in different themes, linkages between science plan themes and other programs funded by the National Science Foundation, and other challenges and opportunities that could have been addressed by the science plan.

Overall, the committee found the science plan presents a strong case for the continuation of scientific ocean drilling, clearly defining its possible benefits to science and society. In particular, studies of the subseafloor biosphere present opportunities to identify microbes that could be useful to humans, and continuing studies of past climate could provide insight into the global and regional climate change predicted for the future. In addition, sampling deeper into the basement of rock of the ocean floor could lead to a better understanding of deep earth processes, especially if technological advances allow more intact cores to be recovered and expand *in situ* monitoring of active tectonic processes.

Overarching Findings

The themes and challenges identified in the science plan are pertinent and well-justified, although there was little guidance as to which of the 14 challenges are most important. Given the financial constraints that the next phase of scientific ocean drilling may face, it may now be appropriate for the scientific ocean drilling community to provide additional guidance on the prioritization of potential drilling objectives.

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.

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.

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. The science plan is justifiably focused on the importance of future drilling challenges and does not explicitly focus on 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 ocean drilling.

A more thorough examination of the areas of overlap among scientific drilling objectives would also be valuable. Although several natural points of synergy between challenges and themes are well described, the science plan would have been strengthened by a more detailed examination of the areas where natural integration could occur between and among the science challenges, which could help use resources more effectively. Integrating multiple drilling objectives in the early planning stages of expeditions would maximize scientific output in relation to costs.

> **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.**

Technology played a vital role in achieving many scientific advances in previous scientific ocean drilling programs. The committee found that transformative science is critically dependent on technological breakthroughs, concluding that any future scientific ocean drilling program should continue to push the technological envelope.

> **Recommendation: Pathways for innovations in technology should be encouraged. In addition, setting aside a small portion of scientific ocean drilling resources specifically to promote technological research and development could greatly increase the potential for ground-breaking science.**

Education, Outreach, and Capacity Building

Since its earliest days, scientific ocean drilling has actively engaged in education and outreach, including primary and secondary, undergraduate and graduate education, and non-research-related activities. These education and outreach activities also build capacity, because they help create an ocean-literate society and engage the next generation of ocean scientists.

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

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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: Robert A. Duce (*Co-Chair*), Texas A&M University; **Arthur Goldstein** (*Co-Chair*), Bridgewater State University, Massachusetts; **Subir K. Banerjee**, University of Minnesota; **William B. Curry**, Woods Hole Oceanographic Institution; **Magnus Friberg,** Swedish Research Council, Stockholm; **Julie A. Huber**, Marine Biological Laboratory, Woods Hole, Massachusetts; **Michael E. Jackson**, UNAVCO, Inc., Boulder, Colorado; **Keith K. Millheim**, Strategic Worldwide LLC, The Woodlands, Texas; **Samuel Mukasa**, University of New Hampshire; **Timothy Naish,** Victoria University of Wellington, New Zealand; **Paul E. Olsen,** Columbia University, Palisades, New York; **Lori L. Summa,** ExxonMobil Upstream Research Company, Houston, Texas; **Anne M. Tréhu,** Oregon State University; **Deborah Glickson** (*Senior Program Officer*), **Elizabeth Eide** *(Senior Program Officer*), **Jeremy Justice** *(Senior Program Assistant, until July 2011)*, **Lauren Harding** (*Program Assistant, from August 2011*), **Ian Brosnan** *(Mirzayan Science and Technology Fellow, Winter 2010)*, National Research Council.

The National Academies appointed the above committee of experts to address the specific task requested by the National Science Foundation. The members volunteered their time for this activity; their report is peer-reviewed and the final product signed off by both the committee members and the National Academies. This report brief was prepared by the National Research Council based on the committee's report.

EXPERT CONSENSUS REPORT

For more information, contact the Ocean Studies Board at (202) 334-2714 or visit http://dels.nas.edu/osb. Copies of *Scientific Ocean Drilling: Challenges and Accomplishments* are available from the National Academies Press, 500 Fifth Street, NW, Washington, D.C. 20001; (800) 624-6242; www.nap.edu.