Scientific Ocean Drilling

ACCOMPLISHMENTS AND CHALLENGES

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

The U.S.-operated *JOIDES* Resolution is a multipurpose drillship that serves the international scientific ocean drilling community. Credit: William Crawford, Integrated Ocean Drilling Program U.S. Implementing Organization (IODP-USIO).

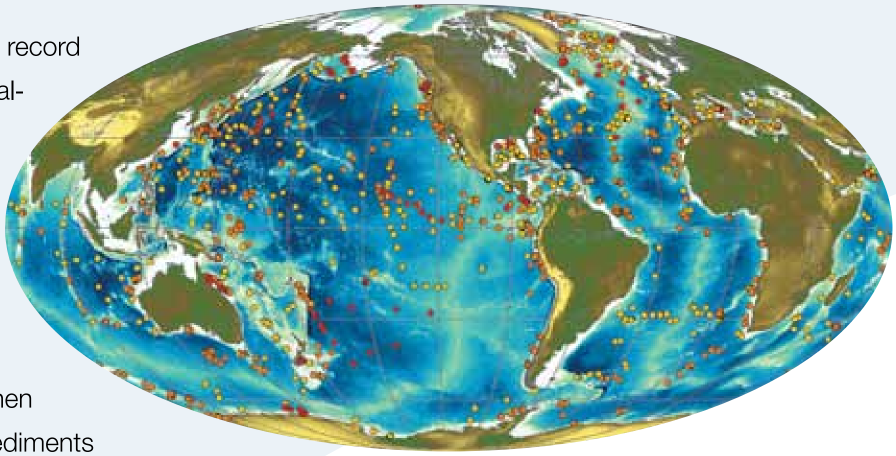
A rich history of Earth's past lies beneath the ocean.

The sediments and rock of the ocean floor contain records of active biological, chemical, and geological processes that have shaped the Earth over millions of years.

Scientific ocean drilling has spurred remarkable progress in understanding many global processes: confirming the theory of plate tectonics, documenting the history of Earth's climate system, investigating the role of fluid flow within the ocean crust, and discovering an extensive subseafloor biosphere that may well inhabit all of the world's oceanic sediments and much of the planet's crystalline crust.

This booklet summarizes the findings of the National Research Council report, *Scientific Ocean Drilling: Accomplishments and Challenges*. The report looks at significant accomplishments enabled by scientific ocean drilling and also assesses the potential for transformative discoveries based on the research described in *Illuminating Earth's Past, Present and Future: The International Ocean Discovery Program Science Plan for 2013-2023,* a science plan for the next decade of scientific ocean drilling.

What is Scientific Ocean Drilling?



Global distribution of drill holes and sampling sites from scientific ocean drilling programs between 1968 and 2011. Credit: IODP-USIO.

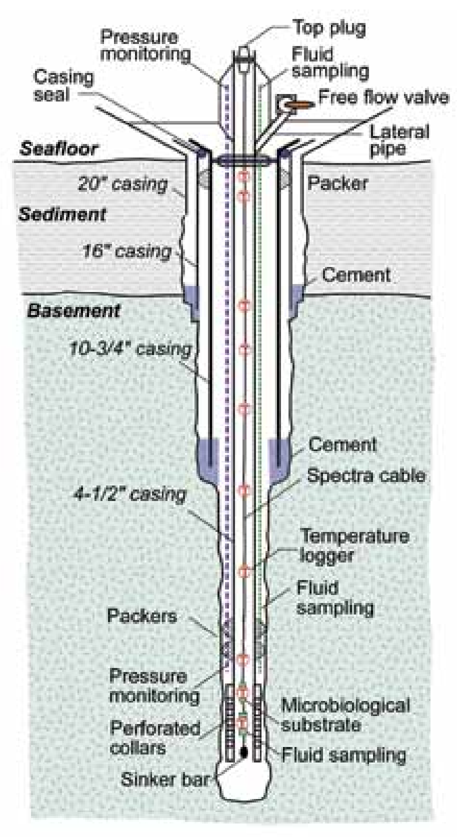
The ocean floor holds a vast record of Earth's history. The basaltic rock that makes up most of the seafloor holds geochemical clues about processes within Earth's interior. Sediments deposited above the rock provide information about conditions that existed when they were laid down. Unlike sediments on land, which can be altered or even completely removed through the actions of wind, water, and tectonics, seafloor sediments have largely been preserved in continuous, undisturbed layers.

Scientists access this record of Earth processes through scientific ocean drilling, which allows them to recover cores —long cylindrical samples—from the seafloor. The rock and sediments are analyzed in research laboratories and archived in repositories for future study. Ocean drilling also enables researchers to collect subseafloor fluids and microbes, as well as geophysical and geochemical data, from the boreholes left behind when a core is extracted.

Put a CORK in it!

Every scientific ocean drilling hole provides scientists with opportunities for discovery. Traditionally, this has been through analysis of the core extracted from the ocean floor. Some holes provide additional opportunities to monitor conditions such as temperature, pressure, and fluid flow in the subseafloor through placement of sensors in the borehole. The process of collecting data from boreholes is complicated by the fact that drilling can disturb natural conditions and result in exchanges between seawater and fluids within the rock or sediment. To allow parameters such as temperature

Scientists prepare a CORK for deployment. Credit: William Crawford, IODP-USIO.



CORKs (Circulation Obviation Retrofit Kits) are devices that seal boreholes off from seawater, more closely mimicking the natural subseafloor environment. CORKs can be used for pressure, seismic, strain, and temperature monitoring; fluid sampling; and microbiological and perturbation experiments. Credit: Modified from Fisher et al., 2011.

and pressure to return to normal, scientists have developed CORKs (Circulation Obviation Retrofit Kits)—devices that seal boreholes off from seawater, more closely mimicking the natural subseafloor environment. Recently, scientists have developed advanced CORKs that can seal multiple separate zones within a single borehole, corresponding to stratification found within the seafloor.

CORE ON DECK!

The following steps explain how an ocean drilling core is collected aboard the drillship and prepared for use by researchers.

1. The drill string is assembled and lowered through the moon pool, an opening in the ship's hull to the water below. A specific drill bit is chosen based on the properties of the sediment or rock that is being drilled.

2. Once the core is extracted and brought back up to the rig floor, technicians carry the core to the catwalk, label it, and cut it into 1.5 meter (about 5 feet) sections.

3. Scientists analyze physical properties of the core, such as density, porosity, and magnetism.

4. The core is split lengthwise into two halves: the working half, which scientists sample for use on board the drillship and back in their laboratories; and the archive half, which is kept unsampled for future comparison. Scientists document the core in detail—including its composition, grain size, and color—and take photos of the core for research purposes.

5. Scientists identify sections they want to sample on ship or store for post-cruise research in their own laboratories.

6. Both halves are stored in refrigerated space in the ship's hold. At the end of the cruise, the cores are stored in an onshore repository under controlled conditions for future use.

Top right: Scientists carefully split a frozen core section. Credit: William Crawford, IODP-USIO.

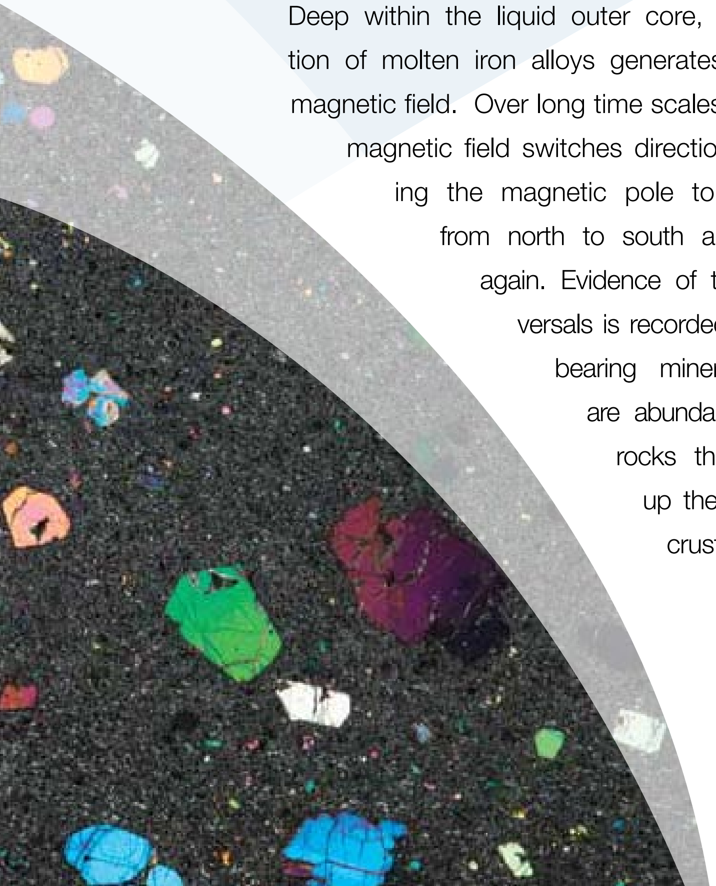
Bottom right: A technician helps carry a core from the drill floor to the catwalk. Credit: William Crawford, IODP-USIO.

CYCLES OF THE SOLID EARTH

SCIENTIFIC OCEAN DRILLING has given researchers better access to the Earth's interior to better understand solid Earth cycles—the processes that generate and modify Earth's crust. Over the last four decades, new discoveries have provided important insights into plate tectonics, the process of continental rifting, the Earth's magnetic field, the architecture of ocean crust, and the processes that generate major earthquakes and tsunamis.

Earth's Magnetic Field

Deep within the liquid outer core, the motion of molten iron alloys generates Earth's magnetic field. Over long time scales, Earth's magnetic field switches direction, causing the magnetic pole to migrate from north to south and back again. Evidence of these reversals is recorded in iron-bearing minerals that are abundant in the rocks that make up the oceanic crust. Ocean drilling has allowed researchers to use the magnetic properties of these rocks to trace the history of seafloor formation over geologic time.



Thin section of a basalt with olivine crystals, viewed under cross-polarized light.
Credit: IODP-USIO.

The Theory of Seafloor Spreading

One of the first major achievements of scientific ocean drilling was the confirmation of seafloor spreading. Ocean drilling allowed researchers to collect sediment samples in a transect across the Mid-Atlantic Ridge in the South Atlantic Ocean. By looking at microscopic organisms within sediment directly above the oceanic crust, researchers discovered that the age of the sediments increased with distance from the ridge crest. Sediment age also correlated well with the parallel, alternating magnetic signatures (corresponding to reversals in Earth's magnetic field) that were recorded in the rocks as they spread away from the mid-ocean ridge. This accomplishment proved to be the lynchpin for establishing the paradigm of plate tectonics,which today serves as the foundation for understanding Earth's processes.

Generating a Geological Time Scale

Scientific ocean drilling data was essential for correlating changes in magnetic intensity

Petrologists work in the core lab. Credit: William Crawford, IODP-USIO.

and orientation with dated marine microfossil records of diversity, abundance, and geochemistry. When combined with astronomical calibration, these disparate fields of study contributed to the development of a precise geological time scale extending 150 million years into the past. Continued refinements using globally distributed samples and increasingly precise dating tools have made the time scale an indispensable tool for determining the rates of many of Earth's processes, both on land and in marine systems.

Continental Breakup and Sedimentary Basin Formation

The process by which continents break apart and initiate seafloor spreading has been a key question for several decades. Throughout Earth's history, continental breakup has usually been accompanied by the development of new ocean crust floor between the rifted continents, yet the complex transition between continental and oceanic crust is still poorly understood. In addition, sedimentary basins along the margins can hold hydrocarbon resources of economic importance.

As early as the mid-1970s, ocean drilling legs were examining the geometry of initial fragmentation of crust at different types of continental margins. Scientists made the discovery that layers of volcanic rock along the magma-rich Northeast Atlantic margins were erupted on land, rather than underwater as had previously been hypothesized. At magma-poor margins along the coast of Spain and Newfoundland, upper mantle rocks separated continental crust from oceanic crust. In combination with other approaches, scientific ocean drilling contributed to understanding the processes of continental breakup, sedimentary basin and hydrocarbon formation, and creation of new seafloor.

Structure, Composition, and Formation of the Ocean Crust

Drilling is the only direct method to investigate the formation, structure, and composition of the oceanic crust and rigid upper mantle (together called the oceanic lithosphere). Early motivation for drilling the ocean crust focused on understanding its layered structure.

A core ready for analysis.
Credit: IODP-USIO.

While initial efforts were hampered by the technical difficulties of drilling into rock, which posed challenges for methods developed to drill softer sediments, engineering innovations have improved hard rock drilling capabilities.

Ocean drilling cores have been used to confirm the age of the oldest oceanic crust, which was formed about 180 million years ago. Because it is much younger than the age of the Earth, this discovery further supported the concept that oceanic crust created at mid-ocean ridges is eventually recycled at subduction zones.

Preliminary observations of drill cores suggested that the structure and composition of oceanic lithosphere are different, depending on the spreading rate of the mid-ocean ridge where it is formed. Furthermore, drilling at "tectonic windows" (regions where rocks that are usually deep in the Earth have been brought to the seafloor through tectonic processes) has allowed scientists to study both lower crust and upper mantle rocks.

A petrologist studies cores of oceanic crust.
Credit: John Beck, IODP-USIO.

Subduction Zone Processes and Seismogenic Zones

Great natural hazards such as volcanoes, earthquakes, and tsunamis can be generated at subduction zones, where two tectonic plates collide and one descends beneath the other. Scientific drilling expeditions have allowed researchers to probe the properties of subduction zones, deepening the scientific understanding of conditions that trigger these geological hazards.

Subduction Zone Processes

Through scientific ocean drilling, scientists are able to collect samples near subduction zone boundaries to help determine the nature of the crust, sediments, and fluids in these regions. These materials have distinctive compositions and can act as tracers for processes leading to volcanic eruptions. Over time, studies have evolved from simply identifying these tracers to constructing comprehensive models that help to understand the balance of materials flowing into and out of subduction regions.

Seismogenic Zone Experiment

Recently, a new scientific ocean drilling initiative, the Seismogenic Zone Experiment (SEIZE), has been initiated. Its objective is to drill through a subduction zone boundary in order to explore the mechanics of large magnitude earthquakes (8.0 or greater) using the

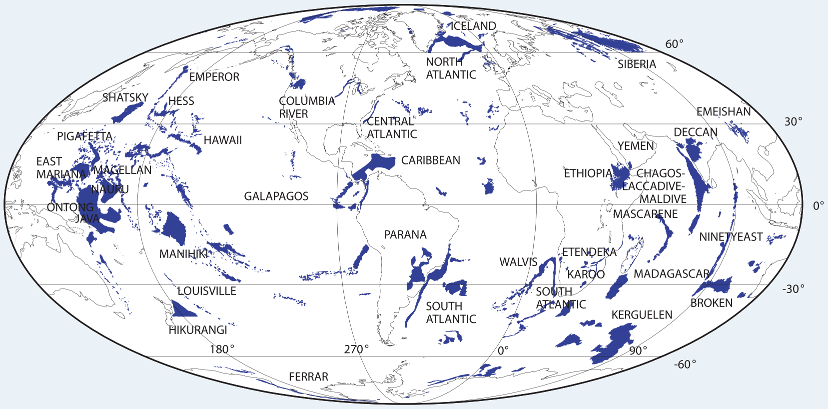
Japanese riser drilling vessel Chikyu. Initial efforts focused on the Nankai Trough off the coast of southeastern Japan, an area with a long history of large earthquakes and devastating tsunamis. An upcoming expedition will focus on the location of the great Tohoku earthquake of March 2011.

History of Arc Volcanism

Scientists have gained new insight into the history of volcanic arcs by studying layers of volcanic ash preserved in ocean sediments. Cores extracted from the Mariana-Izu arc in the Western Pacific Ocean yielded a nearly complete 45 million-year record of arc volcanism, providing insight into how the arc evolved over time. Other ash studies, from cores obtained on the Caribbean Plate, document the episodic nature of explosive volcanism in Central America and indicate that some volcanic eruptions in this region rival the largest super-eruptions in the geologic record.

Large Igneous Provinces

Large igneous provinces form when massive outpourings of basaltic lava occur over geologically short time periods (2-3 million years), creating significantly thicker than normal ocean crust. Large igneous provinces in the ocean are generally related to mantle plumes or hotspots and can cover tens of thousands of square kilometers. Their formation influences ocean chemistry and climatic conditions, and can even affect species extinction and evolution.

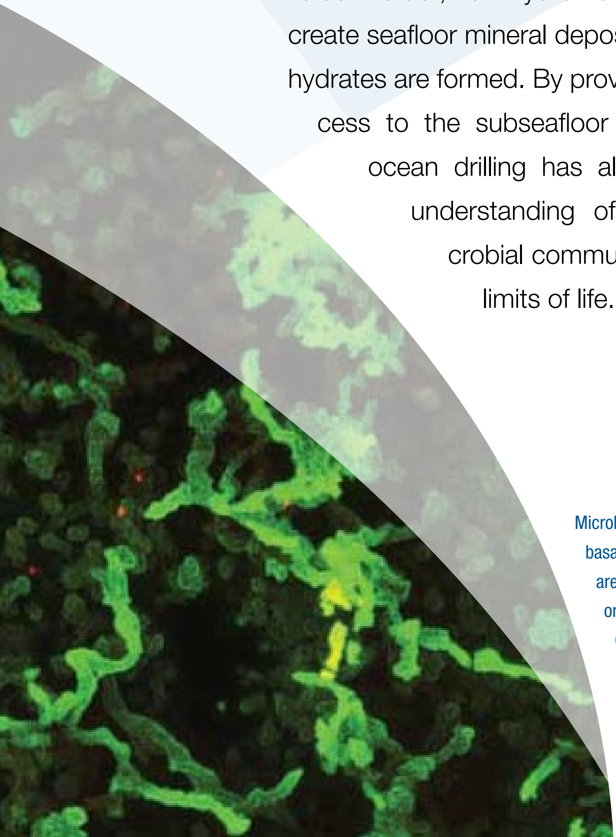


Global locations of large igneous provinces. Credit: Modified from Coffin et al., 2006.

Because large igneous provinces are so thick and are often buried beneath marine sediments, sampling them presents a significant challenge. Four submarine large igneous provinces have been drilled to date, with cores reaching tens to hundreds of meters into the volcanic rock. Pieces of wood and sediment buried in the lava revealed that the Kerguelen Plateau in the southern Indian Ocean was once above sea level, while drilling on the Pacific Ocean's Ontong Java Plateau suggested it formed entirely beneath the sea surface. By dating drill cores from the North Atlantic Volcanic Province, scientists were able to correlate the timing of the eruption that created that large igneous province with the Paleocene-Eocene Thermal Maximum (PETM), a period of rapid global warming about 55 million years ago. This correlation in time suggested a connection between massive volcanic eruptions and the changes in climate, mass extinctions, and ocean anoxia events that occurred at the PETM.

FLUIDS, FLOW, AND LIFE BENEATH THE OCEAN FLOOR

BENEATH THE SEAFLOOR, a natural plumbing system allows fluids to circulate through the ocean crust. These fluids remove heat from Earth's interior, alter the chemistry of the basement rock, and influence the distribution of microbes in the subsurface biosphere. The ability to drill deep into the seafloor has increased our understanding of the role of fluid flow within ocean sediments and basement rock, especially how hydrogeologic systems are connected within the ocean crust. This has led to achievements in understanding how rock and fluids interact, how hydrothermal vent systems create seafloor mineral deposits, and how gas hydrates are formed. By providing the only access to the subseafloor biome, scientific ocean drilling has also revolutionized understanding of subsurface microbial communities living at the limits of life.



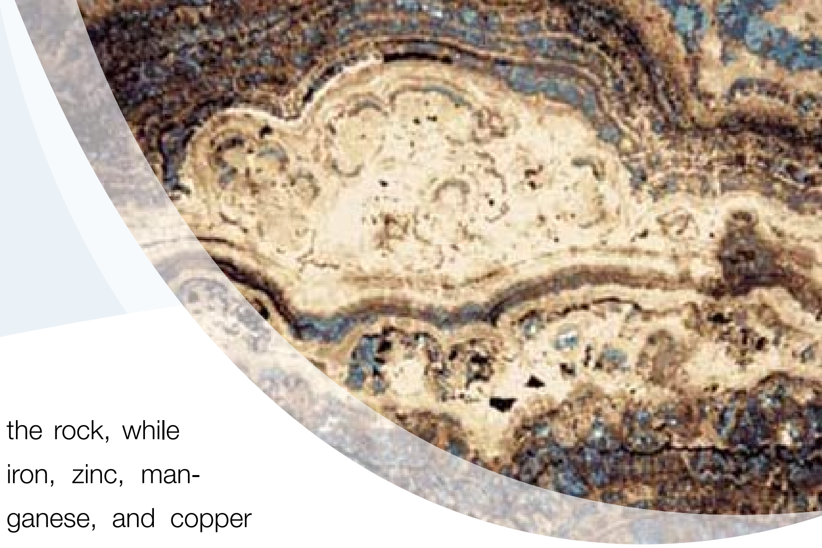
Microbes that colonized chips of basalt placed in a borehole are visualized using green and orange fluorescent dyes. Credit: Beth Orcutt, Bigelow Laboratory for Ocean Sciences.

Heat Flow, Fluid Flow, and Geochemistry

The scale and importance of fluid flow through ocean crust cannot be underestimated—the volume of fluid flowing through the oceanic crust is of the same order of magnitude as the amount of water entering the ocean from all the world's rivers. However, until recently, little was known about the pathways of heat and fluid through the subseafloor. Scientific drilling provides a window on the many chemical, tectonic, biological, and geophysical processes influenced by the interactions between water and rock. These include the magnitude and distribution of fluid pressures, the generation of explosive volcanism, the formation of hydrates and mineral resources, and the distribution of microbial communities. In addition, scientific ocean drilling has spurred the development of new sampling technologies and long-term measurements that help researchers monitor rates and patterns of fluid flow.

Fluid Flow Through Basement Rock

In early experiments, scientists noticed that seawater appeared to be drawn down into the



A thin sliver of pyrite (iron sulfide) from a hydrothermal mound on the Mid-Atlantic Ridge. Credit: IODP-USIO.

upper levels of basalt through drill holes. This indicated that oceanic crust was more permeable than the sediment layers above. Analysis of ocean drilling cores confirmed this hypothesis, showing that shallow basement rock is consistently three to seven times more permeable than the sediment deposited above. Further studies of rock cores demonstrated that basement rock becomes less permeable at greater depths below the ocean floor. The widespread nature of large-scale fluid circulation through basement rock has implications for subseafloor microbial communities and for the exchange of chemicals and heat through the oceans.

Hydrothermal Vent Processes

Seawater enters oceanic crust near mid-ocean ridges through fractures in the rock. As it penetrates more deeply into the crust, the seawater reacts with the hot basement rock and exchanges chemical elements. Magnesium, for example, is absorbed into the rock, while iron, zinc, manganese, and copper are released into the fluid. The acidic, mineral-rich fluid becomes buoyant and discharges at the seafloor. Chemicals in the hydrothermal fluid provide energy to support ecosystems teeming with exotic varieties of shrimp, clams, tubeworms, and other creatures.

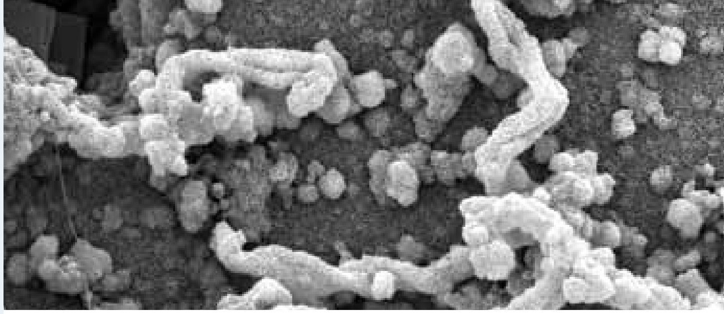
Until the advent of ocean drilling, the only way to study the chemical reactions beneath hydrothermal vents was by collecting the fluids emanating from vents, examining rocks from the seafloor surface, or studying ophiolites —fragments of ocean crust that have been thrust onto continents by collisions between ocean and continental plates. Studying cores obtained through scientific ocean drilling has made critical contributions to understanding the chemistry, geology, and biology of hydrothermal vents and their role in the composition of ocean crust and ocean chemistry.

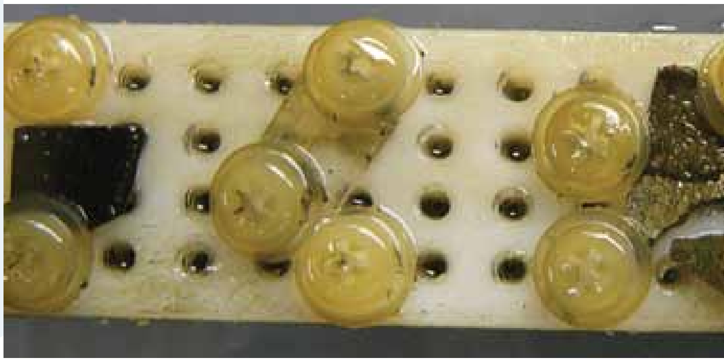
Mineral Deposits

One of the more unexpected outcomes of drilling at hydrothermal sites has been the discovery of massive seafloor and subseafloor mineral deposits. Drilling into a large deposit

Microbiology samples are collected from a sediment core. Credit: John Beck, IODP-USIO.

near the Mid-Atlantic Ridge revealed almost 3 million tons of sulfide. At Middle Valley, located in the northeast Pacific Ocean, scientists found a subsurface deposit of almost 16 percent copper ore. These findings have generated interest in mining subseafloor hydrothermal systems, but there is still much to be learned about the formation and evolution of these deposits. Therefore, communication between scientists and industry will be needed to avoid potential environmental damage from ocean floor mining.





The Subseafloor Biosphere

People have long known that the ocean harbors a diverse array of species, but the microbial life that thrives beneath the seafloor is a much more recent discovery. Scientists first identified subseafloor life in 1955, when bacteria were discovered in marine sediment cores drilled 7.5 meters beneath the seafloor. Since then, researchers have identified microbes at ever greater depths, even finding them in sediments collected at greater than 1,600 meters below the seafloor near Newfoundland. Based on the variety of microbial life observed so far, scientists estimate that the number of microbes living in just the top 500 meters of seafloor sediment is equivalent to 10 percent of all the biomass that lives on Earth's surface.

Life Within Earth's Crust

While most information on subsurface microbial communities has come from sediment cores, in the late 1990s, scientists became interested in microbial activity in the basaltic ocean crust. The ocean crust beneath the sediment is potentially the largest habitat on Earth, as the volume of ocean crust capable of sustaining life is comparable in magnitude to the volume of the world ocean. Ocean drilling core samples show that microbes play an important role in altering basalt rock and

A microbiologist works on core samples in an anaerobic chamber to prevent contamination.
Credit: William Crawford, IODP-USIO.

Top Left: This scanning electron microscope image shows microbes that colonized chips of pyrite placed in a borehole on the Juan de Fuca Ridge flank for 4 years (2004-2008). Credit: Beth Orcutt, Bigelow Laboratory for Ocean Sciences.

Bottom left: Communities of subseafloor microbes grow on polished chips of basalt and pyrite placed into a CORK. The microbes can then be visualized using scanning electron microscopy or fluorescent dyes (above and page 8). Credit: Beth Orcutt, Bigelow Laboratory for Ocean Sciences.

WHAT CAN DEEP-SEA MICROBES TELL US ABOUT THE LIMITS OF LIFE?

The microbes that dwell beneath the seafloor live in some of the harshest conditions on Earth. Light can't penetrate to these depths, so most energy comes from chemical compounds leached from rock. Deeper beneath the ocean floor, nutrients become more scarce and temperature increases. Understanding how deep-dwelling microbes can survive at these depths could help scientists learn more 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 perhaps other planets.

exchanging nutrients between seawater and the crust. Several recent scientific expeditions have focused on drilling into basalt and using CORKs as subseafloor microbial observatories to examine the unique biosphere present within the basement rock.

Gas Hydrates

At the high pressure and low temperatures of the deep ocean, gases such as methane and carbon dioxide can combine with seawater to form an ice-like crystalline substance called gas hydrate. Methane hydrates are most often found at continental margins, where they are sometimes concentrated enough to be considered as a potential energy resource (although there are presently no methods to economically extract them). Hydrates are also of interest because scientists think that the natural release of methane, a potent greenhouse gas, from hydrates could potentially contribute to climate warming. Scientific drilling has played a major role in improving understanding of the distribution of gas hydrates in ocean sediments, as well as hydrate behavior and stability under different temperature and pressure regimes.

Developing Technologies to Study Gas Hydrates

At atmospheric pressure, gas hydrate is stable only at temperatures below -80° C. Therefore, much of the gas hydrate in ocean drilling cores is lost as the core is brought to the surface. The scientific ocean drilling community pioneered new technologies, such as the pressure core sampler, for recovering and analyzing gas hydrate deposits at natural, high pressure conditions.

A chunk of gas hydrate recovered about 6 meters below the seafloor along the Cascadia margin. Credit: IODP-USIO.

EARTH'S CLIMATE HISTORY

THE SEAFLOOR HOLDS a geological archive of Earth's climate history that extends for tens of millions of years, providing critical insights into the patterns and processes of past climate change. This information provides researchers with records of natural variability against which present and future climate change can be compared.

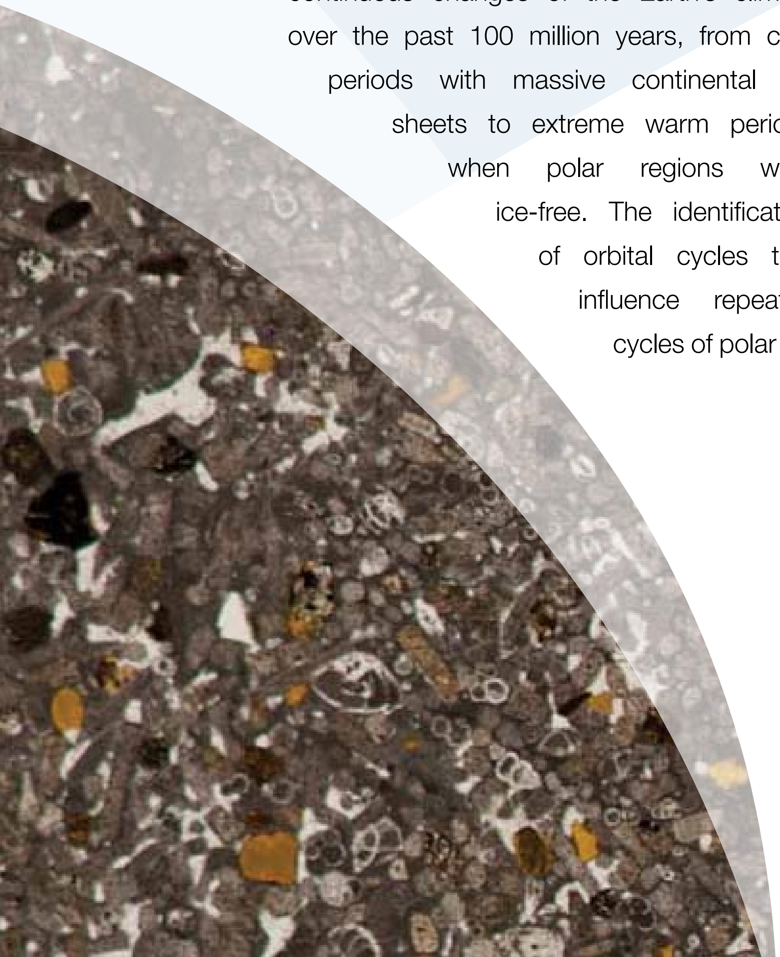
As the length and quality of scientific ocean drilling records has improved, they have contributed to understanding dramatic and continuous changes of the Earth's climate over the past 100 million years, from cold periods with massive continental ice sheets to extreme warm periods when polar regions were ice-free. The identification of orbital cycles that influence repeated cycles of polar ice sheet growth and collapse, as well as global sea level fluctuations of up to 120 meters, remains one of the most fundamental discoveries of scientific ocean drilling.

Past Warm Climate Extremes and the Greenhouse World

More than 3 million years ago, climates were generally warmer than today and the atmosphere contained higher carbon dioxide levels. By studying warm climate extremes recorded in ocean sediments, scientists can learn how the Earth system responded to periods of elevated greenhouse gas levels in the past.

Developing a Timeline of Past Temperatures

Ocean drilling records have improved estimates of Earth's climate sensitivity to higher levels of greenhouse gases and to short-lived perturbations in the carbon cycle. They have also helped scientists determine the sensitivity of ice sheets to elevated greenhouse gas concentrations. Sea surface temperatures reconstructed from drill cores demonstrated that the early Eocene



This thin section of limestone contains numerous shell fragments and small pieces of volcanic glass that can provide information about past climate conditions.
Credit: IODP-USIO.

Scientists sample layers of sediments from cores extracted off the Antarctic coast. Analysis of these samples will help scientists understand changes in ocean temperature, sea ice extent, and primary productivity throughout the last 12,000 years. Credit: Rob McKay, Victoria University of Wellington.

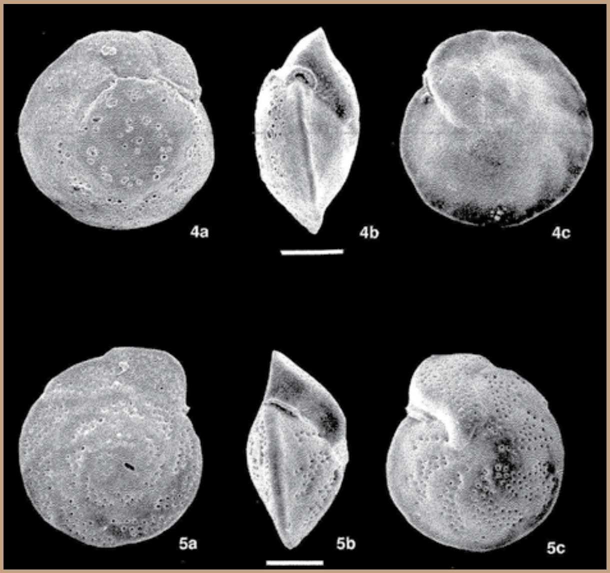
Epoch (from 55 to 48 million years ago) had the warmest climates of the past 65 million years, and that the world was warmer by about 10 to 12° C. Cores recovered from scientific ocean drilling also show that high latitudes reacted more strongly to increases in atmospheric carbon dioxide than areas closer to the equator. Observations of past periods of extreme warmth are important because they help sharpen the performance of climate models in response to higher levels of atmospheric carbon dioxide.

Cenozoic Ice Sheet Evolution and Global Sea Level Change

Changes in sea level reflect how ice sheets in the Antarctic and the Northern Hemisphere have grown and shrunk over time. Studies

PROXY RECORDS IN SCIENTIFIC OCEAN DRILLING

Scientists use different components of marine sediments as "climate proxies"—indicators of past climate and ocean conditions. For example, variations in the types of fossilized plant and animal species found in seafloor sediment can indicate past changes in environmental conditions at a specific location. Fossils can also indicate the age of the various sediment layers, helping scientists determine when environmental changes took place. Geochemical measurements of fossilized shell material can provide insight into past oceanographic conditions, such as temperature, salinity, pH, and the concentration of atmospheric carbon dioxide. Combining physical measurements of past temperatures with chemical measurements indicating atmospheric carbon dioxide concentrations has been particularly valuable for understanding how the climate system responds to changes in atmospheric carbon dioxide levels.

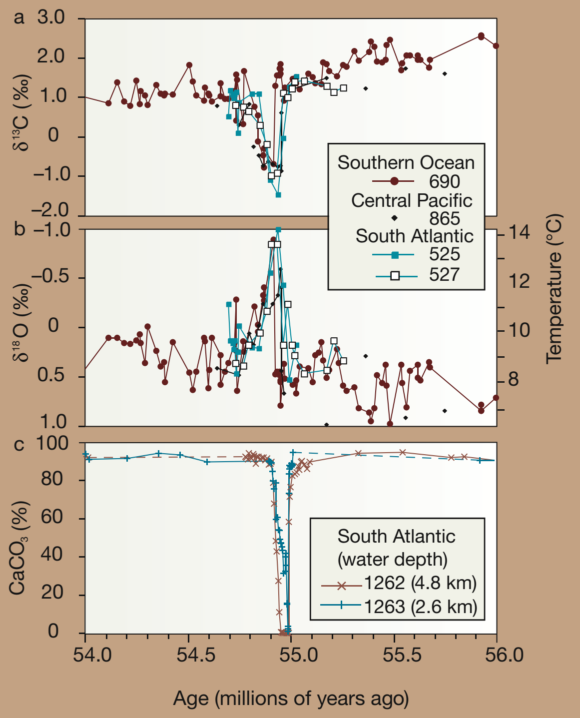


Photomicrographs of foraminifera, single-celled marine organisms that produce calcite or aragonite shells. The shells can be used as climate proxies and can provide clues to past ocean ecology and biogeography. Credit: Mimi Katz, Rensselaer Polytechnic Institute.

PAST CLIMATE CHANGE: THE PALEOCENE-EOCENE THERMAL MAXIMUM

Extreme changes recorded in the carbon chemistry of oceanic fossil shells indicate that about 55.8 million years ago Earth experienced a sudden release of carbon dioxide into the atmosphere, causing temperatures to rise by about 4 to 8° C globally in less than 10,000 years. Because of the timing, which occurred between the Paleocene and Eocene epochs, this event is referred to as the Paleocene-Eocene Thermal Maximum (PETM).

The disruption to the carbon cycle produced widespread ocean acidification and altered the deep ocean ecosystem. By studying scientific ocean drilling cores, scientists found that many species of benthic foraminifera (single-celled organisms that live in the deep sea) became extinct during this time. Piston cores recovered in 2003 from the South Atlantic first documented the size of the PETM carbon release—3,000 gigatons—and the subsequent, several hundred thousand year recovery of ocean chemistry that followed the disruption. The PETM is the best analog of rapid changes in atmospheric carbon dioxide found to date in the geologic record.



A rapid increase in carbon isotope ratios in fossilized shells of seafloor organisms collected at Antarctic, south Atlantic, and Pacific Ocean drill sites indicates a large increase in atmospheric methane and carbon dioxide during the PETM (top panel). This occurs at the same time as 5° C of global warming (middle panel, presented with oxygen isotope values). Ocean acidification that followed the PETM is indicated by a rapid decrease in the abundance of calcium carbonate (lower panel). Credit: Zachos et al., 2008.

of sediment cores accessed through ocean drilling have revolutionized understanding of Earth's climate system during the Cenozoic Era (65.5 million years ago to the present), and have imparted new insights into the behavior of polar ice sheets and their influence on global sea level. Because the behavior of ice sheets and the global climate system in a warming world is currently not well understood, ocean drilling records can provide analogs that help limit the uncertainty around projections of future sea level rise.

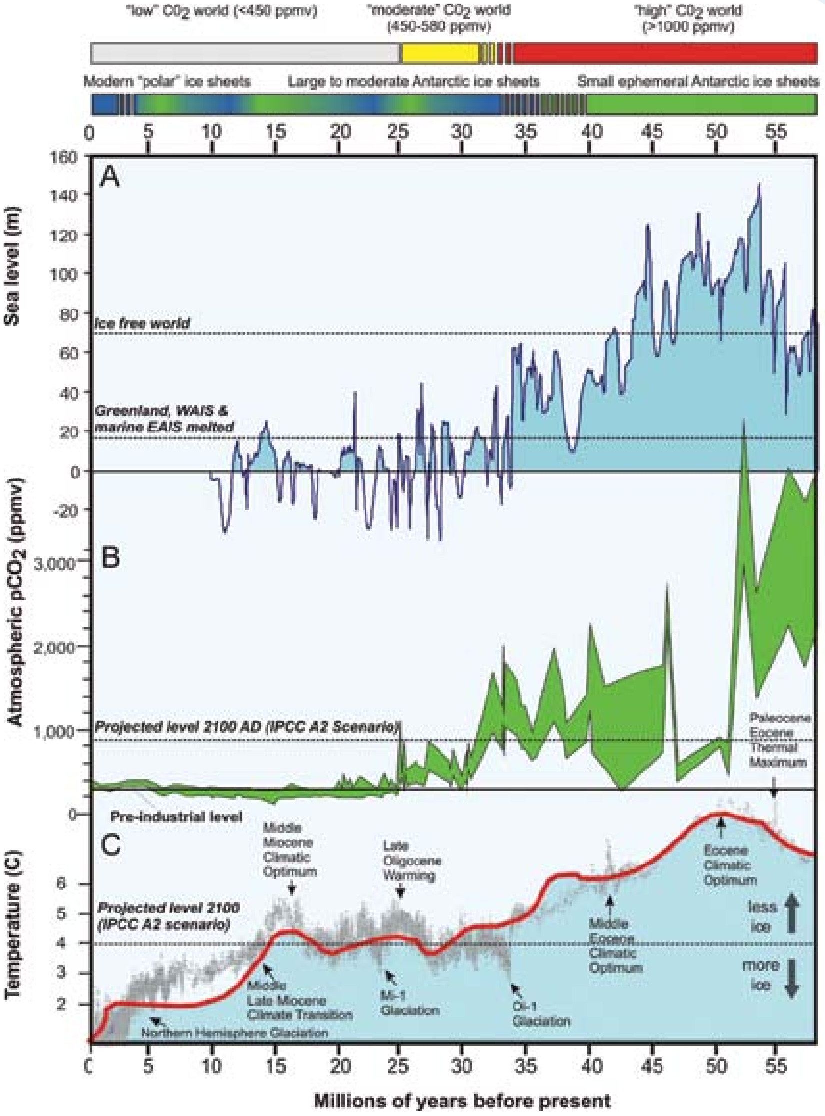
Understanding Polar Ice Sheets

Scientific ocean drilling played an integral role in understanding the initiation of Antarctica glaciation, which marked Earth's transition from a warmer to colder climate system. Cores collected from the Antarctic continental shelf about 40 years ago provided the first evidence that continental glaciation extended back to the Eocene-Oligocene boundary (33 million years ago). This disproved the then-prevailing hypothesis that Antarctica had been extensively glaciated only since the beginning of the Quaternary Era (2.588 million years ago).

In 1987, ocean drilling along continental shelves provided the first direct evidence of continental-scale ice sheets "calving" at the

Antarctic coastline—breaking off in chunks as they meet the ocean. Furthermore, ice-rafted debris—sediments that became trapped in ice and deposited on the ocean floor when the ice melted—collected in the Southern Ocean indicated that the Antarctic ice sheet grew quickly (within a few tens of thousands of years) and caused a drop in global sea level of at least 60 meters.

A Pleistocene fossil brittle star found in a core sample. Credit: IODP-USIO.



Changes in global sea level, atmospheric carbon dioxide concentration, and temperature over the past 55 million years ago, reconstructed from scientific ocean drilling data. (A) The global sea level curve represents changes in sea level in response to fluctuations in polar ice volume. (B) Dramatic variability in atmospheric CO_2 concentrations (shown in green) are recorded in shells and other organic biomarkers preserved in ocean sediments. (C) Changes in global temperature are shown with oxygen isotopes derived from seafloor organisms, representing global ice volume and deep ocean temperatures. Credit: Modified from R. Levy, GNS Science.

OXYGEN ISOTOPES

Naturally occurring oxygen (O) exists in nature in the form of three different isotopes (^{16}O, ^{17}O, and ^{18}O)—atoms with the same number of protons and electrons but with different numbers of neutrons. Changes in the ratio between ^{16}O and ^{18}O are related to temperature variations, changes in evaporation and precipitation, and the amount of Earth's water that is locked in ice sheets. In the shells of microscopic marine organisms, this ratio acts as a chemical signature that reveals information about the temperatures that existed when the organisms were alive. Paleoceanographers use these records to create a temperature timeline that extends back millions of years, providing information about the extent of glaciations and Earth's ancient climates.

In contrast to the early successes in the Antarctic, understanding the Arctic's glacial history took far longer. In the mid-2000s, a strategy that combined drill ships with icebreakers capable of reaching remote, ice-covered areas succeeded in capturing a 55 million year history of climate change in the central Arctic Ocean.

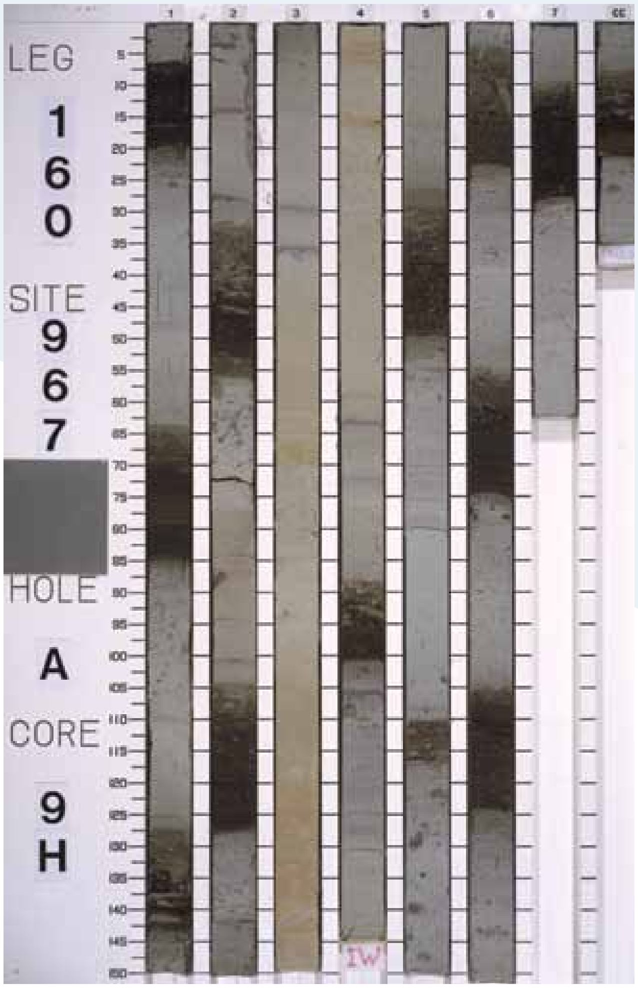
Glacial and Interglacial Cycles

The time period between 3 and 2.5 million years ago saw global cooling and the expansion of continental ice in the Northern Hemisphere. This cooling trend initiated a series of glacial and interglacial cycles controlled by long-term variations in Earth's orbit.

In 1981, scientific ocean drilling contributed to a major increase in understanding these variations, when an almost continuous sediment record was recovered from the high-latitude Atlantic Ocean. At this site, scientists showed that changes in oxygen isotope ratios (see box at left.) were correlated with increases in ice-rafted debris, providing definitive evidence that continental ice sheets had existed nearby. Ocean drilling established the first age for the onset of major continental glaciations, based on observations that only small amounts of ice-rafted debris were found in cores before this time.

Understanding Global Sea Level Change

Ocean drilling along the eastern North American continental margin has provided a 100 million-year record of global sea level change, allowing scientists to identify buried erosional surfaces that correlate with times when sea level fell and interrupted sediment



A sediment core from the eastern Mediterranean Sea demonstrates cyclicity related to orbital forcing. The alternating layers of dark-colored sediments, which are rich in organic matter, and light-colored carbonate ooze are due to changes in the North African monsoon pattern. Credit: IODP-USIO.

deposition. Researchers were able to link these instances of sea level fall with growth of the polar ice sheets. More than 30 oscillations in global sea level during the Oligocene and Miocene Eras (33 to 6 million years ago) were identified.

Coral reef and carbonate rocks drilled from Australia's Great Barrier Reef provide insight into the rapid sea level rise of the last ice age. Credit: European Consortium for Ocean Research Drilling (ECORD)/IODP.

Recent expeditions have also successfully drilled coral reefs and carbonate rocks in Tahiti and the Great Barrier Reef in Australia. The Tahiti expedition recovered excellent records of the last interglacial period (about 125,000 years ago), when global sea level was relatively high, and of the rapid sea level rise since the last ice age. These data provided critical constraints on past sea level high stands and helped quantify the rate of sea level rise.

Orbital Forcing

The study of climate variability due to changes in Earth's orbit provides one of the best examples of an emerging field growing explosively because of scientific ocean drilling. In 1979, new coring technology produced the first long, undisturbed records of marine sediment, allowing scientists to extend the time series of marine oxygen isotopes back 3.5 million years. Expeditions in the early 1980s expanded the knowledge of glacial-interglacial cycles, the timing of Northern Hemisphere glaciations, and the changing nature of the climate system in response to orbital forcing (see box on Milankovitch cycles, p.18). Based on these early successes, a 16-year, global-scale effort to observe and study orbitally-forced climate throughout tropical and high-latitude locations of all ocean basins was initiated. These legs represented a major effort, and its successes are among the most significant for the ocean drilling community.

The sediments collected through scientific ocean drilling have greatly advanced the understanding of orbital climate variability and its causes, and have provided scientists with a framework and time scale to interpret the results of studies from a wide range of disciplines, from the geosciences to archeology, anthropology, and astronomy. By collecting and analyzing long, high resolution records, researchers have been able to construct a blueprint of many processes that affected Earth's climate in the distant past. Recognition of the widespread impact of orbital forcing on climate change has been a major outcome of scientific ocean drilling.

MILANKOVITCH CYCLES

Cycles in the Earth's orbit influence the amount of sunlight that reaches different parts of the Earth at different times of year. In the early 20th century, Serbian geophysicist and civil engineer Milutin Milanković proposed a theory to explain how these orbital changes could explain the history of Earth's ice ages. His work explored how the Earth's orbital cycles—including the direction (23,000 year period) and tilt (42,000 year period) of the Earth's axis, and the shape of its orbit (100,000 year period)—had long-term effects on climate, including the timing of glacial and interglacial cycles. Collectively, these cycles are known as Milankovitch cycles and their effects are known as orbital forcing.

Abrupt Climate Change

In the mid-1980s, scientists observed that ice cores from Greenland recorded a series of rapid and abrupt changes in air temperature over millennial (thousand-year) time scales. Hypothesizing that interactions between the ocean and atmosphere were responsible for this phenomenon, researchers focused on rapid changes of the North Atlantic Ocean's large-scale circulation, which is driven by differences in temperature and salinity between the ocean's surface and its depths. Scientific ocean drilling played a major role in rapidly advancing the knowledge of these shorter-scale temperature swings, first through the use of existing cores from past drilling legs and later through targeted sampling opportunities across the globe. These data have also been used as independent confirmation of the reliability of climate models.

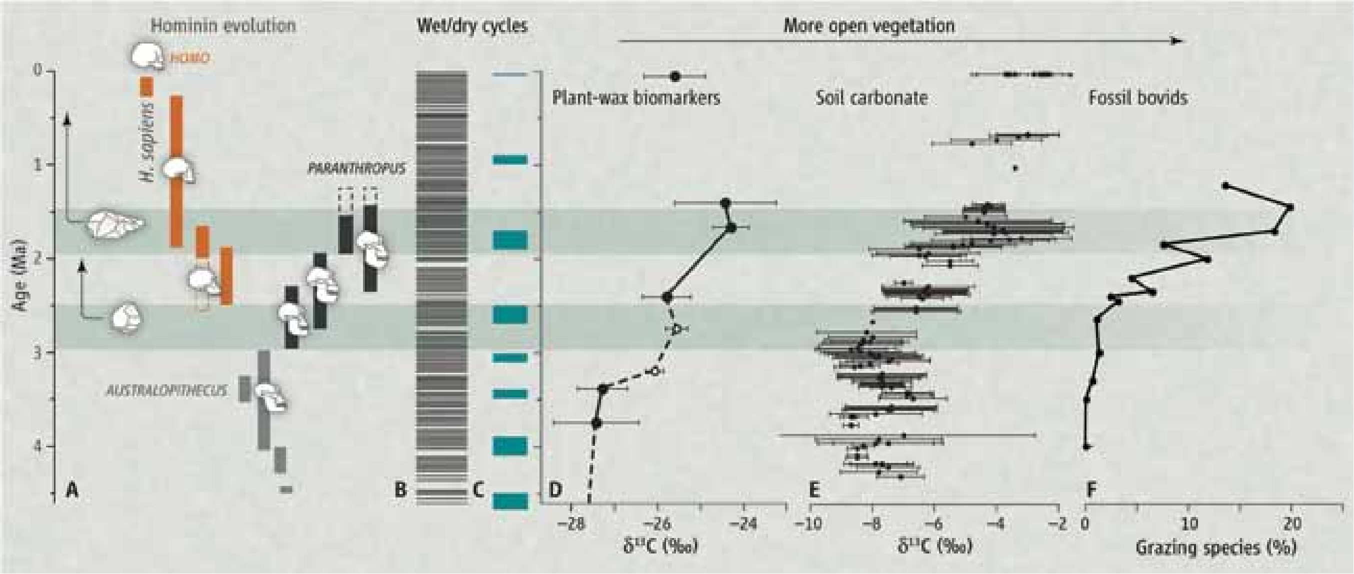
Co-Evolution of Life and the Planet

The presence of life on Earth modifies planetary processes, affecting the composition and properties of the atmosphere, hydrosphere, and the solid Earth. The ocean is an active contributor to Earth system processes and also serves as a repository of sediments that record changes in oceanic life. Ocean drilling is the best way to access this record in a pristine form and with a high level of detail, and has enhanced studies of life processes on the planet.

Many scientific ocean drilling projects have involved biostratigraphy, which is the process of correlating and assigning relative ages of rock or sediment using the fossils contained within them. In addition, oceanic fossils can be used to determine regional and global ecological or chemical changes. Using this record, scientists can gain insight into the reasons behind changing patterns of life on Earth's surface, and have been able to develop new concepts of the relationships between evolution, extinction, and changes in climate.

Documenting Asteroid and Meteorite Impacts

In 1980, a team of researchers found high concentrations of iridium in a sediment layer at the 65.5 million year old boundary between the Cretaceous and Paleogene periods (K-Pg, formerly K-T boundary), the same period as a mass extinction of nearly 75 percent of the world's species. Iridium is an extremely rare chemical element in the Earth's crust, but is found in asteroids and



Scientific ocean drilling has helped reconstruct past climatic conditions that are relevant for the study of human evolution. (A) shows the timing of hominin evolution, including the first appearances of stone tools. In (B) and (C), this is correlated with sediment cores that mark wet and dry cycles related to the North African monsoon (a more detailed view can be seen on page 17) and sedimentary evidence of deep lake conditions in East Africa. (D) and (E) use carbon isotopic analyses of plant biomarkers from scientific ocean drilling and of soil carbonate nodules to indicate the expansion of savannah grassland after 3 million years ago. This is supported by (F), an increase in the relative abundance of African mammals that are adapted to graze in the grassland. Credit: DeMenocal, 2011.

comets, leading to the hypothesis that an asteroid had struck Earth and caused a mass extinction.

Scientists studied existing ocean drilling cores to document the global distribution of the iridium anomaly and ejected particles from the asteroid impact, the effects on marine ecosystems, and the location of the asteroid impact. Sampling of cores during later ocean drilling legs provided further evidence for the iridium anomaly and mass extinction of marine organisms at the K-T boundary, demonstrating the global distribution of these phenomena.

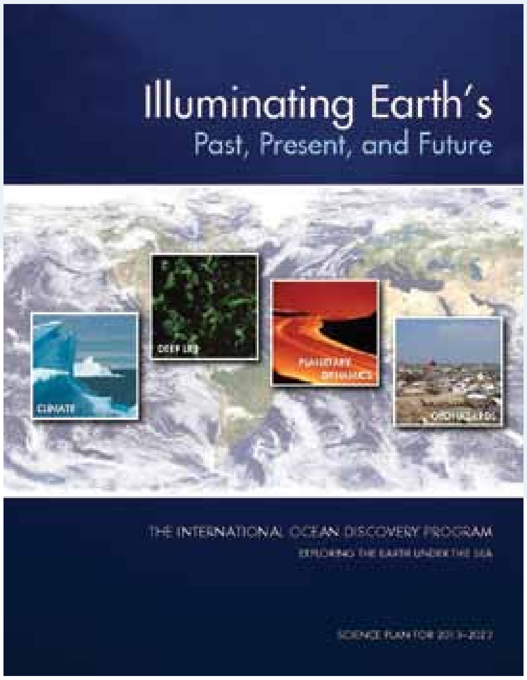
A sediment core across the boundary between the Cretaceous and Paleogene periods, known as the K-T boundary. An asteroid impact is recorded in the dark layer in the middle of the core record, which is composed of ejected material. A thin layer of orange-colored extraterrestrial material lies above the ejecta. The lighter layers of sediment above and below the ejecta contain fossils of ocean microorganisms and demonstrate significant shifts in the type of communities before and after the impact. Credit: IODP-USIO.

Hominin Evolution

Marine sediments hold continuous and detailed records of Cenozoic climate change and species distribution. Recovery of these records through scientific ocean drilling has provided environmental context for explanations of biological changes on the continents—especially the evolution of early humans in Africa. For example, marine sediment cores drilled in the Indian and Southern Atlantic Oceans contain dust that swept across the African continent, providing evidence of fluctuations in Africa’s past climate. Using ocean drilling records in concert with lake and continental drill cores, scientists have found that major steps in the evolution of African hominins and other vertebrates occurred with shifts to more arid, open conditions at specific times during the past 2.8 million years. This correlation has strengthened the links between human origins and their environmental context.

ASSESSMENT OF THE 2013-2023 SCIENCE PLAN

AS THE CURRENT ocean drilling program draws to a close in 2013, scientists, federal agencies, and international partners are already planning for the next program. Part of the planning included a large international meeting of scientists, whose thoughts and suggestions were the basis for drafting a science plan for the proposed 2013-2023 scientific ocean drilling program. The result, the National Science Foundation's *Illuminating Earth's Past, Present, and Future: The International Ocean Discovery Program Science Plan for 2013-2023*, was completed in June 2011.



Illuminating Earth's Past, Present, and Future: The International Ocean Discovery Program Science Plan for 2013-2023, the National Science Foundation's plan for the proposed next phase of scientific ocean drilling, was published in June 2011. Credit: NSF.

One of the major premises of the science plan is that scientific ocean drilling has the potential to continue enabling essential advances in multiple scientific fields, as it has done in past programs. The science plan focuses on the value of Earth science knowledge to meet societal challenges and support better decision making.

The science plan is divided into four research themes: (1) Climate and Ocean Change, (2) Biosphere Frontiers, (3) Earth Connections, and (4) Earth in Motion. Within these themes, there are 14 specific "challenges," or specific research questions. The National Research Council committee was asked to assess the potential for transformative scientific discovery related to the themes and challenges within the science plan.

Themes and Challenges from Illuminating Earth's Past, Present, and Future

The International Ocean Discovery Program Science Plan for 2013-2023

Theme 1 - Climate and Ocean Change: Reading the Past, Informing the Future

1. How Does Earth's Climate System Respond to Elevated Levels of Atmospheric CO_2?
2. How Do Ice Sheets and Sea Level Respond to a Warming Climate?
3. What Controls Regional Patterns of Precipitation, such as those Associated with Monsoons or El Niño?
4. How Resilient is the Ocean to Chemical Perturbation?

Theme 2 - Biosphere Frontiers: Deep Life, Biodiversity, and Environmental Forcing of Ecosystems

5. What are the Origin, Composition, and Global Significance of Subseafloor Communities?
6. What are the Limits of Life in the Subseafloor?
7. How Sensitive are Ecosystems and Biodiversity to Environmental Change?

Theme 3 - Earth Connections: Deep Processes and Their Impact on Earth's Surface Environment

8. What are the Composition, Structure, and Dynamics of Earth's Upper Mantle?
9. How are Seafloor Spreading and Mantle Melting Linked to Ocean Crustal Architecture?
10. What are the Mechanisms, Magnitude, and History of Chemical Exchanges Between the Oceanic Crust and Seawater?
11. How Do Subduction Zones Initiate, Cycle Volatiles, and Generate Continental Crust?

Theme 4 - Earth in Motion: Processes and Hazards on Human Time Scales

12. What Mechanisms Control the Occurrence of Destructive Earthquakes, Landslides, and Tsunami?
13. What Properties and Processes Govern the Flow and Storage of Carbon in the Seafloor?
14. How do Fluids Link Subseafloor Tectonic, Thermal, and Biogeochemical Processes?

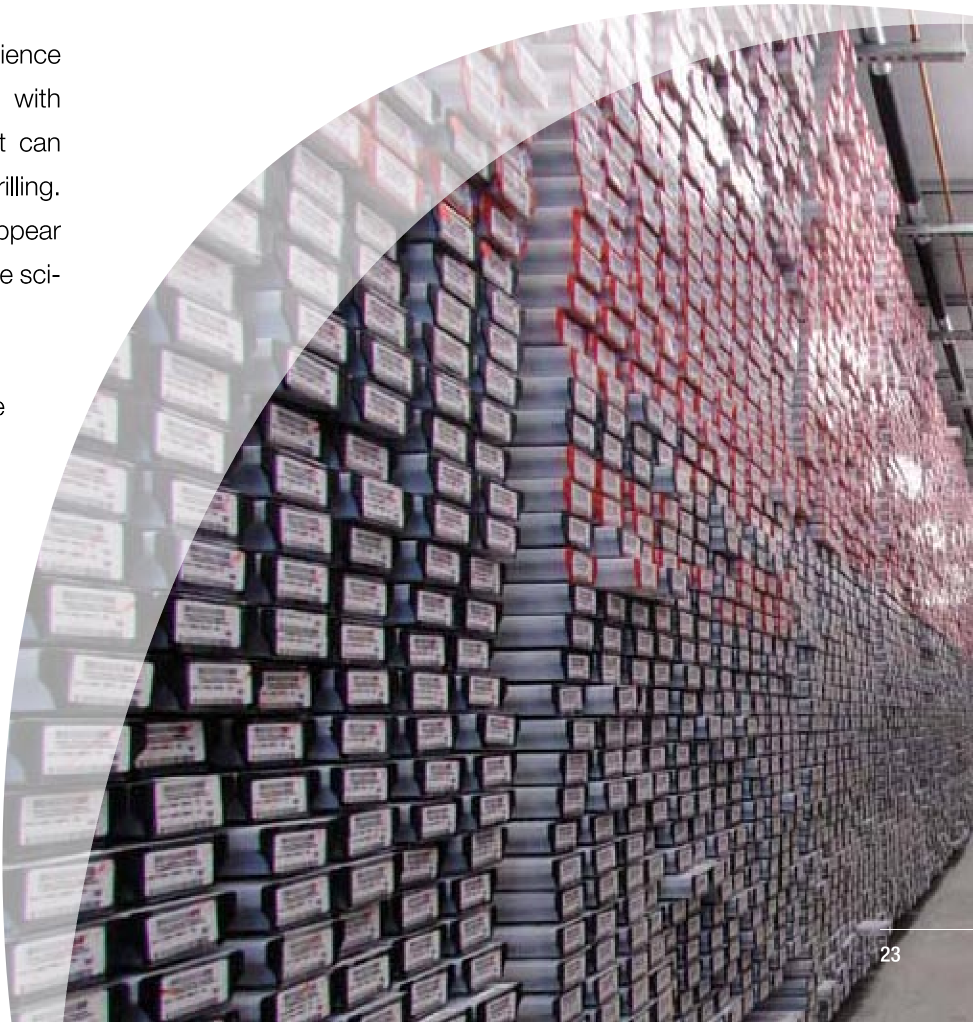
Overall, the committee found that the science plan presents a strong case for the continuation of scientific ocean drilling, clearly defining its possible benefits to science and society. In particular, studies of the subseafloor biosphere present opportunities to identify microbes that could be useful 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 ocean crust 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.

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 determined that the themes and challenges identified in the science plan are pertinent and well-justified, although there is little guidance as to which of the 14 challenges are most important. In times of tighter science budgets, the scientific ocean drilling community may wish to further prioritize possible future drilling objectives.

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 committee's analysis of the past scientific ocean drilling programs found a history of making excellent use of legacy samples and data, which 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.



Cores, packed in tubes, are stored in the core repository. Credit: IODP-USIO.

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.

Although several natural points of synergy between challenges and themes are well described, the committee felt that the science plan would have been strengthened by a more detailed examination of areas of overlap between and among the science challenges, which could help use resources more effectively. For example, integrating multiple drilling objectives in the early planning stages of expeditions would maximize scientific output in relation to costs. There may be opportunities for scientific ocean drilling to further evolve existing approaches to integrating multiple objectives into a single expedition.

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.

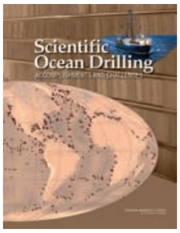
Technology has helped play a vital role in achieving many scientific advances in previous scientific ocean drilling programs. The committee found that transformative science is critically dependent on technological breakthroughs, concluding that any future scientific ocean drilling program should continue 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 groundbreaking science.

Close-up of a drill bit used in scientific ocean drilling. Credit: Johan Lissenberg, Cardiff University & IODP-USIO.

This booklet was prepared by the National Research Council based on the report Scientific Ocean Drilling: Accomplishments and Challenges from the Ocean Studies Board. The project was sponsored by the National Science Foundation.

More information about the report is available at www.dels.nas.edu or by contacting the Ocean Studies Board at (202) 334 2714. To download a free PDF of the report or purchase a hard copy, please visit the National Academies Press website at www.nap.edu or contact the National Academies Press at (800) 624 6242.



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