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Sea changes for scientific ocean drilling

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An era of exploration and discovery beneath the seafloor is coming to an end. Yet there is much more to learn.

With acclaimed author John Steinbeck serving as historian, a group of US scientists and engineers set out in 1961 on a first-of-its-kind mission to drill through the oceanic crust and take the temperature deep beneath the seafloor.[1] Working in waters too deep to drop anchor, the team used a specially adapted barge equipped with a series of outboard motors that enabled them to hold position in the same location for weeks on end. The drilling vessel was topped with a specialized crane, known as a derrick, positioned over a hole in the center of the deck through which the drill string could be lowered. Steinbeck recognized the tremendous potential of the drilling mission, known as Project Mohole: exploring the vast, unexplored terrain beneath the oceans.

Rock samples collected in that first deep-ocean drilling project suggested that the oceanic crust was made of volcanic rocks—an important piece of information that supported the emerging theory of plate tectonics. The visionary project, although falling short of its stated mission of drilling into the mantle, advanced capabilities for both industry and science and inspired decades of scientific ocean drilling and international collaboration. Those efforts have produced a scientific infrastructure of technical, engineering, and managerial know-how, drillships, and a broad multidisciplinary science community of thousands of people that continues to produce groundbreaking discoveries and scientific advances. To read about the history of scientific ocean drilling, see the box on page 33.

Today scientific ocean drilling is positioned as a critical tool for addressing fundamental questions about Earth and its response to climate change, the origins and evolution of life, the hazards associated with earthquakes and tsunamis, and a host of other research areas. The future of scientific ocean drilling, however, remains uncertain as the US retires its drillship, the *JOIDES Resolution*; ends its current NSF-supported drilling program; and pauses to consider how to proceed.

A new international ocean drilling program will be launched on 1 January 2025 by the European Consortium for Ocean Research Drilling and Japan. It will operate expeditions using mission-specific platforms, with vessels and time frames selected to meet the science needs of each mission, rather than the routine two-month expeditions that have been a staple of *JOIDES Resolution* missions. The Japanese drilling vessel *Chikyu* and research vessel *Kaimei* will serve as two primary coring facilities for future scientific ocean discovery work. The stakes are high, and there is concern among the global Earth-sciences community, especially in the US, about losing the unique technical knowledge and collaborative framework honed over many generations. Data from the world's oceans hold the answers to many important outstanding science questions, but they may be harder to solve without a globally ranging drillship akin to the current *JOIDES Resolution*.

The ins and outs of scientific ocean drilling

The sampling of intact geological materials and acquisition of high-quality data from deep within Earth require a set of tools and techniques distinct from those used to drill for oil and natural gas or to construct underwater footings for turbines and bridges. Scientific drilling ships can maintain their position in a range of water depths and current, wind, and wave conditions; recover near-continuous rock and sediment cores in various geological materials; deploy logging instruments that characterize the geophysical properties of the subsurface; and install observatories for capturing dynamic *in situ* information deep underground. Such tools have transformed the ability to study Earth. The results have revolutionized human understanding of its history, geology, and ecology and revealed crucial information about processes that shape our planet.[2]

On the *JOIDES Resolution*, coring begins on the bridge, after the ship arrives at a destination and deploys thrusters that are part of the ship's dynamic positioning system. The thrusters, shown in figure 1, automatically maintain a position, which is critical for coring anywhere that anchoring is not feasible, such as in deep waters. A manual precursor of the technology debuted on the barge for Project Mohole in 1961. Dynamic positioning has since been widely adopted for research and industry purposes and has undergone numerous improvements.

Once in position, the ship prepares for coring by assembling 9.5 m pieces of pipe end over end beneath the derrick. The assembled pipe with a drill bit on the end, together known as the drill string, extends through a hole in the ship's hull, called the moon pool, to the seafloor. A plastic-lined core barrel is lowered through the interior of the pipe. A huge motor in the derrick provides torque for the pipe during drilling.

In soft sediment, a hydraulically actuated system plunges the inner core barrel and liner, with a cutting shoe at the tip, beyond the end of the outer pipe to recover a relatively pristine 9.5-m-long sediment core. The drillers then advance the pipe, replace the inner core liner, and prepare to shoot the next core. Typical depths of soft-sediment core recovery range from 300 m to 500 m below the seafloor but can reach as deep as 700 m (data from Shiny Laurel version 1.0.0, https://doi.org/10.5281/zenodo.10499014). A single hole can yield 30–70 individual cores.

In firmer sediments and basement rock, cores are collected by rotary drilling. The outer drilling pipe rotates through the rock or sediment while the nonrotating inner core barrel with lining advances and trims the core. The *JOIDES Resolution* has drilled down as far as 2100 m beneath the seafloor into the ocean crust. The record for the deepest ocean drilling hole was set by the *Chikyu* in 2019, when it drilled a hole 3250 m beneath the seafloor in the Nankai Trough off the coast of Japan.

The drill string, in its 9.5 m segments, is like a piece of limp spaghetti being lowered 3000–5000 m through the moving ocean. Despite the physical challenges of such a system, scientific ocean drilling has developed the capability not only to core in a specific location but also to thread the drill string back into previously occupied boreholes that have been equipped with a reentry cone and casing system, as shown in figures 1 and 2. The funnel-like

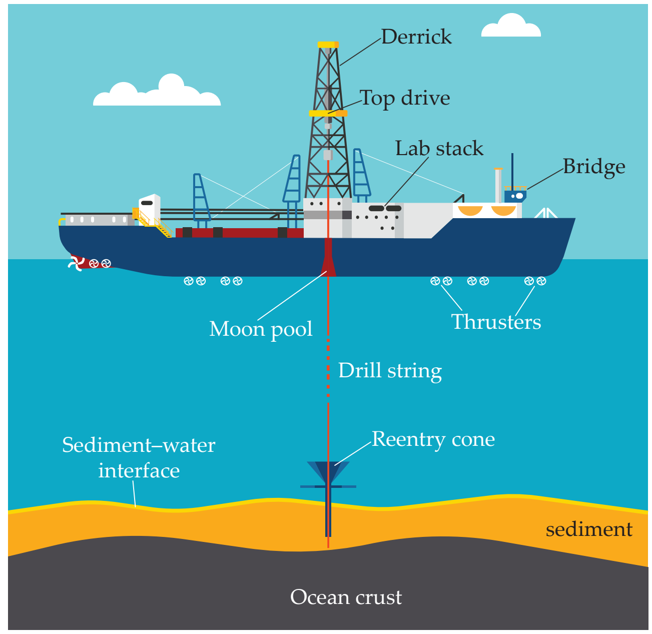


FIGURE 1. *JOIDES RESOLUTION* SCHEMATIC. The US scientific ocean drilling vessel will be retired at the end of 2024, with no replacement in line. (Adapted from International Ocean Discovery Program/*JOIDES Resolution* Science Operator.)

cone allows for reentry and deepening of a hole or for the installation of a borehole observatory—essentially a string of sensors in the seafloor—that can collect data *in situ* over time.

International multidisciplinary science

Joining a drilling expedition, either as science or technical staff, means becoming part of an international team that will typically spend two months together, working 12-hour shifts 7 days a week, to process, measure, and analyze geological materials and data acquired during the expedition (see figure 3). On the *JOIDES Resolution*, much of that work happens at sea; on the mission-specific platform expeditions, only time-sensitive work occurs at sea. Additional processing is done by expedition scientists in a shore-based laboratory. The goals of each expedition are carefully laid out years in advance, along with the technical needs, requirements for safe operating conditions, and essential staff needed to accomplish them.

A typical drilling day on the *JOIDES Resolution*, for example, involves the efforts of more than 100 personnel, including the captain, engineers, drilling team, catering staff, technical staff, and scientists. Drilling crews recover cores or place instruments in the borehole. Once a core is on deck, it is transferred to the technical staff for curation and logging of metadata and then to the scientific team for the collection of a comprehensive series of standard shipboard data and of expedition-specific data. The standard data collected shipboard—such as the core's age, chemical composition, and magnetic polarity and the presence of fossils—have been particularly important hallmarks of scientific ocean drilling. The reliable generation of simple yet diagnostic data provides reconnaissance information for evaluating the success of the current drilling, planning future sampling, and generating hypotheses.

Postcruise work follows up on those preliminary results, through additional sample collection, lab work, data processing, and modeling. Over time, the growing data sets facilitate the discovery of large-scale global patterns of change on Earth's surface through time and space—for example, a 15-million-year global history of organic carbon deposition in the ocean to study biological productivity[3] and a global survey of subseafloor biological respiration from pore-fluid data.[4] Work on the samples and data collected can continue for decades after their initial recovery and is integral to research, education, and training all over the world.

Unveiling geophysical processes

One of the founding motivations for scientific ocean drilling was to collect samples of rock from Earth's mantle. In May 2023, during expedition 399 of the International Ocean Discovery Program (IODP), the *JOIDES Resolution* attempted that goal again by drilling deep into the Atlantis Massif and collecting the longest continuous sequence of rocks with compositions similar to those found in the mantle.[5] Extensional faulting perpendicular to the Mid-Atlantic Ridge formed the Atlantis Massif and introduced lower crustal rocks to the seafloor. Data from that expedition will provide insight into the composition and structure of oceanic lithosphere.

Furthermore, interaction between water and rocks from the lower crust and mantle leads to a form of metamorphism known as serpentinization. Such reactions are hydrothermal alterations of the rocks that produce methane and hydrogen, which are used as energy sources by seafloor microbial communities. Serpentinization and other similar rock–fluid interactions may be occurring at the seafloors of icy ocean worlds in the outer solar system, such as Europa and Enceladus, and thus may create environments conducive to the origin and maintenance of microbial life.[6] As such, scientific ocean drilling plays a critical role as a proxy for understanding astrobiology.

The 2011 magnitude 9.0 Tōhoku-oki earthquake off the coast of Japan exhibited more than 50 m of slip on the fault all the way to the seafloor in the trench. Before that event, researchers had generally thought that such large amounts of earthquake slip were confined to much deeper sections of the fault where an earthquake rupture initiates. The shallow slip in the 2011 event led to an earthquake and a tsunami that was larger in magnitude than expected. Analyses of fault-zone core samples from the Nankai Trough and Japan Trench subduction zones, collected during IODP expeditions 316 and 343, respectively, have subsequently revealed evidence of previous large earthquake ruptures with shallow slip.[7,8] Understanding which faults have experienced large, shallow earthquake slip in the past has huge implications for constraining the conditions that produce tsunami hazards.

The IODP rapid-response drilling expedition 343/343T set out soon after the 2011 earthquake. It collected samples from the fault zone and installed a subseafloor borehole observatory that measured the heat generated along the fault by frictional resistance during the earthquake. The results reveal that the fault zone was incredibly weak—with little resistance to stop the rupture and dissipate energy.[9]

The ability to install observatories deep beneath the seafloor to acquire data and monitor subseafloor systems *in situ* is one of the most exciting and unique aspects of modern scientific ocean drilling (see figure 2). Within the past two decades, some sections of subduction-zone faults have experienced centimeters of slip over the course of hours to months without producing destructive earthquakes. Monitoring those slow-slip events

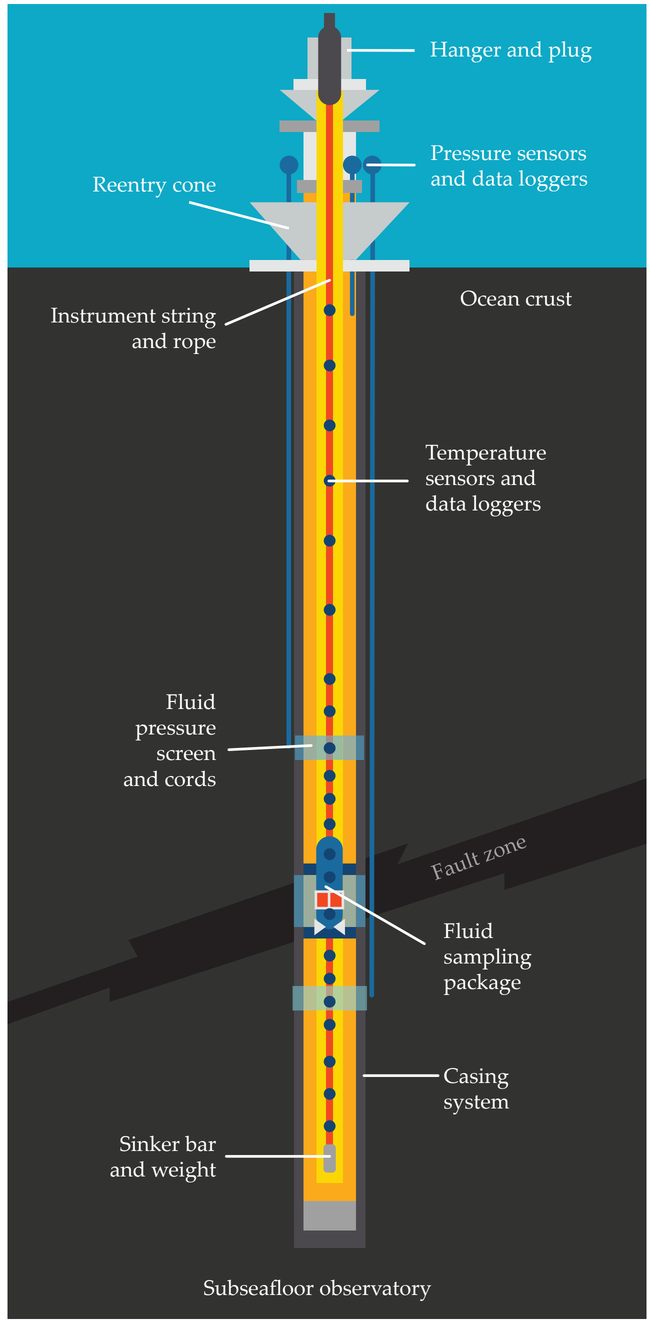


FIGURE 2. SUBSEAFLOOR OBSERVATORIES measure temperature and pressure changes that are used to identify subsurface fluctuations such as slow-slip events on megathrust faults.

is of particular interest for researchers because they affect the stress conditions on faults and can potentially trigger the fast earthquakes that produce damaging shaking.

Those fault systems are mostly far from shore, under the ocean, and difficult to monitor with land-based instruments. Subseafloor borehole observatories installed through scientific ocean drilling, however, have proven remarkably powerful in identifying and characterizing that slip behavior.[10] When even a tiny (roughly 1 cm) amount of slip occurs along a fault, it either squishes or dilates the surrounding rocks, causing the pore-fluid pressure in the rocks to increase or decrease. Those transient subseafloor pressure changes in the rocks are recorded and easily discerned from oceanographic and tidal fluctuations at the seafloor. Borehole observatories in the seafloor are thus more sensitive than approaches that use networks of seismometers and other seafloor georeferencing instruments.

In conjunction with the International Continental Scientific Drilling Program, IODP expedition 364 used a mission-specific platform in 2016 to collect approximately 800 m of drill core from the Chicxulub crater off the Yucatán Peninsula in Mexico. The 66-million-year-old, roughly 200-km-diameter impact crater is linked to the Cretaceous–Paleogene mass extinction that killed off 75% of the world's species, including all nonavian dinosaurs.

Geological materials recovered by the expedition have revealed how large impact events shock and deform the crustal rock and transport large blocks hundreds of meters in size from depths of 10 km to near planetary surfaces within a span of minutes.[11] Cooling of initially molten rocks in the center of the Chicxulub crater drove a vast hydrothermal system for potentially millions of years. Thermophilic bacteria still reside in the crater, which suggests that postimpact hydrothermal systems can spawn ecosystems supported by chemosynthesis.[12] Paleontological observations from sedimentary rocks overlying the crater indicate that life returned to the waters and sediments above ground zero within a span of years, highlighting the ability of life to rebound following a global catastrophe. (For more on research from the Chicxulub core samples, see PHYSICS TODAY, April 2021, page 64.)

Illuminating future climate by studying the past

Scientific ocean drilling has provided many of the data that inform us about past climate change and the resulting effects on the biosphere over the past 200 million years. Because drill cores are collected around the world, ocean drilling enables acquisition of spatially comprehensive data sets that can shed light on regional and global changes in temperature, sea level, ocean circulation, monsoons, evolution of marine microorganisms, and more.[13,14]

Analyses of cores from the ocean floor have elucidated drivers of long-term global warming and cooling, the evolution of tropical monsoon systems, the expansion and contraction of large ice sheets, and the interactions between high-latitude ice growth and low-latitude climates. A series of expeditions encircling the Indian Ocean from 2013 to 2016 revealed the development and intensification of seasonal monsoons in Asia, Africa, and Australia that emerged at least in part as a consequence of tectonically driven Himalayan uplift and mountain building.[13] (For more on seasonal monsoons, see the article by Michela Biasutti, Mingfang Ting, and Spencer Hill, PHYSICS TODAY, September 2023, page 32.)

Coring deep into sandy, submarine fans, built by large rivers draining sediments from Asia, provided data to reconstruct rates of tectonic uplift and landscape evolution and the impact of rising landmasses on ocean and atmospheric circulations. Penetration through the thick river-derived sediment packages proved difficult and limited the depth of drilling, so the history of monsoons before about 15 million years ago remains unsampled.

Earth's polar ice sheets serve as major drivers of global climate and ocean circulation. Decades of work in the deep ocean have documented through geochemical data the variation in the size of polar ice sheets. Yet records from closer to the largest ice sheets are required to truly understand controls on ice-sheet dynamics, the relationship between ice-sheet history and sea level, the temporal evolution of Southern Ocean circulation, and the interplay

FIGURE 3. A DAY IN THE LIFE on the *JOIDES Resolution*. At any given moment, scientists, technicians, and crew members may be working, eating, sleeping, or relaxing on the ship, which operates 24/7. (Courtesy of the International Ocean Discovery Program and the *JOIDES Resolution* Science Operator. Photographers are Tim Fulton, top left, middle left, and second from bottom right; Rosie Sheward, bottom left; Takuya Sagawa, top right; Yiming Yu, second from top right; and Trevor Williams, bottom right.)

between ice, Southern Ocean circulation, and ocean ecosystems. The IODP's Southern Ocean expeditions, including four recent ones conducted in 2018–19, provide unprecedented details about past warm periods, such as evidence for the collapse of the West Antarctic Ice Sheet triggered by ice loss in the Amundsen Sea around 4 million years ago.[15] They also highlight the close coupling between carbon dioxide, ice-sheet dynamics, and ocean temperature.[16] (For a map of the sites drilled over a 54-year period, see figure 4.)

The future of scientific ocean drilling in the US

With the end of IODP2 scheduled for 2024, the international community began planning for the future in 2018. Efforts included developing a broad, forward-looking framework of science priorities[17] and discussing what a new drilling vessel needs to carry out US and global science priorities.[18]

Yet in March 2023, NSF announced that the future of US-supported scientific ocean drilling was uncertain because the cooperative agreement between NSF and Texas A&M University, the operator of the *JOIDES Resolution*, would cease in 2024, four years before the ship's environmental permit expires in 2028. At present, a pathway for US scientists to collect samples from deep beneath the seafloor from 2024 to 2028 remains unclear.

As of the end of 2023, no planning for a new ship has begun. (For more on the *JOIDES Resolution*'s retirement, see Physics Today, September 2023, page 21.)

The decision to retire the *JOIDES Resolution* has numerous impacts in the US. First and foremost, a tremendous amount of science will be put on hold. Most available drilling platforms do not operate in water deeper than 3000 m or have the capability to recover cores from deep within the sediment or crust. Delays in the decisions about a new drillship indicate that the interruption in accessing much of the subseafloor could extend out to 2030 or beyond. An extended period without new data, samples, or shipboard training means that the US is limiting the advancement of a generation of geoscience researchers and technicians.

With an uncertain future for new sampling, some of the community will continue to work with the legacy assets (samples and data) that have been carefully curated by the scientific ocean drilling communities. Yet there are limitations to what has been recovered and curated and to the volume and viability of the remaining materials. For example, geomicrobiology research requires freshly recovered materials to capture the biological signatures of life before the samples degrade in storage or even from the changing environmental conditions shipboard.

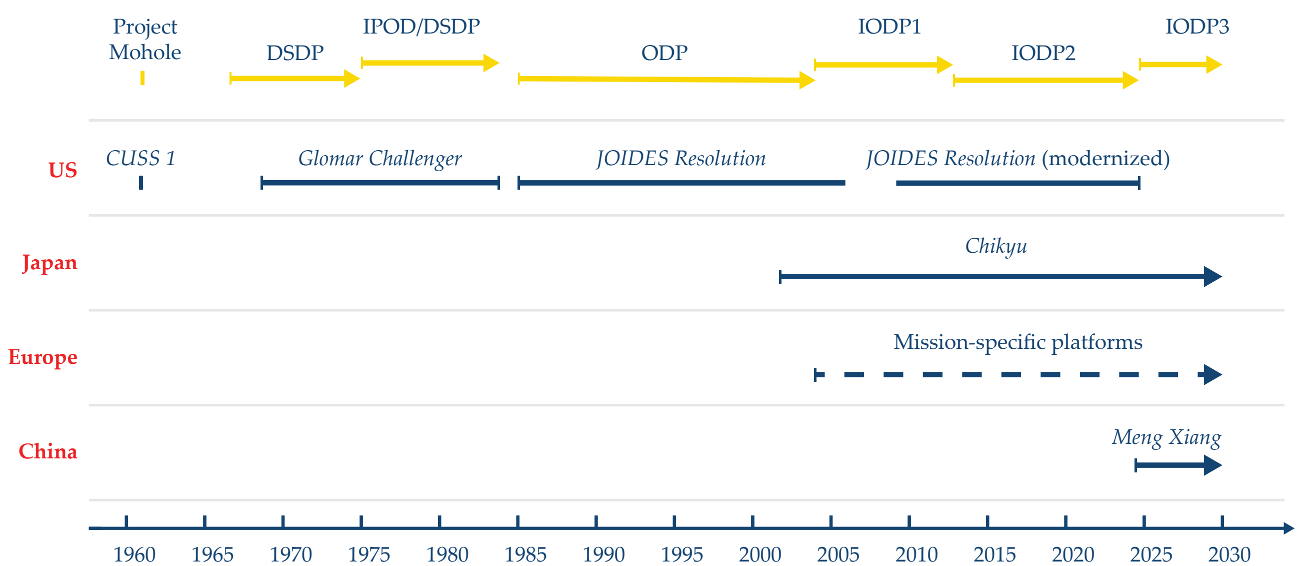
History of scientific ocean drilling

The first scientific ocean drilling expedition, Project Mohole, was conducted in 1961. Five years later, in 1966, NSF funded the establishment of the Deep Sea Drilling Project (DSDP). Starting in 1975, the US was joined by several partners, including France, Japan, the UK, the USSR, and West Germany, to create an international collaboration under the acronym IPOD, for International Phase of Ocean Drilling. That stage established the science-enabling infrastructure to provide technical and logistical staff, a publications office, and funding mechanisms. The infrastructure has evolved over time. With the advent of personal computing and advances in global communications, for example, scientific ocean drilling incorporated information technology and database development.

From 1968 to 1983, the DSDP conducted a series of scientific expeditions with the drilling vessel *Glomar Challenger* and recovered sediment and rock cores from around the world's oceans that provided evidence for plate tectonics, geological-scale climate change, and the evolution of life. The success of the DSDP led to the establishment of its successor, the Ocean Drilling Program (ODP), in 1983 and the acquisition and adaptation of a successor drilling vessel, the *JOIDES Resolution*, which still operates today.

The next phase was conducted in two parts, the Integrated Ocean Drilling Program (IODP1), established in 2003, and the International Ocean Discovery Program (IODP2) which began in 2013. The IODP1 expanded the scope of drilling to include not only the US-run *JOIDES Resolution* but also the *Chikyu* science vessel, designed to drill down to 7000 m below the seafloor and operated by the Japan Agency for Marine-Earth Science and Technology. The IODP1 also included a flexible mission-specific platform program run by the European Consortium for Ocean Research Drilling (ECORD), which currently leases alternative commercially available drilling platforms needed for environments that cannot be drilled with the *JOIDES Resolution* or *Chikyu*. The next international ocean drilling program, IODP3, will be launched on 1 January 2025 by ECORD and Japan, centered around the use of mission-specific platforms.

The *JOIDES Resolution* has been the primary workhorse for scientific ocean drilling; it has hosted about 80% of the expeditions conducted since 2013 because of its flexibility to work in a range of environments and its evolving capabilities. With the scheduled end of its long-term lease in 2024, the potential for scientific progress over the next decade or more is limited by where and how deep the *Chikyu*, mission-specific platform vessels, and the new Chinese vessel *Meng Xiang* can drill.



TIMELINE OF SPECIALIZED SCIENTIFIC OCEAN DRILLING VESSELS

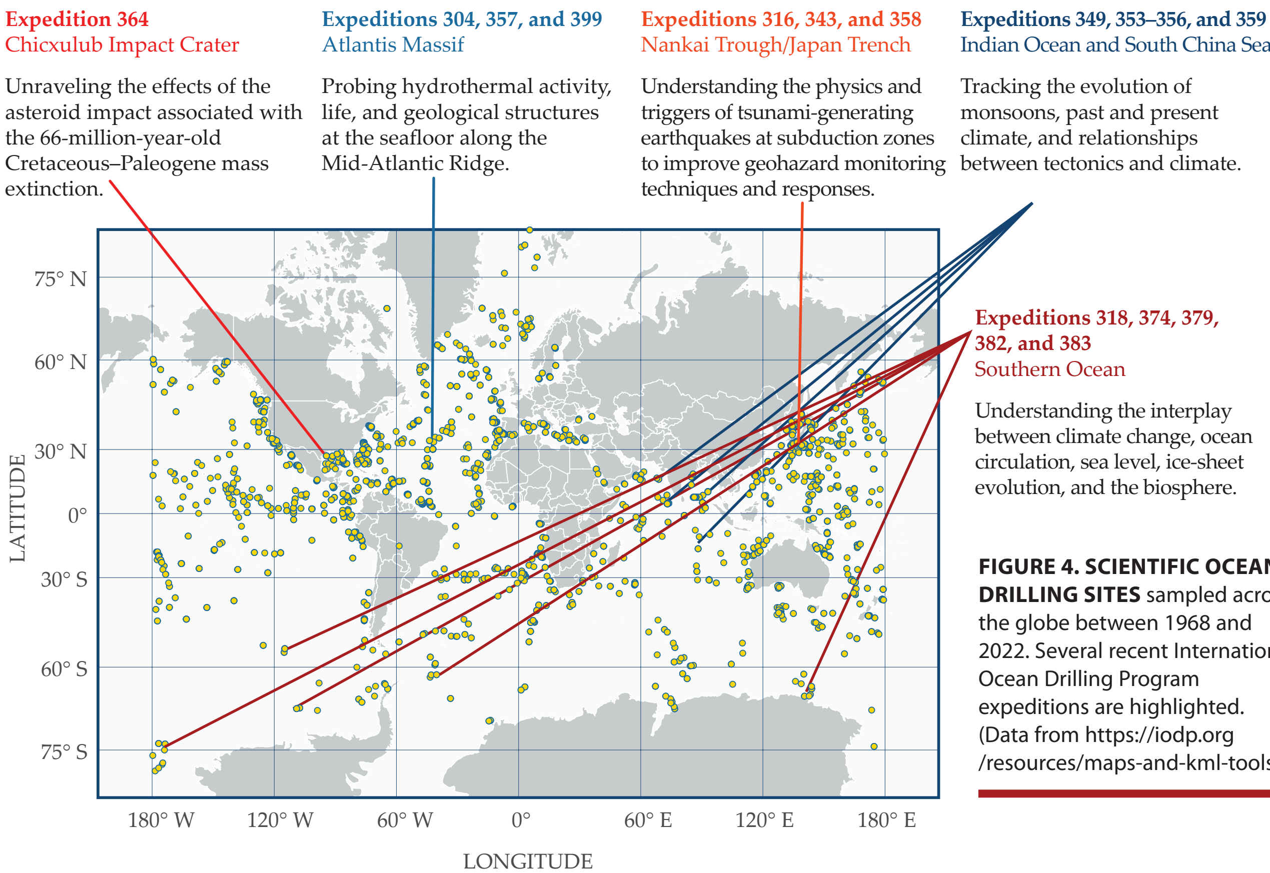


FIGURE 4. SCIENTIFIC OCEAN DRILLING SITES sampled across the globe between 1968 and 2022. Several recent International Ocean Drilling Program expeditions are highlighted. (Data from https://iodp.org/resources/maps-and-kml-tools.)

Observatory-related science that requires new *in situ* measurements cannot be conducted without an appropriate ship for drilling a borehole and installing and recovering the instrumentation and data. Although curated cores may be useful to future climate-oriented work, the coverage of the collections is by no means global in time or space, and some key intervals that were sampled are now depleted.

Scientific ocean drilling has proved incredibly powerful as a means to train students from universities across the US and the world in drilling, collaborating across various science and engineering disciplines, and understanding and interpreting what lies deep underground. The special skills and expertise developed from that work extend beyond the academic realm and are critical for a workforce that will help the US transition to a low-carbon future, especially in the fields of geothermal development, groundwater and environmental management, and carbon dioxide sequestration. Because drilling and geotechnical training opportunities will be sharply limited, losing that science engine will have far-reaching implications. A hiatus in drilling also means a cessation in the development of new technologies that come from the immediacy of needing a problem solved to achieve a specific goal. Because the US has been the global leader in scientific ocean drilling since the field's inception, the current uncertainty is rippling out into the international Earth-sciences community.

After sailing on the first deep-ocean drilling project back in 1961, John Steinbeck wrote that "on this first touching of a new world the way to discovery lies open" (reference 1, page 122). While we celebrate the remarkable accomplishments that scientific ocean drilling has produced since then, we hope that the world of science discovery beneath the oceans will remain accessible for the next generation of US scientists and engineers seeking to tackle Earth's biggest mysteries and uncertainties.

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