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50 Years of Scientific Ocean Drilling

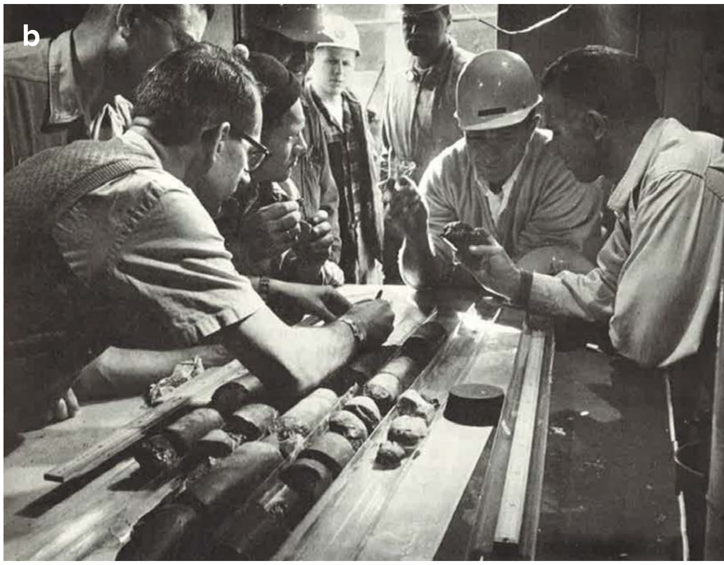
By Keir Becker, James A. Austin Jr., Neville Exon, Susan Humphris, Miriam Kastner, Judith A. McKenzie, Kenneth G. Miller, Kiyoshi Suyehiro, and Asahiko Taira

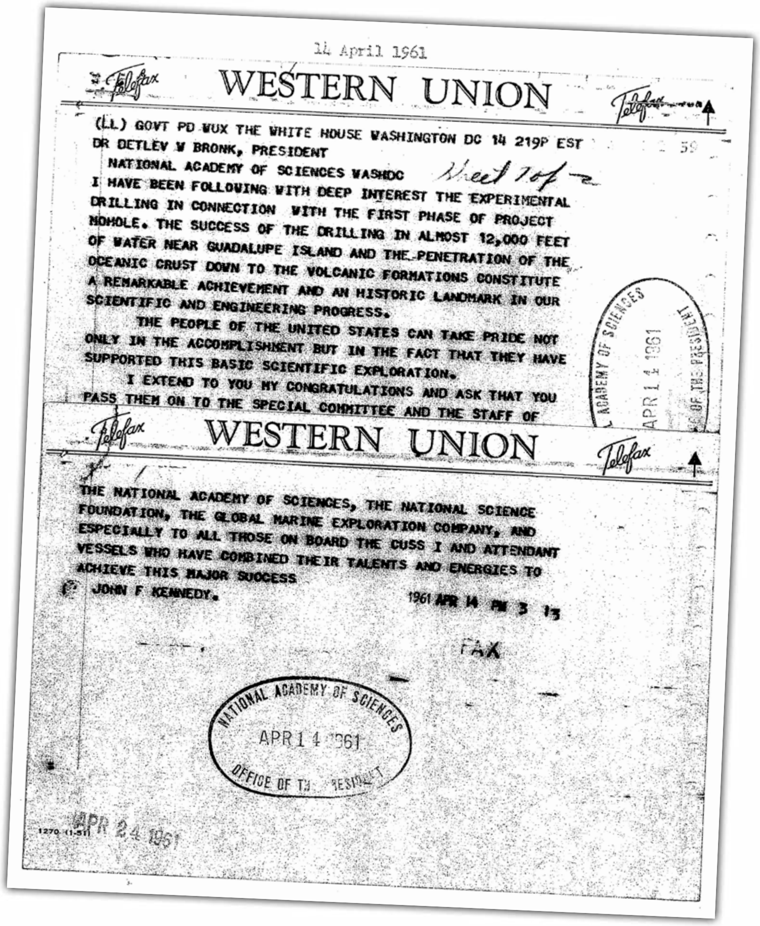
ABSTRACT. Nearly a century after the first systematic study of the global ocean and seafloor by HMS *Challenger* (1871–1876), US scientists began to drill beneath the seafloor to unlock the secrets of the ~70% of Earth's surface covered by the seas. Fifty years of scientific ocean drilling by teams of international partners has provided unparalleled advancements in Earth sciences. Here, we briefly review the history, impacts, and scientific achievements of five decades of coordinated scientific ocean drilling.

PROJECT MOHOLE (1958–1964)

The origins of scientific ocean drilling date back more than 60 years to Project Mohole. Originally suggested in 1957 by Walter Munk and Harry Hess, it was then proposed to the National Science Foundation (NSF) by the famously named, partly self-organized American Miscellaneous Society (AMSOC). At that time, plate tectonics was yet to be formally hypothesized, but it was already known from seafloor seismic refraction studies (e.g., Raitt, 1956) that the Mohorovičić seismic discontinuity between crust and mantle (Moho) was much shallower beneath the ocean floor than the continents. NSF supported phase I of Mohole drilling in 1961 using the Global Marine drilling barge *CUSS I* (Figure 1a), to which four large outboard motors had been added so it could operate as the first dynamically positioned drilling vessel in the world (Bascom, 1961). In a successful demonstration, phase I cored 170 m of sediments and 13 m of underlying basalt at a deepwater site offshore Baja California (Figure 1b). Huge public interest developed, thanks to a prominent article by the famous novelist John Steinbeck in *Life* magazine (Steinbeck, 1961). Recovering subseafloor basalt was a major scientific accomplishment at the time, so much so that it inspired a congratulatory telegram from US President John F. Kennedy

FIGURE 1. (a) The drilling vessel *CUSS I* as used during phase 1 of Project Mohole. (b) A first examination of cores onboard ship during Project Mohole. *Photographs from National Research Council (1961)*

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I HAVE BEEN FOLLOWING WITH DEEP INTEREST THE EXPERIMENTAL DRILLING IN CONNECTION WITH THE FIRST PHASE OF PROJECT MOHOLE. THE SUCCESS OF THE DRILLING IN ALMOST 12,000 FEET OF WATER NEAR GUADALUPE ISLAND AND THE PENETRATION OF THE OCEANIC CRUST DOWN TO THE VOLCANIC FORMATIONS CONSTITUTE A REMARKABLE ACHIEVEMENT AND AN HISTORIC LANDMARK IN OUR SCIENTIFIC AND ENGINEERING PROGRESS.

THE PEOPLE OF THE UNITED STATES CAN TAKE PRIDE NOT ONLY IN THE ACCOMPLISHMENT BUT IN THE FACT THAT THEY HAVE SUPPORTED THIS BASIC SCIENTIFIC EXPLORATION.

I EXTEND TO YOU MY CONGRATULATIONS AND ASK THAT YOU PASS THEM ON TO THE SPECIAL COMMITTEE AND THE STAFF OF

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THE NATIONAL ACADEMY OF SCIENCES, THE NATIONAL SCIENCE FOUNDATION, THE GLOBAL MARINE EXPLORATION COMPANY, AND ESPECIALLY TO ALL THOSE ON BOARD THE CUSS I AND ATTENDANT VESSELS WHO HAVE COMBINED THEIR TALENTS AND ENERGIES TO ACHIEVE THIS MAJOR SUCCESS
JOHN F KENNEDY.

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FIGURE 2. The congratulatory telegram from US President John F. Kennedy at the successful conclusion of phase 1 of Project Mohole.

(Figure 2). However, the effort to continue drilling to the Mohole was derailed by politics when Congress was evaluating various expensive proposals to build an appropriate, custom drilling vessel. As a result, Project Mohole had faded away by 1965. (See Munk, 1980; Maxwell, 1993; and Winterer, 2000, for many fascinating details of the Mohole story.)

JOIDES AND THE DEEP SEA DRILLING PROJECT (1968–1983)

Meanwhile, the directors of four major US oceanographic institutions (Lamont Geological Observatory, Institute for Marine Sciences at the University of Miami, Scripps Institution of Oceanography, and Woods Hole Oceanographic Institution) recognized the value of a concerted program to core the sedimentary record throughout the ocean. In 1964, they signed a memorandum establishing the Joint Oceanographic Institutions Deep Earth Sampling (JOIDES) program. Their vision was to propose to NSF separate scientific drilling "projects" operated by individual oceanographic institutions. The first JOIDES project was a 1965 transect of holes across the Blake Plateau, managed by Lamont and drilled by the chartered vessel *Caldrill*. The Deep Sea Drilling Project (DSDP) was the second JOIDES project, managed by Scripps starting in 1966, including construction of the drilling vessel *Glomar Challenger* (see Spotlight 1). In the summer of 1968, the University of Washington joined JOIDES, and DSDP scientific drilling began with Leg 1 sediment coring in the Gulf of Mexico, in the western Atlantic offshore Bahamas, and on the Bermuda Rise. Originally proposed as an 18-month project, DSDP was so successful that it was extended through 1983. DSDP remained an NSF-funded American effort through 1974 as the National Ocean Sediment Coring (NOSC) program. Between 1973 and 1975, more US institutions and the first international partners (Spotlight 2) joined JOIDES and DSDP for the 1975–1983 International Phase of Ocean Drilling (IPOD), which added an emphasis on penetrating the basaltic basement beneath ocean sediments. In 1975, the first JOIDES Office was established (at Lamont-Doherty Geological Observatory) to coordinate scientific planning for the program, with a subtle change in its title to "Joint Oceanographic Institutions *for* Deep Earth Sampling" (though the acronym remained the same). Scientific ocean drilling has been international ever since (Spotlight 2), and has always been held up as a prime example of successful international scientific collaboration (e.g., Smith et al., 2010).

Revelle (1981) provided an early summary of the scientific impact of DSDP. The most famous DSDP result may well have been direct verification of seafloor spreading by Leg 3 in 1968. That expedition cored and dated the basal sediments immediately above oceanic basement in a transect across the South Atlantic, confirming that crustal age increased nearly linearly with distance from the Mid-Atlantic Ridge spreading center.

DSDP was inherently exploratory and global-ranging, and in that mode made many key scientific contributions—see the section below on Selected Achievements of Scientific Ocean Drilling (1968–2018). DSDP also made important technological contributions, including development of deepwater reentry capabilities (1970) and the hydraulic piston corer (1979) for soft to semi-lithified sediments that continues to be the workhorse of the science of paleoceanography (see Moore and Backman, 2019, in this issue).

OCEAN DRILLING PROGRAM (1983–2003)

In 1983, DSDP was formally concluded, and Texas A&M University was named as the science operator for the Ocean Drilling Program (ODP). Texas A&M

leased a newer and more capable commercial drilling vessel rechristened *JOIDES Resolution* that also included a number of state-of-the-art laboratories for initial analyses (Spotlight 4). Whereas DSDP had been exploratory, ODP was designed as a more thematically driven program, with drilling expeditions based on proposals submitted to the JOIDES advisory structure by the scientific community in response to multi-year science plans (Spotlight 3) developed in periodic international workshops (see section below on Scientific Ocean Drilling and its Advisory Structure). In this planning mode, ODP was very successful across a broad range of scientific themes and gave the community 18 years of continued scientific ocean drilling from 1985 to 2003. NSF provided the majority (about two-thirds) of the financial support throughout ODP, but there were also substantial financial contributions from international partner countries and consortia (Spotlight 2).

INTEGRATED OCEAN DRILLING PROGRAM (2003–2013) AND INTERNATIONAL OCEAN DISCOVERY PROGRAM (2013–2023)

Starting in the mid-1990s, momentum began to develop for a multi-platform continuation of scientific ocean drilling beyond ODP. A new program was envisioned to involve increased international co-funding to make three types of drilling capabilities available to the worldwide scientific community: a riser drilling vessel (Yamada et al., 2019, in this issue) supplied by Japan that was later named *Chikyu* (Japanese for "Earth"; Spotlight 7); continued riserless drilling provided by the United States using a significantly updated *JOIDES Resolution* (Spotlight 4); and mission-specific platforms (MSPs; Spotlight 11) furnished occasionally by the European Consortium for Ocean Research Drilling (ECORD), primarily to access shallow-water and high-latitude scientific targets not suitable for either of the other drillships.

This multi-platform vision was formally realized in late 2003 as the Integrated Ocean Drilling Program (IODP), whose operations began in summer 2004. The first decade of IODP was organized on a model with a significant component of international commingled funding and strong central management provided by IODP Management International Inc. (IODP-MI). Unfortunately, there were delays in launching *Chikyu* and in completing the major overhaul of *JOIDES Resolution* in 2006–2008. Within this first phase of IODP, available funding was not sufficient to achieve the original vision for full-time operations by the two drillships and one or two annual MSP operations. Nevertheless, the first IODP (2003–2013) made significant scientific and technological contributions toward an impressive list of ODP/IODP accomplishments; highlights are listed in a later section on Selected Achievements of Scientific Ocean Drilling (1968–2018), and achievements are documented in more detail by Stein et al. (2014).

For its second 10 years, IODP continued to provide the same two drillships and MSP opportunities, keeping the acronym but changing the program name to the International Ocean Discovery Program. This second phase of IODP significantly simplified the funding and advisory structure, resulting in more efficient operations with no central management organization (Spotlight 5) and an emphasis on regional ship track planning for *JOIDES Resolution* (Spotlight 8).

SCIENTIFIC OCEAN DRILLING AND ITS ADVISORY STRUCTURE

Scientific ocean drilling has always benefited from positive synergy between proposal writers (proponents), a program-based review system, and external peer review starting during ODP. During DSDP, all drilling was exploratory, the community was small, and development and review of drilling expedition plans was often top-down. However, during ODP and the various phases of IODP, all proposals have been reviewed in the context of a succession of community-driven, multi-year, overarching science plans (Spotlight 3). Program-based review panels and committees have evolved through the years, both in number and complexity, from a theme/region focus, with added engineering, logging, and technology panels/working groups, to the comparatively simple current model with a single panel of both "science" and "data" experts who vet all proposals for all platforms and integrate anonymous external peer review. An environmental protection panel, with some members serving for decades, stands guard over the safety of operations. Since the beginning of ODP ~35 years ago, the nurturing of proponents and their ideas has been the key to success, with spectacular results. The program is open to scientists located throughout the globe, and has fostered innovative and transformative science from the tropics to the poles, in every ocean basin, and over every epoch of the last 170 million years.

EDUCATIONAL CONTRIBUTIONS OF SCIENTIFIC OCEAN DRILLING

Spotlight 13 highlights the importance of current IODP efforts in training the next generation of geoscientists, but international scientific ocean drilling has had a long history in this regard since DSDP. Several of the authors of this paper—and many of our colleagues—participated in DSDP expeditions or site surveys during graduate school or early postdoctoral positions. The skills we developed through this participation have been crucial in our career development, and the international networks of scientific contacts we made then have developed into lifelong collaborations. During ODP and IODP, opportunities like this have been provided to graduate students, and many of them have gone on to highly productive careers in the geosciences. In addition, activities have been extended to undergraduates, K–12, and informal education venues. Educators now sail on drilling expeditions and organize many activities, some in real time, to engage students and the public as they study Earth's systems.

SELECTED ACHIEVEMENTS OF SCIENTIFIC OCEAN DRILLING (1968–2018)

Significant accomplishments of scientific ocean drilling in many subjects are explored in more detail in thematic articles in this issue. Major achievements from DSDP and ODP were nicely summarized in the "Major Achievements of Scientific Ocean Drilling" section of the IODP Initial Science Plan (Coffin et al., 2001, pp. 10–16). Stein et al (2014) carefully documented additional achievements from the first phase of IODP. We offer the following as a non-exclusive list of important overall contributions of 50 years of scientific ocean drilling.

Climate, Ocean, and Sea Level History

- Enabled development of the field of pre-Quaternary paleoceanography
- Helped define and refine the geomagnetic polarity timescale and its link to astronomical chronologies back to 66 million years ago, providing key constraints on today's standard Geological Time Scale
- Extended the marine sedimentary record back into the Middle Jurassic (~170 million years ago), allowing reconstruction of planetary history since then at million-year resolution or better
- Tracked changes in atmospheric CO_2 through the Cenozoic and linked these to Earth's surface temperature history
- Documented large carbon-cycle changes associated with marine black shales, anoxic events, and episodes of abrupt climate change such as the Paleocene-Eocene Thermal Maximum
- Linked Earth's orbital variability to long-term climate changes, including the expansion and contraction of global ice volume over millions of years as well as shorter glacial-interglacial cycles
- Enabled construction of a ~100-million-year history of the timing, rates, and estimated amplitudes of global sea level change, documenting the relative contributions to sea level made by tectonics, ice sheet fluctuations, and sediment supply
- Provided high-resolution records of the rates of sea level change of >50 mm yr^{-1} in the last 10–15 thousand years following the Last Glacial Maximum
- Showed that Antarctica was largely ice-free before 35–40 million years ago, with development of continental-scale ice sheets starting at 34–35 million years ago
- Documented the major role of the development of the Circum-Antarctic Current system in glaciation and global thermal evolution in the Cenozoic
- Showed that the Arctic Ocean was a semi-restricted warm sea for much of the early Cenozoic, transitioning through the Miocene to become an ice-covered ocean at about 6 million years ago in the "icehouse world" that continues to the present
- Established the sensitivity of monsoons to climate controls, particularly the linkages between the Indian and Asian monsoons to uplift of the Himalayas during the collision of India with Asia
- Recovered the most complete marine records of the Cretaceous/Paleogene mass extinction 66.05 million years ago (infamous for extinction of the non-avian dinosaurs), linking a large asteroid impact and the mass extinction, and showing that life reestablished robust ecosystems in the impact area within 30,000 years of the impact

> "Fifty years of scientific ocean drilling by teams of international partners has provided unparalleled advancements in Earth sciences."

Plate Tectonics and Geodynamics

- Provided early, direct confirmation of seafloor spreading and the theory of plate tectonics
- Nearly four decades later, long-term seismic observatories in scientific ocean drilling holes beneath the seafloor provided the first direct evidence for the age-dependent growth of the oceanic lithosphere—an essential tenet of plate tectonics
- Provided the first thick sequences of intact oceanic crust below thick layers of marine sediment, revealing the complexity of crustal construction processes, and demonstrating that crustal sections generated at slow-spreading, fast-spreading, and thickly sedimented ridges are distinctly different in architecture
- Advanced our understanding of continental breakup, faulting, rifting, and associated magmatism and processes, constraining the timing of the transition from rifting to seafloor spreading
- Showed that mantle plumes that feed volcanic hotspot systems like the Hawaii-Emperor island and seamount chain may not be stationary but can move at rates half those of plate motions, providing direct input into the debate on the geodynamic nature of Earth's mantle
- Sampled oceanic plateaus formed as large igneous provinces (LIPs) by massive Mesozoic volcanism over short periods, documenting links to Mesozoic anoxic events and suggesting links to

changes in convection in the outer core associated with the "Cretaceous Quiet Zone," during which reversals of Earth's magnetic field were very infrequent

- Illuminated fault zone behavior and related tectonic processes at active plate boundaries where Earth's largest earthquakes and tsunamis are generated
- Investigated the nature of and processes active within subduction zones by drilling through the subduction décollement to recover subducted sediments, formation fluid, and the igneous slab, allowing an initial inventory of Earth materials that are recycled into the mantle by subducting plates
- Revealed the presence of one of the world's largest and the most recent "salt giant" deposited in the late Miocene Mediterranean Sea as a result of a temporary closure or restriction of the connection to the Atlantic Ocean during the Messinian Salinity Crisis 5.97–5.33 million years ago

Biosphere and Subseafloor Hydrogeology

- Confirmed that a previously unsampled biosphere exists within sediments as deep as 2.4 km below the seafloor, within aerobic open-ocean sediments under low-energy extremes, and within the volcanic carapace of the oceanic crust
- Enabled development of first-order estimates on the extent and limits of life in the subseafloor environment, demonstrating through borehole observatories that subseafloor microbial communities are dynamic over time and play important biogeochemical roles in elemental cycling
- Revealed significant flows of fluids through virtually all parts of the seafloor, from mid-ocean ridges to deep-sea trenches
- Documented the relationships among fluid circulation and the alteration and aging of the oceanic crust
- Revealed for the first time the internal structure of seafloor massive sulfide deposits
- Successfully sampled subseafloor gas hydrate formations to investigate their role in the carbon cycle, climate, and slope stability
- Recovered deeply sourced (many kilometers) mantle serpentinites in subduction forearc mud volcanoes as well as associated slab-derived fluids with elevated pH, methane, and hydrogen concentrations that support unusual microbial and megafauna biota
- Developed subseafloor borehole hydrological observatory systems with long-term monitoring capabilities that enabled scientists to conduct short- and long-term in situ experiments within Earth's crust, revealing for the first time the actual directions of flow of subseafloor fluids.

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