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What Lies Beneath: The Formation and Evolution of Oceanic Lithosphere

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What Lies Beneath

THE FORMATION AND EVOLUTION OF OCEANIC LITHOSPHERE

By Katsuyoshi Michibayashi, Masako Tominaga, Benoît Ildefonse, and Damon A.H. Teagle

Reentry cone deployment through the *JOIDES Resolution* moonpool, Expedition 375, Hikurangi Subduction Margin. *Photo credit: Tim Fulton, IODP JRSO*

ABSTRACT. Sampling the upper mantle via scientific ocean drilling remains elusive. Although the technologies required for drilling to the Moho still don't exist, we have made significant progress over the last five decades in piecing together the complex geology of the oceanic crust. Here, we highlight key findings that reveal the architecture of oceanic crust and the thermal, physical, and chemical processes that are responsible for the growth and structure of the oceanic lithosphere. These advances result from enduring efforts to drill and collect downhole geophysical logs of oceanic crust near both slow and fast spreading ridges.

INTRODUCTION

Scientific ocean drilling commenced through the initiation of Project Mohole in 1961, about the same time as Apollo moon landing ambitions were first articulated. It has been almost 60 years since the American Miscellaneous Society conceived of the idea for Project Mohole and 50 years since the launch of the Deep Sea Drilling Project (DSDP) in 1968. Scientific ocean drilling is an essential approach to directly access Earth's interior and is arguably science's most successful international collaboration. Although this cooperation has greatly expanded from the DSDP (1968–1983), through the Ocean Drilling Program (ODP, 1983–2003) to the Integrated Ocean Drilling Program (IODP, 2003–2013), and to the International Ocean Discovery Program (IODP, 2013–2023), gaining a better understanding of the dynamics of our planet remain challenging due to the technical difficulties of drilling holes deeper than 100–200 m into the oceanic crust's igneous basement.

A compilation of holes drilled into in situ oceanic crust by scientific ocean drilling since the beginning of DSDP through 2018 highlights the problem: only 38 holes are deeper than 100 m and only 20 are deeper than 200 m (Figures 1 and 2; e.g., Ildefonse et al., 2007b, 2014). The first attempt was DSDP Hole 332A drilled on Leg 37 in 1974 (Aumento et al., 1977). The total amount of igneous oceanic crust recovered represents less than 2% of the material archived in the DSDP, ODP, and IODP core repositories. Despite this relative paucity of material, scientific ocean drilling has provided essential and hitherto unavailable observations that are advancing our understanding of the processes that "repave" nearly 70% of Earth's surface over short geological timescales (<200 million years). We have better knowledge of oceanic crust architecture, magmatic accretion processes in

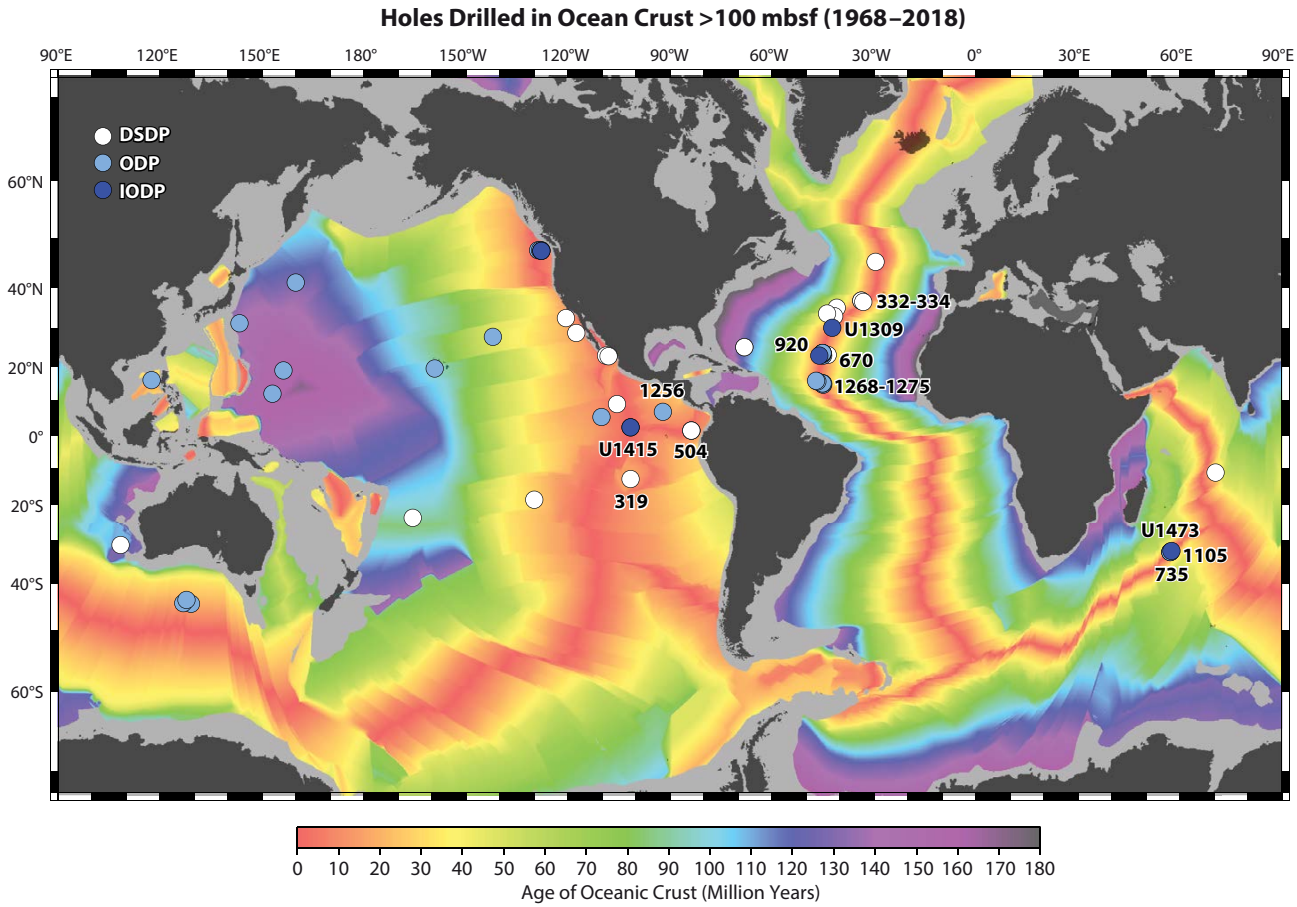

FIGURE 1. Compilation showing holes drilled >100 meters below seafloor (mbsf) into the basement of intact oceanic crust and tectonically exposed lower crust and upper mantle from 1968 to 2018 (see drill hole sections in Figure 2). Sites mentioned in the text are labeled. Seafloor age based on age grid by Müller et al. (2008, revised version 3; www.earthbyte.org/). This map does not include "hard rock" drill holes in seamounts, oceanic plateaus, back-arc basement, hydrothermal mounds, or passive continental margins.

the centers of mid-ocean ridge spreading centers, and the nature and magnitudes of hydrothermal exchange between the ocean and the oceanic lithosphere, and scientific ocean drilling samples led to the discovery of a deep microbial rock-hosted biosphere.

With the results from 50 years of scientific ocean drilling, we now know that in all ocean basins a volcanic basement lies beneath an almost omnipresent blanket of sediments, created by a system of mid-ocean ridges that together form the largest magmatic province on Earth, generating more than 20 km^3 of new oceanic crust each year. Roughly two-thirds of the magma derived from the partial melting of upper mantle peridotite cools and crystallizes as plutons in the lower portion of the oceanic crust; the remainder erupts as basalt and forms the upper one-third of this basement.

Here, we focus on the importance of basement drilling and the advancements in our understanding of the key differences in ocean crust architecture as a function of plate tectonic setting and related thermal, physical, and chemical processes. We summarize early attempts in the 1960s and current plans to reach the Mohorovičić Discontinuity (Moho) at the lower ocean crust boundary with the upper mantle, and we discuss how scientific ocean drilling has informed us on the major differences in oceanic crust created in fast and ultra-slow spreading settings.

PROJECT MOHOLE

Project Mohole[1] has been an iconic aspiration in the Earth sciences, a fundamental driver of scientific ocean drilling and a focus of five decades of enduring collaborations between the United States and its international partners (Hsü, 1992). Originally, Project Mohole provided a geoscience foil to the nascent US space program. The essence of Project Mohole was to retrieve samples of Earth's mantle by penetrating the Moho, a major global seismic boundary between Earth's crust and upper mantle. Seismologists had already subdivided the oceanic crust into seismic layers: Layer 1 comprising low P-wave velocity sediments ($V_p < 3$ km s^{-1}); Layer 2 having low P-wave velocity and a steep velocity gradient, with V_p ranging from ~3.5 km s^{-1} to ~6.7 km s^{-1}, typical of basalt; and Layer 3 having high velocity and a more gentle velocity gradient (V_p of 6.7–7.1 km s^{-1}) that we now know is typical of gabbro. However, an abrupt increase at the base of Layer 3 to $V_p > 8$ km s^{-1} was found to mark the Moho and was interpreted to be the boundary between the gabbros of the lower oceanic crust and the ultramafic (peridotitic) rocks of the uppermost mantle.

The ultimate proposal was to drill to the Moho in the deep ocean where Earth's crust is relatively thin (~6 km; National Research Council, 1957; Bascom, 1961). Attempting such an effort on land would have been impractical because the drilling equipment would have to withstand high in situ temperatures at great depths while drilling through the much thicker (>30 km) continental crust. In addition, cores sampled by ocean drilling offer a simpler and "cleaner" record of major geological processes, rather than the complex geology sampled by a terrestrial deep hole that would have resulted from multiple global tectonic ~400–500 million-year-long "Wilson cycles." If successful, the highly ambitious and technically challenging Project Mohole would have yielded new observations on the age and composition of the seafloor, while providing evidence for the theory of continental drift that at the time remained controversial and strongly debated.

Project Mohole comprised a three-phase plan (National Research Council, 1959). Phase 1 focused on modifying a

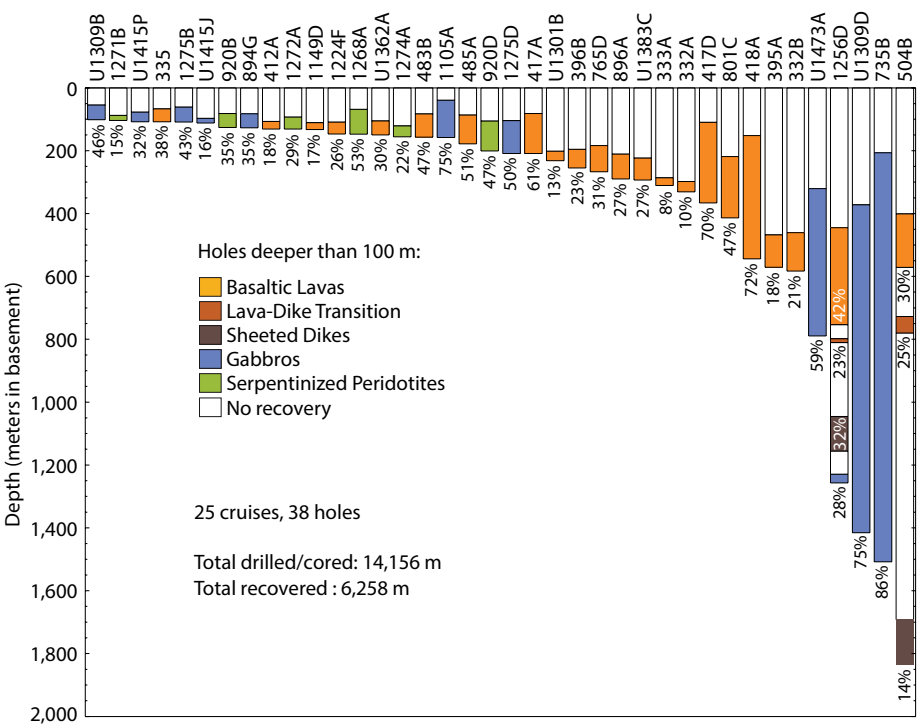

FIGURE 2. Compilation showing scientific ocean drilling holes that penetrated >100 m into the basement of intact oceanic crust and tectonically exposed lower crust and upper mantle from 1968 to 2018 (see drill hole locations in Figure 1). The number designation for each hole and the recovery (in percent) for each of the basement lithologies are indicated. This compilation does not include "hard rock" drill holes in seamounts, oceanic plateaus, back-arc basement, hydrothermal mounds, or passive continental margins.

[1] The US National Academies of Sciences, Engineering and Medicine offer a special website, Project Mohole: Commemorating the Accomplishments of Project Mohole—1961–2011, where a unique collection of photographs, video, original narratives, and historical documents can be found (http://www.nationalacademies.org/mohole/index.html).

drilling vessel for deepwater operations and testing the vessel and equipment in deep water far offshore. This required the development of new capabilities, including: (1) navigational and thruster technologies to keep a floating vessel at a single deep-ocean location, now known as "dynamic positioning" and a universal feature on any modern-day research vessel, and (2) a strategy that would allow subsequent visits to reenter the drill holes and resume drilling efforts (Bascom, 1961). The scientific objective of Phase 1 was to core as deep as possible into the ocean bottom, while Phase 2 was planned to use a more advanced vessel, and Phase 3 was intended to culminate in drilling through the Moho.

After ocean-going trials off La Jolla, California, Project Mohole Phase 1 began with drilling experiments near Guadalupe, Mexico, in March and April 1961. The drilling barge *CUSS I* (named after the four oil companies that had developed it: Continental, Union, Shell, and Superior) drilled 183 m into the seafloor in 3,558 m of water, and yielded 13 m of basalt beneath 170 m of sediment (National Research Council [U.S.] AMSOC Committee, 1961). This was the first in situ demonstration that the oceanic basement comprises (young) basaltic lavas, and that seismic Layer 2 is basalt. Project Mohole Phase 1 was a major early step in the exploration of Earth's interior, with scientists receiving a congratulatory telegram from US President John F. Kennedy: "The success of the drilling in almost 12,000 feet of water near Guadalupe 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 National Academies of Sciences, Engineering and Medicine, 2011; see Becker et al., 2019, in this issue, Figures 1 and 2 for photos of *CUSS I* and this telegram).

Notwithstanding this early success, Project Mohole became mired in political controversy and was terminated in 1966 before further holes were drilled. Despite Project Mohole not achieving its original goal of drilling to the mantle, the project contributed to a "movement" in the solid Earth community, cumulating in the global acceptance of the theory of plate tectonics. Moreover, Project Mohole not only showed that scientific ocean drilling could successfully drill into and recover core samples from oceanic basement but also illustrated that ocean drilling is an essential tool for gathering otherwise inaccessible information about how our dynamic planet operates (Teagle and Ildefonse, 2011). Project Mohole led to formation of the US Deep Sea Drilling Project (DSDP), whose first expedition sailed in 1968.

EARLY YEARS: PENROSE MODEL AND CORING IN OCEANIC CRUST

The earliest years of DSDP concentrated on recovering long sediment cores to refine marine sediment-based biostratigraphy models and to validate the theory of seafloor spreading by dating the sediments directly overlying the oceanic basement (DSDP Leg 3; Maxwell et al., 1970). When the very top of the oceanic basement was "tapped" below the sediment column, recovered samples were recognized as pillow lavas, providing the first direct evidence of lava that was rapidly cooled in a subaqueous environment. These samples became the center of a debate on the origin of commonly juxtaposed rock strata observed in locations such as the Troodos Massif, Cyprus (e.g., Gass, 1968; cf. Miyashiro, 1973) and other orogenic belts. Geologists working on these so-called ophiolites reached a consensus statement during the 1972 Penrose Field Conference that defined these rock sequences in the context of the new paradigm of seafloor spreading, in what is now referred to as the Penrose model (Anonymous, 1972). This statement developed the widely accepted model that ophiolites are ancient and largely intact sections of oceanic crust preserved on land that comprise, from bottom to the top: (1) ultramafic rocks of the upper mantle, (2) gabbros, (3) a sheeted dike complex, (4) basaltic lavas, commonly pillow basalts, and (5) associated sedimentary deposits such as ribbon cherts, thin shale interbeds, and minor limestones (Figure 3a). The Penrose model raised the enduring science question as to whether ophiolites represent a direct analog for in situ oceanic crust beneath the modern seafloor (e.g., Panayotou, 1980; Gass, 1990), and this question, in turn, has been an important motivation for drilling the oceanic crust (e.g., Dilek et al., 2000).

The first international efforts to drill deeply into the oceanic crust were DSDP Leg 34 in 1973–1974 on the Nazca Plate in the Eastern Pacific Ocean (Yeasts et al., 1976), and DSDP Leg 37 in 1974 on the western flank of the Mid-Atlantic Ridge, south of the Azores Plateau (Aumento et al., 1977). These legs recovered, for the first time, tens of meters of basaltic core samples from upper oceanic crust (e.g., 59 m in Site 319 during Leg 34; >100 m in Holes 332A,B and 333A during Leg 37; Figures 1 and 2). It is also noteworthy that cores from Leg 37 Site 334 in the Atlantic recovered small amounts of gabbro and serpentinized peridotite from the presumed deeper layer in a typical Penrose style of oceanic lithosphere, at relatively shallow (117 meters below sediment-basement contact) subseafloor depths (Aumento et al., 1977), suggesting a vertical and lateral crustal heterogeneity and demonstrating that the Penrose model is an end member model itself (Figure 3; Ildefonse et al., 2014).

DEEP DRILLING IN FAST-SPREADING CRUST

Although less than 20% of the modern mid-ocean ridge system is creating new seafloor at fast rates (>80 mm yr^{-1} full rate), nearly half of the oceanic crust created over the last 200 million years formed at fast-spreading ridges (Teagle et al., 2012; Ildefonse et al., 2014). Deep drilling into oceanic crust at a few sites in the Eastern Pacific, including the Cocos Plate (ODP Holes 504B and 1256) and the Hess Deep (IODP Site U1415), has

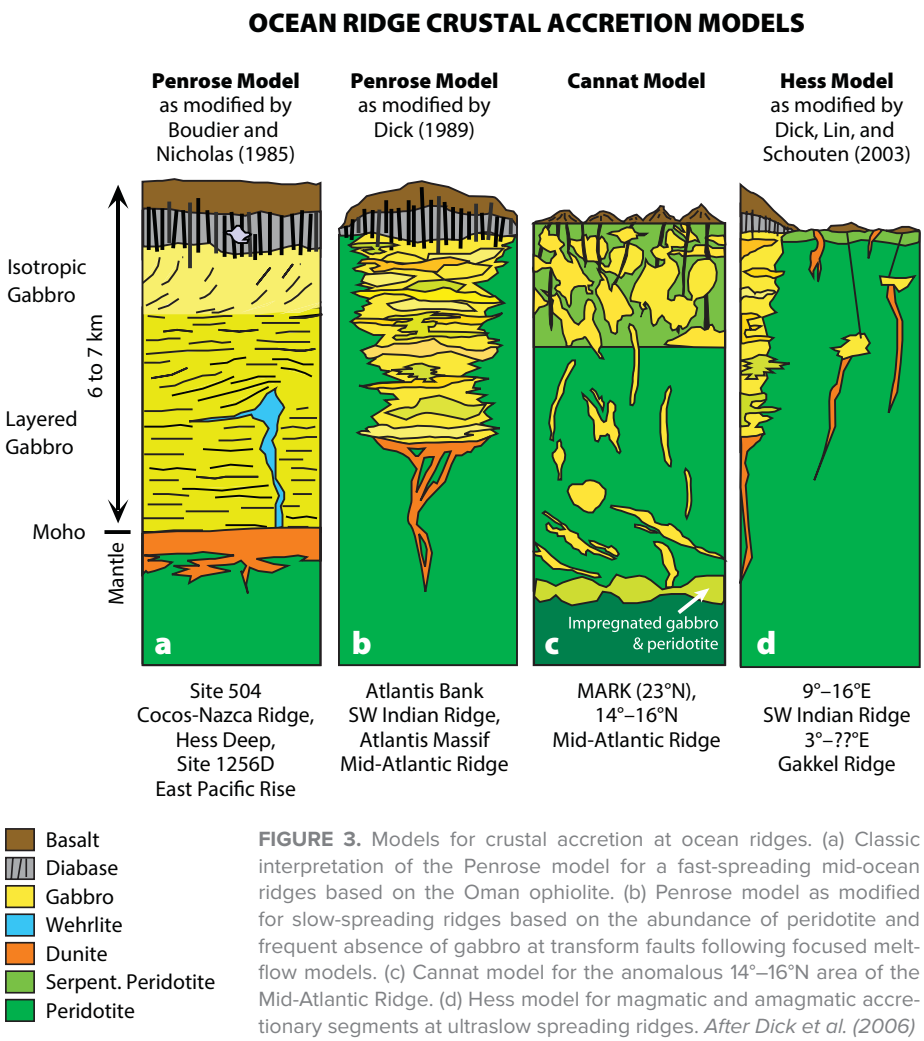

FIGURE 3. Models for crustal accretion at ocean ridges. (a) Classic interpretation of the Penrose model for a fast-spreading mid-ocean ridges based on the Oman ophiolite. (b) Penrose model as modified for slow-spreading ridges based on the abundance of peridotite and frequent absence of gabbro at transform faults following focused melt-flow models. (c) Cannat model for the anomalous 14°–16°N area of the Mid-Atlantic Ridge. (d) Hess model for magmatic and amagmatic accretionary segments at ultraslow spreading ridges. *After Dick et al. (2006)*

led to a widely accepted model of ocean crust architecture that is very similar to, and confirms in large terms, the Penrose model. Drilling has also provided insights into the nature of key seismic boundaries found in fast-spreading oceanic crust and into the role of alteration, grain size and texture, and composition in controlling these boundaries.

DSDP/ODP Reference Hole 504B: Nazca Plate

DSDP/ODP Hole 504B, located in 6 million year old crust 200 km south of the Costa Rica Rift in the eastern equatorial Pacific, has long been a "reference" site for intact oceanic crust formed at an intermediate- to fast-spreading center (Figures 1 and 2) between the oceanic Cocos (north) and Nazca (south) tectonic plates. It is the deepest hole drilled into the igneous oceanic crust, penetrating 2,111 meters below seafloor (mbsf) and 1,836.5 m into the subbasement over the course of seven ODP and DSDP legs since 1979 (DSDP Legs 69, 70, and 83, and ODP Legs 111, 137, 149, and 148; Cann et al., 1983; Anderson et al., 1985; Alt et al., 1986, 1993, 1996; Becker et al., 1988, 1992; Dick et al., 1992). The hole was also visited during DSDP Leg 92 in 1983 for downhole logging and sampling of borehole fluids (Leinen et al., 1986) and will be revisited in 2019 (IODP Expedition 385T; Tominaga et al., in press). ODP Leg 148 in 1993 was the last time Hole 504B was deepened, this time by 111 m. Further penetration is currently prevented because portions of a drill bit are stuck in the hole (Alt et al., 1993).

The lithologic sequence in Hole 504B consists (from top to bottom) of 274.5 m of sediment, 571.5 m of volcanic rocks, a 209 m transition zone, and 1,050 m of a sheeted dike complex (Figure 2; Alt et al., 1996). The hydrothermal alteration of the volcanic section in Hole 504B involves a series of processes that entail interaction with oxidizing seawater at low temperatures, with intensity decreasing downward. These processes and their effects on the volcanic section are generally similar to those in other oceanic upper crustal sections. The transition zone and upper dikes (down to 1,500 mbsf) were altered in a subsurface mixing zone, where hydrothermal fluids upwelling through the dikes mixed with cooler seawater circulating in the overlying more permeable volcanic rocks. Mineral assemblages in the cored permeable pillow basalts in the transition zone indicate that during hydrothermal circulation, a maximum temperature of ~350°–380°C may have been reached. This is typical of greenschist facies metamorphism that includes such alteration minerals as chlorite, actinolite, and albite-oligoclase (Alt et al., 1996). The lower dikes (1,500–2,111 mbsf) were hydrothermally altered at temperatures exceeding 400°C, resulting in the formation of hornblende and calcic secondary plagioclase, which then subsequently were overwritten by similar reactions that produced the pillow basalt greenschist assemblages at ~300°–400°C. Alteration of the sheeted dikes from Hole 504B is heterogeneous, with recrystallization controlled by fracturing and fluid access (Alt et al., 1996). Defining the position of the seismic transition between Layer 2 (basalts) and Layer 3 (gabbros) in Hole 504B depends upon the scale of observation, but appears to correlate with observed progressive changes in porosity and hydrothermal alteration (Alt et al., 1996). Therefore, the nature of the transition from sheeted dikes to gabbros in Hole 504B remains obscured.

ODP-IODP Superfast Hole 1256D: Cocos Plate

ODP Hole 1256D (Figures 1 and 2) was designed as a deep borehole to sample the cumulate gabbros of the lower

oceanic crust and to penetrate deeper into the oceanic crustal sequence than Hole 504B. Hole 1256D is located in 3,635 m of water in the Guatemala Basin (6°44.2'N, 91°56.1'W) on the Cocos Plate in the eastern equatorial Pacific Ocean. Ocean crust at the site formed around 15 million years ago during a sustained episode of superfast ocean ridge spreading (>200 mm yr^{-1}; Wilson, 1996) at the East Pacific Rise. The site formed on a ridge segment that is at least 400 km long, located ~100 km north of the ridge-ridge-ridge (RRR) triple junction between the Cocos, Pacific, and Nazca Plates.

The deep drilling campaign at Site 1256 was aimed at understanding the formation, architecture, and evolution of oceanic crust formed at "superfast" plate spreading rates. It has been the focus of four scientific ocean drilling cruises (ODP Leg 206 and IODP Expeditions 309, 312, and 335; Wilson et al., 2003; Teagle et al., 2006, 2012). Hole 1256D was the first scientific ocean drilling borehole prepared for deep drilling in oceanic crust. A large funnel, or reentry cone, was installed at the seafloor and then secured downhole with almost 270 m of 16-inch casing through the 250 m thick sedimentary overburden, and then cemented into the uppermost basement (Wilson et al., 2003). During ODP Leg 206, the borehole was deepened through an ~810 m thick sequence of basaltic lavas and a thin (~346 m) sheeted dike complex, the lower 60 m of which shows evidence for the formation of granoblastic textures (i.e., rocks with a dense arrangement of large equidimensional minerals with sutured boundaries) that typically result from high temperature contact metamorphism (Teagle et al., 2006). During IODP Expedition 312, the first gabbroic rocks were encountered at 1,407 mbsf (Wilson et al., 2006; Teagle et al., 2006) at a depth where the hole entered a complex dike–gabbro transition zone that includes two gabbro lenses (20–50-m thick) intruding into basalt dikes with the same high-temperature granoblastic textures (Figure 4). IODP Expedition 335 returned to Hole 1256D in 2011 with the ambition of deepening the hole several hundred meters into the cumulate gabbroic rocks of intact lower oceanic crust. However, drilling in this hole advanced only minimally to 1,521 mbsf (Figure 4), as a number of significant engineering challenges were encountered during the expedition that prevented deepening of the hole beyond this "hardened" metamorphic unit (Teagle et al., 2012).

Based on regional seismic refraction data, the transition from basalt Layer 2 to gabbro Layer 3 at Site 1256 occurs between 1,200 m and 1,500 m into basement (Wilson et al., 2003). An examination of shipboard and post-cruise discrete sample measurements, wireline logging data, and vertical seismic velocity profiling suggests that the base of Hole 1256D is at, or very close to, the Layer 2–3 transition (Swift et al., 2008; Gilbert and Salisbury, 2011). In addition, simple mass balance calculations indicate that the average basalt in Hole 1256D must

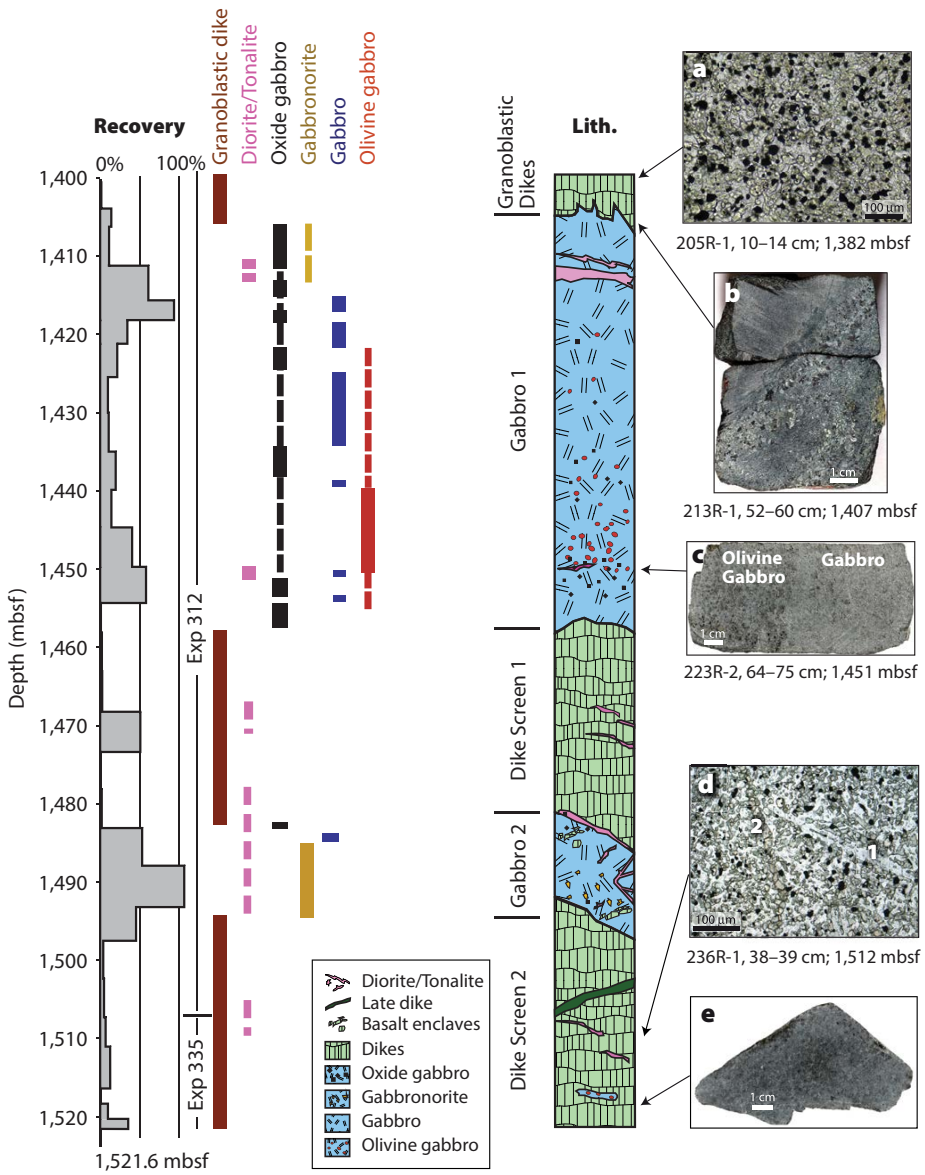

FIGURE 4. Plutonic section from the lower portion of Hole 1256D on the Cocos Plate with a few representative photomicrographs of key samples (modified after Ildefonse et al., 2014). The distribution of rock types is expanded proportionately in zones of incomplete recovery. (a) Photomicrograph of a dike completely recrystallized to a granoblastic texture. (b) Uppermost dike/gabbro boundary. (c) Sharp modal contact between a medium-grained olivine gabbro and a gabbro. (d) Photomicrograph of a granoblastic basalt. (e) Medium-grained, orthopyroxene-bearing olivine gabbro.

have lost more than 30% of its original liquid mass, implying that at least 300 m of cumulate gabbro formed as a residue during ocean crust formation must be present in the crust below the present base of Hole 1256D (Teagle et al., 2006). However, encountering gabbro already at a shallower depth within Layer 2 reinforces previous inferences that factors such as porosity and hydrothermal alteration (Detrick et al., 1994; Alt et al., 1996; Carlson, 2010) are more important than rock type or grain size in controlling the location of the seismic Layer 2–3 transition. This is an important advance in our understanding of oceanic crustal architecture, despite the fact that the Moho at the base of the oceanic crust could still be thousands of meters below the hole. Future scientific ocean drilling and the deepening of Hole 1256D is required to characterize the true nature of the Layer 2–3 "basalt to gabbro" seismic transition at Site 1256.

IODP Site U1415: Hess Deep

IODP Hess Deep Expedition 345 in 2012/2013 was designed to sample lower crustal primitive gabbroic rocks that formed at the fast-spreading East Pacific Rise (EPR) in order to test models of magmatic accretion and the intensity of hydrothermal cooling at depth (Gillis et al., 2014a, 2014b). The Hess Deep rift zone in the equatorial Pacific Ocean formed by deep lithospheric extension in front of the westward-propagating Cocos-Nazca spreading center, exposing oceanic crust that formed at the fast-spreading (130 mm yr^{-1}) EPR (Gilles et al., 2014a). This site is unique in that it is the only place where the lower crust and the upper crust have been extensively sampled by submersible or remotely operated vehicle (ROV) as well as drilling, by ODP Leg 147 (Gillis et al., 1993). Previous studies of known seafloor exposures of lower plutonic rocks have suggested that layering exists in the gabbroic section.

IODP Site U1415 recovered primitive olivine gabbros and troctolites (a pyroxene-depleted version of gabbro) at one 35 m deep hole (U1415I) and two ~110 m deep holes (U1415J and U1415P shown in Figures 1 and 2) located within 100 m of each other (Gilles et al., 2014b). The cores recovered at Site U1415 can be placed more than 2 km beneath the sheeted dike-plutonic transition and thus may represent the lower plutonic half of the EPR fast-spreading crust (Gilles et al., 2014a). The abundance of layering in the material recovered from Site U1415, along with the absence of other intermixed, more evolved lithologies, distinguishes the lower gabbroic crust at Hess Deep from crustal sections recovered from other ODP-IODP expeditions to slow-spreading ridges. These observations support previous models that invoke strong spreading rate and thermal control on magma chamber processes at mid-ocean ridges; however, the style of layering and banding, as well as the observed lithologies, differ from the mid-ocean ridge basalt-like Oman ophiolite, which has been used as a fast-spreading-ridge analogue and informed the initial Penrose model (Figure 3; Gillis et al., 2014a). IODP Hess Deep Expedition 345 thus provides a reference section for primitive fast-spreading lower crust that did not previously exist. This highlights the need for scientific ocean drilling to address questions related to the origin, evolution, and heterogeneity of the lower oceanic crust.

DEEP DRILLING IN SLOW-SPREAD CRUST AND OCEANIC CORE COMPLEXES

It is well known from dredging and ROV sampling that a continuous gabbroic layer does not exist at slow-spreading ridges and at tectonically formed oceanic core complexes exposed in these slow spreading environments (e.g., Whitehead et al., 1984; Mutter et al., 1985; McCarthy et al., 1988; Dick, 1989; Cannat, 1993; Tucholke and Lin, 1994). Moreover, the abundance of serpentinized peridotite in dredge hauls from rift valley and fracture zone walls (Aumento and Loubat, 1971; Thompson and Melson, 1972; Fisher et al., 1986; Dick, 1989; Cannat, 1993) raised the possibility that serpentinization can be a significant component of seismic Layer 3 "gabbros" in these settings (Figure 3), as originally suggested by Hess (1962). Without scientific ocean drilling, no truly representative section of seismic Layer 3 (which may not be the same everywhere) is likely to be obtained in situ in these oceanic slow spreading settings and core complexes, leaving its composition, state of alteration, and internal structure almost entirely a matter of inference.

ODP Hole 735B: Atlantis II Fracture Zone

In 1997, ODP drilled Hole 735B through a 1,508 m section of coarse gabbro in tectonically exposed lower crust on a wave-cut platform that flanks the Atlantis II Fracture Zone on the slow-spreading Southwest Indian Ridge (Figures 1 and 2). The sequence of rocks sampled in Hole 735B (Figure 5) is unlike that in a Penrose-type ophiolite, in Hess Deep, or in layered intrusions found on land. Some of its attributes, including the lack of well-developed layering, and the presence of small 100 m to 500 m intrusions, are similar to the typical structural characteristics of ophiolites believed to have formed in slow-spreading environments, such as the Trinity or Josephine ophiolites, although these on-land ophiolite sequences are believed to be incomplete (Dick et al., 1999). The results from Hole 735B documented a systematic variation in igneous petrology, structure, and alteration with depth, unlike that expected in crust formed in association with large magma chambers or even melt lenses now inferred to exist beneath fast-spreading ridges (Dick et al., 1999). They provide a first assessment of synkinematic igneous differentiation in which the upper levels of the gabbroic crust are enriched in late differentiated melts by means of tectonic processes, rather than the simple gravitationally driven crystallization differentiation often seen in layered intrusions of large terrestrial magma chambers.

ODP Legs 109 and 209: Mid-Atlantic Ridge Rift Valleys

ODP Leg 109, Site 670, on the west wall of the Mid-Atlantic Ridge median valley near 23°10'N targeted the lowermost oceanic crust, and for the first time drilled and sampled serpentinized mantle peridotites (Bryan et al., 1988). In the same area, south of the Kane Fracture Zone, a total of 95 m of serpentinized peridotites were recovered from a 200 m deep hole at Site 920, ODP Leg 153 (Figures 1 and 2; Cannat et al., 1995). Together, these two ODP expeditions demonstrated that the internal stratigraphy of the lower oceanic crust at slow-spreading ridges is governed as much by the dynamic processes of alteration and tectonics as by igneous processes. More recently, ODP Leg 209 (Sites 1268–1275; Figures 1 and 2) returned to drill in the peridotite-rich area around the 15°20'N fracture zone and revealed that the upper oceanic lithosphere in this slow-spreading setting is primarily composed of peridotite and gabbro and that the seafloor is inundated with uncovered fault surfaces (Kelemen et al., 2004). This leads to the conclusion that mantle denudation and plate spreading are accommodated by a combination of high-displacement, low-angle (so-called "rolling hinge") normal faults that lead to the formation of oceanic core complexes and secondary lower-displacement normal faults (Schroeder et al., 2007) that in turn expose the observed ultramafic basement rocks.

IODP Expeditions 304, 305, and 357: Atlantic Massif Ocean Core Complex

IODP Expeditions 304, 305, and 357 specifically targeted those types of denuded fault surfaces and a related ocean core complex, the Atlantis Massif at 30°N, which is located at the inside corner of the intersection between the Mid-Atlantic Ridge (MAR) and the Atlantis Fracture zone. Two holes were drilled during IODP Expeditions 304 and 305 at Site U1309 (Figures 1 and 2) into the footwall of the detachment fault (Blackman et al., 2006, 2011). This work was continued during IODP Expedition 357, which drilled a series of shallow holes into the Lost City hydrothermal field using seabed rockdrills (Früh-Green et al., 2016). Based on the common occurrence of serpentinized mantle peridotite along the south flank of the southern ridge as well as geophysical studies (e.g., Blackman et al., 1998, 2002), fresh mantle peridotite was predicted to occur at reasonably shallow depths (~800 mbsf), allowing drilling to access samples of the mantle for the first time (Canales et al., 2004; Blackman et al., 2011). In stark contrast to geophysical predictions, Hole U1309D sampled a 1,415 m long section of gabbroic rocks in the Central Dome core of the Atlantis Massif, with 75% recovery, but no peridotitic lithologies were encountered (Figure 5). Paleomagnetic data obtained from the IODP core samples indicated that the footwall of the detachment fault

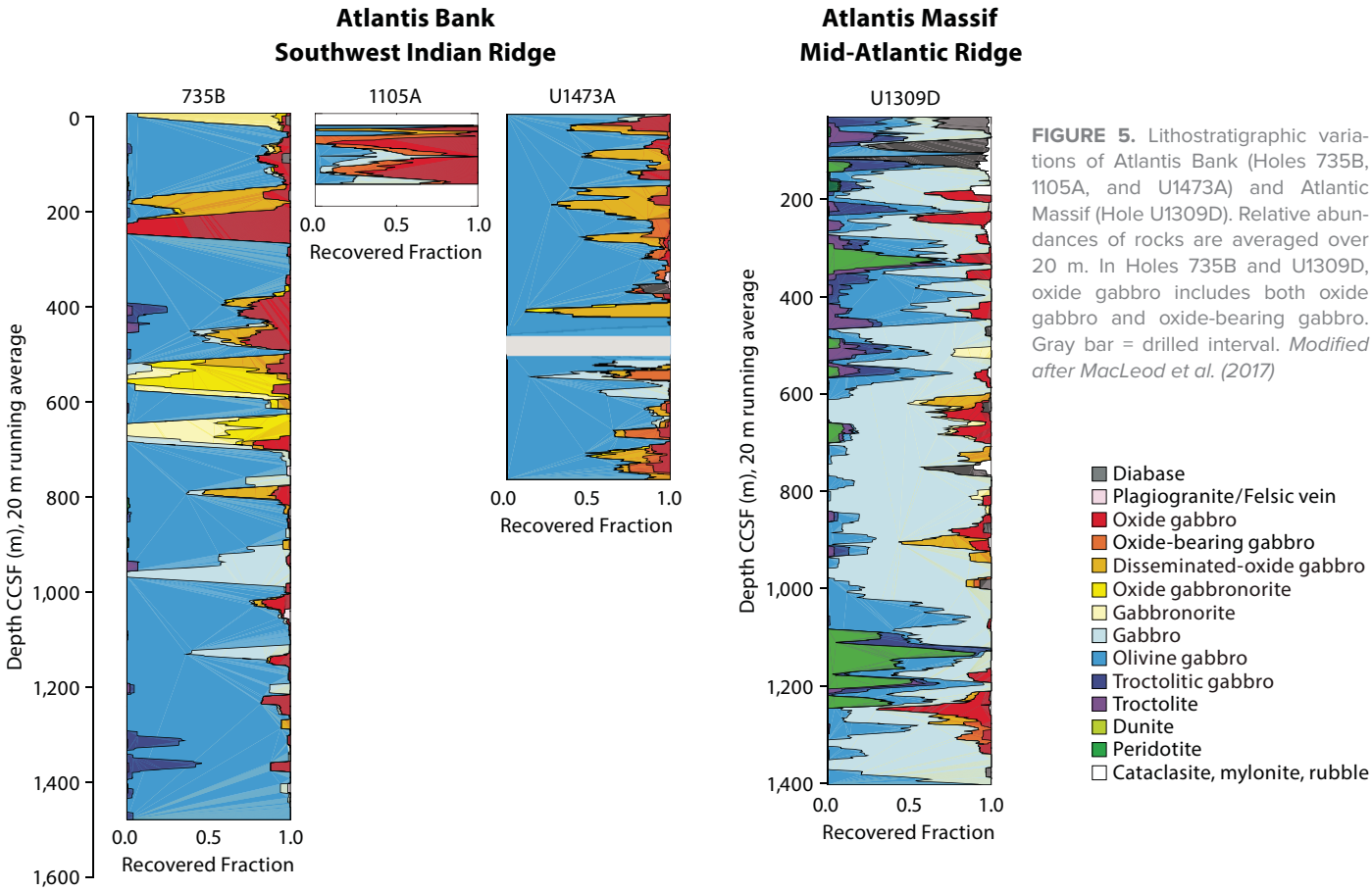

FIGURE 5. Lithostratigraphic variations of Atlantis Bank (Holes 735B, 1105A, and U1473A) and Atlantis Massif (Hole U1309D). Relative abundances of rocks are averaged over 20 m. In Holes 735B and U1309D, oxide gabbro includes both oxide gabbro and oxide-bearing gabbro. Gray bar = drilled interval. *Modified after MacLeod et al. (2017)*

rotated at least 45° around a MAR-parallel horizontal axis (Morris et al., 2009; Blackman et al., 2011), consistent with the "rolling hinge" model (e.g., Wernicke and Axen, 1988; Buck, 1988).

Only three thin (<1 m) intervals of ultramafic rocks, interpreted as residual mantle peridotites, were encountered, and they were intercalated within gabbroic rocks in the upper 225 m of the section (Tamura et al., 2008) in Holes U1309B and U1309D. If the small amount of serpentinized peridotite recovered from Hole U1309D is representative of the bulk makeup of Atlantis Massif, the potential of a bulk expansion during the serpentinization of such altered peridotite is not likely to contribute significantly to the uplift of the Central Dome (Blackman et al., 2011). It is interesting to note that the 16 holes drilled by ODP and IODP into the footwall have reached four different oceanic core complexes, including the Atlantis Massif, and gabbroic sections were encountered exclusively at all holes. These findings indicate that the domal morphology of the core complexes results from the exhumation and unroofing of large gabbroic plutons by the associated detachment faults (e.g., Ildefonse et al., 2007a). Future scientific ocean drilling into both in situ slow-spreading oceanic crust and related oceanic core complexes is needed (1) to fully understand the relationship between tectonics and magmatism in oceanic crust formation, (2) to determine the importance of serpentinization in the lower oceanic crust and upper mantle, and (3) to fully grasp how serpentinization affects the seismic character of the oceanic lithosphere and the nature of the Moho.

MOHO TO MANTLE—FUTURE AND ONGOING DRILLING EFFORTS

Despite the successes of drilling into oceanic crust formed at both fast- and slow-spreading centers, drilling through the Moho and into the upper mantle remains a long-term aspiration, dating to the first Project Mohole operations in 1961. The Mohole-to-Mantle (M2M) proposal (Umino et al., 2012) re-articulated the major planetary science goals that could be achieved by sampling in situ upper mantle peridotite and investigating the nature of the Mohorovičić seismic discontinuity using the riser drilling vessel *Chikyu*. This ambition remains a flagship proposal for future *Chikyu* drilling and would require penetrating at least ~6,000 m of igneous oceanic crust formed at a fast-spreading ridge and an additional ~500 m into the oceanic upper mantle.

To determine the best site for M2M drilling, a large number of factors must be considered (Ildefonse et al., 2010). Any appropriate site should be in the shallowest possible water depths, implying close proximity to the axis of an active fast-spreading mid-ocean ridge. On the other hand, the hole should also be in the coldest possible oceanic lithosphere, implying mature oceanic crust and thus located a significant distance away from an active fast spreading ridge. Balancing those two opposing constraints limits potential M2M sites to three areas off the coasts of Hawaii, Baja California, and Costa Rica (Figure 6; Teagle and Ildefonse, 2011). All potential sites are in the Pacific because the oceanic crust there was created faster than in other ocean basins. As described above, seismic and geologic studies indicate that fast-spreading oceanic crust is relatively uniform and conforms most closely to the end-member Penrose model (Figure 3), making those sites ideal and possibly most representative of the general processes of ocean crust formation. Although a site survey was conducted off the coast of Hawaii in 2017 (Ohira et al., 2018) and funding for future site surveys on the Cocos Plate have been secured, realization of project Mohole continues to require a major funding commitment and political and scientific will. While preparing for eventual M2M drilling, any other scientific ocean drilling expedition, specifically at sites where the Moho is apparently shallower, may provide further insight into ocean crust architecture, the role of serpentinization, and the significance of the seismic Layer 2-3 and Moho boundaries.

IODP Expedition 360 was the first leg of Phase I of SloMo (shorthand for "The Nature of the Lower Crust and Moho

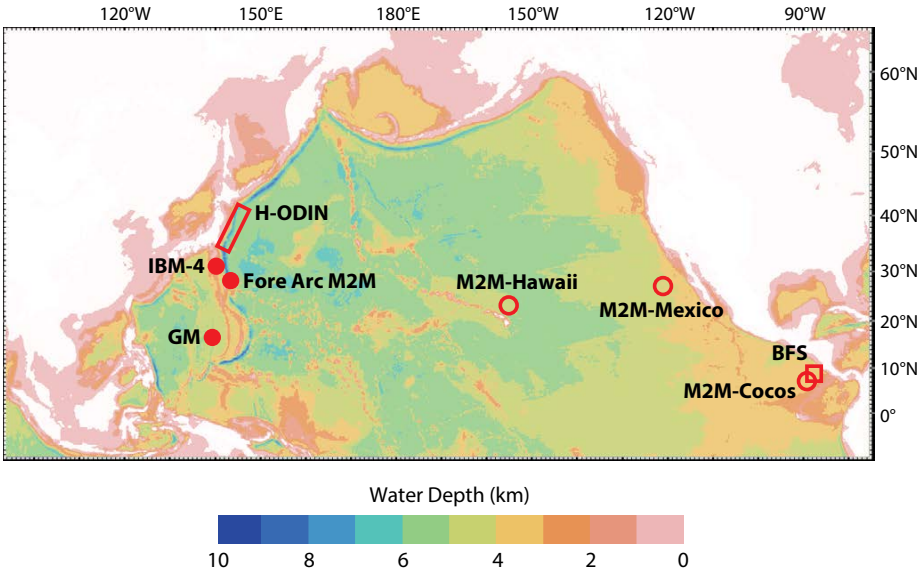

FIGURE 6. Bathymetric map of the Pacific Ocean showing the locations of potential drilling sites for IODP proposals using the riser drilling vessel *Chikyu*: the Mohole to Mantle (M2M) drilling projects (Umino et al., 2012; open circles), bending-fault hydrology of the old incoming plate (H-ODIN; rectangle; Morishita et al., 2015), bending-fault serpentinization (BFS; square; Morgan et al., 2014), direct sampling of forearc peridotite (Fore Arc M2M; solid circle; Michibayashi et al., 2016), Godzilla Megamullion (GM; solid circle; Ohara et al., 2018), and the middle crust in the continent (IBM-4; solid circle; Tatsumi et al., 2010). *Modified after Morishita (2017)*

at Slower Spreading Ridges"), a multiphase drilling project that proposes to drill through the Moho at Atlantis Bank at the ultraslow-spreading Southwest Indian Ridge (MacLeod et al., 2017). By penetrating this fundamental seismological boundary, SloMo is testing the hypothesis that the Moho, at this locality in particular and at slow- and ultraslow-spreading ridges in general, may represent an alteration boundary due to serpentinization within the upper mantle, rather than an igneous crust-mantle transition or a hard physical boundary. If the Moho represents the former and thus is a serpentinization front, the igneous crust/mantle boundary could lie at any depth above the seismic boundary (MacLeod et al., 2017).

IODP Hole U1473A (Figure 2) was drilled on the summit of Atlantis Bank during Expedition 360, 1–2 km away from two previous ODP holes: Hole 735B drilled during ODP Leg 118 in 1987 (Dick et al., 1999; 2000) and Hole 1105A drilled during ODP Leg 179 in 1998 (Casey et al., 2007). While exploring the lateral variability of the stratigraphy in comparison with Holes 735B and 1105A (Figure 5), the principal aim of Expedition 360 was to drill as deep as possible through lower crustal gabbro and leave a hole open and ready to be deepened during a second expedition. A target depth of 1,300 mbsf was estimated, derived from prior experience of drilling conditions at Atlantis Bank; however, Hole 1473A was only drilled to 789.7 mbsf and terminated in massive gabbro cut by isolated dikes (Figures 2 and 5; MacLeod et al., 2017). SloMo next will attempt to reoccupy and deepen the hole with the overall goal of penetrating the crust-mantle transition, which is believed to be as much as ~2.5 km above the Moho; additional drilling, potentially using the riser vessel *Chikyu*, is likely to be necessary to penetrate the Moho itself, at ~5 km below the seafloor (MacLeod et al., 2017).

Another approach to sampling upper mantle materials is to drill and core fresh lower igneous crust and the underlying uppermost mantle peridotite, as accreted during the initiation of a subduction zone. A prime IODP focus has been the study of subduction initiated around ~52–48 million years ago at the Izu-Bonin-Mariana trench (e.g., Ishizuoka et al., 2011; Reagan et al., 2017, 2019; see also Arculus et al., 2019, in this issue), where gabbroic and ultramafic rocks are exposed on the landward slope of the Bonin Trench in the Northwest Pacific (Figure 6). Drilling at this location provides future opportunities to realize a key objective of the M2M mantle drilling (Michibayashi et al., 2016) that differs fundamentally from the M2M itself and SloMo, which both focus on the formation of the oceanic crust during seafloor spreading.

CONCLUDING REMARKS

For 50 years, scientific ocean drilling has contributed significantly to our understanding of the variability in the architecture of oceanic lithosphere. The style of accretion critically depends on the balance between magma production, hydrothermal cooling, and tectonics, which to a first order is related to spreading rate. Seismic, bathymetric, and marine geological observations indicate that oceanic crust formed at fast spreading rates (with full rates >80 mm yr^{-1}) has a relatively constant architecture, compared to crust formed at slow to ultra-slow spreading rates (<40 mm yr^{-1}), and is similar to the Penrose model for ophiolites (Ildefonse et al., 2014). Scientific ocean drilling at ultra-slow spreading centers and at oceanic core complexes has shown that their crustal architectures are very different and that serpentinization likely plays a prominent role in changing the nature of those crustal sections. Deeper drilling efforts to penetrate the core-mantle boundary and the Moho remain the missing piece of the puzzle to help us advance our understanding of ocean crust formation and mantle dynamics. For the upcoming next generation ocean drilling scientists, we end with the following quote by Bahcall (1990): "I believe that the most important discoveries will provide answers to questions that we do not yet know how to ask and will concern objects that we can not yet imagine."

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