2.7 What Lies Beneath

The goal to use scientific ocean drilling to sample upper mantle remains elusive. However, in absence of the required technologies to drill to the Moho, over the last five decades we have made significant progress in piecing together an astounding picture of the complex geology of the ocean crust. Here we highlight the key findings that reveal the architecture of ocean 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 geophysically log ocean crust in the vicinity of both slow and fast spreading ridges.

2.7 What Lies Beneath: The Formation and Evolution of Oceanic Lithosphere

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Introduction

Scientific ocean drilling commenced through the initiation of Project MoHole in 1961, about the same time as the Apollo moon-landing ambitions were being first articulated. It has been almost 60 years since Project MoHole was first conceived by the American Miscellaneous Society, and 50 years since the launch of Deep Sea Drilling Project (DSDP) in 1968. Scientific ocean drilling is an essential approach to directly access the interior of the Earth and is arguably science's most successful international collaboration. Although this co-operation 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), 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 igneous basement of the oceanic crust.

A compilation of holes into *in situ* ocean crust cored by scientific ocean drilling since the beginning of DSDP to 2018 highlights that only 38 holes deeper than 100 m have been cored in oceanic crust and only 20 deeper than 200 m (Figs. 1 and 2; e.g., Ildefonse et al., 2007a; 2014), with the first being DSDP Hole 332A on Leg 37 in 1974 (Aumento et al., 1977). The total amount of recovered igneous ocean crustal material represents less than 2% of the cores in the repositories of DSDP, ODP and IODP. However, despite this relative paucity of material, scientific ocean drilling has provided essential and hitherto unavailable observations for advancing our understanding of the processes that "re-pave" nearly 70% of Earth's surface over short geological time scales (<200 million years). These include better knowledge of ocean crustal architecture, magmatic accretion processes in the centers of mid-ocean ridge spreading centers, the nature and magnitudes of hydrothermal exchange between the oceans and the oceanic lithosphere, and the discovery of a deep microbial rock-hosted biosphere.

With the results from fifty years of scientific ocean drilling, we now know that in all ocean basins a volcanic basement lies beneath an almost omnipresent blanket of sediments, formed by a system of mid-ocean ridges that together form the largest magmatic province on Earth, generating more than 20 km^3 of new 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 is erupted as basalt and forms the upper one-third of this basement.

Here we focus on the importance of basement drilling and our 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 1960's and current plans to reach the Mohorovičić Discontinuity (Moho) at the lower ocean crust boundary with the upper mantle, and we will discuss how scientific ocean drilling has informed us on the major differences in ocean crust created in fast and ultra-slow spreading settings.

Project MoHole (1)

(1) The National Academies of Sciences, Engineering and Medicine have established the special website for Project MoHole, where there are a unique collection of photographs, video, original narratives, and historical documents (The National Academies of Sciences, Engineering and Medicine, 2011).

Project MoHole has been an iconic aspiration in Earth sciences, as 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). At the time, it provided a geoscience foil to the nascent U.S. space program. The essence of Project MoHole was to retrieve samples of the Earth's mantle through its oceanic crust by penetrating the Mohorovičić Discontinuity (Moho), a major global seismic anomaly that we now take to define the boundary between Earth's crust and mantle. Seismologists had already subdivided the ocean crust into seismic layers, with Layer 1 comprising low P-wave velocity sediments (Vp < 3 km/s); Layer 2 having low P-wave velocity and a steep velocity gradient, with Vp ranging from ~3.5 to ~6.7 km/s, typical of basalt; and Layer 3 having high velocity and a more gentle velocity gradient (Vp of 6.7 to 7.1 km/s) that we now know is typical of gabbro. However, an abrupt increase at the base of Layer 3 to seismic velocities of Vp > 8 km/s was found to mark the Moho and was interpreted to be the boundary with ultramafic (peridotitic) rocks of the uppermost mantle.

The ultimate proposal was to drill to the Moho in the deep oceans where the Earth's crust is relatively thin (~6 km; National Research Council, 1957; Bascom, 1961). Attempting such an effort on land would have been impractical, since the drilling equipment would have to withstand high *in* *situ* temperatures at great depths in 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 drilling vessel for deep-water operations and testing of the vessel and equipment in deep water far off-shore. This required the development of new technological capabilities, including: (i) navigational and thruster implementation to keep a floating vessel at a single location in the deep ocean, now known as "dynamic positioning" and a universal feature on any modern-day research vessel; and (ii) a strategy that would allow subsequent visits to re-enter 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 planned to culminate in the drilling through the Mohorovičić Discontinuity.

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 CUSS1 (named after the four oil companies that had developed it: Continental, Union, Shell and Superior) drilled 183 meters into the ocean floor in 3,558 meters 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 U.S. President 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).

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 plate-tectonics theory. Moreover, Project MoHole successfully showed that scientific ocean drilling cannot only drill into and recover core samples from ocean basement, but it illustrated that ocean drilling is an essential tool to gather otherwise inaccessible information that reveals how our dynamic planet operates (Teagle and Ildefonse, 2011). This led to formation of the U.S. Deep Sea Drilling Project (DSDP) with its first expeditions in 1968.

Early Years: Penrose Model and Coring in Oceanic Crust

The earliest years of the DSDP effort concentrated on drilling long sediment cores to validate the theory of seafloor spreading, by dating of the deepest sediments directly overlying the oceanic basement (DSDP Leg 3; Maxwell et al., 1970) and to refine marine sediment-based biostratigraphy models. Pillow lavas were recognized when the very tops of the ocean basement were "tapped" and provided direct evidence of rapidly cooled lava in subaqueous environments, making those the center of a debate on the origin of commonly juxtaposed rock strata, including pillow lavas, basaltic dikes, gabbros, serpentinised ultramafic rocks, and marine sediments, as routinely observed in ophiolites such as Troodos Massif, Cyprus (e.g., Gass, 1968; *cf.* Miyashiro, 1973) and other orogenic belts. Geologists working on ophiolites reached a consensus statement during the *1972 Penrose Field Conference*, defining 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 (Fig. 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 ocean crustal drilling (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; Figs. 1 and 2). Also noteworthy is 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 upon itself (Fig. 3; Ildefonse et al., 2014).

Deep Drilling in Fast-Spreading Crust

Although less than 20% of the modern ridge system is spreading at fast rates (>80 mm/y full rate), nearly half of the oceanic crust that was created over the last 200 million years formed at fast-spreading ridges (Teagle et al., 2012; Ildefonse et al., 2014). Scientific ocean drilling at a few deep drilled sites within fast-spreading crust have led to a widely accepted model of ocean crust architecture that is very similar to and confirms in large terms the Penrose model. These include drilling in crust of the Cocos Plate in the Eastern Pacific (ODP Holes 504B and 1256) and in the Hess Deep (IODP Site U1415) providing insight into the nature of key seismic layer boundaries in fast-spreading ocean crust and the role of alteration, grain size and texture, and composition in controlling these boundaries.

DSDP/ODP Reference Hole 504B on the Nazca Plate

DSDP/ODP Hole 504B, located in 6 Ma crust, 200 km south of the Costa Rica Rift in the eastern equatorial Pacific, has long been a "reference" site for intact ocean crust formed at an intermediate to fast-spreading ocean ridge (Figs. 1 and 2) between the oceanic Cocos (north) and Nazca (south) tectonic plates. This hole is the deepest scientific drill hole into the igneous oceanic crust, penetrating 2,111 meters below seafloor (mbsf) and 1,836.5 m into the sub-basement (below a thin veneer of ~274 m of sediment) 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; Becker et al., 1988; 1992; Dick et al., 1992; Alt et al., 1993; 1996). 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 re-visited in 2019 (IODP Expedition 385T; Tominaga et al., 2019). During ODP Leg 148, the last deepening of Hole 504B was achieved, deepening it by a final 110.6 m, but further penetration is currently prevented due to portions of a drill bit being stuck in the hole (Alt et al., 1993).

The lithologic sequence in DSDP/ODP Hole 504B consists (from top to bottom) of 274.5 m sediment, 571.5 m of volcanic rocks, a 209 m transition zone, and 1,050 m of a sheeted dike complex (Fig. 2; Alt et al., 1996). The hydrothermal alteration of volcanic section in DSDP/ODP Hole 504B involves a series of processes involving 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. The cored permeable pillow basalts in the transition zone have mineral assemblages that indicate that during hydrothermal circulation a maximum temperature of ~350–380°C may have been reached, typical of greenschist facies metamorphism and including alteration minerals like chlorite, actinolite, and albite-oligoclase (Alt et al., 1996). The lower dikes (1,500–2,111 mbsf) underwent hydrothermal alteration with 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 access of fluids (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 on the Cocos Plate

ODP Hole 1256D (Figs. 1 and 2) was designed as a deep borehole to sample the cumulate gabbros of the lower ocean crust and to penetrate deeper into the ocean 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 Ma, during a sustained episode of superfast ocean ridge spreading (>200 mm/year; Wilson, 1996) at the East Pacific Rise (EPR). The site formed on a ridge segment that is at least 400 km long and located ~100 km north of the ridge-ridge-ridge (RRR) triple junction between the Cocos, Pacific, and Nazca plates.

The deep-drilling so-called "superfast" campaign at Site 1256 was aimed at understanding the formation, architecture, and evolution of oceanic crust formed at *superfast* plate spreading rates, and 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 ocean crust, performed by installing a large reentry cone secured with almost 270 m of 16-inch casing through the 250-m-thick sedimentary overburden and 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 (Fig. 4). IODP Expedition 335 returned to Hole 1256D 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 (Fig. 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 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 have lost more than 30% of its original liquid mass as solid gabbro, in other words implying the presence of at least 300 m of cumulate gabbro that was formed as a residue during ocean crust formation and 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 on the oceanic crustal architecture, as recovered from a deep hole such as Hole 1256D, despite the fact that the Moho at the base of the ocean 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 in the Hess Deep

IODP Hess Deep Expedition 345 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 westwards-propagating Cocos-Nazca spreading center, exposing oceanic crust that formed at the fast-spreading (130 mm/year) 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 underwater vehicle and drilling by ODP Leg 147 (Gillis et al., 1993). Previous studies of known sea-floor 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 Figs. 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 a strong spreading rate and thermal control on magma chamber processes at mid-ocean ridges; however, the variation in style of layering and banding, the differences in the observed lithologies, differs from the MORB-like Oman ophiolite, which has been used as a fast-spreading-ridge analogue and informed the initial Penrose model (Fig. 3; Gilles et al., 2014a). IODP Hess Deep Expedition 345 thus provides a reference section for primitive fast-spreading lower crust that did not exist before. This highlights the necessity of scientific ocean drilling to address questions related to the origin, evolution and heterogeneity of the lower crust.

Deep Drilling in Slow-Spread Crust and Oceanic Core Complexes

It has been well known from dredging and remotely operated vehicle (ROV) sampling that a continuous gabbroic layer does not exist at slow-spreading ridges and at oceanic core complexes that are tectonically formed and exposed in these 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) has raised the possibility that serpentinization can be a significant component of seismic Layer 3 "gabbros" in these settings (Fig. 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 in the Atlantis II Fracture Zone

Hole 735B drilled a 1,508-m section of coarse gabbro body in a tectonically exposed, lower crustal section on a wave-cut platform that flanks the Atlantis II Fracture Zone on the slow-spreading Southwest Indian Ridge (Figs. 1 and 2). The sequence of rocks sampled in Hole 735B (Fig. 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- 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, quite unlike expectations from the crustal formation in association with large magma chambers or even the melt lens now inferred to exist beneath fast-spreading ridges (Dick et al., 1999). It provides 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 simple gravitationally driven crystallization differentiation that are often seen in terrestrial large magma chamber layered intrusions.

ODP Legs 109 and 209 on the 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 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 (Figs. 1 and 2; Cannat et al., 1995). Together, these two ODP expeditions demonstrated that the internal stratigraphy of the lower ocean 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; Figs. 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 ultra-mafic basement rocks.

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

IODP Expeditions 304, 305, and 357 specifically targeted those type 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 (Figs. 1 and 2) and into the footwall of the detachment fault (Blackman et al., 2006; 2011). This work was continued during IODP Expedition 357 that drilled a series of shallow holes into the Lost City hydrothermal systems 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 ~~(Figs. 1 and 2)~~ 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 (Fig. 5). Paleomagnetic data in the IODP core samples indicated at least 45° of tilt occurring as a counter-clockwise rotation around a MAR-parallel horizontal axis, confirming that the footwall must have rotated significantly along the detachment fault (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 (<1m) intervals of ultramafic rocks, interpreted as residual mantle peridotites, were encountered 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 ODP and IODP have drilled 16 holes into the footwall to four different oceanic core complexes, including the Atlantis Massif, and at all holes exclusively gabbroic sections were encountered. This shows that the domal morphology of these core complexes would be the consequence of having larger gabbroic plutons being exhumed and unroofed by the associated detachment faults (e.g., Ildefonse et al., 2007b). Future scientific ocean drilling in both *in situ* slow spreading ocean crust and related oceanic core complexes is needed to fully understand the relation between tectonics and magmatism in the formation of the ocean crust, to deduce the importance of serpentinization in the lower ocean crust and upper mantle, and to fully grasp its effect on the seismic character of the oceanic lithosphere and the nature of the Moho.

Moho to Mantle – Future and Ongoing Drilling Efforts

Despite the aforementioned drilling successes into both fast and slow spreading ocean crust, drilling through the Moho and into the upper mantle remains a long-term aspiration, ever since 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 the sampling *in situ* upper mantle peridotite and investigating the nature of the Mohorovičić seismic discontinuity (Moho) using the riser drilling vessel *D/V Chikyu*. This ambition remains a flagship proposal for future drilling by the *D/V Chikyu* and would require drilling through at least ~6,000 m of igneous oceanic crust, formed from a fast-spreading ridge, and an additional ~500 m into the ocean lithospheric upper mantle.

To determine the best site for the M2M proposal drilling, a large number of factors remain to be considered (Ildefonse et al., 2010). Any appropriate site should be in the shallowest possible water depths, implying close proximity to a mid-ocean ridge where new crust is generated. On the other hand, it should also be in the coldest possible oceanic lithosphere, implying a matured ocean crust and thus located a significant distance away from an active fast spreading ridge. Balancing those two opposing constraints does limit the potential M2M sites to three areas off the coasts of Hawaii, Baja California and Costa Rica, respectively (Fig. 6; Teagle and Ildefonse, 2011). All potential sites are in the Pacific because the ocean crust there is formed faster than in other oceans. As described above, seismic and geological studies indicate that fast-spreading ocean crust is relatively uniform and conforms most closely to the end-member Penrose model (Fig. 3), making those sites ideal and most representative of maybe the general processes of ocean crust formation. Although a site survey has been 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 major commitment of funding and political and scientific will. In preparation for M2M, any other scientific ocean drilling expedition, specifically at sites where the Moho is apparently shallower, may provide further insight in ocean crust architecture, the role of serpentinization, and the significance of the seismic Layer 2-3 and Moho boundaries.

IODP Expedition 360 has been the first leg of Phase I of the SloMo Project, a multiphase drilling program that proposes to drill through the Moho seismic discontinuity at Atlantis Bank at the ultraslow-spreading Southwest Indian Ridge (MacLeod et al., 2017). By penetrating this fundamental seismological boundary, the SloMo Project 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 (Fig. 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 (Fig. 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 drilled to 789.7 mbsf only and terminated into massive gabbro cut by isolated dikes (Figs. 2 and 5; MacLeod et al., 2017). The SloMo project 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 D/V *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 initiation at the Izu-Bonin-Marianna trench around ~52–48 Ma (e.g., Ishizuoka et al., 2011; Reagan et al., 2017, 2019; see also Arculus et al, this volume) where gabbroic and ultramafic rocks are exposed on the landward slope of the Bonin Trench in the NW Pacific (Fig. 6). This 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 the SloMo project, which both focus on the formation of the oceanic crust during sea-floor 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 ocean crust formed at fast spreading rates (with full rates >80 mm per year) has a relatively constant architecture, compared to crust formed at slow to ultra-slow spreading rates (<40 mm per year), and is similar to the Penrose model for ophiolites (Ildefonse et al., 2014). Scientific ocean drilling at ultra-slow spreading centers and oceanic core complexes has shown much larger heterogeneity in the crustal architecture and in addition a likely prominent role of serpentinization in changing the nature of those crustal sections. Deeper drilling efforts to penetrate the core-mantle boundary and the Moho seismic discontinuity remain the missing piece of the puzzle to help us advance our understanding of mid-ocean ridge formation and mantle dynamics. For the uprising 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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References

Alt, J.C., J. Honnorez, C. Laverne, and R. Emmermann. 1986. Hydrothermal alteration of a 1 km section through the upper oceanic crust, Deep Sea Drilling Project Hole 504B: mineralogy, chemistry, and evolution of seawater–basalt interactions. *Journal of Geophysical Research: Solid Earth* 91(B10): 10309-10335, https://doi.org/10.1029/JB09liB10p10309.

Alt, J.C., H. Kinoshita, L.B. Stokking, and the Shipboard Scientific Party. 1993. *Proceeding of ODP, Initial Reports*, 148, College Station, TX (Ocean Drilling Program), https://doi.org/10.2973/odp.proc.ir.148.1993.

Alt, J.C., H. Kinoshita, L.B. Stokking, and P.J. Michael, eds. 1996. *Proceeding of ODP, Scientific Results*, 148, College Station, TX (Ocean Drilling Program), https://doi.org/10.2973/odp.proc.sr.148.1996.

Anderson, R.N., J. Honnorez, K. Becker, and the Shipboard Scientific Party. 1985. *Initial Reports, DSDP*, 83, Washington (U.S. Government Printing Office). https://doi.org/10.2973/dsdp.proc.83.1985.

Anonymous. 1972. *Ophiolites*. Prepared by Participants of *Penrose Field Conference*, *Geotimes* 17:24-25.

Aumento, F., and H. Loubat. 1971. The Mid-Atlantic Ridge near 45°N. XVI. Serpentinized ultramafic intrusions. *Canadian Journal of Earth Sciences* 8: 631-663, https://doi.org/10.1139/e71-062.

Aumento, F., W.G. Melson, and DSDP Leg 37 Scientific Party. 1977. *Initial Reports of the deep sea drilling project, Volume 37*, Washington (U.S. Government Printing Office), 1008 pp., https://doi.org/10.2973/dsdp.proc.37.1977.

Bahcall, J.N. 1990. *Science with the Hubble space telescope*, Statement to the Subcommittee on Space Science and Applications of the U.S. House of Representatives, Washington, DC, 15 pp.

Bascom, W. 1961. *A Hole In The Bottom Of The Sea: The Story Of The Mohole Project*. Doubleday and Company, Garden City, NY, 352 pp.

Becker, K., H. Sakai, and Shipboard Scientific Party. 1988. *Proceedings of the Ocean Drilling Program, Initial Reports, Part A*, 111, College Station, TX (Ocean Drilling Program), https://doi.org/10.2973/odp.proc.ir.111.1988.

Becker, K., G. Foss, and Shipboard Scientific Party. 1992. *Proceedings of the Ocean Drilling Program, Initial Reports*, 137, College Station, TX (Ocean Drilling Program), https://doi.org/10.2973/odp.proc.ir.137.1992.

Bickle, M., R. Arculus, P. Barrett, R. DeConto, G. Camoin, K. Edwards, F. Fisher, F. Inagaki, S. Kodaira, N. Ohkouchi, H. Pälike, C. Ravelo, D. Saffer, and D. Teagle. 2011. *Illuminating Earth's Past, Present and Future The Science Plan for the International Ocean Discovery Program 2013 - 2023.* IODP: Integrated ocean drilling program, Washington, DC, 92 pp.

Blackman, D., J.R. Cann, B. Janssen, and D. K. Smith. 1998. Origin of extensional core complexes: evidence from the Mid-Atlantic Ridge at Atlantis Fracture Zone. *Journal of Geophysical Research* 103: 21315-21321, https://doi.org/10.1029/98JB01756.

Blackman, D., B. Ildefonse, B.E. John, Y. Ohara, D.J. Miller, C.J. MacLeod, and the Expedition 304/305 Scientists. 2006. *Proceedings of the Integrated Ocean Drilling Program, Volume 304/305*. Prepared by U. S. Implementing Organization Science Services, Texas A&M University, Integrated Ocean Drilling Program Management International, Inc., the Integrated Ocean Drilling Program, Washington, DC, https://doi.org/10.2204/iodp.proc.304305.2006.

Blackman, D., B. Ildefonse, B.E. John, Y. Ohara, D.J. Miller, N. Abe, M. Abratis, E.S. Andal, M. Andreani, S. Awaji, J.S. Beard, D. Brunelli, A.B. Charney, D.M. Christie, J. Collins, A.G. Delacour, H. Delius, M. Drourin, F. Einaudi, J. Escartín, B.R. Frost, G. Früh-Green, P.B. Fryer, J.S. Gee, M. Godard, C.B. Grimes, A. Halfpenny, H.-E. Hansen, A.C. Harris, A. Tamura, N.W. Hayman, E. Hellebrand, T. Hirose, J.G. Hirth, S. Ishimaru, K.T.M. Johnson, G.D. Karner, M. Linek, C.J. MacLeod, J. Maeda, O.U. Mason, A.M. McCaig, K. Michibayashi, A. Morris, T.

Nakagawa, T. Nozaka, M. Rosner, R.C. Searle, G. Suhr, M. Tominaga, A. von der Handt, T. Yamasaki, X. Zhao. 2011. Drilling constraints on lithospheric accretion and evolution at Atlantis Massif, Mid-Atlantic Ridge 30°N. *Journal of Geophysical Research* 116:B07103-B07129, https://doi.org/10.1029/2008JB007931.

Blackman, D., J.A. Karson, D.S. Kelley, J.R. Cann, G.L. Früh-Green, J.S. Gee, S.D. Hurst, B.E. John, J. Morgan, S.L. Nooner, D.K. Ross, T.J. Schroeder, and E.A. Williams. 2002. Geology of the Atlantis Massif (Mid-Atlantic Ridge, 30°N): Implications for the evolution of an ultramafic oceanic core complex. *Marine Geophysical Research* 23:443-469, https://doi.org/10.1023/B:MARI.0000018232.14085.75.

Bryan, W.B., T. Juteau, and Shipboard Scientific Party. 1988. *Proceedings of the Ocean Drilling Project, Initial Reports (Part A),* 109, Ocean Drilling Program, College Station, TX, https://doi.org/10.2973/odp.proc.ir.106109.1988.

Buck, W.R. 1988. Flexural rotation of normal faults. *Tectonics* 7:959–973, https://doi.org/10.1029/TC007i005p00959.

Canales, J.P., B.E. Tucholke, and J.A. Collins. 2004. Seismic reflection imaging of an oceanic detachment fault: Atlantis megamullion (Mid-Atlantic Ridge, 30°10'N). *Earth and Planetary Science Letters* 222:543-560, https://doi.org/10.1016/j.epsl.2004.02.023.

Cann, J.R., D.K. Blackman, D.K. Smith, E. McAllister, B. Janssen, S. Mello, E. Avgerinos, A.R. Pascoe, and J. Escartín. 1997. Corrugated slip surfaces formed at ridge-transform intersections on the Mid-Atlantic Ridge. *Nature* 385:329-332, https://doi.org/10.1038/385329a0.

Cann, J.R., M.G. Langseth, J. Honnorez, R.P. Von Herzen, S.M. White, and Shipboard Scientific Party, 1983. *Initial Reports of the Deep Sea Drilling Project,* 69, Washington (U. S. Government, Printing Office), https://doi.org/10.2973/dsdp.proc.69.1983.

Cannat, M. 1993. Emplacement of mantle rocks in the seafloor at mid-ocean ridges. *Journal of Geophysical Research* 98:4163-4172, https://doi.org/10.1029/92JB02221.

Cannat, M., J.A. Karson, D.J. Miller, and Shipboard Scientific Party. 1995. *Proceedings of the Ocean Drilling Project, Initial Report,* 153, Ocean Drilling Program, College Station, TX, https://doi.org/10.2973/odp.proc.ir.153.1995.

Carlson, R.L. 2010. How crack porosity and shape control seismic velocities in the upper oceanic crust: modeling downhole logs from Holes 504B and 1256D. *Geochemistry, Geophysics, Geosystems* 11:Q04007, https://doi.org/10.1029/2009GC002955.

Casey, J.F., D. Banerji, and P. Zarian, 2007. Leg 179 synthesis: geochemistry, stratigraphy, and structure of gabbroic rocks drilled in ODP Hole 1105A, Southwest Indian Ridge. Pp. 1-125 in P*roceedings of the Ocean Drilling Program, Scientific Results*, 179. J.F. Casey and D.J. Miller eds, College Station, TX (Ocean Drilling Program), https://doi.org/10.2973/odp.proc.sr.179.001.2007.

Detrick, R., J. Collins, R. Stephen, and S. Swift. 1994. In situ evidence for the nature of the seismic Layer 2/3 boundary in oceanic crust. *Nature* 370: 288–290, https://doi.org/10.1038/370288a0.

Dick, H.J.B. 1989. Abyssal peridotites, very slow spreading ridges and ocean ridge magmatism. Pp71-105 in *Magmatism in the Ocean Basins.* A.D. Saunders and M.J. Norry eds, Geological Society Special Publication London, 42, https://doi.org/10.1144/GSL.SP.1989.042.01.06.

Dick, H.J.B., J. Erzinger, L.B. Stokking, and Shipboard Scientific Party, 1992. *Proceedings of the Ocean Drilling Program, Initial Reports*, 140, College Station, TX (Ocean Drilling Program), https://doi.org/10.2973/odp.proc.ir.140.1992.

Dick, H.J.B., J.H. Natland, D.J. Miller, et al. 1999. *Proceedings of the Ocean Drilling Program, Initial Reports,* 176, Texas A&M University, Ocean Drilling Program, College Station, TX (Ocean Drilling Program). https://doi:10.2973/odp.proc.ir.176.1999.

Dick, H.J.B., J.H. Natland, J.C. Alt, W. Bach, D. Bideau, J.S. Gee, S. Haggas, J.G.H. Hertogen, G. Hirth, P.M. Holm, B. Ildefonse, G.J. Iturrino, B.E. John, D.S. Kelly, E. Kikawa, A. Kingdon, P.J. LeRoux, J. Maeda, P.S. Meyer, D.J. Miller, H.R. Naslund, Y.-L. Niu, P.T. Robinson, J. Snow, R.A. Stephen, P.W. Trimby, H.-U. Worm, A. Yoshinobu. 2000. A long in situ section of the lower ocean crust: results of ODP Leg 176 drilling at the Southwest Indian Ridge. *Earth and Planetary Science Letters 179*:31–51, https://doi.org/10.1016/S0012-821X(00)00102-3.

Dick, H.J.B., J.H. Natland, and B. Ildefonse. 2006. Past and future impact of deep drilling in the oceanic crust and mantle. *Oceanography* 19:72-80, https://doi.org/10.5670/oceanog.2006.06

Dilek, Y., E.M. Moore, D. Elthon, A. Nicolas, eds. 2000. *Ophiolites and oceanic crust: new insights from field studies and the ocean drilling program*. Geological Society of America Special Paper 349, Boulder, Corolado, 552 pp.

Fisher, R.L., H.J.B. Dick, J.H. Natland, and P.S. Meyer, 1986. Mafic/ultramafic suites of the slowly spreading southwest Indian Ridge: Protea exploration of the Antarctic Plate Boundary, 24°E-47°E. Ophioliti 11:147-178.

Früh-Green, G.L., B.N. Orcutt, S.L. Green, C. Cotterill, and the Expedition 357 scientists, 2016. *Atlantis Massif Serpentinization and Life.* Proceedings of the International Ocean Discovery Program, Volume 357: College Station, TX (International Ocean Discovery Program), https://doi.org/10.14379/iodp.proc.357.2017.

Gass, I.G. 1968. Is the Troodos massif of Cyprus a fragment of Mesozoic ocean floor? Nature 220: 39-42.

Gass, I.G. 1990. Ophiolites and oceanic lithosphe. Pp1-10 in *Ophiolites, Oceanic Crustal Analogues, Proceedings of the Symposium 'TROODOS 1987'*. J. Malpas, E.M. Moores, A. Panayiotou, and C. Xenophontos, eds, Geological Survey Department, Nicosia.

Gilbert, L.A., and M.H. Salisbury. 2011. Oceanic crustal velocities from laboratory and logging measurements of Integrated Ocean Drilling Program Hole 1256D. *Geochemistry Geophysics Geosystems* 12:Q09001, https://doi.org/10.1029/2011GC003750.

Gillis, K.M., C. Mével, J. Allan, and Shipboard Scientific Party, 1993. *Proceedings of the Ocean Drilling Program, Initial Reports*, 146, College Station, TX (Ocean Drilling Program), https://doi.org/10.2973/odp.proc.ir.147.1993.

Gillis, K.M., J.E. Snow, A. Klaus, N. Abe, A.B. Adrião, N. Akizawa, G. Ceuleneer, M.J. Cheadle, K Faak, T.J. Falloon, S.A. Friedman, M. Godard, G. Guerin, Y. Harigane, A.J. Horst, T. Hoshide, B. Ildefonse, M.M. Jean, B.E. John, J. Koepke, S. Machi, J. Maeda, N.E. Marks, A.M. MaCaig, R. Meyer, A. Morris, T. Nozaka, M. Python, A. Saha, and R.P. Wintsch, 2014a. Primitive layered gabbros from fast-spreading lower oceanic crust. *Nature* 505:204-207, https://doi.org/10.1038/nature12778.

Gillis, K.M., J.E. Snow, A. Klaus, G. Guerin, N. Abe, N. Akizawa, G. Ceuleneer, M.J. Cheadle, Á, Adrião, K. Faak, T.J. Falloon, S.A. Friedman, M.M. Godard, Y. Harigane, A.J. Horst, T. Hoshide, B. Ildefonse, M.M. Jean, B.E. John, J.H. Koepke, S. Machi, J. Maeda, N.E. Marks, A.M. McCaig, R. Meyer, A. Morris, T. Nozaka, M. Python, A. Saha, and R.P. Wintsch, 2014b. *Proceeding of the Integrated Ocean Drilling Program, Volume 335*, Prepared by U. S. Implementing Organization Science Services, Texas A&M University, Integrated Ocean Drilling Program Management International, Inc., the Integrated Ocean Drilling Program, Washington, DC, https://doi.org/10.2204/iodp.proc.345.2014.

Hess, H.H. 1962. *History of ocean basins*. Pp. 599-620 in Petrological Studies: A Volume in Honor of A.F. Buddington. A.E.J. Engel et al. eds, Boulder, CO (Geological Society of America), https://dx.doi.org/10.1130/Petrologic.1962.599

Hsü, K.J. 1992. *Challenger at Sea A Ship That Revolutionized Earth Science*, Princeton University Press, Princeton, New Jersey, 464 pp.

Ildefonse, B., P.A. Rona, and D. Blackman. 2007a. Drilling the crust at mid-ocean ridges: An “in depth” perspective. *Oceanography* 20:66-77, https://doi.org/10.5670/oceanog.2007.81.

Ildefonse, B., D.K. Blackman, B.E. John, Y. Ohara, D.J. Miller, C.J. MacLeod, and Integrated Ocean Drilling Program Expeditions 304/305 Science Party. 2007b. Oceanic core complexes and crustal accretion at slow-spreading ridges. *Geology* 35:623–626, https://doi.org/10.1130/G23531A.1.

Ildefonse, B., N. Abe, D.K. Blackman, J.P. Canales, Y. Isozaki, S. Kodaira, G. Myers, M.R. Nedimovic, D.A.H. Teagle, S. Umino, and D.S. Wilson. 2010. The MoHole: a crustal journey and mantle quest, workshop in Kanazawa, Japan, 3–5 June 2010. *Scientific Drilling* 10:56–62, https://doi.org/10.2204/iodp.sd.10.07.2010.

Ildefonse, B., N. Abe, M. Godard, A. Morris, D.A.H. Teagle, and S. Umino. 2014. *Chapter 4.2.1 - Formation and evolution of oceanic lithosphere: new insights on crustal structure and igneous geochemistry from ODP/IODP sites 1245, U1309, and U1415*. Pp. 449-505 in Developments in Marine Geology, 7, https://doi.org/10.1016/B978-0-444-62617-2.00017-7.

Ishizuoka, O., K. Tani, M.K. Reagan, K. Kanayama, S. Umino, Y. Harigane, I. Sakamoto, Y. Miyajima, M. Yuasa, and D.J. Dunkley. 2011. The timescales of subduction initiation and subsequence evolution of an oceanic island arc. *Earth and Planetary Science Letters* 306:229-240, https://doi.org/10.1016/j.epsl.2011.04.006.

Karson, J.A. 1990. *Seafloor spreading on the Mid-Atlantic Ridge: Implications for the structure of ophiolites and oceanic lithosphere produced in slow-spreading environments*. Pp. 547-553 in Proceedings of Symposium Troodos 1987. J. Malpas, ed., Geological Survey Department, Nicosia.

Kelemen, P.B., E. Kikawa, D.J. Miller, and Shipboard Scientific Party. 2004. *Proceedings of the Ocean Drilling Project, Initial Report,* 209, Ocean Drilling Program, College Station, TX, https://doi.org/10.2973/odp.proc.ir.209.2004.

Leinen, M., D.K. Rea, and Shipboard Scientific Party, 1986. *Initial Reports, DSDP*, 92, Washington (U. S. Government Printing Office), https://doi.org/10.2973/dsdp.proc.92.1986.

McCarthy, J., J.C. Mutter, J.L. Morton, N.H. Sleep, and G.A. Thompson, 1988. Relic magma chamber structures preserved within the Mesozoic North Atlantic crust? *Geological Society of America, Bulletin* 100:1423-1436, https://doi.org/10.1130/0016-7606(1988)100<1423:RMCSPW>2.3.CO;2 .

MacLeod, C.J., H.J.B. Dick, P. Blum, and the Expedition 360 Scientists, 2017. *Southwest Indian Ridge Lower Crust and Moho.* Proceedings of the International Ocean Discovery Program, 360: College Station, TX (International Ocean Discovery Program), https://doi.org/10.14379/iodp.proc.360.2017.

Maxwell, A.E. and the Shipboard Scientific Party, 1970. *Initial Reports of the Deep Sea Drilling Project, Volume III*. Prepared for the National Science Foundation by the University of California Scripps Institution of Oceanography, Washington (U. S. Government Printing Office), 806 pp. https://doi.org/10.2973/dsdo.proc.3.1970.

Michibayashi, K., M. Reagan, S. Umino, A. Okamoto, K. Takai, T. Morishita, O. Ishizuka, Y. Harigane, J. Kimura, T. Hanyu, Y. Ohara, N. Abe, Y. Tamura, S. Ona, S. Saito, T. Fujiwara, M. Yamashita, G. Fujie, K. Obana, and S. Kodaira, 2016. *898-Pre: Oceanic to Proto-Arc Mantle Transformation: Fore Arc M2M (Moho-to-Mantle) in the Bonin Trench, Northwestern Pacific. IODP Proposal*, http://www.iodp.org/proposals/active-proposals.

Miyashiro, A. 1973. The Troodos Complex was probably formed in an island arc. *Earth and Planetary Science Letters* 25:217-222.

Morishita, T. 2017. Drilling into deep-seated hard rocks of the oceanic plate formed at the Mid-Ocean Ridge: results and future perspectives: Deep-seated Hard Rock Drilling. *Journal of the Geological Society of Japan* 123:185-205.

Morishita, T., G. Fujie, S. Ono, J. Morgan, D. Teagle, M. Yamano, S. Saito, S. Kodaira, J. Kimura, N. Abe, P. Kelemen, B. Ildefonse. 2015. *886-Pre: Bend-fault hydrology in the old incoming plate. IODP Proposal*, http://www.iodp.org/proposals/active-proposals.

Morgan, J., T. Henstock, D. Teagle, P. Vannucchi, G. Fujie, S. Kodaira, I. Grevemeyer, L. Ruepke, H. Villinger, C. Ranero, B. Ildefonse, K. Johnson, P. Kelemen, M. Schrenck. 2014. *876-Pre: Bend-Fault Serpentinization: Oceanic Crust and Mantle Evolution from Ridge through Trench. IODP Proposal*, http://www.iodp.org/proposals/active-proposals.

Morris, A., J.S. Gee, N. Pressling, B.E. John, C.J. MacLeod, C.B. Grimes, and R.C. Searle. 2009. Footwall rotation in an oceanic core complex quantified using reoriented Integrated Ocean Drilling Program core samples, *Earth and Planetary Science Letters* 287:217–228, https://doi.org/10.1016/j.epsl. 2009.08.007.

Müller, R.D., M. Sdrolias, C. Gaina, and W.R. Roest. 2008. Age, spreading rates, and spreading asymmetry of the world's ocean crust. *Geochemistry, Geophysics, Geosystems* 9:Q04006, https://doi. org/10.1029/2007GC001743.

Mutter, J.C., and North Atlantic Transect (NAT) Study Group, 1985. Multichannel seismic images of the oceanic crust's internal structure: evidence for a magma chamber beneath the Mesozoic Mid-Atlantic Ridge. *Geology* 13:629-632, https://doi.org/10.1130/0091-7613(1985)13<629:MSIOTO>2.0.CO;2.

National Research Council. 1957. *The AMSOC Project to Drill a Hole to the Mohorovicic Discontinuity*. Prepared for the AMSOC committee by Harry H. Hess, Division of Earth Sciences, Washington DC, 5 pp.

National Research Council. 1959. *A Report by The AMSOC Committee on Drilling Thru the Earth's Crust A Study of Desirability and Feasibility of Drilling a Hole to the Mohorovicic Discontinuity*. Publication 717, National Academy of Sciences/National Research Council, Washington, DC, 20 pp.

National Research Council (U.S.). AMSOC Committee. 1961. *Experimental Drilling in Deep Water at La Jolla and Guadalupe Sites*. Issue 914 of National Research Council Publication, National Academy of Sciences/National Research Council Washington, DC, 183 pp.

Ohira, A., S. Kodaira, G. F. Moore, M. Yamashita, T. Fujiwara, Y. Kaiho, S. Miura, and G. Fujie. 2018. Active-source seismic servey on the northeastern Hawaiian Arch: insights into crustal structure and mantle reflectors. *Earth, Planets and Space* 70:121, https://doi.org/10.1186/s40623-018-0891-8.

Panayotou, A., ed. 1980. *Proceedings of the International Ophiolite Symposium in Cyprus, 1979*, Geological Survey, Nicosia, 781 pp.

Reagan, M.K., D.E. Heaton, M.D. Schmitz, J.A. Pearce, J.W. Shervais, and A.A.P. Koppers. 2019. Forearc ages reveal extensive short-lived and rapid seafloor spreading following subduction initiation. *Earth and Planetary Science letters* 506:520-529, https://doi.org/10.1016/j.epsl.2018.11.020.

Reagan, M.K., J.A. Pearce, K. Petronotis, R.R. Almeev, A.J. Avery, C. Carvallo, T. Chapman, G.L. Christeson, E.C. Ferré, M. Godard, D.E. Heaton, M. Kirchenbaur, W. Karz, S. Kutterolf, H. Li, Y. Li, K. Michibayashi, S. Morgan, W.R. Nelson, J. Prytulak, M. Python, A.H.F. Robertson, J.G. Ryan, W.W. Sager, T. Sakuyama, J.W. Shervais, K. Shimizu, and S.A. Whattam. 2017. Subduction initiation and ophiolite crust: new insights from IODP drilling. *International Geology Review* 59:1439-1450, https://doi.org/10.1080/00206814.2016.1276482.

Schroeder, T., M.J. Cheadle, H.J.B. Dick, U. Faul, J.F. Casey, P.B. Kelemen, 2007. Nonvolcanic seafloor spreading and corner-flow rotation accommodated by extensional faulting at 15°N on the Mid-Atlantic Ridge: A structural synthesis of ODP Leg 209. *Geochemistry, Geophysics, Geosystems* 8:Q06015, https://doi.org/10.1029/2006GC001567.

Swift, S., M. Reichow, A. Tikku, M. Tominaga, L. Gilbert, 2008. Velocity structure of upper ocean crust at Ocean Drilling Program Site 1256. *Geochemistry, Geophysics, Geosystems* 9:Q10O13, https://doi.org/10.1029/2008GC002188.

Tamura, A., S. Arai, S. Ishimaru, and E.S. Andal. 2008. Petrology and geochemistry of peridotites from IODP Site U1309 at Atlantis Massif, MAR 30°N: micro- and macroscale melt penetrations into peridotites. *Contributions to Mineralogy and Petrology* 155:491–509, https://doi.org/10.1007/s00410-007-0254-0.

Tatsumi, Y., K. Kelley, R. Arculus, M. Arima, S. Debari, J.B. Gill, O. Ishizuka, Y. Kaneda, J. Kimura, S. Kodaira, Y. Ohara, J. Pearce, S.M Straub, N. Takahashi, Y. Tamura, K. Tani. 2010. *698-Full3: Continental crust formation at intra-oceanic arc: ultra-deep drilling to the middle crust* *of the Izu-Bonin-Mariana arc. IODP Proposal*, http://www.iodp.org/proposals/active-proposals.

The National Academies of Sciences, Engineering and Medicine. 2011. *Project Mohole.* http://www.nationalacademies.org/mohole/index.html.

Teagle, D., and B. Ildefonse. 2011. Journey to the mantle of the Earth. *Nature* 471:437-439. https://doi.org/10.1038/471437a.

Teagle, D.A.H., J.C. Alt, S. Umino, S. Miyashita, N.R. Banerjee, D.S. Wilson, and the Expedition 309/312 Scientists. 2006. *Superfast Spreading Rate Crust 2 and 3, Proceeding of the Integrated Ocean Drilling Program, Volume 309/312*, Prepared by U. S. Implementing Organization Science Services, Texas A&M University, Integrated Ocean Drilling Program Management International, Inc., the Integrated Ocean Drilling Program, Washington, DC, https://doi.org/10.2204/iodp.proc.309312.2006.

Teagle, D.A.H., B. Ildefonse, P. Blum, and the Expedition 335 Scientists. 2012. *Superfast Spreading Rate Crust 4, Proceeding of the Integrated Ocean Drilling Program, Volume 335*, Prepared by U. S. Implementing Organization Science Services, Texas A&M University, Integrated Ocean Drilling Program Management International, Inc., the Integrated Ocean Drilling Program, Washington, DC, https://doi.org/10.2204/iodp.proc.335.2012.

Thompson, G., and W.G. Melson, 1972. The petrology of oceanic crust across fracture zones in the Atlantic Ocean: evidence of a new kind of sea-floor spreading. *Journal of Geology* 80:526-538, https://doi.org/10.1086/627779.

Tominaga, M., B. Orcutt, and P. Blum. 2019. *Panama Basin Crustal Architecture (504B) & Restoring Hole 896A. IODP Expedition 385T*, Scientific Prospectus, in press.

Tucholke, B.E., and J. Lin, 1994. A geological model for the structure of ridge segments in slow-spreading ocean crust. *Journal of Geophysical Research* 99:11937-11958, https://doi.org/10.1029/94JB00338.

Tucholke, B.E., J. Lin, and M.C. Kleinrock. 1998. Megamullions and mullion structure defining oceanic metamorphic core complexes on the Mid-Atlantic Ridge. *Journal of Geophysical Research* 103:9857–9866, https://doi.org/10.1029/98JB00167.

Umino, S., L. Crispini, P. Tartarotti, D.A.H. Teagle, J. C. Alt, S. Miyashita, N. R. Banerjee. 2008. Origin of the sheeted dike complex at superfast spread East Pacific Rise revealed by deep ocean crust drilling at Ocean Drilling Program Hole 1256D. *Geochemistry Geophysics Geosystems* 9:Q06008, https://doi.org/10.1029/2007GC001760.

Umino, S., B. Ildefonse, P.B. Kelemen, S. Kodaira, K. Michibayashi, T. Morishita, D.A.H. Teagle and the MoHole proponents. 2012. *805-MDP: MoHole to Mantle (M2M). IODP Proposal*, http://www.iodp.org/proposals/active-proposals.

Whitehead, J.A., H.J.B. Dick, and H. Shouten, 1984. A mechanism for magmatic accretion under spreading centers. *Nature* 312: 146-148, https://doi.org/10.1038/312146a0.

Wilson, D.S., D.A.H. Teagle, G.D. Acton, and ODP Leg 206 Scientific Party. 2003. *Proceedings of the Ocean Drilling Program, Initial Reports, 206*, Ocean Drilling Program, College Station, TX, https://doi.org/10.2973/odp.proc.ir.206.2003.

Wilson, D. S., D.A.H. Teagle, J.C. Alt, N.R. Banerjee, S. Umino, S. Miyashita, G.D. Acton, R. Anma, S.R. Barr, A. Belghoul, J. Carlut, D.M. Christie, R.M. Coggon, K.M. Cooper, C. Cordier, L. Crispini, S.R. Durand, F. Einaudi, L Galli, Y. Gao, J. Geldmacher, L.A. Gilbert, N.W. Hayman, E. Herrero-Bervera, N. Hirano, S. Holter, S. Ingle, S. Jiang, U. Kalberkamp, M. Kerneklian, J. Koepke, C. Laverne, H.L.L. Vasquez, J. Maclennan, S. Morgan, N. Neo, H. J. Nichols, S.-H. Park, M. K. Reichow, T. Sakuyama, T. Sano, R. Sandwell, B. Scheibner, C.E. Smith-Duque, S.A. Swift, P. Tartarotti, A.A. Tikku, M. Tominaga, E.A. Veloso, T. Yamasaki, S. Yamazawa, and C. Ziegler. 2006. Drilling to gabbro in intact ocean crust. *Science* 312:1016-1020, https://doi.org/10.1126/science.112690.

Wernicke, B., and G.J. Axen. 1988. On the role of isostasy in the evolution of normal fault systems, *Geology* 16:848–851, https://doi.org/10.1130/0091-7613 (1988)016<0848:OTROII>2.3.CO;2.

Yeasts, R.S., S.R. Hart, and DSDP Leg 34 Scientific Party. 1976. *Initial Reports of the Deep Sea Drilling Project, Volume 34*, Washington (U.S. Government Printing Office), 814 pp., https://doi.org/10.2973/dsdp.proc.34.1976.

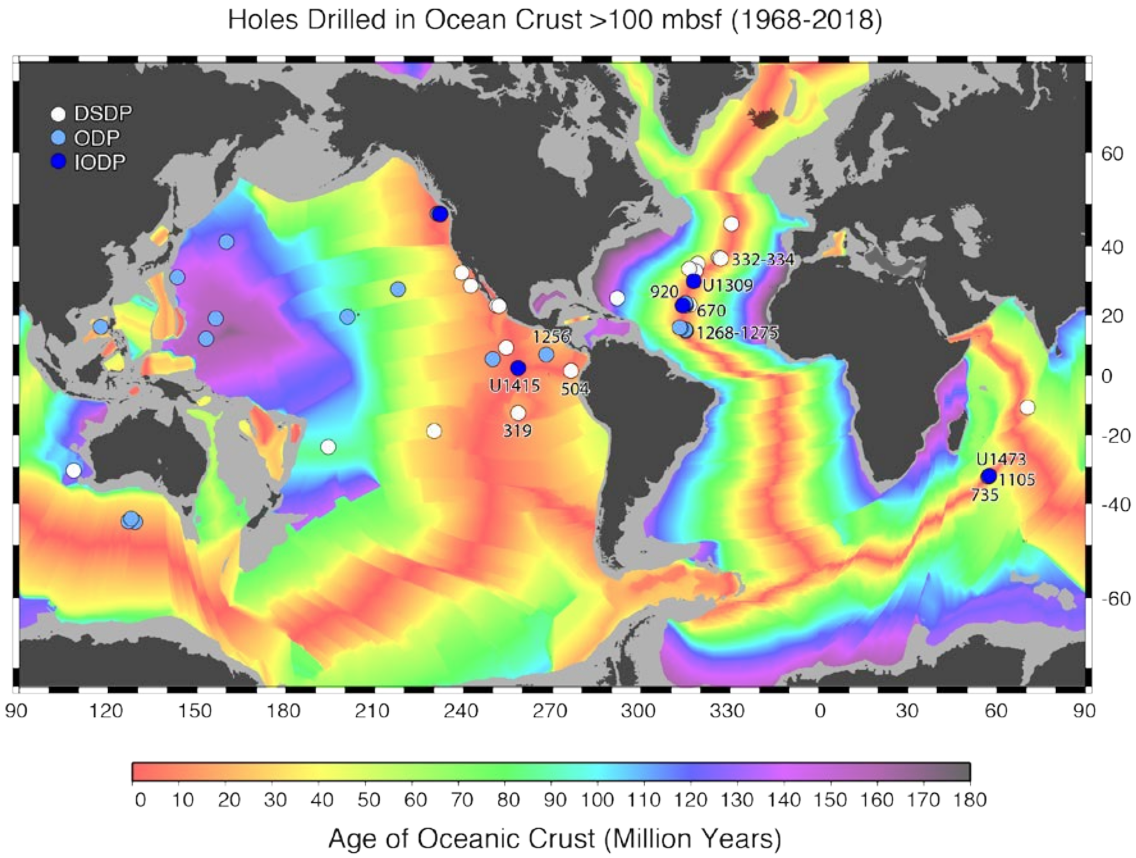

Figure 1. Compilation showing holes drilled >100 m into the basement of intact ocean crust and tectonically-exposed lower crust and upper mantle from 1968 to 2018 (drill hole sections in Figure 2). Sites mentioned in the text are labeled. Seafloor age based on age grid by Müller et al. (2008 revised 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.

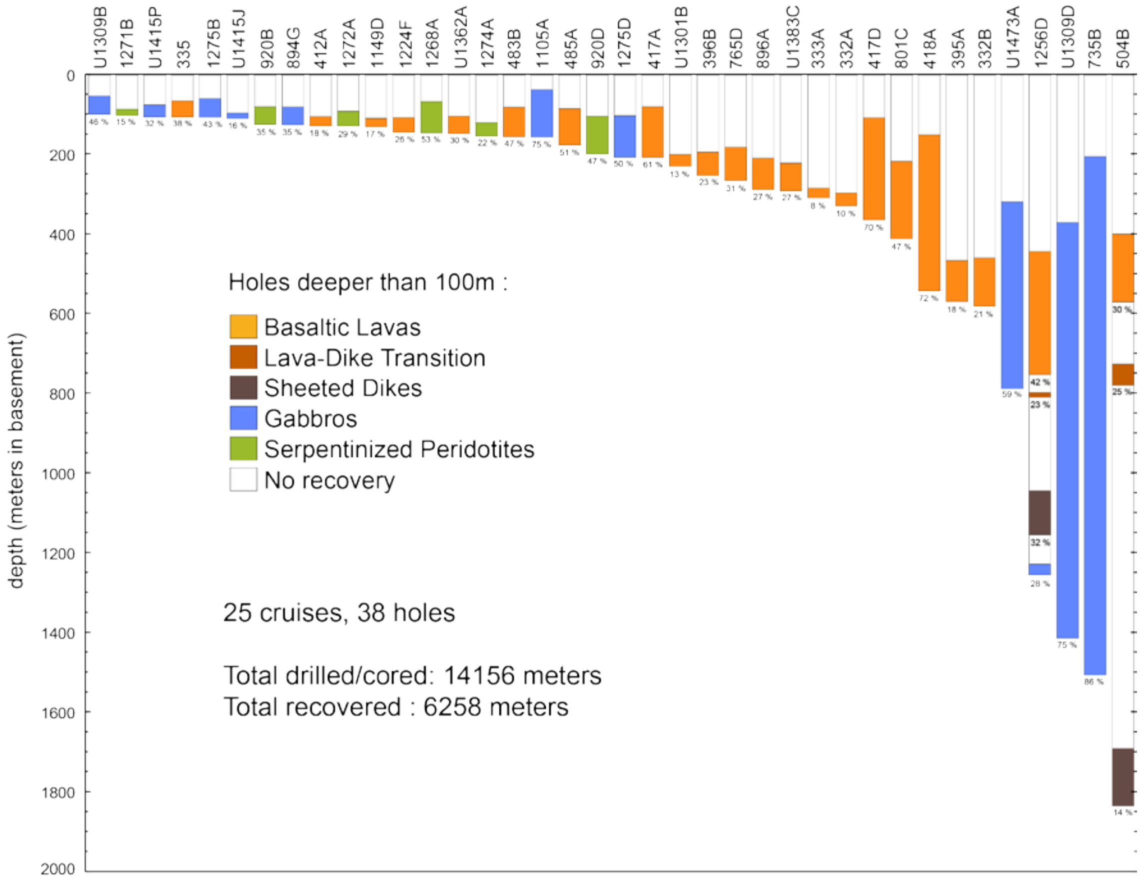

Figure 2. Compilation showing holes drilled >100 m into the basement of intact ocean crust and tectonically-exposed lower crust and upper mantle from 1968 to 2018 (drill hole locations in Figure 1). For each hole are indicated the hole number and the recovery (in percent) for each of the basement lithologies.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

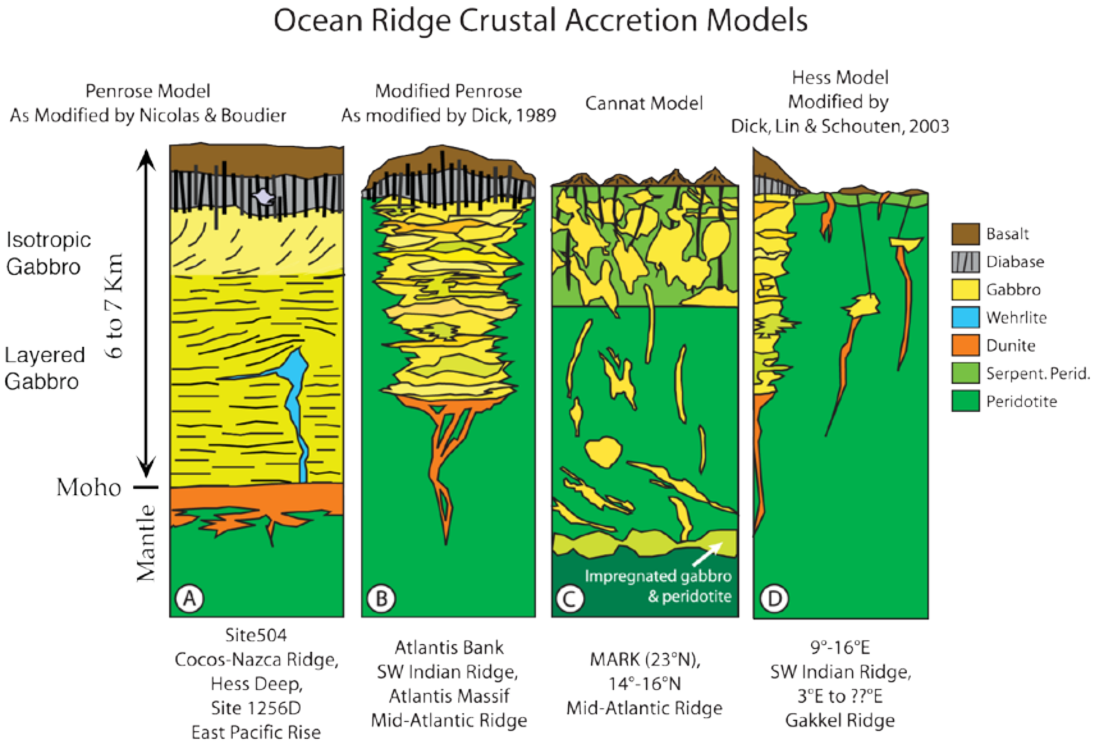

Figure 3. Models for crustal accretion at ocean ridges after Dick et al. (2006). A. Classic interpretation of the Penrose model for a fast spreading mid-ocean ridges based on the Oman Ophiolite. B. Penrose model as modified for slow-spreading ridges based on the abundance of peridotite and frequent absence 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.

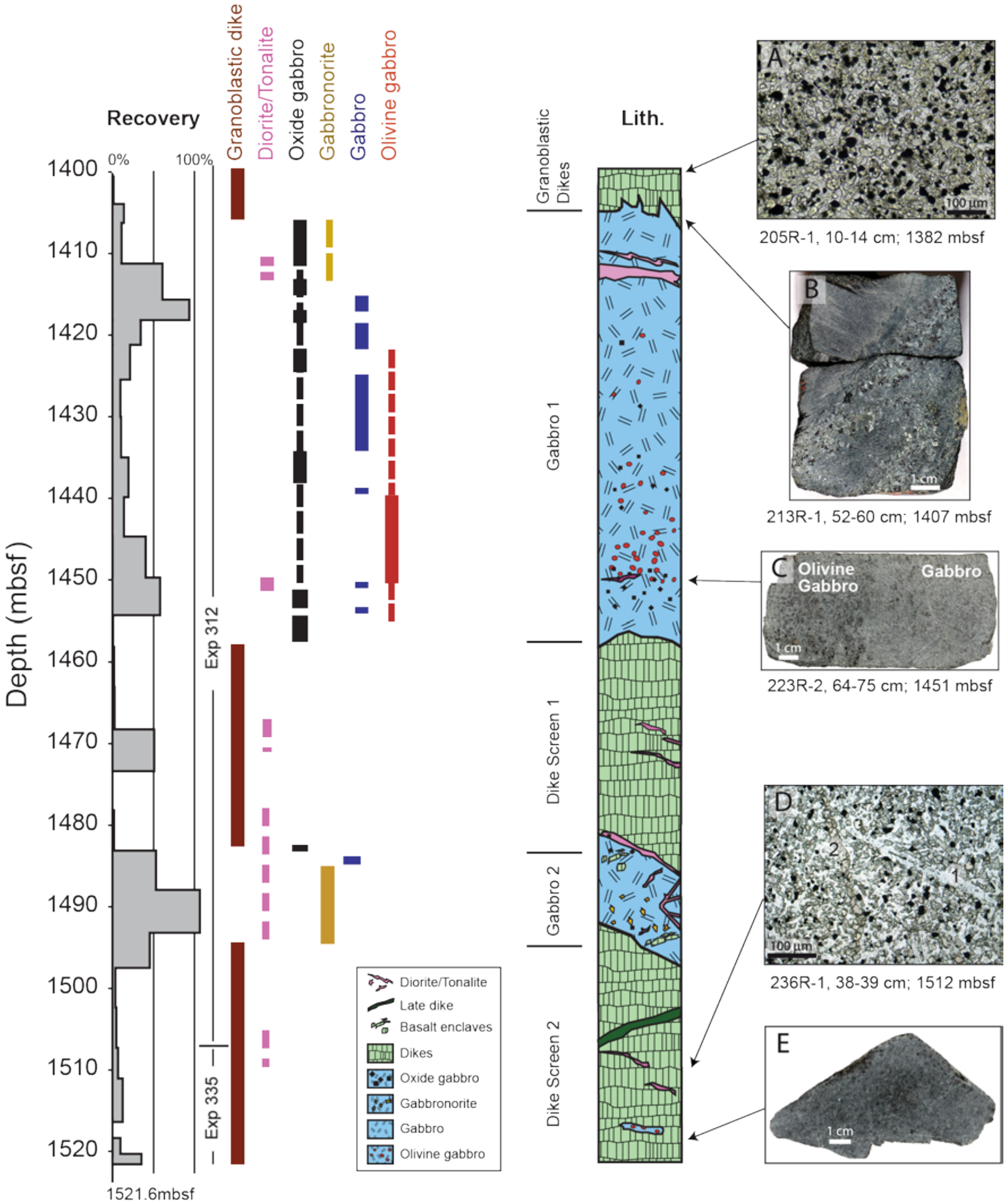

Figure 4. Plutonic section from the lower portion of Hole 1256D with a few representative photomicrographs of key samples (modified after Ildefonse et al., 2014). The distribution of rock types is expanded proportionately in zones of incomplete recovery. (A) Photomicrograph of a dike completely recrystallized 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.

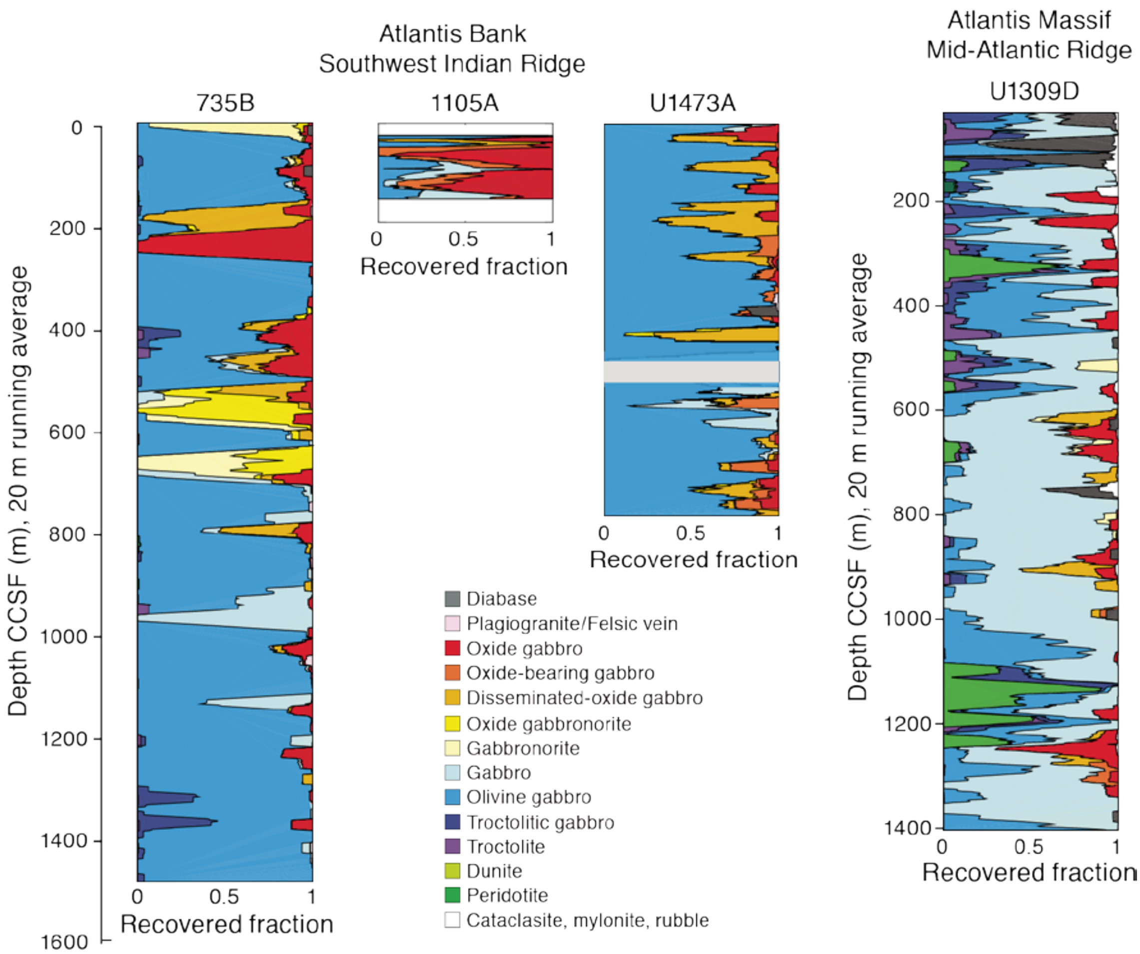

Figure 5. Lithostratigraphic variations of Atlantis Bank (Holes 735B, 1105A, and Hole U1473A) and Atlantic Massif (Hole U1309D). Relative abundances of rocks are averaged over 20 m. In Holes 735B and U1309D, oxide gabbro includes both oxide gabbro and oxide-bearing gabbro. Gray bar: drilled interval.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

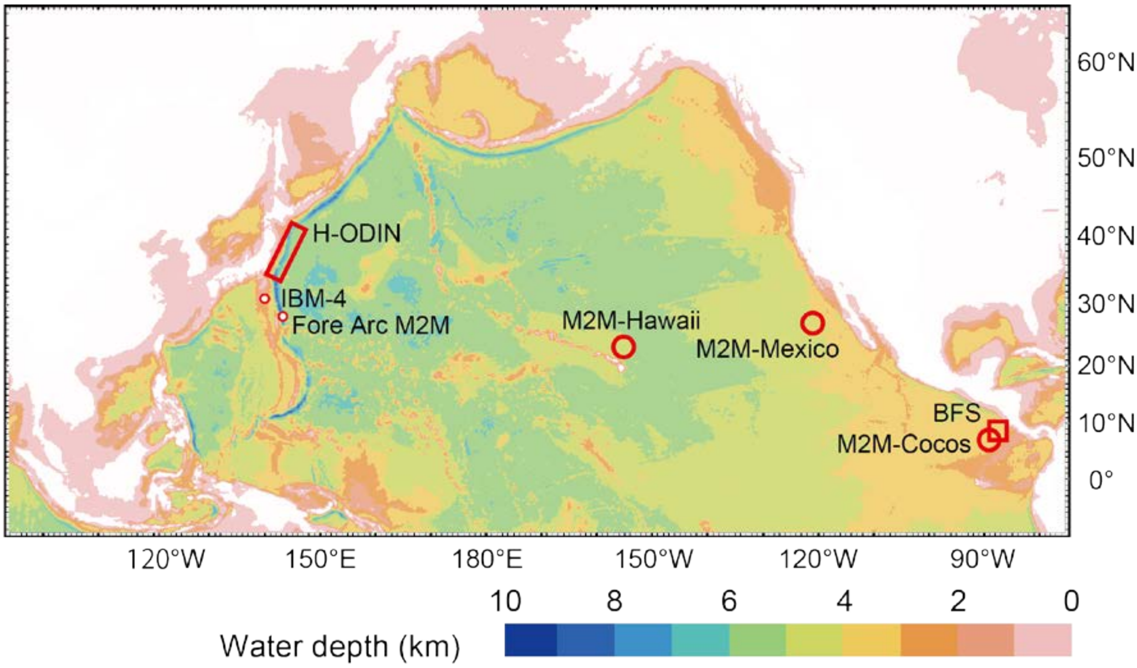

Figure 6. Bathymetric map of the Pacific Ocean showing the locations of potential drilling sites for IODP CHIKYU proposals: the Mohole to Mantle (M2M) drilling projects (Umino et al., 2012; open circles), bending-fault hydrology of the old incoming plate (H-ODIN; rectangle; Morishita et al., 2015), bending-fault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