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Deep drilling of intact ocean crust: harnessing past lessons to inform future endeavors[1]

Expedition 335 Scientists[2]

Chapter contents

Introduction

This chapter provides a review of the scientific imperatives for deep drilling of oceanic crust, a review of past successes and challenges with deep drilling, thoughts on the siting of deep boreholes, and final comments on scientific ocean drilling programmatic changes that would enhance the success of deep drilling experiments in ocean lithosphere.

The case for deep drilling of intact ocean crust

Drilling a complete in situ section of ocean crust has been an unfulfilled ambition of Earth scientists for many decades and provided the impetus for the conception of scientific deep ocean drilling. The production of new crust at mid-ocean ridges lays the foundation of the plate tectonic cycle and is a dominant process that has resurfaced >60% of our present-day planet since the Early Jurassic (<200 Ma). Magma eruption and intrusion, along with ocean floor hydrothermal exchange, are the principal mechanisms of heat and material transfer from the mantle to the crust, oceans, and atmosphere. The ocean crust is an environment of steep thermal, physical, and chemical gradients potentially with many of the ingredients required to initiate primordial life, as there is growing evidence for an enduring, active subsurface basalt-hosted microbial biosphere (e.g., Fisk et al., 1998; Bach and Edwards, 2003; Santelli et al., 2008; Rouxel et al., 2008; McLoughlin et al., 2009; McCarthy et al., 2011). Evidence for microbial activity was also recently reported in ~1 m.y. old gabbros collected during Integrated Ocean Drilling Program (IODP) Expedition 304/305 (Mason et al., 2010). Chemical exchanges between the ocean and crust over a wide range of temperatures exert major controls on seawater chemistry and partially buffer inputs from the erosion and weathering of continents brought to the oceans by rivers, glaciers, and groundwater (e.g., Palmer and Edmond, 1989; Vance et al., 2009).

Unfortunately, many of the key questions regarding the formation and evolution of the oceanic crust that are primary scientific goals of the IODP Initial Science Plan and numerous forerunner questions remain unanswered despite 50 years of scientific ocean drilling. This is principally due to the cursory sampling of the ocean crust, and in particular an absence of continuous deep

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[2] **Expedition 335 Scientists' addresses.**

crustal sections (see Wilson, Teagle, Acton, et al., 2003; Teagle et al., 2004; Dick et al., 2006; Ildefonse et al., 2007c). These fundamental questions remain compelling and increasingly relevant to understanding the wider Earth system with the growing appreciation of the interdependency between geological, climatic, and biogeochemical cycles.

Why study crust forming at fast spreading rates?

The vast majority (~70%) of magma derived from the mantle is brought into the Earth's crust at the mid-ocean ridges, and approximately two-thirds of that magma cools and crystallizes in the lower portion of the oceanic crust. Seismic, bathymetric, and marine geological observations indicate that ocean crust formed at fast spreading rates (full rate > 80 mm/y) is much less variable than crust formed at slow spreading rates (<40 mm/y) and is closer to the ideal "Penrose" pseudostratigraphy developed from ophiolites (Anonymous, 1972). Hence, extrapolating fast-spreading accretion processes from a few sites might reasonably describe a significant portion of the Earth's surface. Although <20% of modern ridges are moving apart at fast spreading rates (Fig. **F1**), nearly 50% of present-day ocean crust and ~30% of the Earth's surface was produced at this pace of spreading (Fig. **F2**). The great majority of crust subducting into the mantle over the past ~200 m.y. formed at fast-spreading ridges (Müller et al., 2008), making characterizing this style of crust most relevant for understanding the recycling of crustal and ocean-derived components back into the mantle.

The spreading rate of the oceanic lithosphere has profound effects on the style of crustal accretion at mid-ocean ridges because of changing balances between plate motion, magma production, conductive and hydrothermal cooling, detachment tectonics, and serpentinization of the upper mantle (e.g., Dick, 1989; Cannat et al., 1995, 2004, 2009; Chen and Phipps Morgan, 1996; Dick et al., 2003; Escartin et al., 2008). Although insights on the formation of intrusive crust at detachment-dominated, slow-spread lithosphere have been obtained (Ocean Drilling Program [ODP] Legs 118, 153, 176, and 209 and IODP Site U1309; e.g., Dick et al., 2000; Blackman, Ildefonse, John, Ohara, Miller, MacLeod, and the Expedition 304/305 Scientists, 2006; Kelemen, Kikawa, Miller, et al., 2004; Ildefonse et al., 2007a; Blackman et al., 2011), the thermal regime and the melt supply and delivery in these settings differs significantly from those of the axial zone in fast-spreading lithosphere. Detailed understanding of the relatively uniform mechanisms operating at fast-spreading ridges would provide a vital benchmark against which heterogeneous accretion at slow-spreading ridges could be compared.

The need for basic geologic observations of ocean crustal architecture

Basic observations regarding the architecture of in situ present-day ocean crust, including rock types, geochemistry, and thicknesses of the volcanic, dike, and plutonic sections, are yet to be made. It is a fundamental weakness of our knowledge of the ocean crust that we are as yet unable to relate seismic and magnetic imaging of the ocean crust and geochemical inferences to basic geologic observations. We do not have a predictive understanding of the factors controlling the thicknesses of seismic and geological layers in the oceanic crust, which greatly precludes our ability to interpret regional geophysical data in geological terms. Drilling a few deep drill holes into intact ocean crust and studying samples having a range of seismic behaviors could greatly increase the confidence with which we interpret geophysical data and its use as a three-dimensional regional mapping tool (e.g., Fig. **F3**). Earth scientists often loosely speak of "Layer 3" when referring to the plutonic rocks of the ocean crust. However, the geological meaning and physical causes of the transition from seismic Layer 2 to Layer 3 velocities remain poorly understood. In Deep Sea Drilling Project (DSDP) Hole 504B, the only place where the Layer 2–3 transition has been penetrated in situ, the Layer 2–3 transition occurs near the middle of the ~1 km thick sheeted dike complex, where the transition to gabbroic rocks is at least 600 m deeper in the crust (Alt, Kinoshita, Stokking, et al., 1993; Detrick et al., 1994). At Site 504 the change from Layer 2 to Layer 3 appears to be related to changes in the secondary hydrothermal mineralogy (Alt et al., 1996) and/or crack porosity (Carlson, 2010). Whether this observation from the intermediate spreading rate crust sampled in Hole 504B is applicable to other spreading rates or ocean crust in general is yet to be tested.

Marine magnetic anomalies are one of the key observations that led to the development of plate tectonic theory, through the recognition that the ocean crust records the changing polarity of the Earth's magnetic field through time (Vine and Matthews, 1963). Micrometer-sized grains of titanomagnetite within the erupted basalt are generally accepted to be the principal recorders of marine magnetic anomalies, but recent studies of tectonically exhumed lower crustal rocks and serpentinized upper mantle indicate that these deeper rocks may also be a significant source of the magnetic anomaly signal (Kikawa and Ozawa, 1992; Pariso and Johnson, 1993; Shipboard Scientific Party, 1999; Gee and Kent, 2007). Whether these deeper rocks have a significant influence on the magnetic field in undisrupted crust is unknown, as is the extent of secondary magnetite growth in gabbros and mantle assemblages away from transform faults. Sampling the plutonic layers of the crust could refine the Vine-Matthews hypothesis by characterizing the magnetic properties of gabbros and peridotites through drilling intact ocean crust, on a well-defined magnetic stripe, away from transform faults.

The most prominent melt feature observed by multichannel seismic experiments at fast-spreading mid-ocean ridges is a low-velocity zone some tens of meters thick, hundreds of meters across axis, and commonly continuous for many hundreds of kilometers along axis (e.g., Kent et al., 1994). This low-velocity zone is interpreted to be a dominantly magma rich lens (e.g., Detrick et al., 1987; Vera et al., 1990; Hussenoeder et al., 1996; Singh et al., 1998) that overlies a lower crustal region of reduced *P*- and *S*-wave velocities interpreted to be a hot crystal mush zone containing no more than a few percent of interstitial melt (e.g., Caress et al., 1992; Sinton and Detrick, 1992; Dunn et al., 2000). The roles of the low-velocity zone and axial magma lens in constructing fast-spreading ocean crust remain controversial. A family of elegant thermally based numerical models attempts to build the lower crust from the continuous subsidence of cumulate layers formed at the base of the axial melt lens (Fig. F4) (Sleep, 1975; Henstock et al., 1993; Phipps-Morgan and Chen, 1993; Quick and Denlinger, 1993). These models have major implications for the composition and deformation of the lower crust, but many of these predictions are not borne out by observations in ophiolites or the limited fast-spread plutonic ocean crust drilled to date. For example, petrologic observations from Hess Deep suggest that the uppermost gabbros, interpreted to represent the axial melt lens that formed the crust, are late-stage melt fractions, even more differentiated than erupted mid-ocean-ridge basalt (MORB), and question the significance of the axial melt lens in the formation of the lower oceanic crust (e.g., Natland and Dick, 2009).

The itinerary of melt formed by the partial melting of the mantle to its eruption on the seafloor remains poorly understood. For more than two decades it has been assumed that the compositions of MORB erupted onto the ocean floor can be interpreted as a direct result of mantle melting (e.g., Klein and Langmuir, 1987; McKenzie and Bickle, 1988). The evolved chemistry of MORB and rarity of very primitive lavas indicate that nearly all lavas erupted at the ridge crests are processed in magma chambers. However, whether fractionation is solely responsible for magma chemistry remains unquantified. Recent results from fast- and slow-spreading ridges (e.g., Rubin and Sinton, 2007; Lissenberg and Dick, 2008; Suhr et al., 2008; Godard et al., 2009; Drouin et al., 2009, 2010) indicate that significant reactions can occur between melts and lower crustal cumulates or mantle rocks. The extent to which melt-rock interactions bias our current understanding of mantle melting processes cannot be assessed without studying the genetically conjugate cumulate rocks with their daughter extrusive lavas (and ultimately the source mantle rocks). Eventually, what will be required is a bulk chemical inventory of a complete section of ocean crust.

The manner of passage of melt through the lower crust to the axial melt lens or to feed the dike and volcanic layers also remains poorly understood. Gabbros that crop out in ophiolites commonly exhibit fine-scale modal and geochemical layering, but these textures are difficult to reconcile with models of grain boundary flow of upwelling magma through a lower crust that mostly comprises a crystal mush (e.g., Korenaga and Kelemen, 1997). Discrete channels that feed magma into the axial melt lens or higher levels are yet to be identified in intact ocean crust (cf. MacLeod and Yaouancq, 2000).

The latent and specific heat from cooling and crystallizing magma is the principal driving force for hydrothermal circulation, with the energy available a function of the volume, distribution, and timing of magma intrusions. Within a few hundred meters of the ridge axis, the ocean crust appears completely solid to seismic waves and a clear Moho is generally observed. This requires that, at the very least, the latent heat of crystallization and sensible heat for cooling the magma to the solidus for the ~6 km of new crust at the ridge must have been exported from the system. The timescales are too short (<25,000 y) for this heat export to be achieved solely by conduction, requiring advection of heat by hydrothermal circulation. How this can be achieved in the upper crust is easy to envisage, but the importance and geometry of latent and sensible heat extraction from the deep crust by hydrothermal fluids remain poorly known and provide a key difference in competing models of magmatic accretion at fast-spreading ridges (Fig. F4) (Sleep, 1975; Henstock et al., 1993; Dunn et al., 2000; Garrido et al., 2001; Maclennan et al., 2005).

The compositions of fluids venting into the ocean at high-temperature black smokers and other types of vents are controlled by the physiochemical conditions and the extents of fluid-rock reactions within the crust (e.g., Mottl, 1983; Seyfried et al., 1999; Jupp and Schultz, 2000; Coumou et al., 2008). The rate of cooling of magma is in turn controlled by the extent of fracturing and resulting permeability, the consequent geometry and vigor of high- and low-temperature hydrothermal circulation, and the rates of fluid-rock exchanges. Some numerical models and ophiolite data (e.g., Maclennan et al., 2005; Bosch et al., 2004; Gregory and Taylor, 1981) require that seawater circulation extends to depths of several kilometers close to the ridge axis to mine the latent heat from deep in the crust and hence directly controls accretionary processes in the lower crust. Unfortunately, deep circulating fluid fluxes are poorly determined, and the conclusive geochemical tests of this scenario in an intact section of ocean crust remain to be conducted (e.g., Coogan et al., 2002, 2005; Van Tongeren et al., 2008). Sparse analyses of hydrothermal veins from gabbros indicate insufficient fluid volumes to significantly cool the lower crust (Coogan et al., 2007). The chemistry of black-smoker fluids suggests rock-dominated fluid exchange with the crust and regional recharge, but faults may play a role in facilitating the penetration of seawater-derived fluids to enable the cooling of the deep crust (e.g., Coogan et al., 2006). However, to date there is little evidence from intact ocean crust on whether faults, or other channels for seawater penetration down into the lower crust, are important for cooling the lower crust and for the advection of ocean-derived geochemical tracers or microbial populations to depth (e.g., Mason et al., 2010). Microbial populations seek out high thermal/chemical gradients; hence, the variation in the location/properties of faults and other zones of enhanced crustal fluid recharge are expected to determine the diversity of the ecosystem at depth within the crust.

An important recent advance comes from the recognition that the sheeted dike complexes of all intermediate to fast-spread systems studied (DSDP Hole 504B and ODP Hole 1256D and seafloor samples from Hess Deep and Pito Deep tectonic windows) provide relatively consistent estimates of axial high-temperature fluid fluxes (e.g., Teagle et al., 1998a, 2003; Gillis et al., 2005; Barker et al., 2008; Harris et al., 2008; Harris, 2011; Coggon, 2006; Nielsen et al., 2006; Chan et al., 2002). These estimates are all much lower than hydrothermal fluxes estimated from global seawater budgets, hydrothermal vent observations (e.g., Elderfield and Schultz, 1996), or studies of ophiolites (Bickle and Teagle, 1992), but their consistency with thermal calculations gives confidence in their validity. This sets the stage for estimates of chemical fluxes between this zone and the oceans and the impact of axial hydrothermal alteration on global chemical cycles (e.g., Davis et al., 2004; Vance et al., 2009).

Deep scientific ocean drilling is the only approach that can provide basic geologic observations on the formation and evolution of fast-spreading ocean crust

To date there remains a near-complete lack of direct observations regarding the accretion occurring beneath the dike layer at fast-spreading ridges. Importantly, we have well-developed but competing theoretical and geological models of the styles of magmatic accretion at fast-spreading ridges (Fig. **F4**). These models have been developed from a wide evidence base from marine geology and geophysics, as well as studies of ophiolites. Unfortunately, none of the best preserved ophiolites likely formed in major ocean basins (e.g., Miyashiro, 1973; Rautenschlein et al., 1985; Miyashita et al., 2003; Stern, 2004). Although ophiolite outcrops will continue to provide invaluable inspiration for ocean crustal studies, their direct relevance to intact ocean crust remains unproven. Although tests have been developed, the appropriate materials and observations to challenge these hypotheses remain elusive because the key processes of crustal accretion occur through magma intrusion deep within the crust. These critical samples and data can only be recovered by deep scientific drilling of intact ocean crust.

Summary of scientific ocean drilling of the ocean basement, "Project Mohole" to IODP Expedition 335

In March–April 1961, the drilling barge *CUSS1* undertook the first scientific ocean drilling operation off Guadalupe Island, ~240 km west of Baja California (Mexico). This expedition, beautifully reported in *LIFE* magazine by the novelist John Steinbeck and the renowned science photographer Fritz Goro, was the first (and eventually only) concrete manifestation of Project Mohole. This project was a very ambitious endeavor proposed in the late 1950s by the American Miscellaneous Society (AMSOC), an informal group of notable US scientists, mostly geophysicists and oceanographers associated with the Office of Naval Research, including Harry Hess and Walter Munk. The principal aim was to drill through the oceanic crust, through the Mohorovicic discontinuity, and to retrieve samples from Earth's mantle. In his book *A Hole in the Bottom of the Sea*, Willard Bascom, Director of Project Mohole, records that the AMSOC elaborated on and initiated the project over a wine breakfast at Munk's La Jolla home in April

1957, following on from original ideas discussed by Walter Munk and Harry Hess (Bascom, 1961). Bascom also notes that probably the first written suggestion for a deep penetration down into the mantle was given by Frank Estabrook, an astrophysicist from the Basic Research branch of the US Army in Pasadena (California, USA) in a letter "Geophysical Research Shaft" published in *Science* in 1956 (Estabrook, 1956).

IODP Expedition 335, the fourth expedition of the "Superfast" campaign to core an intact section of ultrafast-spread oceanic crust, coincided with the fiftieth anniversary of the drilling expedition in 1961 (Teagle and Ildefonse, 2011). The US National Academy of Science has launched a web page to commemorate the innovative accomplishments of Project Mohole (**www.nationalacademies.org/mohole.html**). These accomplishments include the invention of dynamic positioning, the drilling guide horn, and deepwater drill hole reentry—all conceived and accomplished years before the offshore petroleum industry ventured into the open ocean. The drilling expedition in 1961 cored for the first time seismic Layer 2 and demonstrated with core that the uppermost ocean crust was made up of basaltic lavas. This achievement received a personal letter of congratulations from President Kennedy. Unfortunately, following divorce from the original scientific architects and vast cost overruns, Project Mohole progressively lost momentum with no further drilling accomplished, resulting in the ignominious termination of the project by the US Congress in 1965 (Shor, 1985; Greenberg, 1974). Despite often being recounted as a major geopolitical fiasco, this project has had an enduring impact on the Earth sciences by demonstrating that drilling in the deep ocean was technically feasible. This coincided with the formulation and growing acceptance of plate tectonic theory and recognition of the high-resolution geological records and key roles played by the oceanic crust and overlying sediments in major Earth cycles. Project Mohole's direct offspring was the pioneering Deep Sea Drilling Project (DSDP) that initiated more than 40 years of international collaboration for scientific ocean drilling.

Since the start of DSDP in 1968, oceanic basement has been drilled in a range of geodynamic settings, and a compilation of holes into the ocean crust cored by scientific ocean drilling since the beginning of DSDP is presented in Table **T1** and Figures **F5** and **F6.** This compilation does not include other "hard rock" drill holes in oceanic plateaus, arc basement, hydrothermal mounds, or passive margins. Only 34 holes deeper than 100 m have been cored in oceanic crust since DSDP Leg 37 in 1974 (see Fig. **F6**). The recovered material represents <2% of the ~330 km of cores recovered to date by DSDP, ODP, and IODP. In spite of this relatively cursory sampling, scientific drilling has contributed significantly to advance knowledge of ocean crust architecture and mid-ocean-ridge accretion and hydrothermal processes (e.g., Alt et al., 1996; Teagle et al., 1998b; Dick et al., 2000, 2006; Ildefonse et al., 2007a, 2007c; Wilson et al., 2006; Blackman et al., 2011). Hole 504B, located on 6.9 Ma crust formed at an intermediate rate at the Costa Rica Rift (Fig. **F5**), remains the deepest hole (2111 mbsf) in all of scientific ocean drilling (Alt et al., 1996). This site was host to drilling and other experiments over eight DSDP and ODP legs and was the first hole to penetrate completely through the volcanic lava sequences and ~1 km into sheeted dikes. It remains a reference hole for hydrothermal alteration of the ocean crust (e.g., Alt et al., 1986a, 1986b) and the geological structure of seismic Layers 2A, 2B, and 2C (e.g., Carlson, 2011). Hole 504B is the only location where the seismic Layer 2/3 boundary has been sampled in situ (Detrick et al., 1994; Carlson, 2010). However, a complete, continuous section of intact, homogeneous fast-spread crust down to the cumulate gabbro layers has yet to be drilled and remains a first-order scientific target for ocean drilling for the ocean crust research community (e.g., Dick and Mével, 1996; Murray et al., 2002; Teagle et al., 2004, 2009; Ildefonse et al., 2007b, 2010a, 2010b; Ravelo et al., 2010; IODP Science Plan 2013–2023 **[campanian.iodp.org/NSP/iodp_sci_plan_broch.pdf]**). Recently, IODP Expedition 312 penetrated to the base of the sheeted dike complex and the uppermost gabbro in Hole 1256D, which was the first sampling of the transition to plutonic rocks in intact ocean crust (Teagle, Alt, Umino, Miyashita, Banerjee, Wilson, and the 309/312 Scientists, 2006; Wilson et al., 2006). Further deepening of Hole 1256D into cumulate gabbros was the primary sampling objective of Expedition 335.

Criteria for the siting of deep drill holes and considerations for achieving deep drilling objectives

Deep drilling into intact and rifted ocean crust has posed, and will continue to present, major technical and programmatic challenges to scientific ocean drilling. Only four holes, DSDP Hole 504B, ODP Holes 735B and 1256D, and IODP Hole U1309D (Figs. **F5, F6;** Table **T1**), have been cored deeper than 1 km into oceanic basement, and these penetrations are arguably the greatest technical achievements of scientific ocean drilling. All were “hard won” multi-expedition experiments. From the experiences of drilling these holes, there are important lessons to be learned for the siting, planning, and implementation of future deep drilling of the oceanic basement (Table T2). Other deep objectives may be targeted by future scientific ocean drilling (e.g., subvolcanic zones of large igneous provinces and arcs), for which these observations are also relevant. Here, we present a short review of deep drilling operations in the four >1 km basement holes penetrated by scientific ocean drilling, listed above. Although Holes 504B and 1256D drilled into intact ocean crust have been fraught with more drilling challenges than holes spudded directly into gabbro in oceanic core complexes (Holes 735B and U1309D), even those holes have proved troublesome to initiate (Hole U1309D) or maintain (Hole 735B).

Drilling deep holes in crustal hard rocks: tales of patience and perseverance

Difficulties encountered during Expedition 335 well illustrate the challenges faced by deep drilling of oceanic crust, especially while scientific ocean drilling operates in an expedition mode. On site at Hole 1256D, 93% of our time was spent on hole remediation and stabilization operations, with only 3–4 days spent coring (~4%). The interval cored eventually represents only ~4% of our initial depth objective for the time scheduled for Expedition 335. Several problems were encountered for the very first time in the history of scientific ocean drilling, and many lessons were learned or relearned (see detailed descriptions in **“Operations”** in the “Expedition 335 summary” chapter [Expedition 335 Scientists, 2012]). The main lesson is that patience and perseverance are required, and given that problems are always encountered, in some cases major problems, when drilling deep holes in intact crust, this must be taken into account at the program scheduling stage to achieve success in drilling deep in the ocean crust.

Here we summarize the operational challenges encountered during this expedition, together with past hard rock drilling experience and difficulties, in particular when drilling deep in intact oceanic crust. This section addresses one of the recommendations made at the MoHole workshop in Kanazawa, Japan, in June 2010 (Ildefonse et al., 2010a), which is to assess the past experience in scientific ocean crustal drilling for optimizing the engineering development and drilling operations for a future MoHole project. Although the various events that led to tool or pipe failure and equipment loss in various drill holes have been reported in past leg and expedition reports and partially assessed by ODP and IODP, there is no directly available self-consistent documentation of drilling challenges in deep ocean crustal boreholes. This section compiles the history of problematic and sometimes traumatic events in the four deepest holes drilled to date in the ocean crust.

Among the four boreholes deeper than 1000 m in basement (Table T1; Figs. F5, F6), two of them, Holes 504B and 1256D, were drilled in the Pacific Ocean crust and penetrated through the upper crustal lavas and into the underlying sheeted dike complex.

DSDP/ODP Hole 504B

Hole 504B is located in the eastern equatorial Pacific (1°13.611′N; 83°43.818′W; Fig. F7) and is the deepest hole (2111 mbsf) ever drilled by scientific ocean drilling programs since the launch of DSDP in 1968 (e.g., Becker et al., 1989; Alt et al., 1996). Operations in Hole 504B were carried out over eight legs (DSDP Legs 69, 70, 83, and 92 and ODP Legs 111, 137, 140, and 148) between 1979 and 1993 (only seven of these eight legs were coring legs; Leg 92 returned to Hole 504B for downhole logging operations). The detail of operations can be consulted in the Site 504 chapters of these eight leg reports (Cann, Langseth, Honnorez, Von Herzen, White, et al., 1983; Honnorez, Von Herzen, et al., 1983; Anderson, Honnorez, Becker, et al., 1985; Leinen, Rea, et al., 1986; Becker, Sakai, et al., 1988; Becker, Foss, et al., 1992; Dick, Erzinger, Stokking, et al., 1992; Alt, Kinoshita, Stokking, et al., 1993). The full suite of operations in Hole 504B is summarized in Table T3, and major perturbing events are reported in Figure F8. All together, the time spent in experiencing various hardware failures and subsequent remediation represents ~28% of the total time spent drilling, coring, logging, and sampling in Hole 504B (~205 days). During Leg 148, the coring bottom-hole assembly (BHA) became so thoroughly stuck at the bottom of the hole that it was necessary to sever the pipe. Subsequent operations recovered part of this material and milled much of the remainder, but the hole was abandoned with the coring bit, the float valve, and the lower support bearing remaining at the bottom (Alt, Kinoshita, Stokking, et al., 1993). It should be noted that because Leg 148 directly followed ODP Leg 147 to Hess Deep (Gillis, Mével, Allan, et al., 1993), during which significant equipment was consumed because of coring and fishing operations, Leg 148 sailed without the full complement of fishing and milling equipment, and new equipment, materials, and personnel needed to be sent from shore to try to resurrect the hole (e.g., a fishing expert and drilling jars/intensifiers). The scheduling of back-to-back, independent hard rock expeditions can put major stress on implementation organization resources.

ODP/IODP Hole 1256D

Hole 1256D is located in the Guatemala Basin on the Cocos plate, eastern Pacific (6°44.16′N; 91°56.06′W; Fig. F7), and is the only hole to date that reached the transition zone between the sheeted dike complex and the lower crustal gabbros in fast-spreading, intact ocean crust (Wilson et al., 2006). The first contact between dike and gabbros was recovered at 1406.5 mbsf on 13 December 2005 at 1400 h UTC. The detail of operations in Hole 1256D can be consulted in the Site 1256 chapters of the ODP Leg 206 *Initial Reports* volume (Wilson, Teagle, Acton, et al., 2003) and the Expedition 309/312 *Proceedings* volume (Teagle, Alt, Umino, Miyashita, Banerjee, Wilson, and the Expedition 309/312 Scientists, 2006). The full suite of operations in Hole 1256D is summarized in Table T4, and major perturbing events are reported in Figure F9. Most of our operation time during Expedition 335 (see "Operations" in the "Expedition 335 summary" chapter [Expedition 335 Scientists, 2012] for a detailed narrative) was used for (1) reopening the hole to the bottom and (2) cleaning the bottom of the hole after losing most of the first coring bit used. The three previous scientific ocean drilling expeditions required to build the upper crustal infrastructure for deep drilling and then advancing Hole 1256D to >1500 mbsf represent a significant investment for the ocean drilling community. Consequently, determined efforts have been made to resuscitate Hole 1256D and prepare and preserve it for future deepening during Expedition 335. The first problem was encountered in the 920–950 mbsf interval, where an obstruction encountered on the initial reentry prevented penetration to the bottom of the hole. Coring started 15.3 days after our first reentry in Hole 1256D. Our second major problem occurred shortly after that, when our first coring C9 bit disintegrated after cutting two cores. A long period of reaming and fishing continued until the end of the expedition, which concluded with logging operations, the retrieval of a final core (335-1256D-239R), and cementing activities to stabilize the hole for a future return to Hole 1256D.

Gabbro drilling at oceanic core complexes at slow-spreading ridges: Holes 735B and U1309D

The two other deep holes (Hole 735B at the Southwest Indian Ridge and Hole U1309D at the Mid-Atlantic Ridge) were drilled in gabbroic plutons in the footwall of oceanic core complexes in slow-spread crust. They were initiated in bare rock (with only a few meters of soft sediment for Hole U1309D). The uppermost 20 m of Hole U1309D was cased using a hammer-in-casing technique to provide a safe and viable reentry system for a deep hole. Hole U1309D was drilled over two back-to-back expeditions in 2005 (Blackman, Ildefonse, John, Ohara, Miller, MacLeod, and the Expedition 304/305 Scientists, 2006), whereas Hole 735B was drilled during two ODP legs 10 years apart (in 1987 and 1997; Robinson, Von Herzen, et al., 1989; Dick, Natland, Miller, et al., 1999). Both holes were drilled to their terminal depth (1508 and 1415.5 mbsf for Holes 735B and U1309D, respectively) without major trouble related to drilling or coring. Gabbro has been the easiest lithology to drill and core in oceanic crust so far.

In Hole U1309D the only major difficulty encountered was related to the installation of the casing using the hammer-in-casing technique (see Blackman, Ildefonse, John, Ohara, Miller, MacLeod, and the Expedition 304/305 Scientists, 2006, for further details regarding the casing operations). The casing operation succeeded in Hole U1309D after a failed first attempt (IODP Hole U1309C). However, the casing could not penetrate deeper than 20.5 mbsf, leaving 4.5 m standing above the seafloor. The reentry cone was deployed at that point, and coring operations proceeded without noticeable incident until the end of Expedition 305, with an average total recovery of ~75%. Hole U1309D remains open for potential reentry and future deepening. The minimum temperature at the bottom of the hole is 110°C (Blackman, Ildefonse, John, Ohara, Miller, MacLeod, and the Expedition 304/305 Scientists, 2006).

Hole 735B was similarly easy to drill, and the recovery at ~86% is the highest achieved in oceanic hard rocks to date. It is the second deepest hole in oceanic basement after Hole 504B (1836.5 m) and the deepest penetration into slow-spread crust. The only major incident that unfortunately resulted in losing the hole occurred 12 days before the end of Leg 176, a few hours after coring had resumed following ~1 day of interrupted operations due to bad weather conditions (see Dick, Natland, Miller, et al., 1999, for a detailed narrative of the incident). The drill string failed following contact with a ledge in the hole when the vessel heaved down during a pipe connection make-up, and the BHA and 1403 m of drill pipe were lost in the hole. The first fishing attempt retrieved 497 m of drill pipe; the hole was abandoned at the end of Leg 176 after a total of eight unsuccessful fishing attempts, alternated with several milling runs. A combination of bad weather and bad luck was, in this case, the cause of failure.

Hess Deep, ODP Leg 147: a tectonic window into fast-spread lower oceanic crust

Another historical record of hard rock drilling challenges and incidents is Leg 147 to Hess Deep in the eastern Pacific (Fig. F7) (Gillis, Mével, Allan, et al., 1993). The westward propagation of the tip of the Cocos-Nazca plate boundary into crust formed ~1 m.y. ago on the eastern side of the East Pacific Rise has resulted in the exposure of lower ocean crust and serpentinized upper mantle (e.g, Francheteau et al., 1992; Karson et al., 1992; Karson, 2002). This tectonic window provides an alternative approach to drilling through intact ocean crust (e.g., Holes 504B and 1256D), but to date drilling into Hess Deep gabbros and serpentinized peridotites has been very difficult to achieve, partly because of the very rugged topography and complex tectonic settings, resulting in boreholes probably intersecting numerous fault zones. A series of problems was encountered at the two sites, including difficulties to set up a three-legged hard rock base (HRB) designed for handling slopes as steep as 35°, hole deviation, and lost BHAs (see Gillis, Mével, Allan, et al., 1993, for a complete narrative of these events).

Drilling young unsedimented lavas

Drilling young basalt has also proved very difficult, especially when holes are spudded directly into bare rocks. All basaltic holes reported in Table T1 and Figure F6 were drilled in areas with a significant sediment cover that assists in the initiation, stabilization, and progress of the boreholes. Drilling in zero-age basaltic crust during DSDP (Leg 54) and ODP (Leg 142) at the East Pacific Rise was unsuccessful (Rosendahl, Hekinian, et al., 1980; Storms, Batiza, et al., 1993). More recent attempts have also had relatively limited success, recovering at best a few tens of centimeters before the holes had to be abandoned, such as at several sites attempted during Leg 209 at the Mid-Atlantic Ridge in the 15°20′ Fracture Zone area (Kelemen, Kikawa, Miller, et al., 2004). Initiating and progressing a hole deeper than ~20 m (with very poor recovery) in the young basaltic hanging wall of the Atlantis Massif Core Complex also failed in spite of 11.5 days of continuous efforts, despite using the hard rock reentry system and rotary core barrel (RCB) coring successfully deployed to drill into gabbros during the same expedition (Expedition 304/305; Blackman, Ildefonse, John, Ohara, Miller, MacLeod, and the Expedition 304/305 Scientists, 2006).

Considerations for the location of scientific wells with deep objectives

Location

Although the overriding justification for the siting of drill holes must be scientific grounds, there is no doubt that geographic location plays a major role in the successful scheduling of operations at sites that require multiple visits to accomplish objectives. The proximity of a site only a few days steaming from a major port where resupply can occur greatly reduces expensive and fuel-consuming transit days and provides maximum operational days on site. This siting also reduces transport distances for equipment dispatch should unanticipated drilling situations occur (e.g., the dispatch of drilling jars/intensifiers and a specialist engineer to Hole 504B during Leg 148; Alt, Kinoshita, Stokking, et al., 1993) (Table T3). Proximity to shipping routes frequently transited by the drillship (e.g., the Panama Canal) facilitates repeated scheduling at higher frequencies than more remote locations. A benign 12 month weather window allows maximum flexibility for the scheduling of return visits and the efficient arrangement of expeditions to locations with more restricted weather conditions.

Sediment cover

Presently there is no effective technology to routinely initiate deep (or even shallow) holes in volcanic rocks directly exposed at the seafloor (e.g., Legs 54 and 142 and Expedition 304; see **"Drilling young unsedimented lavas"**). Even a small amount of sediment greatly stabilizes the drill bit and assists in the initiation of drilling (e.g., ODP Leg 187 and IODP Expedition 329). Deep drilling of volcanic and deeper rocks of the oceanic basement requires the installation of a reentry cone and subsurface casing, but presently this infrastructure can only be set successfully in volcanic rocks where there is thick sedimentary cover. The installation of a reentry cone has not been successfully attempted in a bare rock environment, with the exception of Hole U1309D in gabbroic basement (see **"Gabbro drilling at oceanic core complexes at slow-spreading ridges: Holes 735B and U1309D"**). This lack of success has led to a bias toward operations in regions of anomalously thick sediment cover, such as crust formed in the equatorial high-productively zone (±1° of the Equator; e.g., DSDP Holes 504B and 896A and ODP Hole 1256D), on ocean crust very close to the continental margin (e.g., Juan de Fuca Ridge, ODP Leg 168 and

IODP Expeditions 301 and 327), or in very old crust (e.g., DSDP Holes 417D and 418A and ODP Hole 801C; Donelly, Francheteau, Bryan, Robinson, Flower, Salisbury, et al., 1980; Lancelot, Larson, et al., 1990; Plank, Ludden, Escutia, et al., 2000). The deepest hole spudded into bare volcanic rock is only 50 m deep, and drilling was fraught with equipment failure and poor hole conditions (ODP Hole 648B, Mid-Atlantic Ridge; Detrick, Honnorez, Bryan, Juteau, et al., 1988). Generally at least 100 m of sedimentary overburden is required to mount a reentry cone supported by 20 inch casing, the minimum upper hole infrastructure recommended for deep drilling (e.g., Hole 1256D).

Seismic velocities and alteration

Young lavas are highly fractured, and it has proven difficult to initiate, maintain, and progress drill holes in young volcanic rocks. At the ridge axis, lava commonly flows beneath a thin, brittle carapace of quenched magma. These fragile surfaces collapse beneath subsequent lava flows, resulting in layers of poorly consolidated volcanic materials (e.g., Gregg and Fink, 1995; Gregg and Chadwick, 1996; Umino et al., 2000). Even more massive flows tend to have rubbly flow tops composed of glassy material that makes up substantial portions of the flows. Low-temperature hydrothermal alteration that occurs on the ridge flanks for millions of years leads to the precipitation of clays, principally Mg saponite, and other secondary minerals (e.g., celadonite, minor iron oxyhydroxides, calcium carbonate, and zeolites; Alt et al., 1986a) that replace mesostasis, fill fractures, and form breccia cements. Secondary mineral precipitation provides greater cohesion within the lava pile. This cohesion is reflected at a regional scale by increased seismic *P*-wave velocities (e.g., Carlson, 1998; Christeson et al., 2007) compared to younger crust closer to the spreading axis. However, these secondary minerals provide only weak bonding to fractured rocks. At any particular crustal age or region, relatively high seismic velocities probably reflect thicker or a greater abundance of massive lava flows relative to sheet flows, pillow lavas, or hyaloclastites. These latter lava morphologies are likely to be more highly fractured and include greater proportions of voids that present drilling hazards. Targeting areas with relatively higher seismic velocities will increase the probability of encountering stable formations in the uppermost basement, greatly increasing the chances of initiating a stable deep borehole, as demonstrated by the siting of Hole 1256D. However, drilling only more massive lavas may lead to a bias against more permeable and more altered oceanic crust, underestimation of hydrothermal exchanges between the oceanic crust and seawater, and overestimation of in situ physical properties (e.g., discrete sample *P*-wave velocities).

Age-depth-temperature

For crust in all oceans, ocean depth and conductive heat flow are inversely proportional to the square root of the age of the ocean crust (e.g., Lister, 1972). Although older ocean crust is cooler at depth and lower basement temperatures should improve drilling and wireline tool performance, targets will be significantly deeper, increasing pipe trip and wireline times. Water depth and the total target depth are important considerations for the siting of a future riser drilling approach to core beyond the Moho and to a significant distance (hundreds of meters) into the upper mantle (e.g., Ildefonse et al., 2007b, 2010a, 2010b). Plans are being formulated for the development of an ultra-deepwater riser capability for the D/V *Chikyu*, but these enhanced capabilities are unlikely to be developed beyond ~4000 m water depth.

There is a discernible conductive heat flow anomaly out to ~65 m.y., indicating that the transport of heat by low-temperature hydrothermal circulation of seawater-derived fluids becomes on average negligible beyond this age (e.g., Stein and Stein, 1994). However, in individual regions, hydrothermal flow occurs wherever hydrological gradients can be established because of basement topography, variable sediment cover, or seamounts that penetrate the sediment overburden and provide pathways for the ingress of seawater and egress of basement fluids (e.g., Wheat and Fisher, 2008; Von Herzen, 2004). Whether this fluid flow is always accompanied by significant chemical reaction or microbial stimulus is as yet unconstrained. Dating of secondary minerals formed by low-temperature hydrothermal alteration remains challenging (e.g., Waggoner, 1993), but assessment of basement calcium carbonate veins, generally one of the latest phases to form, suggests that effective chemical exchange is complete within a few tens of millions of years of crustal formation (e.g., Coggon et al., 2010). There have been major changes in ocean chemistry since the Cretaceous and through the Tertiary (e.g., Stanley and Hardie, 1998; Lowenstein et al., 2001; Horita et al., 2002; Coggon et al., 2010). Hence ocean crust formed in the Cretaceous was altered in very different thermal and chemical (and biological?) regimes compared to the modern ocean (e.g., Alt and Teagle, 1999). To understand the role of ocean crustal formation and hydrothermal circulation in the global geochemical cycles of modern Earth, it would be sensible to target ocean crust formed in the past 20 to 30 m.y.

Program considerations for the attainment of deep targets by scientific ocean drilling

Establishing the ideal location for drilling is only part of the challenge of successfully drilling moderately deep holes (2–3 km) to recover the samples and data necessary to address long-standing primary goals of scientific ocean drilling. Experience from Holes 504B and 1256D indicates that such experiments require multiple expeditions to achieve their target depths. A total of ~500 m penetration per expedition is an upper limit for coring in the upper crust, with lesser advances and more frequent drilling challenges as these holes get deeper and rocks metamorphosed at higher pressures and temperatures are encountered (Figs. **F8, F9, F10;** Tables **T1, T3, T4**). Penetration and core recovery rates have been low to very low in the two sheeted dike complex sections drilled to date (Holes 504B and 1256D). Average rates of recovery and penetration in the dike section of Hole 1256D are 32% and 0.8 m/h, respectively. The average rate of recovery in the sheeted dike complex of Hole 504B was a miserly 11%. However, experience to date suggests that gabbroic rocks can be cored relatively rapidly at high rates of recovery (e.g., Hole U1309D: penetration rate = 2 m/h; recovery ≥75%), so when the dike–gabbro transition zone is breached, solid progress through the plutonic section can be anticipated.

Long uncased sections through lava flows can result in major problems with wall stability and clearing of drill cuttings as boreholes get deeper. Lava sections are commonly strongly enlarged and out of gauge (>20 inches) for long intervals because of continued spalling of fractured material from the borehole walls. Borehole wall damage is exacerbated by multiple passes of the drill string because of the numerous pipe trips needed to drill a deep hole (e.g., 93 reentries in Hole 504B and 62 reentries in Hole 1256D as of the end of Expedition 335; Tables **T3, T4**). Hole intervals with large diameters (>12 inches) greatly reduce the efficiency of high-viscosity mud sweeps to clear deep holes of fine cuttings. The hydraulic horsepower of the lifting fluid is reduced because of velocity decreases and fluid turbulence when mud sweeps leave regions of in-gauge hole and enter more cavernous zones. Hole enlargements also provide cavities where cuttings not swept from the hole can temporarily collect and subsequently become continuously recycled within the borehole.

Although Hole 1256D was established with the infrastructure to install two more casing strings (13⅜ inches and 10¾ inches) within the 16 inch casing that was cemented into basement, drilling during ODP Leg 206 and IODP Expedition 309 proceeded quickly in the upper crust without an apparent need to case the lava sequences to maintain hole stability. However, as Hole 1256D has been drilled deeper, clearing cuttings from the hole to keep the drill bit clear of debris has become increasingly difficult. Large amounts of coarse-grained basaltic sand were recovered in the fishing tools and the BHA during three consecutive fishing runs while trying to retrieve the broken bit during Expedition 335 (see **"Operations"** in the "Expedition 335 summary" chapter [Expedition 335 Scientists, 2012]), attesting to the accumulation of cuttings in the hole.

Scientific ocean drilling has little experience in casing long sequences (hundreds of meters) of oceanic basement and a poor armory of underreaming tools for opening hard rock basement holes to the diameters required for the insertion of a casing. For example, the insertion of 13⅜ inch casing requires reaming an 18½ inch hole beneath 16 inch casing. Casing hundreds of meters of a deep borehole in igneous basement would be a high risk, costly, and ship-time consuming operation that would produce no new scientific output until completed and drilling was resumed. However, it would greatly improve the stability and hydrodynamics of deep basement boreholes. A regular drilling-then-casing approach to investigate the lower oceanic crust (target depth = 2–3 km) will require a long-term commitment by the scientific ocean drilling community to a particular site and experiment and as many as 10 expeditions to complete. The possibility that even such a highly engineered approach could still fail to reach its target would have to be acknowledged and accepted by the community. The development of untethered casing sleeves or targeted wall rock cementing (as tested for the first time during Expedition 335) are options that should be considered. Such approaches might be effective at securing unstable formations and more palatable to a multidisciplinary program with competing science drivers and constant assessment of the outputs. Nevertheless, the potentially transformative science that could be yielded by a deep borehole through the upper crust and down into cumulate gabbro is going to require long-term commitment and investment in time on site, as well as technology and external expertise (e.g., consultant drilling engineers and casing, fishing, cementing, and hardware experts).

It is very unlikely that without significant good fortune deep targets in intact ocean crust can be achieved in the current science advisory configuration. The peer-review system that has overseen the progress of both Holes 504B and 1256D has required the reevaluation of new proposals following the successful completion of each drilling increment. A system similar to the "complex drilling proposals" used for riser experiments must be extended to riserless targets that require multiple expeditions to achieve important scientific goals.

Such is the capriciousness of hard rock coring that scientific ocean drilling may have to consider new approaches if it is to ever successfully address some of the major science questions that remain unanswered after more than 50 years. There are unlikely to ever be "quick wins" with targets that require multiexpedition deep boreholes. Expedition 335 was initially scheduled by the IODP-MI Operation Task Force as a short cruise (~4 weeks), despite the explicit recommendations of the postexpedition 309/312 Operational Review Task Force "to maximize on-site time for deep drilling expeditions" (Recommendation 309/312-03; see 309_312_ORTF.PDF in REPORTS in **"Supplementary material"**). Flexibility in expedition scheduling may be a low-impact means to achieve deep objectives. Back-to-back expeditions to a single target could be scheduled. This approach was successful at drilling Hole U1309D deeper than 1400 mbsf during Expeditions 304 and 305. Commonly, the ship has been moved off a deep hole after the significant investment in engineering and cleaning operations that have succeeded in preparing the hole for deep drilling. For example, Expedition 312 drilled >100 m of the dike–plutonic transition zone in Hole 1256D following significant hole remediation operations but left an open clean deep hole. Five years later, most of Expedition 335 scheduled time was spent on hole remediation. Mechanisms are needed for revising expedition schedules so that drilling can continue in deep boreholes when progress is actually being made. This would require the movement of crew, scientists, and supplies to and from the rig so that drilling and hole cleaning can continue, as well as the temporary postponement of the immediately following expeditions. Clearly, this would be a major departure from the standard operating style of the *JOIDES Resolution* within ODP and IODP and a challenge to the science advisory and scheduling structure. It would require community acceptance that could be difficult to achieve. However, the present standard "1 proposal = 1 expedition" approach is not an effective process to reach targets that require multiple expedition deep drilling. Unless the community and the drilling program are able to develop new approaches to achieving deep targets, the lack of closure on science questions that can only be addressed by deep drilling will continue to stain future renewal documents with a perceived lingering staleness due to a continued recycling of unaccomplished goals.

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Figure F1. Distribution of spreading rates for major active plate boundaries, presented (**A**) in histogram form and (**B**) as cumulative distribution. Rates are the best-fit rates of the MORVEL model (DeMets et al., 2010), and ridge length is measured as the component perpendicular to spreading direction. Horizontal lines on the cumulative plot show the range of spreading rate for each plate pair, with line width scaled approximately to plate boundary length. Plate-pair labels follow the MORVEL (mid-ocean ridge velocities) convention, except in the Indian Ocean where the southeast, southwest, and northwest branches of the ridge system are grouped for 2–3 plate pairs to simplify labeling. NB = Nubia plate, SA = South America plate, NZ = Nazca plate, PA = Pacific plate, NA = North America plate, CO = Cocos plate, EU = Eurasian plate, SWIR = Southwest Indian Ridge, SEIR = Southeast Indian Ridge, AN = Antarctic plate, AR = Arabia plate, SM = Somalia plate, RI = Rivera plate, NWIR = Northwest Indian Ridge, JF = Juan de Fuca plate.

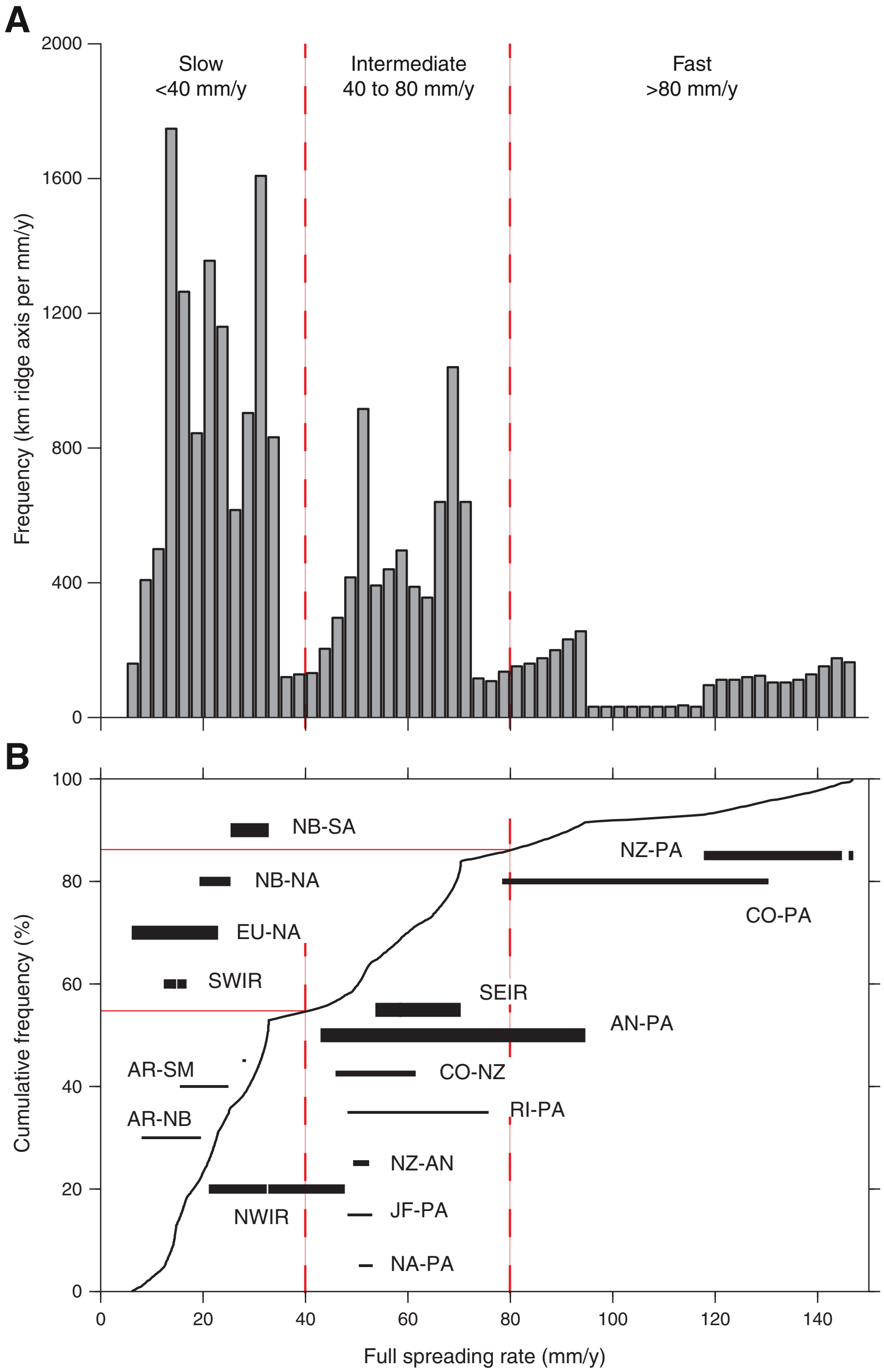

Figure F2. **A.** Global view of ocean crust colored by spreading rate at time of formation, based on age and spreading rate grids by Müller et al. (2008), revised version 3 (www.earthbyte.org/). **B.** Histogram comparing the proportions of the present-day ocean crust that formed at slow, intermediate, and fast spreading rates, based on the rate grid plotted in A. Tabulation includes variation of grid-cell area with latitude. Labeled spreading rates are twice the half rate for comparison with full rates.

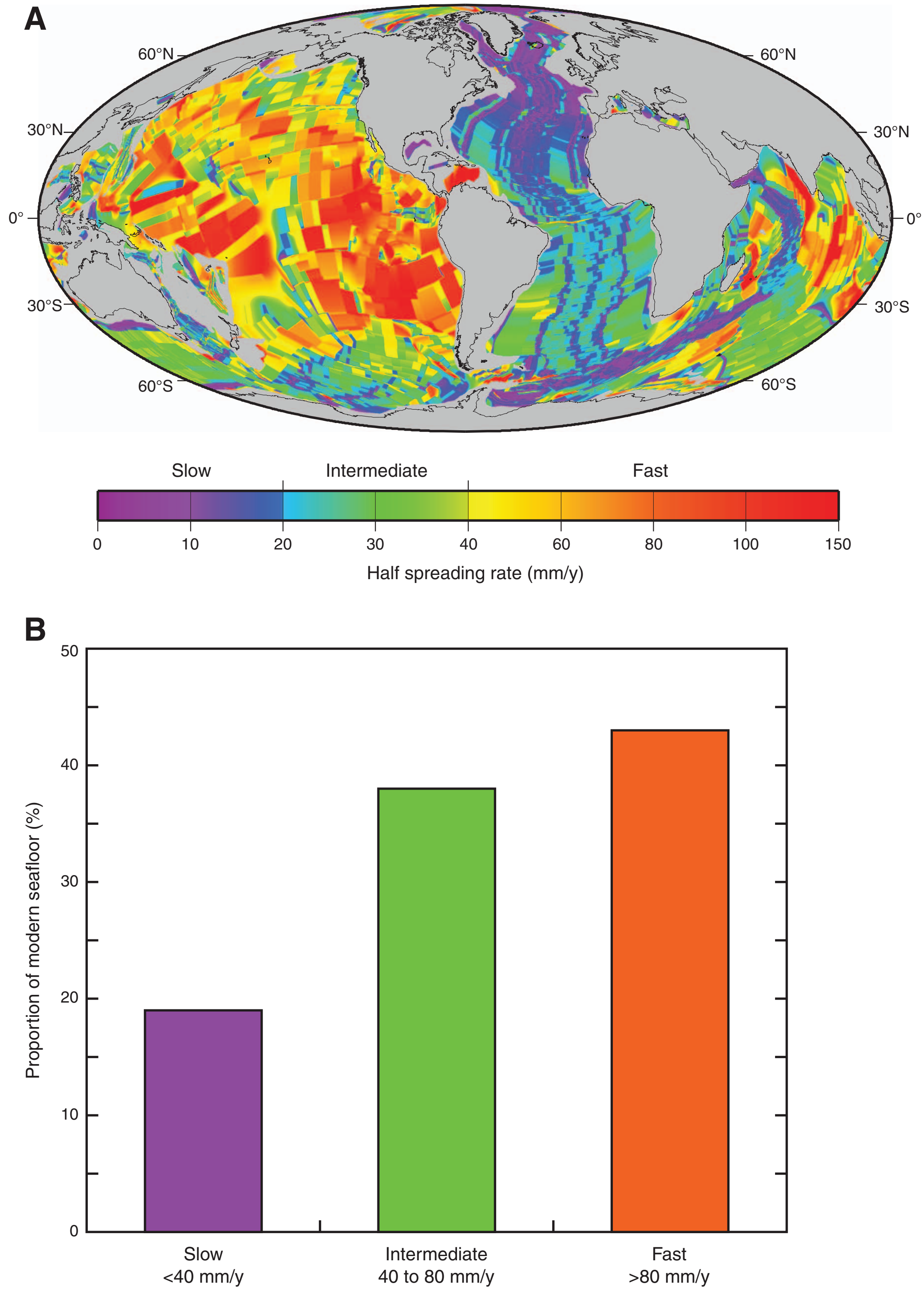

Figure F3. A. Contour map of seismic *P*-wave velocity at the top of basement in the Site 1256 area, based on tomographic inversion of seismic refraction data (A.J. Harding, pers. comm., 2005). The low-velocity area west of the center may reflect pillow lavas or other porous formation. The high-velocity area extending southeast from Site 1256 may reflect the extent of the ponded lava sequence drilled at the top of Site 1256. OBH = ocean bottom hydrophone. **B.** Geological sketch map of the Site 1256 area (GUATB-03) showing bathymetry, alternate site locations, and selected top-of-basement velocity contours from A. The larger velocity contour line partially encloses velocity >4.82 km/s, which we interpret as a plausible proxy for the presence of thick ponded lava flows, as encountered at Site 1256. The smaller contour encloses velocities <4.60 km/s, possibly reflecting a greater portion of pillow lavas than elsewhere in the region. Alternate reentry Sites 3D and 3E are 0.5–1.0 km from Site 1256 and are not shown in the figure. MCS = multichannel seismic.

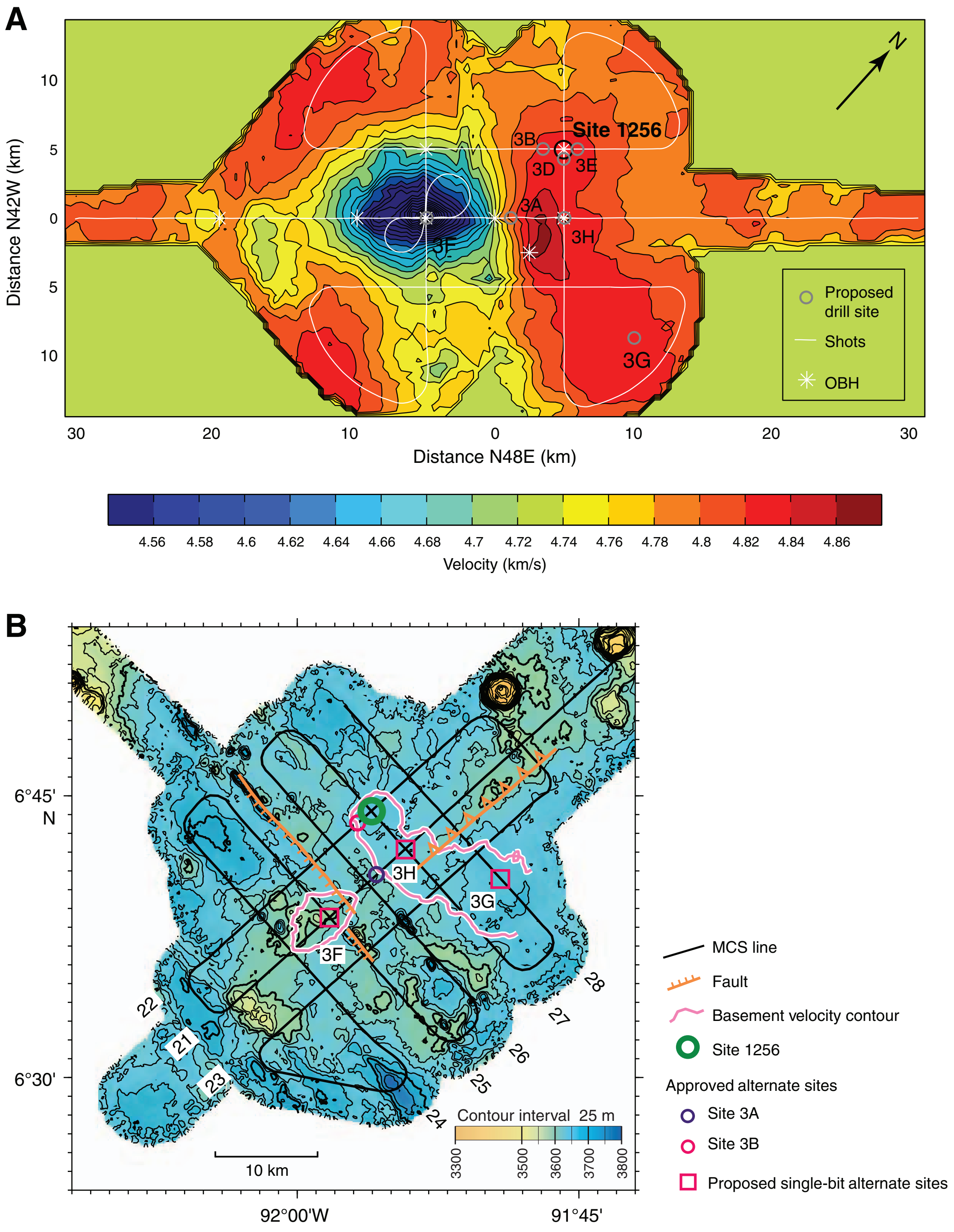

Figure F4. Schematic drawings of crustal accretion models (modified from Korenaga and Kelemen, 1997). Black arrows show the movement of the solid lower crust; blue arrows show the dominant zones where hydrothermal circulation will remove latent and sensible heat; red arrows show the movement of magma—this is unknown in all models. **A.** Gabbro glacier ductile flow model (e.g., Henstock et al., 1993; Phipps Morgan and Chen, 1993; Quick and Denlinger, 1993). Ductile flow down and outward from a high-level axial magma chamber constructs the lower crust. **B.** Hybrid model of ductile flow with sill intrusions (e.g., Boudier et al., 1996). **C.** "Sheeted" or "stacked" sill model of in situ formation of the lower crust by on-axis sill intrusions (e.g., Bédard et al., 1988; Kelemen and Aharonov, 1998; Kelemen et al., 1997; MacLeod and Yoauancq, 2000). **D.** Schematic relative variations in the general trends of latent heat release, bulk Mg#, strain rate, cooling rate, hydrothermal fluid flux, fluid temperature, and intensity of high-temperature (HT) alteration with depth predicted by end-member "gabbro glacier" (with mainly conductive cooling of the lower crust) and "sheeted sill" (with convective cooling of the lower crust) models of crustal accretion (original figure by R. Coggon).

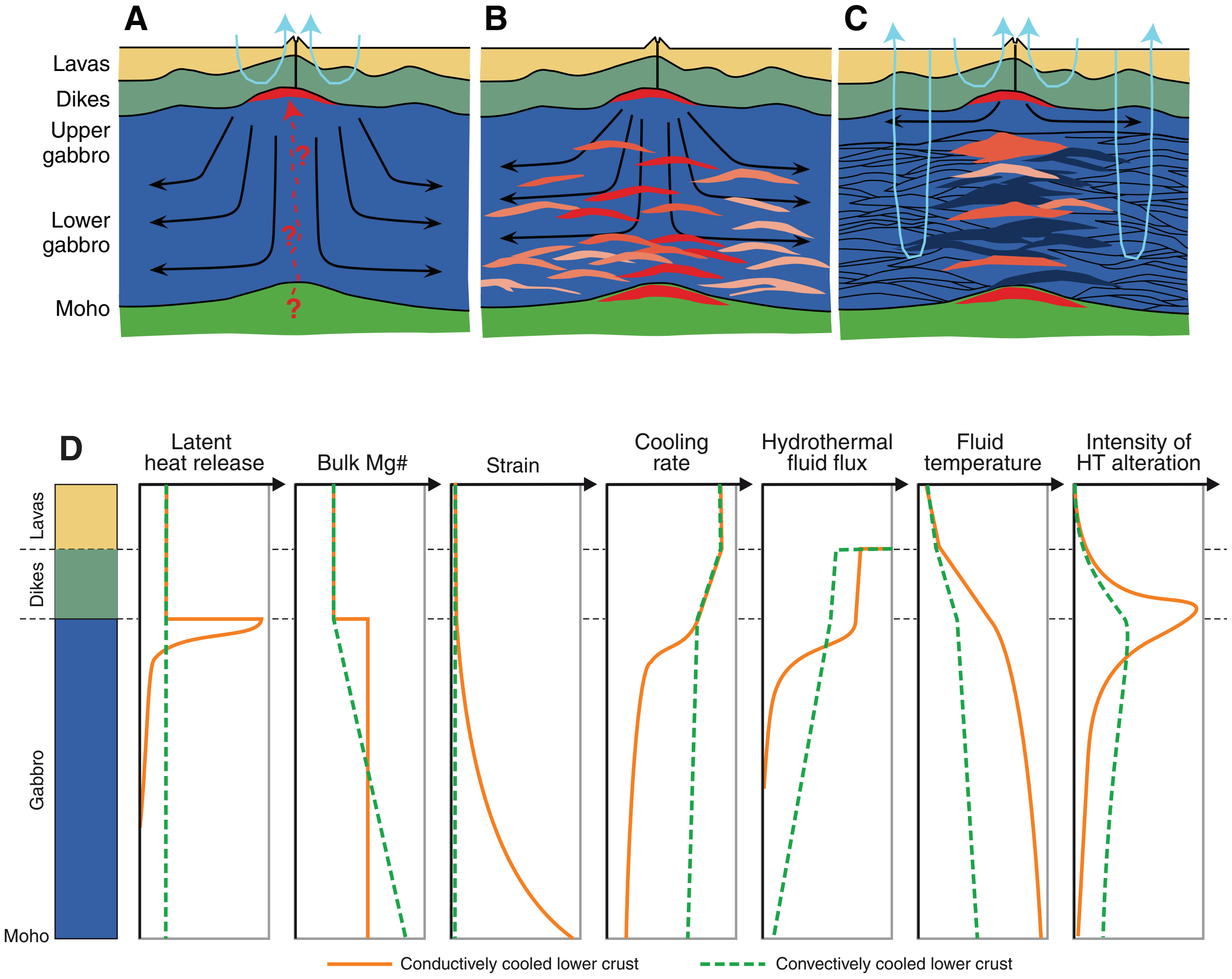

Figure F5. Map of ocean floor age, based on age grid by Müller et al. (2008), revised version 3 (**www.earthbyte.org/**). Symbols represent DSDP, ODP, and IODP holes drilled in ocean crust >100 mbsf from 1974 to 2011. Holes deeper than 500 m in intact and rifted oceanic crust are labeled. This map does not include "hard rock" drill holes in oceanic plateaus, arc basement, hydrothermal mounds, or passive margins.

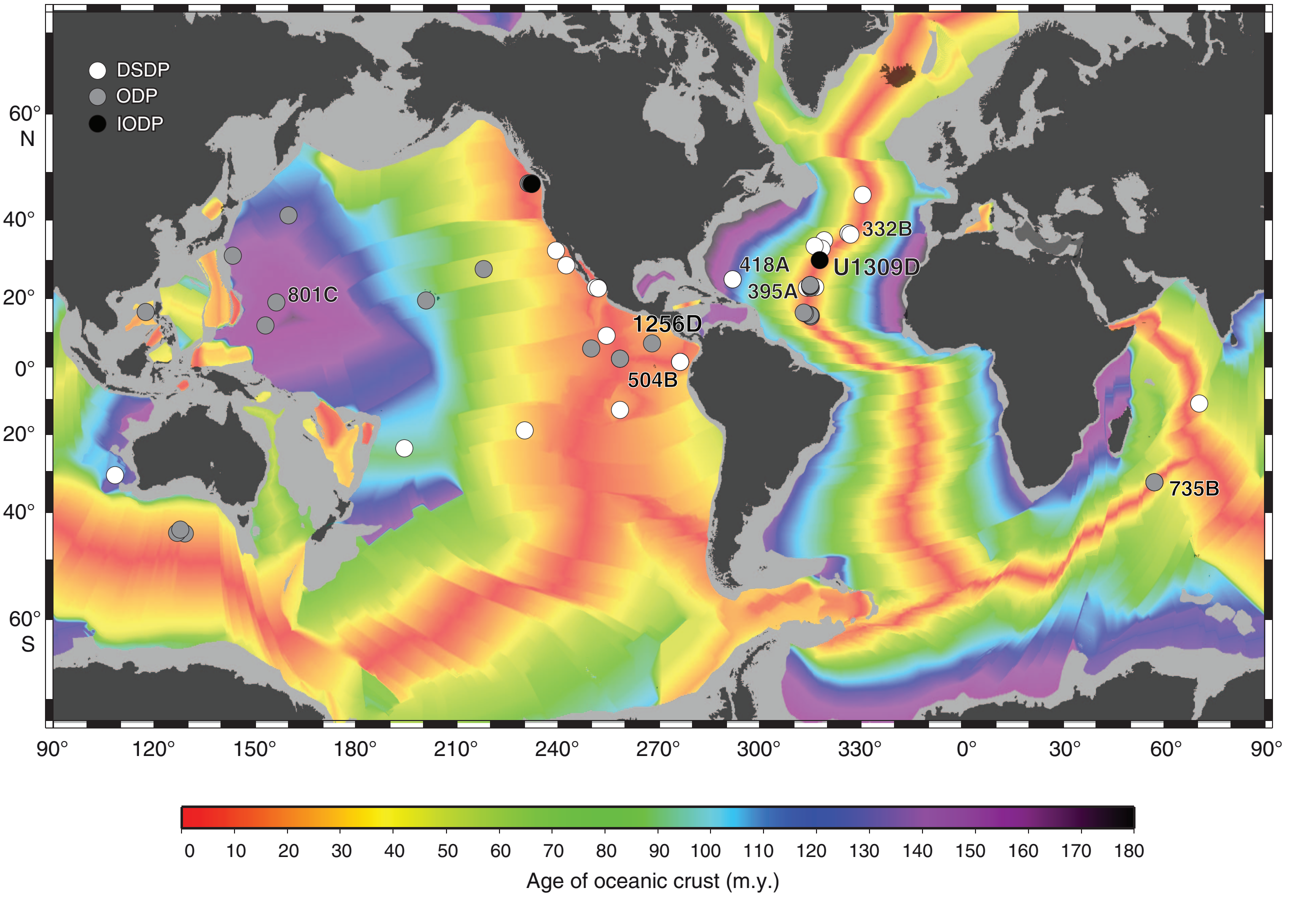

Figure F6. Compilation chart showing holes drilled >100 m in intact crust and tectonically exposed lower crust and upper mantle from 1974 to 2010 (drill hole locations in Fig. F5). For each hole are indicated the hole number and the recovery (in percent) for each lithology. This compilation does not include "hard rock" drill holes in oceanic plateaus, arc basement, hydrothermal mounds, or passive margins.

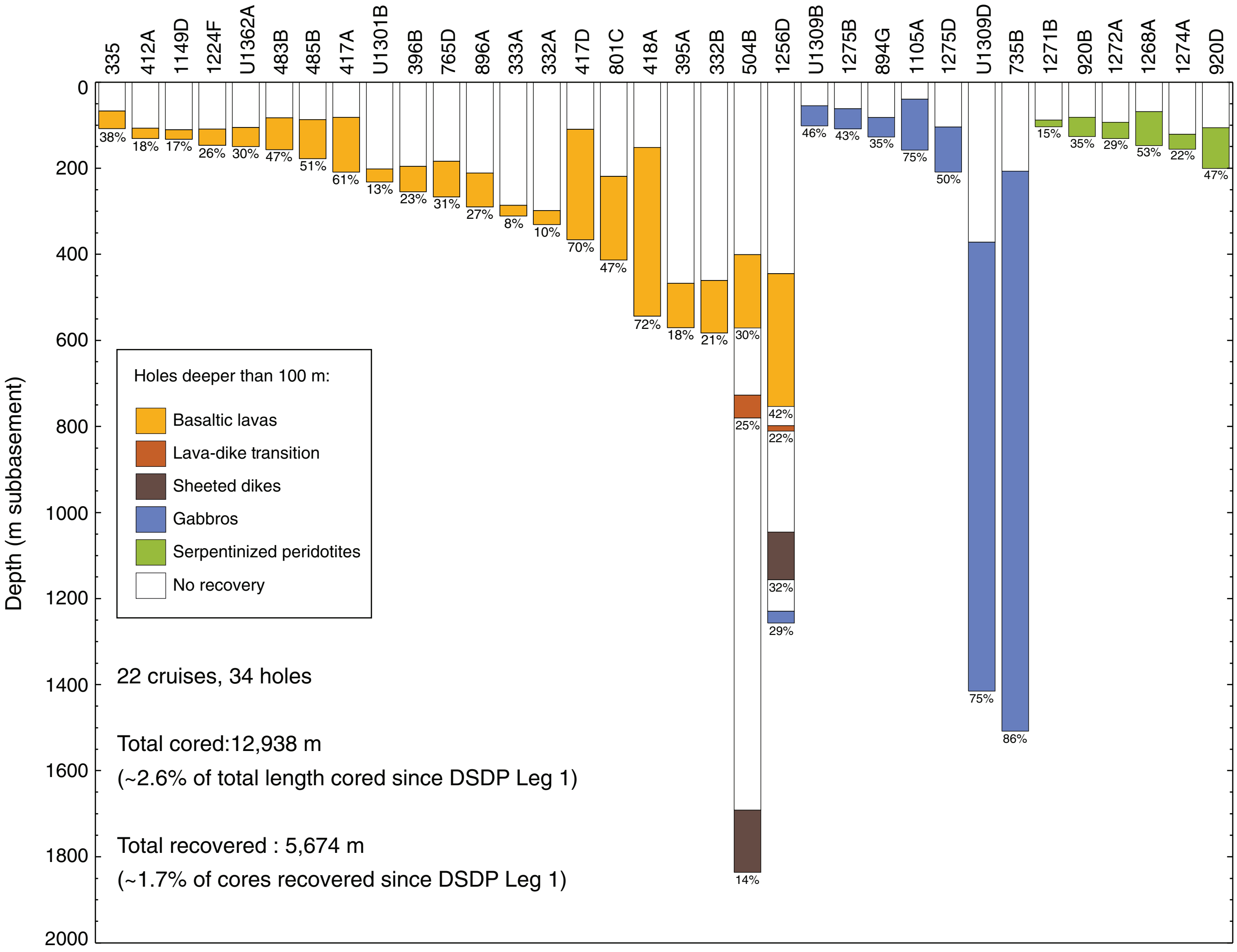

Figure F7. Age map of the Cocos plate and corresponding regions of the Pacific and Nazca plates. Isochrons at 5 m.y. intervals have been converted from magnetic anomaly identifications according to the timescale of Cande and Kent (1995). Selected DSDP and ODP sites that reached basement are indicated by circles. The wide spacing of the 10 to 20 Ma isochrons to the south reflects the extremely fast (200–220 mm/y) full spreading rate. FZ = fracture zone.

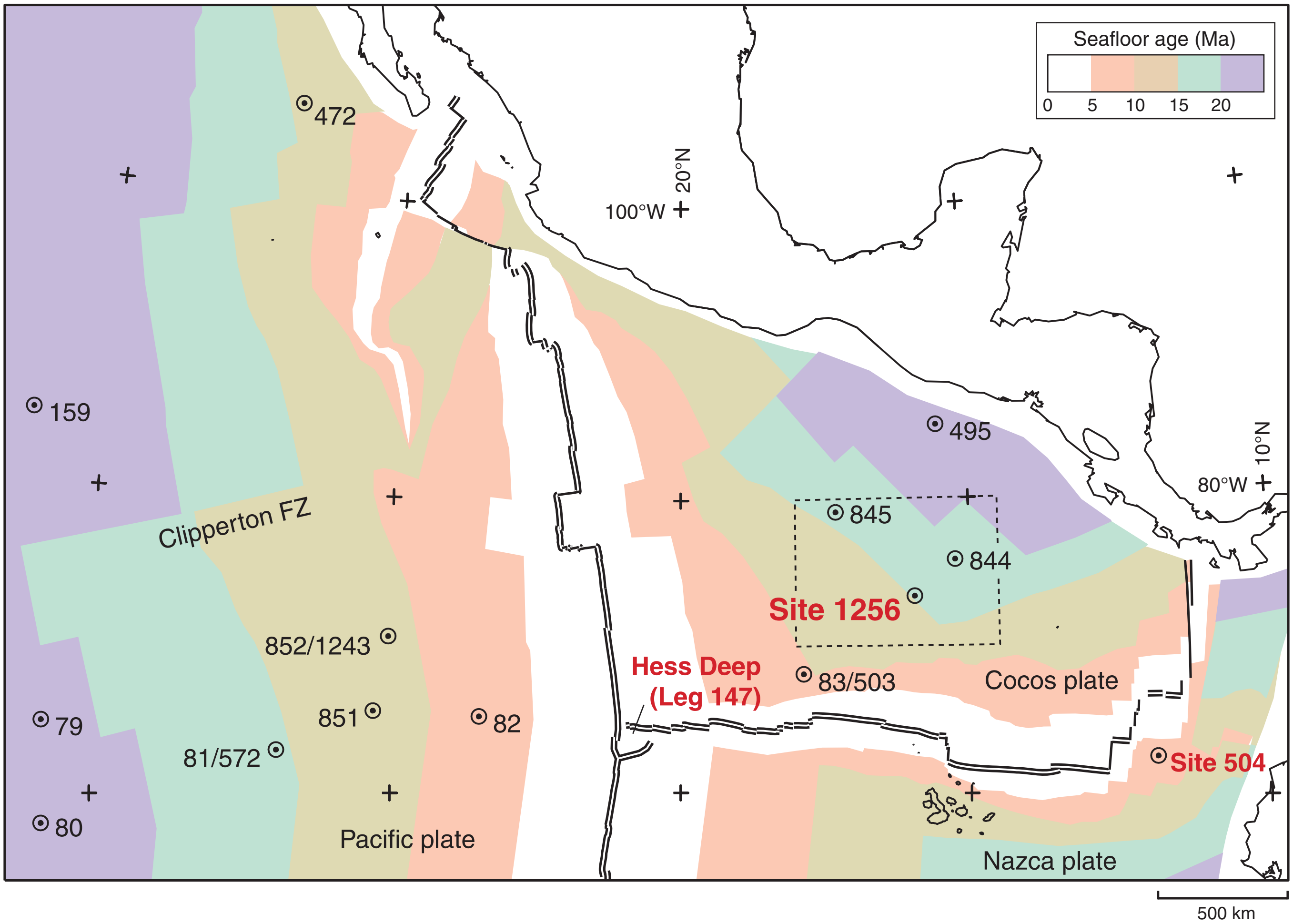

Figure F8. Time vs. depth plot for Hole 504B. Width of colored bars is proportional to the duration of DSDP and ODP legs. Major hardware failure and remediation events are reported at the depth to which they occurred. Pie charts indicate, at the end of each cruise, cumulative proportions of time spent in casing, logging, coring, and tool breaking/hole remediation since the start of operations in Hole 504B. BHA = bottom-hole assembly, FMS = Formation MicroScanner.

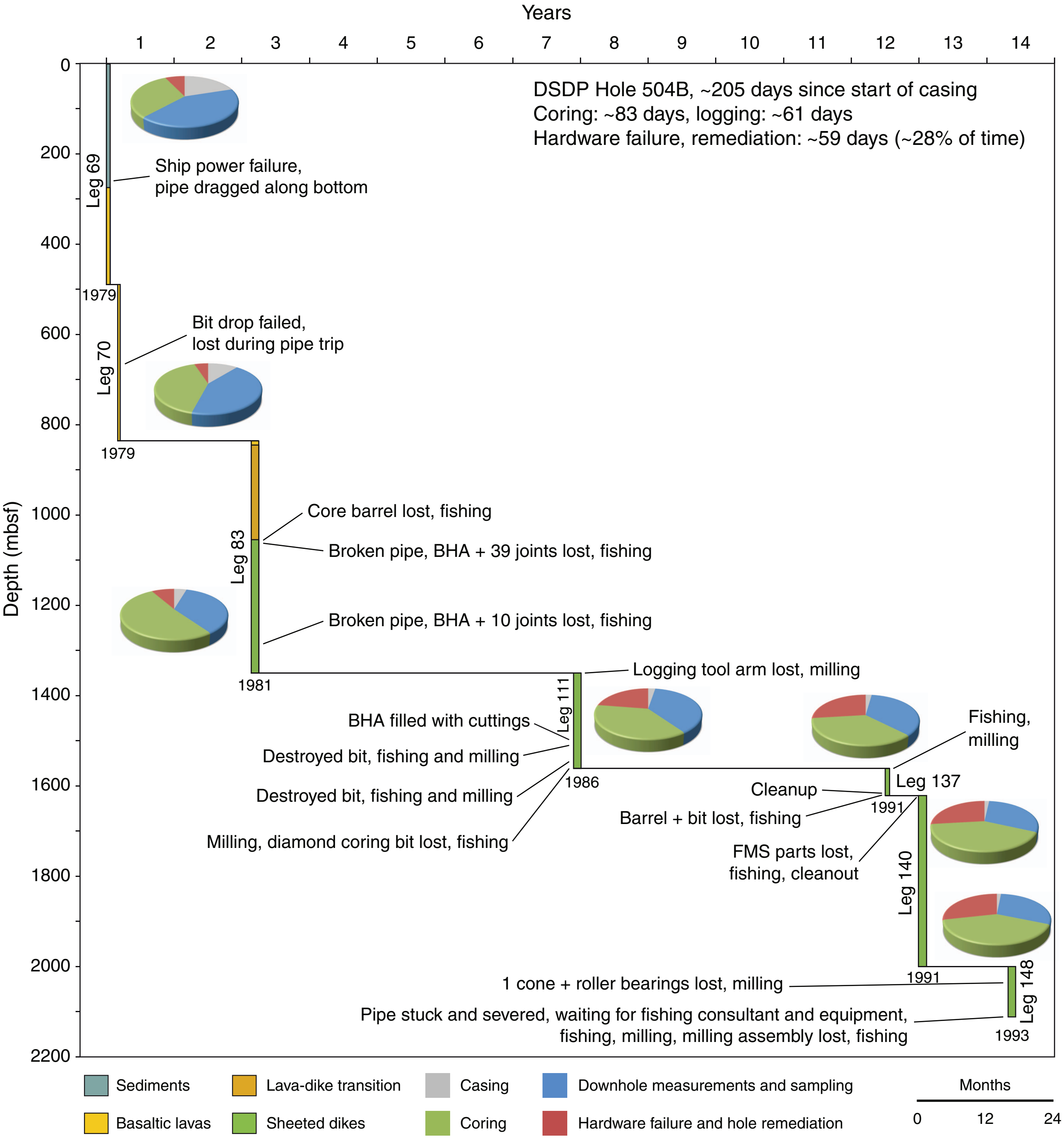

Figure F9. Time vs. depth plot for Hole 1256D. Width of colored bars is proportional to the duration of ODP legs and IODP expeditions. Major hardware failure and remediation events are reported at the depth to which they occurred. Pie charts indicate, at the end of each cruise, cumulative proportions of time spent in casing, logging, coring, and tool breaking/hole remediation and stabilization since the start of operations in Hole 1256D. BHA = bottom-hole assembly, FMS = Formation MicroScanner.

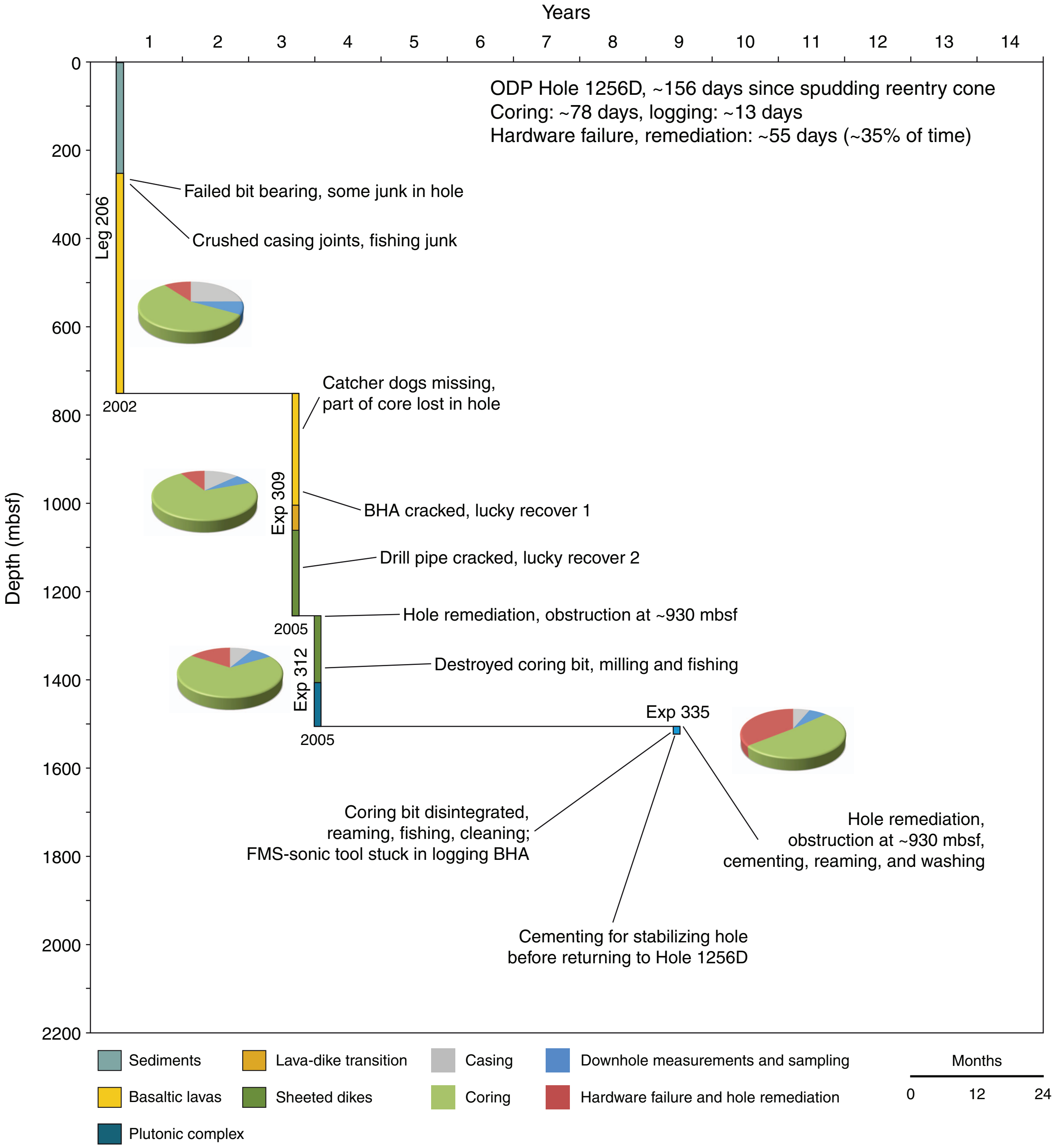

Figure F10. Plot showing the progressive deepening of Holes 504B and 1256D over eight and four scientific ocean drilling expeditions, respectively. Colored bars show the subdivision of time on site into casing, coring, downhole logging, and hole remediation activities.

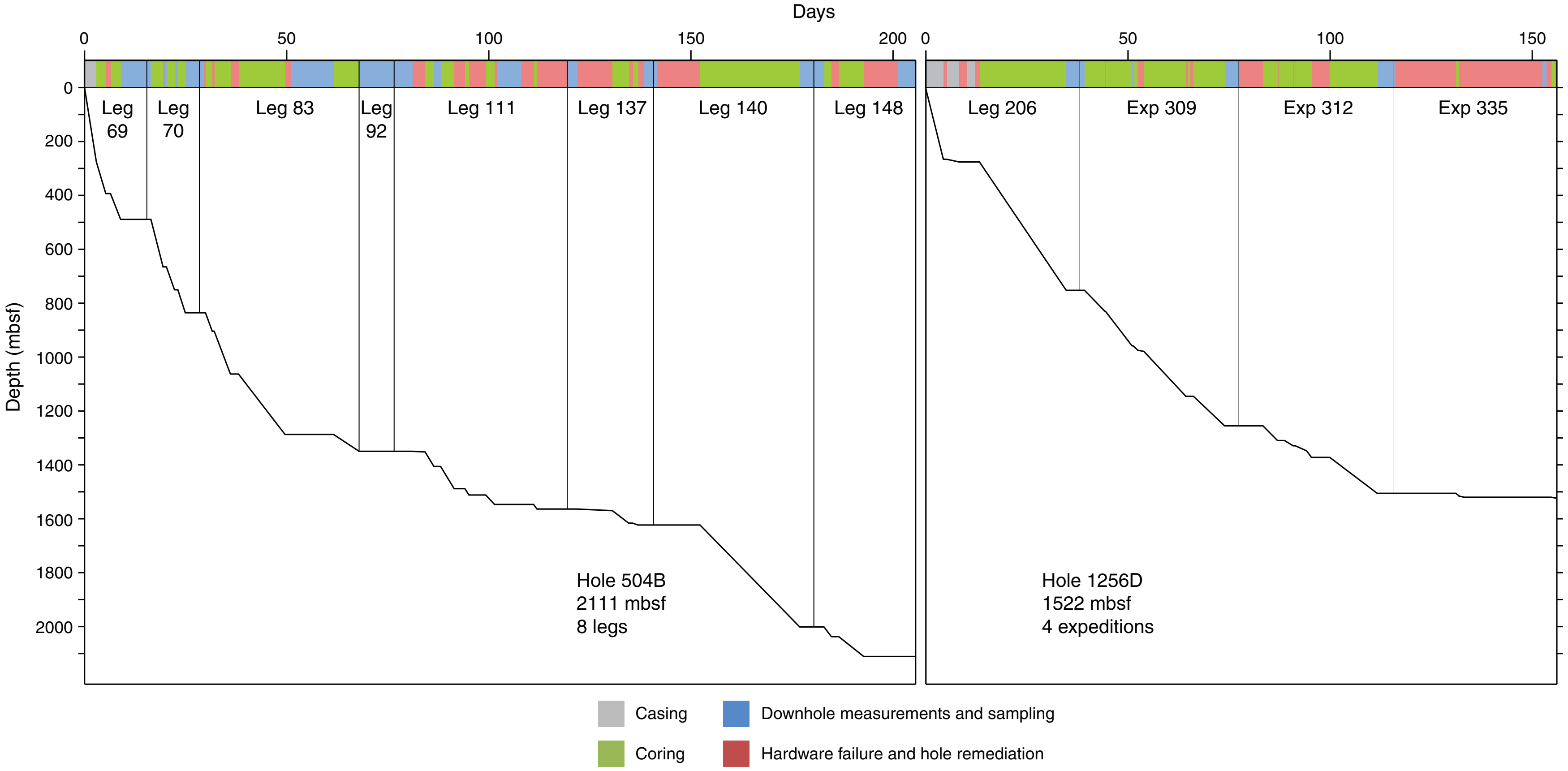

Table T1. Drill holes into oceanic basement in intact crust and tectonically exposed lower crust and upper mantle. (Continued on next two pages.)

Leg/Expedition	Hole	Latitude	Longitude	Ocean	Water depth (m)	Age (Ma)	Sediment thickness (m)	Basement penetration (m)	Recovery (%)	Spreading rate (S/I/F 40/80)	Comments	Lithology
24	238	11°09.21′S	70°31.56′E	Indian	2844.5	30	506	81	50	S/I	Projection of Chagos-Laccadive Plateau	Basaltic lavas
26	257	30°59.16′S	108°20.99′E	Indian	5278	120	262	65	50	S/I	Wharton Basin off Perth, Australia	Basalt and breccia
34	319A	13°01.04′S	101°31.46′W	Pacific	4296	16	98	59	25	F	Bauer Deep, 13°S East Pacific Rise	Basaltic lavas
37	332A	36°52.72′N	33°38.46′W	Atlantic	1851	3.5	104	331	10	S	Mid-Atlantic Ridge 36°–37°N	Basalt, basalt breccia, and interlayered sediments
37	332B	36°52.72′N	33°38.46′W	Atlantic	1983	3.5	149	583	21	S	Mid-Atlantic Ridge 36°–37°N	Basalt and basalt breccia
37	333A	36°50.45′N	33°40.05′W	Atlantic	1665.8	3.5	218	311	8	S	Mid-Atlantic Ridge 36°–37°N	Basalt and basalt breccia
37	335	37°17.74′N	35°11.92′W	Atlantic	3188	15	454	108	38	S	Mid-Atlantic Ridge 36°–37°N	Basaltic lavas
45	395A	22°45.35′N	46°04.90′W	Atlantic	4485	7.3	92	571	18	S	Mid-Atlantic Ridge 23°N	Basaltic lavas and breccia
45	396	22°58.88′N	43°30.95′W	Atlantic	4450	9	126	96	33	S	Mid-Atlantic Ridge 23°N	Basaltic lavas
46	396B	22°59.14′N	43°30.90′W	Atlantic	4459	13	151	255	23	S	Mid-Atlantic Ridge 23°N	Basalt and breccia
49	410A	45°30.53′N	29°28.56′W	Atlantic	2987	9	331	49	38	S	Mid-Atlantic Ridge 45°N	Basaltic lavas
49	412A	36°33.74′N	33°09.96′W	Atlantic	2626	1.6	163	131	18	S	Mid-Atlantic Ridge 33°N	Basalt flows and intercalating limestone
51–53	417A	25°06.63′N	68°02.48′W	Atlantic	5478.2	110	208	209	61	S	Western Atlantic	Basaltic lavas
51–53	417D	25°06.69′N	68°02.81′W	Atlantic	5489	110	343	366	70	S	Western Atlantic	Basaltic lavas
51–53	418A	25°02.10′N	68°03.44′W	Atlantic	5519	110	324	544	72	S	Western Atlantic	Basaltic lavas
54	428A	09°02.77′N	105°26.14′W	Pacific	3358.5	2.3	63	53	39	F	9°N East Pacific Rise	Basaltic lavas
63	469	32°37.00′N	120°32.90′W	Pacific	3802.5	17	391	63	34	I	Off California coast	Basaltic lavas
63	470A	28°54.46′N	117°31.11′W	Pacific	3554.5	15	167	49	33	I	Off California coast	Basaltic lavas
65	482B	22°47.38′N	107°59.60′W	Pacific	3015	0.5	137	93	54	I	Off Gulf of California	Massive basalt and interlayered sediment
65	482D	22°47.31′N	107°59.51′W	Pacific	3015	0.5	138	50	50	I	Off Gulf of California	Massive basalt and interlayered sediment
65	483	22°53.00′N	108°44.90′W	Pacific	3084	2	110	95	40	I	Off Gulf of California	Massive basalt and pillow basalt with interlayered sediments
65	483B	22°52.99′N	108°44.84′W	Pacific	3084	2	110	157	47	I	Off Gulf of California	Massive basalt and pillow basalt with interlayered sediments
65	485A	22°44.92′N	107°54.23′W	Pacific	2996.5	1.2	153.5	178	51	I	Off Gulf of California	Massive basalt and interlayered sediments
68	501	1°13.63′N	83°44.06′W	Pacific	3466.9	6.6	264	73	60	I	South flank of Costa Rica Rift	Basaltic lavas
69/70/83/111/137/140/148	504B	1°13.611′N	83°43.818′W	Pacific	3474	6.6	270	1841	20	I	South flank of Costa Rica Rift	Basalt, stockwork, and diabase
82	559	35°07.45′N	40°55.00′W	Atlantic	3754	35	238	63	37	S	West flank of Mid Atlantic Ridge 35°N	Basaltic lavas
82	562	33°08.49′N	41°40.76′W	Atlantic	3172	12	240	90	45	S	West flank of Mid Atlantic Ridge 33°N	Pillow basalt and massive basalt
82	564	33°44.36′N	43°46.03′W	Atlantic	3820	35	284	81	43	S	West flank of Mid Atlantic Ridge 34°N	Pillow basalt and minor massive basalt
91	595B	23°49.34′S	165°31.61′W	Pacific	5615	80	70	54	28	F	Central South Pacific	Vesicular aphyric basalt
92	597C	18°48.43′S	129°46.22′W	Pacific	4164	30	53	91	53	F	West flank South East Pacific Rise 18°S	Massive basalt flows
106/109	648B	22°55.32′N	44°56.825′W	Atlantic	3326	0	0	50	12	S	Mid-Atlantic Ridge 23°N	Pillow basalt
109	670A	23°9.996′N	45°1.932′W	Atlantic	3625	0	0	77	6	S	Mid-Atlantic Ridge, MARK, 23°N	Serpentinized peridotite
118/176	735B	32°43.395′S	57°15.959′E	Indian	720	11.8	0	1508	86	S	Atlantis Bank, Southwest Indian Ridge	Gabbro
123	765D	15°58.56′S	117°34.51′E	Indian	5713.8	140	928	267	31	F	Argo Abyssal Plain	North–east mid-ocean-ridge basaltic lavas

Table T1 (continued). (Continued on next page).

Leg/Expedition	Hole	Latitude	Longitude	Ocean	Water depth (m)	Age (Ma)	Sediment thickness (m)	Basement penetration (m)	Recovery (%)	Spreading rate (S/I/F 40/80)	Comments	Lithology
129/185	801C	18°38.538′N	156°21.59′E	Pacific	5674	170	462	414	47	F	Western North Pacific	Pillow basalt, basalt flows, and breccias
129	802A	12°5.778′N	153°12.63′E	Pacific	5980	120	509	51	33	F	Western North Pacific	Basaltic lavas
136	843B	19°20.54′N	159°5.68′W	Pacific	4418	95	243	71	37	F	West of Hawaii	Basaltic lavas
147	894E	2°18.059′N	101°31.524′W	Pacific	3014	1	0	29	11	F	Hess Deep	Gabbro
147	894F	2°17.976′N	101°31.554′W	Pacific	3025	1	0	26	7	F	Hess Deep	Gabbro
147	894G	2°17.976′N	101°31.554′W	Pacific	3023	1	0	127.5	35	F	Hess Deep	Gabbro
147	895A	2°16.638′N	101°26.766′W	Pacific	3821	1	0	17	14	F	Hess Deep	Serpentinized peridotite
147	895B	2°16.638′N	101°26.760′W	Pacific	3821	1	0	10	10	F	Hess Deep	Serpentinized peridotite
147	895C	2°16.632′N	101°26.772′W	Pacific	3820	1	0	38	15	F	Hess Deep	Serpentinized peridotite
147	895D	2°16.638′N	101°26.778′W	Pacific	3821	1	0	94	20	F	Hess Deep	Serpentinized peridotite
147	895E	2°16.788′N	101°26.790′W	Pacific	3753	1	0	88	37	F	Hess Deep	Serpentinized peridotite
147	895F	2°16.902′N	101°26.790′W	Pacific	3693	1	0	26	8	F	Hess Deep	Serpentinized peridotite
148	896A	1°13.006′N	83°43.392′W	Pacific	3459	6.6	179	290	27	I	South flank of Costa Rica Rift	Basaltic lavas
153	920B	23°20.310′N	45°1.038′W	Atlantic	3339	<1	0	126.4	35.3	S	Mid-Atlantic Ridge, MARK, 23°N	Serpentinized peridotite
153	920D	23°20.322′N	45°1.044′W	Atlantic	3338	<1	0	200.8	47.3	S	Mid-Atlantic Ridge, MARK, 23°N	Serpentinized peridotite
153	921A	23°32.460′N	45°1.866′W	Atlantic	2488	<1	0	17.1	18.1	S	Mid-Atlantic Ridge, MARK, 23°N	Gabbro
153	921B	23°32.478′N	45°1.842′W	Atlantic	2490	<1	0	44.1	19.4	S	Mid-Atlantic Ridge, MARK, 23°N	Gabbro
153	921C	23°32.472′N	45°1.830′W	Atlantic	2495	<1	0	53.4	11.4	S	Mid-Atlantic Ridge, MARK, 23°N	Gabbro
153	921D	23°32.442′N	45°1.830′W	Atlantic	2514	<1	0	48.6	12.7	S	Mid-Atlantic Ridge, MARK, 23°N	Gabbro
153	921E	23°32.328′N	45°1.878′W	Atlantic	2456	<1	0	82.6	21.4	S	Mid-Atlantic Ridge, MARK, 23°N	Gabbro
153	922A	23°33.162′N	45°1.926′W	Atlantic	2612	<1	0	14.6	63.2	S	Mid-Atlantic Ridge, MARK, 23°N	Gabbro
153	922B	23°31.368′N	45°1.926′W	Atlantic	2612	<1	0	37.4	25.6	S	Mid-Atlantic Ridge, MARK, 23°N	Gabbro
153	923A	23°32.556′N	45°1.896′W	Atlantic	2440	<1	0	70	57.2	S	Mid-Atlantic Ridge, MARK, 23°N	Gabbro
153	924B	23°32.460′N	45°0.858′W	Atlantic	3170	<1	0	30.8	8.7	S	Mid-Atlantic Ridge, MARK, 23°N	Gabbro
153	924C	23°32.496′N	45°0.864′W	Atlantic	3177	<1	0	48.5	23.1	S	Mid-Atlantic Ridge, MARK, 23°N	Gabbro
168	1025C	47°53.250′N	128°38.880′W	Pacific	2602	1.237	106	41	37	I	Juan de Fuca Flank	Basalt
168	1026B	47°45.759′N	127°45.552′W	Pacific	2658	3.511	256	39	5	I	Juan de Fuca Flank	Basalt
168	1026C	47°46.261′N	127°45.186′W	Pacific	2669	3.516	229	19	3.5	I	Juan de Fuca Flank	Basalt
168	1032A	47°46.776′N	128°7.320′W	Pacific	2645	2.621	290	48	6.5	I	Juan de Fuca Flank	Basalt
179	1105A	32°43.135′S	57°16.652′E	Indian	714	11.8	0	158	75	S	Atlantis Bank, Southwest Indian Ridge	Gabbro
185	1149D	31°18.79′N	143°24.03′E	Pacific	5818	133	307	133	17	F	Western North Pacific	Pillow basalt, basalt flows, and breccias
187	1162B	44°37.9′S	129°11.3′E	Indian	5464	18	333	59	17	I	Australian-Antarctic Discordance	Basaltic lavas and breccia
187	1163A	44°25.5′S	126°54.5′E	Indian	4354	17	161	47	33	I	Australian-Antarctic Discordance	Basaltic lavas
187	1164B	43°45.0′S	127°44.8′E	Indian	4798	18.5	150	66	16	I	Australian-Antarctic Discordance	Basaltic lavas
191	1179D	41°04.8′N	159°57.8′E	Pacific	5563.9	129	377	98	44	F	Western North Pacific	Basaltic lavas
200	1224F	27°53.36′N	141°58.77′W	Pacific	4967.1	46	28	147	26	F	Central Pacific	Basaltic lavas
203	1243B	5°18.07′N	110°04.58′W	Pacific	3868	11	110	87	25	F	Western flank East Pacific Rise 5°N	Basaltic lavas
206	1256C	6°44.18′N	91°56.06′W	Pacific	3634.7	15	251	89	61	F	Cocos plate eastern flank East Pacific Rise	Basaltic lavas
206/309/312	1256D	6°44.16′N	91°56.06′W	Pacific	3634.7	15	250	1257.1	37.1	F	Cocos plate eastern flank East Pacific Rise	Basaltic lavas, sheeted dike, and varitextured gabbro
209	1268A	14°50.755′N	45°4.641′W	Atlantic	3007		0	147.6	53.3	S	Mid-Atlantic Ridge 15°20′N	Serpentinized peridotite
209	1270A	14°43.342′N	44°53.321′W	Atlantic	1951		0	26.9	12.2	S	Mid-Atlantic Ridge 15°20′N	Gabbro
209	1270B	14°43.265′N	44°53.225′W	Atlantic	1909		0	45.9	37.4	S	Mid-Atlantic Ridge 15°20′N	Gabbro
209	1270C	14°43.284′N	44°53.091′W	Atlantic	1822		0	18.6	10.6	S	Mid-Atlantic Ridge 15°20′N	Gabbro
209	1270D	14°43.270′N	44°53.084′W	Atlantic	1817		0	57.3	13.4	S	Mid-Atlantic Ridge 15°20′N	Gabbro
209	1271A	15°2.222′N	44°56.887′W	Atlantic	3612		0	44.8	12.9	S	Mid-Atlantic Ridge 15°20′N	Serpentinized peridotite

Table T1 (continued).

Leg/Expedition	Hole	Latitude	Longitude	Ocean	Water depth (m)	Age (Ma)	Sediment thickness (m)	Basement penetration (m)	Recovery (%)	Spreading rate (S/I/F 40/80)	Comments	Lithology
209	1271B	15°2.189′N	44°56.912′W	Atlantic	3585		0	103.8	15.3	S	Mid-Atlantic Ridge 15°20′N	Serpentinized peridotite
209	1272A	15°5.666′N	44°58.300′W	Atlantic	2560		0	131	28.6	S	Mid-Atlantic Ridge 15°20′N	Serpentinized peridotite
209	1274A	15°38.867′N	46°40.582′W	Atlantic	3940		0	155.8	22.2	S	Mid-Atlantic Ridge 15°20′N	Serpentinized peridotite
209	1275B	15°44.486′N	46°54.208′W	Atlantic	1562		0	108.7	43.1	S	Mid-Atlantic Ridge 15°20′N	Gabbro
209	1275D	15°44.440′N	46°54.217′W	Atlantic	1554		0	209	50	S	Mid-Atlantic Ridge 15°20′N	Gabbro
301	U1301A	47°45.209′N	127°45.833′W	Pacific	2656	3.5	262	108	0	I	Juan de Fuca Ridge flank; no coring (CORK)	Basaltic lavas
301	U1301B	47°45.229′N	127°45.826′W	Pacific	2655	3.5	265	318	12.9	I	Juan de Fuca Ridge flank; recovery is only for the 232 m of cored basement	Basaltic lavas
304	U1309B	30°10.108′N	42°7.110′W	Atlantic	1642	2	2	99.8	45.9	S	Mid-Atlantic Ridge 30°N	Gabbro
304/305	U1309D	30°10.120′N	42°7.113′W	Atlantic	1645	2	2	1413.3	74.8	S	Mid-Atlantic Ridge 30°N	Gabbro
327	U1362A	47°45.663′N	127°45.672′W	Pacific	2661	3.5	236	292	29.6	I	Juan de Fuca Ridge flank; recovery is only for the 150 m of cored basement	Basaltic lavas

Compilation does not include other "hard rock" drill holes in oceanic plateaus, arc basement, hydrothermal mounds, or passive margins. S = slow, I = intermediate, F = fast. MARK = Mid-Atlantic Ridge Kane Fracture Zone. CORK = circulation obviation retrofit kit. This table is available in **ASCII** and in Microsoft Excel format (see 104_T1.XLS in CHAPTER_104 in TABLES in **"Supplementary material"**).

Table T2. Preferred conditions for the siting of multiple-expedition deep drill holes for successful drilling and scheduling.

Criteria	Preferred conditions	Site 1256
Geographic parameters:		
Transit from major ports	<5 days: maximizes time on site and allows emergency resupply	🟩 2 to 3.5 days from Mexican and Central American ports
Proximity to oft-transited regions	Preferred: ensures site is rarely far removed from region of operations	🟩 3.5 days from Pacific end of Panama Canal
Weather window	12 months	🟩 12 months
Geological parameters:		
Installation of reentry cone and casing	Sediment overburden of ~100 m or more	🟩 ~250 m
Seismic velocity	Higher V_P likely to indicate less fracture formations	🟩 Targeted region of relatively high V_P
Thermal state	Lower temperatures at depth with age (>20 Ma), <200°C at target depth	🟥 15 Ma ~125°C at 2000 mbsf ~300°C at Moho
Potential for riser drilling	<4000 m water depth	🟩 3635 m water depth
Age of ocean crust	<30 Ma to investigate modern Earth system	🟩 15 Ma
Magnetic measurements	Original location ± more than 20° of Equator for magnetic polarity determination from azimuthally unoriented core. Avoid north–south oriented ridge segments as inclination insensitive to tilting	🟥 Formed 1°N on approximately north–south ridge segment

For more information on seismic velocity, see Figure **F23** in the "Expedition 335 summary" chapter (Expedition 335 Scientists, 2012). Green = Site 1256 meets preferred conditions, red = Site 1256 does not meet preferred conditions.

Table T3. Summary of operations at Hole 504B (DSDP Legs 69, 70, 83 and 92; ODP Legs 111, 137, 140 and 148). (Continued on next four pages.)

Leg	Date	Time (h)	Depth (mbsf)	Comment	Brief run description	Time (days)
69	**8 Oct 1979**	**2145**	**260.5**	**Start coring from 260.5 mbsf (Cores 1 and 2 in sediments).**	**Reentry 1 for casing (after washing + coring sediments)**	**3.09**
69	10 Oct 1979	1330	275	Start casing to 275 mbsf.		
69	12 Oct 1979	0000	275	Start coring in basement, bit Run 1, Core 3.	Reentry 2, coring bit Run 1, Cores 3–16	2.27
69	14 Oct 1979	0630	393	End coring bit Run 1, Core 16.		
69	14 Oct 1979			Operations in Hole 504C for half a day.		
69	15 Oct 1979	2000	393	Ship power failure and drift northward; drill string dragged along soft sediments. Inspection of drill pipe and magnaflux most vulnerable sections.		1.10
69	16 Oct 1979	2230	393	Start coring bit Run 2, Core 17.	Reentry 3, coring bit Run 2, Cores 17–29	2.54
69	19 Oct 1979	1130	489	End coring bit Run 2, Core 29.		
69	20 Oct 1979	2020	489	Downhole experiments and logging. NB: Pipe stuck after packer sampling.	Reentry 4, downhole measurements	6.45
69	25 Oct 1979	2225	489	End of downhole experiments and logging.		
69					**Total:**	**15.47**
70	**3 Dec 1979**	**1343**	**489**	**Reentry in hole, <2 months after previous operations.**		
70	3 Dec 1979	1343	489	Temperature measurement.	Reentry 5, downhole measurements	1.01
70	4 Dec 1979	1400	489	Start coring bit Run 3, Core 30.	Reentry 6, coring bit Run 3, Cores 30–49	2.98
70	7 Dec 1979	1331	665	End coring bit Run 3, Core 49.		
70	7 Dec 1979	2130	665	Bit drop on seafloor unsuccessful, hence no logging; bit lost during pipe trip.	Bit lost on seafloor	0.33
70	8 Dec 1979	1232	665	Reentry, temperature measurement, and water sample.	Downhole measurements	0.63
70	8 Dec 1979	1245	665	Start coring bit Run 4, Core 50.	Reentry 7, coring bit Run 4, Cores 50–60	2.00
70	10 Dec 1979	1232	750.5	End coring bit Run 4, Core 60.		
70	11 Dec 1979	0750	750.5	Reentry, temperature measurement, and water sample.	Downhole measurements	0.80
70	11 Dec 1979	0800	750.5	Start coring bit Run 5, Core 61.	Reentry 8, coring bit Run 5, Cores 61–70	1.85
70	13 Dec 1979	0415	836	End coring bit Run 5, Core 70.		
70	13 Dec 1979	1055	836	Downhole logging.	Reentry 9, downhole measurements	3.42
70	16 Dec 1979	1420	836	End of downhole logging.		
70					**Total:**	**13.03**
83	**23 Nov 1981**	**0632**	**836**	**Reentry in hole, 2 years after previous operations.**		
83	23 Nov 1981	0632	836	Temperature profile and water sampling.	Reentry 10, downhole measurements	1.27
83	24 Nov 1981	1300	836	Bowen hydraulic unit (heave compensator) lost hydraulic pressure.		0.24
83	24 Nov 1981	1845	836	Start coring bit Run 1, Core 71.	Reentry 11, coring bit Run 6, Cores 71–85	1.65
83	26 Nov 1981	1022	904.5	Leak in stem between power sub and swivel; pipe tripped up to casing; 12 h lost.		0.50
83	26 Nov 1981	2220	904.5	Resume coring, Core 80.		0.58
83	27 Nov 1981	1210	964.5	End coring bit Run 1, Core 85.		
83	27 Nov 1981	1210	964.5	Start coring bit Run 2, Core 86.	Reentry 12, coring bit Run 7, Cores 86–97	3.21
83	30 Nov 1981	1710	1057.5	Core barrel (Core 96) left in hole; two fishing attempts.		0.12
83	30 Nov 1981	2000	1062	Resume coring.		0.16
83	30 Nov 1981	2100	1062	End coring bit Run 2, Core 97; broken pipe.		
83	30 Nov 1981	2100	1062	Broken pipe, BHA + 39 joints of drill pipe lost in hole.	Reentry 13, fishing drill string	1.09
83	1 Dec 1981	2310	1062	First attempt fishing broken pipe failed.		
83	2 Dec 1981	2010	1062	Second attempt fishing broken pipe succeeded. 2.5 days lost; BHA (4 collars + coring assembly) filled with finely ground basalt.	Reentry 14, fishing drill string	0.88
83	4 Dec 1981	0643	1062	Start coring bit Run 3, Core 98.	Reentry 15, coring bit Run 8, Cores 98–111	4.40
83	7 Dec 1981	0541	1166	End coring bit Run 3, Core 111.		
83	8 Dec 1981	0207	1166	Start coring bit Run 4, Core 112 (F94CK bit with smaller core guide, 4.5 m cores; no improved core recovery).	Reentry 16, coring bit Run 9, Cores 112–120	2.68
83	9 Dec 1981	2155	1207.5	End coring bit Run 4, Core 120 (bit lost tungsten carbide inserts).		
83	10 Dec 1981	2054	1207.5	Start coring bit Run 5, Core 121 (back to previous bit type, with 2-7/16 inch size).	Reentry 17, coring bit Run 10, Cores 121–126	2.47
83	12 Dec 1981	0905	1253.5	End coring bit Run 5, Core 126 (bit lost tungsten carbide inserts).		
83	13 Dec 1981	0247	1253.5	Start coring bit Run 6, Core 127 (F94CK bit).	Reentry 18, coring bit Run 11, Cores 127–130	1.91
83	14 Dec 1981	0700	1287.5	End coring bit Run 6, Core 130; broken pipe.		

Table T3 (continued). (Continued on next page).

Leg	Date	Time (h)	Depth (mbsf)	Comment	Brief run description	Time (days)
83	14 Dec 1981	0700	1287.5	Broken pipe, BHA + 10 joints of drill pipe lost in hole.	Reentry 19, fishing drill string	1.39
83	15 Dec 1981	1626	1287.5	Fishing broken pipe. 1.5 day lost; 2 days added to the leg!		
83	16 Dec 1981	0820	1287.5	Downhole logging. NB: cable stripped for sonic sonde.	Reentries 20–23, downhole measurements	10.73
83	20 Dec 1981	0805	1287.5	Downhole logging. NB: 1 bowspring of top centralizer of sonic sonde broke; 1.5 m piece lost in hole.		
83	23 Dec 1981	1443	1287.5	Packer run.		
83	25 Dec 1981	0106	1287.5	Packer run.		
83	26 Dec 1981	0952	1287.5	Packer run.		
83	28 Dec 1981	0536	1287.5	Start coring bit Run 7, Core 131 (F94CK bit). NB: junk from logging tool wasn't fished.	Reentry 24, coring bit Run 12, Cores 131–135	3.57
83	29 Dec 1981	2337	1322	End coring bit Run 7, Core 135. NB: BHA + Bowen power sub magnafluxed.		
83	31 Dec 1981	0030	1322	Start coring bit Run 8, Core 136.	Reentry 25, coring bit Run 13, Cores 136–141	2.78
83	1 Jan 1982	1815	1350	End coring bit Run 8, Core 141.		
83					**Total:**	**39.61**
92	**8 Apr 1983**	**0706**	**1350**	**Reentry in Hole, 2 years after previous operations.**		
92	8 Apr 1983	0900	1350	Extensive downhole measurements and logging program. Oblique seismic experiment was an ordeal (quoting the leg report); missing connectors for the seismometer + other floods and failures.	Reentry 26, downhole measurements	8.63
92	16 Apr 1983	2215	1350	End of downhole measurements.		
92					**Total:**	**8.63**
111	**30 Aug 1986**	**0000**	**1350**	**Reentry in hole, 3 years after previous operations, 5 years after last coring.**		
111	30 Aug 1986	0000	1350	Downhole logging and water sampling.	Reentry 27, downhole measurements	4.50
111	3 Sep 1986	1200	1350	RFT logging tool lost one clamping arm.		
111	3 Sep 1986	1200	1352.8	Junk mill run. Milled metal and rubber (packer from Leg 83).	Reentry 28, milling metal junk	3.08
111	6 Sep 1986	1400	1352.8	Start coring bit Run 1, Core 142 (F99CK bit).	Reentry 29, coring bit Run 14, Cores 142–147	2.18
111	8 Sep 1986	1815	1406.8	End coring bit Run 1, Core 147. NB: Core 147 stuck in BHA.		
111	10 Sep 1986	1045	1406.8	Packer run. Second packer damaged when POOH.	Reentry 30, downhole measurements	1.69
111	11 Sep 1986	1100	1406.8	Start coring bit Run 2, Core 148 (RBI type C7). Difficult drilling conditions (good only when high circulation rates maintained).	Reentry 31, coring bit Run 15, Cores 148–158	3.33
111	13 Sep 1986	1845	1488.1	End coring bit Run 2, Core 158. Junk still present at bottom, some recovered in boot basket.		
111	14 Sep 1986	0245	1488.1	BHA filled with cuttings during pipe trip down. Circulation lost. POOH.	Reentry 32, lost circulation	2.72
111	16 Sep 1986	1200	1488.1	Start coring bit Run 3, Core 159 (C-57 bit).	Reentry 33, coring bit Run 16, Cores 159–161	1.00
111	17 Sep 1986	1200	1511.5	End coring bit Run 3, Core 161. Bit failure.		
111	17 Sep 1986	2000	1511.5	Bit completely destroyed. Four cones and much of the steel core guide lost in hole.	Reentries 34 to 36, milling and fishing metal junk	4.20
111	18 Sep 1986	0100	1511.5	First of a series of three fishing pipe trips (junk baskets and mill).		
111	21 Sep 1986	1645	1511.6	End of fishing runs (mill Core 162M).		
111	22 Sep 1986	1200	1511.6	Start coring bit Run 4, Core 163 (DSDP/Smith F99CK bit).	Reentry 37, coring bit Run 17, Cores 163–167	2.15
111	23 Sep 1986	2015	1547.5	End coring bit Run 4, Core 167 (last core stopped after 1.6 m, core barrel not retrieved).		
111	24 Sep 1986	0830	1547.5	Bit completely destroyed. Four cones lost; worse shape than previous one. Special fishing and milling tools air-freighted to Ecuador and brought to JR by tuna vessel *Sirius* while logging Hole 504B and coring Sites 677 and 678.	Bit destroyed, waiting for fishing tools	0.51
111	24 Sep 1986	1000	1547.5	Downhole experiments (packer, VSP) and logging.	Reentry 38, downhole measurements	5.93
111	30 Sep 1986	0645	1547.5	JR left Site 504 for coring sediments at Sites 677 and 678 for 5 days.		
111	5 Oct 1986	0500	1547.6	Milling and fishing (1 junk basket run + 1 mill run). Not much junk back in the basket (3 rocks, no cone). Mill Core 168M.	Reentries 39 and 40, milling and fishing metal junk	3.21
111	8 Oct 1986	1000	1547.6	Start coring bit Run 5, Core 169 (DSDP/Smith F99CK bit).	Reentry 41, coring bit Run 18, Cores 169–170	0.81
111	9 Oct 1986	0530	1562.1	End coring bit Run 5, Core 170. Bad drilling condition during Core 170R; bit returned worn but in one piece.		

Table T3 (continued). (Continued on next page).

Leg	Date	Time (h)	Depth (mbsf)	Comment	Brief run description	Time (days)
111	9 Oct 1986	0530	1562.1	Bit in very worn condition, with much damage from junk, but in one piece.	Reentry 42, milling metal junk with newly arrived tool	7.51
111	9 Oct 1986		1562.1	Arrival of Ecuadorian tuna vessel *Sirius* with new fishing and milling equipment.		
111			1562.1	New flat-bottom junk mill run with two baskets.		
111			1562.1	Diamond core bit run (9-27/32 inch NOR Geoset diamond core bit). Bit + float valve + lower support bearing + inner core barrel lost in hole.	Reentry 43, diamond coring bit lost	
111			1562.1	Start of four fishing pipe trips; first one retrieved the core barrel.	Reentries 44–47, fishing metal junk	
111	16 Oct 1986	1745	1562.1	End of fishing runs; junk remained in the hole.		
111					**Total:**	**42.81**
137	**7 Apr 1991**	**1800**	**1562.1**	**Reentry in hole, 4.5 years after previous operations.**		
137	7 Apr 1991	1800	1562.1	Downhole logging and water sampling	Reentry 48, downhole measurements	2.38
137	10 Apr 1991	0300	1562.1	End of initial logging		
137	10 Apr 1991	0300	1570	Remedial/cleanout operations. First use of Bowen full-flow reverse circulation junk basket (little junk recovered) followed by five successive milling runs and by a tricone Smith F7 run (hole deepened to 1570 mbsf). Milling and drilling Cores 171M and 172M.	Reentries 49–55, fishing and milling metal junk, cleanout	8.88
137	19 Apr 1991	0000	1570	Start coring bit Run 1, Core 173 (RBI C7 bit).	Reentry 56, coring bit Run 19, Cores 173–175	1.58
137	19 Apr 1991	1945	1595.3	End coring bit Run 1, Core 175. Broken inserts.		
137	20 Apr 1991	1400	1595.3	Start coring bit Run 2, Core 176 (RBI C7 bit).	Reentry 57, coring bit Run 20, Cores 176–178	2.40
137	21 Apr 1991	1100	1615.5	End coring bit Run 2, Core 178. Drive rows destroyed on all cones.		
137	22 Apr 1991	2330	1618.4	Cleanup run with tricone bit and junk baskets (Core 179M).	Reentry 58, cleanout	0.94
137	23 Apr 1991	2200	1618.4	Start coring bit Run 3, Core 180M. Test of diamond coring (7-7/8 inch Hobic core bit).	Reentry 59, coring bit Run 21 (diamond bit), Core 180M	0.27
137	24 Apr 1991	0430	1620.4	End coring bit Run 3, Core 180M. Very low penetration, good recovery (55%). Bit completely worn.		
137	24 Apr 1991	0430	1620.4	Start coring bit Run 4, Core 181M. Test of diamond coring (7-7/8 inch Christensen mining bit).	Reentry 60, coring bit Run 22 (diamond bit), Core 181M	1.08
137	25 Apr 1991	0630	1621.5	End coring bit Run 4, Core 181M. Very low penetration, good recovery (123%!).		
137	25 Apr 1991	0630	1621.5	60 ft outer barrel + bit lost in hole.	Reentries 61–63, fishing metal junk	1.23
137			1621.5	Start of remedial/cleanout operations. Three attempts failed. Overshot assembly lost in hole.		
137			1621.5	No more appropriate fishing tool available on board. Modification of available tool.	Reentry 64, fishing metal junk	
137			1621.5	New fishing attempt failed.		
137	26 Apr 1991	1200	1621.5	Downhole logging (BHTV) and flowmeter/packer experiment.	Reentry 65, downhole measurements	2.59
137	29 Apr 1991	0215	1621.5	End of logging; departure from Site 504.		
137					**Total:**	**21.34**
140	**1 Oct 1991**	**1430**	**1621.5**	**Reentry in hole, 5 months after previous operations.**		
140	1 Oct 1991	1430	1621.5	Downhole logging.	Reentry 66, downhole measurements	0.90
140	2 Oct 1991	1200	1621.5	FMS arm, bowspring, and pad parts lost in hole.		
140			1621.5	Three more fishing runs with different tools (spears + grapples, tapper tap). Grapple lost in hole at end of third attempt.	Reentries 67–71, fishing metal junk	10.50
140			1621.5	Other attempt with tapper tap (shorter nose), failed.		
140			1621.5	Fishing run with ship-built “double dog” fishing tool. Recovered part of the fish; diamond-impregnated bit, near-bit bottom stabilizer, FMS parts, and miscellaneous small pieces of junk left in hole.		
140			1621.5	9-7/8 inch tricone cleanout run.	Reentry 72, cleanout	
140			1621.5	Taper tap fishing run. Recovered rest of the fish.	Reentry 73, fishing metal junk	
140			1621.8	9-7/8 inch tricone cleanout run (Core 184M).	Reentry 74, cleanout	
140	13 Oct 1991	0000	1621.8	Start coring bit Run 1, Core 185. New type of 9-7/8 inch H87F bits.	Reentry 75, coring bit Run 23, Cores 185–189	1.71
140	14 Oct 1991	1705	1655.1	End coring bit Run 1, Core 189.		
140	14 Oct 1991	1705	1655.1	Start coring bit Run 2, Core 190.	Reentry 76, coring bit Run 24, Cores 190–195	2.37
140	17 Oct 1991	0200	1696.5	End coring bit Run 2, Core 195.		
140	17 Oct 1991	0200	1696.5	Start coring bit Run 3, Core 196.	Reentry 77, coring bit Run 25, Cores 196–198	1.99
140	19 Oct 1991	0150	1719.4	End coring bit Run 3, Core 198.		
140	19 Oct 1991	0150	1719.4	Start coring bit Run 4, Core 199.	Reentry 78, coring bit Run 26, Cores 199–204	3.33
140	22 Oct 1991	0950	1757	End coring bit Run 4, Core 204.		

Table T3 (continued). (Continued on next page).

Leg	Date	Time (h)	Depth (mbsf)	Comment	Brief run description	Time (days)
140	22 Oct 1991	0950	1757	Start coring bit Run 5, Core 205.	Reentry 79, coring bit Run 27, Cores 204–211	3.00
140	25 Oct 1991	0950	1806	End coring bit Run 5, Core 211.		
140	25 Oct 1991	0950	1806	Start coring bit Run 6, Core 212.	Reentry 80, coring bit Run 28, Cores 212–219	3.07
140	28 Oct 1991	1135	1865.5	End coring bit Run 6, Core 219.		
140	28 Oct 1991	1135	1865.5	Start coring bit Run 7, Core 220.	Reentry 81, coring bit Run 29, Cores 220–225	3.06
140	31 Oct 1991	1255	1920	End coring bit Run 7, Core 225.		
140	31 Oct 1991	1255	1920	Start coring bit Run 8, Core 226.	Reentry 82, coring bit Run 30, Cores 226–231	2.48
140	3 Nov 1991	0030	1957.3	End coring bit Run 8, Core 231. All driver-row inserts on all cones chipped 80%.		
140	3 Nov 1991	0030	1957.3	Start coring bit Run 9, Core 232.	Reentry 83, coring bit Run 31, Cores 232–235	2.23
140	5 Nov 1991	0600	1980.7	End coring bit Run 9, Core 235. Inner 80% of each cone missing.		
140	5 Nov 1991	0600	1980.7	Start coring bit Run 10, Core 236.	Reentry 84, coring bit Run 32, Cores 236–238	1.45
140	6 Nov 1991	1650	2000.4	End coring bit Run 10, Core 238. Bit 3/16 inch under gauge and teeth broken or chipped due to junk already in hole.		
140	7 Nov 1991	0500	2000.4	Downhole logging.	Reentry 85, downhole measurements	3.46
140	10 Nov 1991	0350	2000.4	End of logging.		
140					**Total:**	**39.56**
148	**28 Jan 1993**	**0450**	**2000.4**	**Reentry in hole, 1 year and 3 months after previous operations.**		
148	28 Jan 1993	0450	2000.4	Downhole logging (temperature + water sampling).	Reentry 86, downhole measurements	2.63
148	30 Jan 1993	2000	2000.4	Start coring bit Run 1 Core 239. Security 9-7/8 inch rotary coring bit.		
148	1 Feb 1993	1635	2038.2	End coring bit Run 1 Core 243.	Reentry 87, coring bit Run 33, Core 243	1.86
148	1 Feb 1993	1635	2038.2	One cone + roller bearings lost in hole.		
148	1 Feb 1993	1635	2038.2	Milling run with junk basket. Large pieces of bit-cone material retrieved + 3 bearings, 16 inserts, klusterite from the mill, and 173 g of miscellaneous junk.	Reentry 88, milling metal junk	1.78
148	3 Feb 1993	1120	2038.2	Start coring bit Run 2, Core 244 (RBI C9 bit + junk basket).	Reentry 89, coring bit Run 34, Cores 244–246	1.39
148	4 Feb 1993	2035	2056.7	End coring bit Run 2, Core 246. Teeth and middle rows of all cones broken. Junk basket recovered 660g of metal, including 3 large pieces from the cone noses and 11 bit inserts.		
148	4 Feb 1993	2035	2056.7	Start coring bit Run 3, Core 247 (RBI C9 bit + junk basket).	Reentry 90, coring bit Run 35, Cores 247–248	1.16
148	6 Feb 1993	0025	2061.8	End coring bit Run 3, Core 248. Teeth cracked in the middle row of two cones, small inserts lost. Junk basket recovered 94 g of metal.		
148	6 Feb 1993	0025	2061.8	Start coring bit Run 4, Core 249 (RBI C7 bit + junk basket).	Reentry 91, coring bit Run 36, Cores 249–250	1.12
148	7 Feb 1993	0315	2089.9	End coring bit Run 4, Core 250. Teeth on the heel rows of three cones chipped, small inserts missing. Junk basket recovered 86 g of metal.		
148	7 Feb 1993	0315	2089.9	Start coring bit Run 5, Core 251 (RBI C9 bit).	Reentry 92, coring bit Run 37, Cores 251–253	2.46
148	9 Feb 1993	1415	2111	End coring bit Run 5, Core 253.		
148	9 Feb 1993	1415	2111	Pipe stuck and severed. BHA left in hole. Operations discontinued until the arrival of a fishing consultant and a shipment of fishing tools.	Severing the drill string; waiting for fishing consultant and tools	1.91
148	11 Feb 1993	1200	2111	Drilling at site 896 for ~9 days.		
148	20 Feb 1993	1200	2111	Return to Hole 504B to meet the boat bringing fishing consultant and equipment.		6.56
148	21 Feb 1993		2111	Fishing run with Bowen super jar. BHA retrieved; bit, float valve, and lower support bearing left in hole, together with two pieces of schlumberger explosive rod.	Reentry 93, fishing drill string	
148	22 Feb 1993		2111	Milling run with Petco concave mill, with junk baskets and bowen super jar. Bottom of mill completely worn; baskets recovered >1.7 kg of metal.	Reentry 94, milling drill string	
148			2111	Milling run with same configuration as previous one. Petco mill, 2 junk baskets, bit sub, 3 drill collars, and 0.38 m of Bowen super jar joined the collection of junk in the hole!	Reentry 95, milling drill string; more junk in the hole!	
148	24 Feb 1993		2111	Last fishing run; retrieved the fish. Coring bit, float valve, and lower support bearing still in hole. The second mill showed no evidence off having milled anything. Borehole had collapsed, depositing 19 m of rubble on top of the remaining fish.	Reentry 96, fishing drill string + milling tool; coring bit, float valve, and lower support bearing left in hole	
148	27 Feb 1993	0130	2111	Downhole logging.	Reentry 97, downhole measurements	2.44
148	1 Mar 1993	1200	2111	JR departed for additional coring at site 896 for ~3 days.		
148	4 Mar 1993	1200	2111	Water sample + VSP.	Reentry 98, downhole measurements	2.00

Table T3 (continued).

Leg	Date	Time (h)	Depth (mbsf)	Comment	Brief run description	Time (days)
148	6 Mar 1993	1200	2111	End of operations in Hole 504B. Final sentence of the coring operations section in the Leg 148 site chapter: "With the proper equipment, milling operations on a return trip to Hole 504B would be simple and straightforward...."	End of Hole 504B	
148					**Total:**	**25.31**
504B					**Total:**	**205.74**

Times have sometimes been estimated based on average rates of penetration or on average pipe trip duration, as they were not always available in the operation section of the Site 504 chapter of the leg's *Initial Reports* volume (Cann, J.R., Langseth, M.G., Honnorez, J., Von Herzen, R.P., White, S.M., et al., 1983; Honnorez, J., Von Herzen, R.P., et al., 1983; Anderson, R.N., Honnorez, J., Becker, K., et al., 1985; Shipboard Scientific Party, 1986, 1988, 1992a, 1992b, 1993). Gray = beginning and end of legs, casing operations; blue = downhole measurements; green = coring; red = hardware failure and hole remediation. BHA = bottom-hole assembly, RFT = retrievable formation tester, POOH = pull out of hole, JR = *JOIDES Resolution*, VSP = vertical seismic profile, NOR = Geoset diamond core bit, BHTV = Borehole Televiewer tool, FMS = Formation MicroScanner. This table is available in **ASCII** and in Microsoft Excel format (see 104_T3.XLS in CHAPTER_104 in TABLES in **"Supplementary material"**).

Table T4. Summary of operations at Hole 1256D (ODP Leg 206; IODP Expeditions 309/312 and 335). (Continued on next eight pages.)

Leg	Date	Time	Depth (mbsf)	Comment	Brief run description	Time (days)
206	**23 Nov 2002**	**0345**	**0**	**Spud reentry cone and jet-in 20 inch casing.**	**Initiate Hole 1256D, 20 inch casing**	**1.69**
206	24 Nov 2002	1035	95	End jetting. Reach 95 mbsf; release CADA.		
206	24 Nov 2002	2015	95	Bit at rotary table. Change to BCR BHA.		
206	25 Nov 2002	0815	95	Drill 21-1/2 inch hole at 95 mbsf.		
206	27 Nov 2002	0445	267	End drilling at ~17 m into basement.	Reentry 1, drilling 21.5 inch hole into basement	2.70
206	27 Nov 2002	1300	267	Bit at rotary table. Failed bit bearing left junk in hole.		
206	28 Nov 2002	0000	267	Cleaning, work 2 junk baskets.	Reentry 2, cleanout	0.94
206	28 Nov 2002	0330	268	End cleaning, advance 1 m into basement.		
206	28 Nov 2002	1140	268	Bit at rotary table. Change to BCR BHA.		
206	28 Nov 2002	2000	268	Resume drilling 21-1/2 inch hole at ~17 m in basement.	Reentry 3, drilling 21.5 inch hole into basement	2.08
206	30 Nov 2002	0030	276.1	Begin wiper trip. TD = 276.1 mbsf (26.1 m in basement).		
206	30 Nov 2002	0415	276.1	Displace hole with 150 bbl sepiolite and 100 bbl barite.		
206	30 Nov 2002	1330	276.1	Bit at rotary table. Rig-up for 16 inch casing.		
206	1 Dec 2002	0417	276.1	Casing wet at 0417 h.	Reentry 4, casing	0.88
206	1 Dec 2002	1040	276.1	Detect crushed joint. Stop running casing.		
206	2 Dec 2002	0004	276.1	Recover casing. Replace 4 joints and casing collar.	Replace casing	1.04
206	2 Dec 2002	1135	276.1	Casing wet at 1135 h.	Reentry 4, casing, WOW	0.80
206	2 Dec 2002	2008	276.1	Reentry 4. Weather getting bad; heave = ~2.5 m.		
206	2 Dec 2002	2315	276.1	Clear seafloor. POOH due to heave = ~4 m.		
206	3 Dec 2002	0650	276.1	Reentry. WOW for 5.75 h.	WOW	
206	3 Dec 2002	1730	276.1	Land casing. Work stuck casing for 3.75 h.		
206	3 Dec 2002	1745	276.1	Cement casing with 30 bbl cement.	Reentry 5, cement casing	0.92
206	4 Dec 2002	0500	276.1	CADA tool on surface.		
206	4 Dec 2002	0630	276.1	Begin to run in hole. Coring Bit 1: CC4 SN BX-020.		1.20
206	4 Dec 2002	1815	276.1	Start to drill cement. Attempted core/dropped chisel.	Reentry 6, coring Bit 1, coring cement	
206	5 Dec 2002	0955	276.1	Tested bottom of hole and found junk.		0.26
206	5 Dec 2002	1615	276.1	Bit at rotary table.		
206	6 Dec 2002	0230	276.1	Start fishing with Bowen fishing magnet. Work junk baskets and magnet 1 h.	Reentry 7, fishing metal junk	0.80
206	6 Dec 2002	1130	276.1	Bit at rotary table. Clean magnet.		
206	7 Dec 2002	0045	276.1	Work junk basket before coring.	Reentry 8, coring Bit 2, Cores 2R–21R	4.38
206	7 Dec 2002	0100	276.1	Begin coring Bit 2 (clean hole), CC-7 SN BP-723. Cores 2R–21R.		
206	10 Dec 2002	1203	406	Work stuck pipe (stuck when sinker bars pulled).		
206	10 Dec 2002	2040	406	Bit at rotary table: hr = 49.58; cored = 129.9 m (158.0 m in basement).		
206	11 Dec 2002	0845	406	Begin coring Bit 3 (Bit 3: CC-7 SN BP-737). Cores 22R–35R.	Reentry 9, coring Bit 3, Cores 22R–35R	4.43
206	15 Dec 2002	0655	494	Bit at rotary table: hr = 62.9; cored = 88.0 m (244.0 m in basement).		
206	15 Dec 2002	1800	494	Begin coring Bit 4 (Bit 4: CC-9 SN BF-857, no junk basket).	Reentry 10, coring Bit 4, Cores 36R–46R	4.03
206	19 Dec 2002	0740	571	Bit at rotary table: hr = 57.8; cored = 77.0 m (321.0 m in basement). Cores 36R–46R.		
206	19 Dec 2002	1915	571	Begin coring Bit 5 (Bit 5: CC-9 SN BF-738). 3 m soft fill.	Reentry 11, coring Bit 5, Cores 47R–57R	3.95
206	23 Dec 2002	0625	655	Bit at rotary table: hr = 59.4; cored = 84.0 m (405.0 m basement). Cores 47R–57R.		
206	23 Dec 2002	1845	655	Begin coring Bit 6 (Bit 6: CC-9 SN BF-740). Cores 58R–74R.	Reentry 12, coring Bit 6, Cores 58R–74R	4.69
206	27 Dec 2002	2300	752	Bit at rotary table: hr = 64.9; cored = 97.0 m (502.0 m basement).		
206	28 Dec 2002	0622	752	Reentry 13 (logging BHA). Rig-up for logging.	Reentry 13, downhole measurements	3.18
206	30 Dec 2002	2030	752	Rig-down from logging. BGRM did not work; 2 runs. Triple combo, FMS, BGRM, UBI, WST.		
206	31 Dec 2002	0325	752	Bit at rotary table.		
206	31 Dec 2002	0330	752	Beacon recovered after 45 days. Under way to Balboa.		
206					Total:	**37.99**
309	**16 Jul 2005**	**1945**	**752**	**Hole reentered 2.5 years after previous operations.**		
309	17 Jul 2005	0030	752	WSTP and APCT runs.	Reentry 14, downhole measurements	1.41
309	17 Jul 2005	1015	752	Rig up logging equipment		
309	18 Jul 2005	0530	752	End logging (triple combo, FMS).		

Table T4 (continued). (Continued on next page).

Leg	Date	Time	Depth (mbsf)	Comment	Brief run description	Time (days)
309	18 Jul 2005	1500	752	Begin RCB coring Bit 1, Cores 75R–85R.	Reentry 15, coring Bit 7, Cores 75R–85R	4.19
309	22 Jul 2005	1000	821	Bit 1 on deck. Two trimming inserts missing from one cone, 1/16 inch under gauge.		
309	22 Jul 2005	1200	821	Begin coring Bit 2 (C9), Core 86R.	Reentry 16, coring Bit 8, Core 86R	0.86
309	23 Jul 2005	0635	830.6	All core catcher dogs missing; some core fell out of the drill string. Next barrel pulled after noting high pump pressures; deplugger deployed twice.	Core catcher fingers missing	0.17
309	23 Jul 2005	1045	830.6	Resume coring, Cores 87R–96R.	Cores 87R–96R	2.91
309	26 Jul 2005	0830	897.8	Coring Bit 8 on deck. Some broken inserts, ~3/16 inch under gauge.		
309	26 Jul 2005	1000	897.8	Begin coring Bit 3 (BF-854), Cores 97R–107R.	Reentry 17, coring Bit 9, Cores 97R–107R	3.65
309	30 Jul 2005	0000	958.8	Coring Bit 3 on deck. One broken insert, 1/4 inch under gauge.		
309	30 Jul 2005	1000	958.8	WSTP sample.		0.20
309	30 Jul 2005	1445	958.8	Begin coring Bit 4 (BF-856), Cores 108R–111R.	Reentry 18, coring Bit 10, Cores 108R–111R	1.18
309	31 Jul 2005	0905	974.4	After retrieving Core 110R, pressure drop after dropping core barrel. Core barrel pulled, deplugger deployed. Pressure still lower than normal.		1.51
309	31 Jul 2005	1745	979.2	While retrieving Core 111R, pressure drop noted again (~200–250 psi) when lifting BHA off bottom. Pressure increased when weight applied, indicating a crack in BHA. Crack ~300° of the circumference of the 3/4 inch thick bit sub wall (~15 inches from the bit).		
309	1 Aug 2005	0300	979.2	Coring Bit 10 on deck. One broken insert, ~3/16 inch under gauge.		
309	1 Aug 2005	0630	972.2	Begin coring Bit 5 (BF-858), Cores 112R–126R.	Reentry 19, coring Bit 11, Cores 112R–126R	3.96
309	5 Aug 2005	0200	1051.3	Coring Bit 5 on deck. One broken insert, one missing insert, 1/16 inch under gauge.		
309	5 Aug 2005	0215	1051.3	Begin coring Bit 6 (BF-741), Cores 127R–138R.	Reentry 20, coring Bit 12, Cores 127R–138R	3.67
309	8 Aug 2005	1800	1108.9	Bit 12 on deck. One broken insert, one missing insert, 1/16 inch under gauge. Three gauge inserts missing, all from the same row.		
309	8 Aug 2005	1815	1108.9	Begin coring Bit 7 (BF-742), Cores 139R–146R.	Reentry 21, coring Bit 13, Cores 139R–146R	2.81
309	11 Aug 2005	1330	1145.2	While cutting Core 146R, pressure drop noted (100 psi); 350 psi pressure drop noted when drill string pulled off bottom. Core 146R recovered. POOH.		0.40
309	11 Aug 2005	2300	1145.2	BHA on deck. All drill collars and subs inspected. No cracks in BHA.		
309	12 Aug 2005	0415	1145.2	Begin coring Bit 8 (BF-853).		0.61
309	12 Aug 2005	1345	1145.2	Check drill string for cracks with VIT + high-vis mud pill (no pressure increase while filling with seawater every 25 stands). Jet of drilling mud (crack) seen streaming from the 5 inch pipe ~2 stands above the 5-1/2 inch transition pipe.		0.74
309	12 Aug 2005	2030	1145.2	Drill string pulled back and bottom 2 stands of 5 inch pipe replaced.		
309	13 Aug 2005	0730	1145.2	Resume coring, Cores 147R–158R.	Reentry 22, coring Bit 14, Cores 147R–158R	3.51
309	16 Aug 2005	1945	1203.8	Bit 8 on deck. Lost ~2/3 of gauge cutters on 1 cone, 2 cones lost core trimming cutters. Bearings of 3 cones very loose; 1 cone could not be turned.		
309	16 Aug 2005	2000	1203.8	Deploy coring Bit 9 (CL-540), Cores 159R–170R.	Reentry 23, coring Bit 15, Cores 159R–170R	4.26
309	20 Aug 2005	1040	1255.1	Wiper trip.		
309	21 Aug 2005	0200	1255.1	Bit 15 on deck. Some inserts missing from the cones, 4 gauge cutters missing.		
309	21 Aug 2005	0800	1255.1	Reentry for logging.	Reentry 24, downhole measurements	3.46
309	24 Aug 2005	0500	1255.1	Logging completed (triple combo, FMS-sonic, UBI, WST).		
309	24 Aug 2005	1300	1255.1	Depart location.		
309					**Total:**	**38.72**
312	**15 Nov 2005**	**0730**		**Hole reentered 3 months after previous operations.**		
312	15 Nov 2005	2030	1255.1	Trip in to 927 mbsf with coring Bit 1 (C9).		0.67
312	15 Nov 2005	2330	1255.1	Wash and ream to 944 mbsf. Maximum penetration = 1051 mbsf. The 927–944 mbsf interval seemed very tight. Generous mud flushes.	Reentry 25, coring Bit 16, tight hole at 927–944 mbsf	1.66
312	17 Nov 2005	1525	1255.1	On deck.		
312	17 Nov 2005	2100	1255.1	Trip in to 903 mbsf with more aggressive tricone drilling bit (F-2 Smith tricone).	Reentry 26, tricone, wash and ream	2.64
312	18 Nov 2005	0830	1255.1	Wash and ream 903–1255 mbsf (~40 h). Bit stuck at 1198 mbsf for 45 min.		
312	20 Nov 2005	0030	1255.1	Trip out.		
312	20 Nov 2005	0650	1255.1	On deck.		
312	20 Nov 2005	1215	1255.1	Trip in to 1161 mbsf with coring Bit 2 (C9).	Reentry 27, coring Bit 17	1.02
312	20 Nov 2005	2330	1255.1	Wash and ream 1161–1255 mbsf. Debris in bit throat cleared by deplugger round trip.		

Table T4 (continued). (Continued on next page).

Leg	Date	Time	Depth (mbsf)	Comment	Brief run description	Time (days)
312	21 Nov 2005	0715	1255.1	RCB coring 1255.1–1309.7 mbsf (Cores 172R–182R).	Cores 172R–182R	
312	24 Nov 2005	1015	1309.7	On deck (normal wear on cutting structures of the cones, 3/16 inch under gauge, core guides extremely worn).		
312	24 Nov 2005	1600	1309.7	Trip in to 1205 mbsf with coring Bit 3 (C9).	Reentry 28, coring Bit 18	0.61
312	25 Nov 2005	0100	1309.7	Wash and ream 1205–1310.1 mbsf.		0.19
312	25 Nov 2005	0530	1309.7	RCB coring 1310.1–1329.1 mbsf (Cores 183R–187R).	Cores 183R–187R	1.44
312	26 Nov 2005	1600	1329.1	Round trip deplugger at 1329 mbsf.		0.06
312	26 Nov 2005	1730	1329.1	Resume coring 1329.1–1343.5 mbsf (Cores 188R–190R).	Cores 188R–190R	1.35
312	28 Nov 2005	0030	1345.5	On deck (similar to previous, 10 inserts missing from the gage row on 1 cone, chipped teeth on nose region of all 4 cones).		
312	28 Nov 2005	0600	1345.5	Trip in to 1247 mbsf with coring Bit 4 (C9).	Reentry 29, coring Bit 19	0.75
312	28 Nov 2005	1830	1345.5	Wash and ream 1247–1343.5 mbsf.		0.09
312	28 Nov 2005	2045	1345.5	RCB core 1343.5–1348.3 mbsf (Core 191R).	Core 191R	0.41
312	29 Nov 2005	0630	1348.3	Repair standpipe flow sensor.		0.11
312	29 Nov 2005	0830	1348.3	Wash ahead 1299–1348 mbsf.		
312	29 Nov 2005	0915	1345.5	Resume coring 1348.3–1367.5 mbsf (Cores 192R–196R).	Cores 192R–196R	1.88
312	1 Dec 2005	0620	1367.5	On deck (less worn than previous bit, worked only 40.2 h. Few missing and chipped inserts on the gauge row of the cones).		
312	1 Dec 2005	1215	1367.5	Trip in to 1285 mbsf with coring Bit 5 (C7; it was hoped that a more aggressive cutting structure would increase ROP and recovery).	Reentry 30, coring Bit 20	0.82
312	2 Dec 2005	0200	1367.5	Wash and ream 1285–1367.5 mbsf.		0.07
312	2 Dec 2005	0345	1367.5	RCB coring 1367.5–1372.8 mbsf (Cores 197R–200R). Very slow average ROP (0.3 m/h).	Cores 197R–200R	1.22
312	3 Dec 2005	0900	1372.8	Erratic high torque, unable to penetrate further (T/D stalled each time the bit was placed on bottom). Trip out and clear seafloor.	Broken bit	0.13
312	3 Dec 2005	1200	1372.8	On deck (Bit 20 was missing 3 cones and most of the fourth one).		
312	3 Dec 2005	1745	1372.8	Trip in to 1298.0 mbsf with fishing magnet + junk baskets.	Reentry 31, fishing	0.99
312	4 Dec 2005	0400	1372.8	Wash to 1372.8 mbsf and work junk baskets.		
312	4 Dec 2005	0845	1372.8	Trip out.		
312	4 Dec 2005	1150	1372.8	On deck (large fragments of cone and bearing material recovered from magnet face).		
312	4 Dec 2005	1730	1372.8	Trip to 1278.0 mbsf; wash to 1372.8 mbsf with 9.5 inch concave mill + 2 junk baskets.	Reentry 32, milling	1.16
312	5 Dec 2005	0630	1372.8	Mill junk.		
312	5 Dec 2005	1015	1372.8	Flush hole with 50 bbl high-vis mud sweep.		
312	5 Dec 2005	1110	1372.8	Mill junk.		
312	5 Dec 2005	1230	1372.8	Trip out.		
312	5 Dec 2005	1545	1372.8	On deck.		
312	6 Dec 2005	0515	1372.8	Trip to 1294.0 mbsf; wash to 1372.8 mbsf with 9.5 inch concave mill + 1 junk basket.	Reentry 33, milling	1.16
312	6 Dec 2005	1015	1372.8	Mill junk.		
312	6 Dec 2005	1430	1372.8	Flush hole with 50 bbl high-vis mud sweep and trip out.		
312	6 Dec 2005	1930	1372.8	On deck (milling tour worn, very small pieces of cone and bearing material in junk basket); change to fishing magnet number 2 + 2 junk baskets.		
312	7 Dec 2005	0200	1372.8	Trip to 1295.0 mbsf with Bowen fishing magnet + 2 junk baskets.	Reentry 34, fishing	0.97
312	7 Dec 2005	1300	1372.8	Wash 1295–1372.8 mbsf.		
312	7 Dec 2005	1430	1372.8	Work magnet and junk baskets.		
312	7 Dec 2005	1530	1372.8	Trip out.		
312	7 Dec 2005	1850	1372.8	On deck (metal in magnet only fillings, with no solid fragments).		
312	8 Dec 2005	0003	1372.8	Trip to 1294 mbsf with RCB Bit 6 (C9), wash to 1372.8 mbsf, core 1372.8–1398.6 mbsf (Cores 202R–209R).	Reentry 35, coring Bit 21, Cores 202R–209R	3.56
312	11 Dec 2005	0820	1398.6	On deck (Bit 6: uniform wear on the cones consistent with rotating hours).		
312	11 Dec 2005	1545	1398.6	Trip to 1326 mbsf with RCB Bit 7 (C9), wash to 1398.6 mbsf, core 1398.6–1444.6 mbsf (Cores 210R–221R).	Reentry 36, coring Bit 22, Cores 210R–221R; dike/gabbro boundary in Core 213R, on deck at 0800 h on 13 Dec 2005	3.99
312	15 Dec 2005	0810	1444.6	On deck (Bit 8: uniform wear on the cones consistent with rotating hours).		

Table T4 (continued). (Continued on next page).

Leg	Date	Time	Depth (mbsf)	Comment	Brief run description	Time (days)
312	15 Dec 2005	1345	1444.6	Trip to 1368 mbsf with RCB Bit 8 (C9), wash to 1444.6 mbsf, core 1444.6–1507.1 mbsf (Cores 222R–234R.	Reentry 37, coring Bit 23, Cores 222R–234R	4.14
312	19 Dec 2005	0300	1507.1	Treat hole for logging and flush with mud.		
312	19 Dec 2005	1135	1507.1	RCB Bit 8 on deck; change to logging BHA.		
312	19 Dec 2005	1715	1507.1	Trip to 289 mbsf and rig up for logging.	Reentry 38, downhole measurements	4.25
312	23 Dec 2005	1200	1507.1	End logging (triple combo, VSI, FMS-sonic, UBI, FMS, TAP/DLL/SGT).		
312	23 Dec 2005	1730	1507.1	Trip out and secure for voyage.		
312					**Total:**	**38.42**
335	**19 Apr 2011**	**1730**	**1507.1**	**Hole rentered 5.5 years after previous operations.**		
335	19 Apr 2011	1800	1507.1	Continue to RIH with 5-1/2 inch drill pipe to 925.0 mbsf, where formation took 25,000 lb. Cancel attempt to obtain temperature log and water sample.	Reentry 39, Run 335-1, attempt to obtain temperature profile and water sample	0.02
335	19 Apr 2011	2145	1507.1	Pull back in the hole 925.0–891.9 mbsf.	Obstruction at ~925 mbsf, washing and reaming	1.91
335	19 Apr 2011	2330	1507.1	Run in with T/D and work pipe at 920–925 mbsf, where problems were encountered during Expedition 312. Erratic torque with T/D current = 500 A.		
335	20 Apr 2011	0115	1507.1	Pull back 920–891.5 mbsf and change out swivel packing.		
335	20 Apr 2011	0245	1507.1	Resume washing/reaming 891.5–923.3 mbsf. Work stuck pipe from 0415 to 0515 h; rotation lost. Unable to apply >10,000 lb WOB without stalling T/D. Circulate a total of 600 bbl of hi-vis gel during the 24 h period. Unable to penetrate deeper than 923.3 mbsf. Pump 150 bbl sweep at 923.3 mbsf.		
335	21 Apr 2011	0600	1507.1	POOH from 923.3 mbsf. Bit clears rotary at 1550 h.		
335	21 Apr 2011	1545	1507.1	Make up new Reed 9-7/8 inch tricone (more aggressive structure), bit sub with float valve, and tandem set of boot baskets. RIH with the drill pipe to 892.1 mbsf.	Reentry 40, Run 335-2, tricone + 2 junk baskets, washing and reaming	1.64
335	22 Apr 2011	0445	1507.1	Wash/ream hole from 892.1 to bridge at ~920 mbsf. Pump 50 bbl hi-vis mud sweep.		
335	22 Apr 2011	0630	1507.1	Work stuck pipe.		
335	22 Apr 2011	0745	1507.1	Wash/ream hole from ~920 mbsf. Circulate 100 bbl hi-vis mud sweep.		
335	22 Apr 2011	1000	1507.1	Work stuck pipe.		
335	22 Apr 2011	1200	1507.1	Wash/ream hole from ~923 mbsf. Unable to pass bridge.		
335	22 Apr 2011	2100	1507.1	POOH, clear seafloor at 0005 h and rotary table at 0605 h. Lay out junk baskets and bit. Contents of junk baskets inconclusive; yielded some basaltic cuttings ranging from small gravel to rounded pebbles. Expedition 312 logs indicate a large washed out zone at ~920–935 mbsf; decision to attempt to stabilize with a 5 bbl cement plug.		
335	23 Apr 2011	0700	1507.1	Make up cementing BHA with used Reed tricone bit without jets and 2 stands of drill collars. RIH to bridge at 922 mbsf.	Reentry 41, Run 335-3, cementing (5 bbl)	0.93
335	23 Apr 2011	1845	1507.1	Make up circulating head, lo-torque valves, and pressure test to 1500 psi.		
335	23 Apr 2011	1915	1507.1	Pump 5 bbl of 16 ppg cement slurry.		
335	23 Apr 2011	1930	1507.1	Displace drill string with seawater (1 × volume).		
335	23 Apr 2011	2000	1507.1	Lay out circulating head and pull back in the hole with the drill string to 806.9 mbsf.		
335	23 Apr 2011	2030	1507.1	Flush drill string with seawater (3 × volume).		
335	23 Apr 2011	2145	1507.1	Lay out circulating head and POOH. Bit at rotary table at 0515 h.		
335	24 Apr 2011	0515	1507.1	Make up new 9-7/8 inch Atlas tricone bit, inspect float, pick up 2 drill collar stands from derrick. Trip drill string to 922 mbsf.	Reentry 42, Run 335-4, tricone, washing and reaming	1.04
335	24 Apr 2011	1930	1507.1	Pull back in the hole to 890.6 mbsf, run in hole with T/D to 922 mbsf.		
335	24 Apr 2011	2045	1507.1	Attempt to wash/ream though bridge; high erratic torque; maximum T/D = 650 A.		
335	24 Apr 2011	2145	1507.1	Pull back with T/D to 890.6 mbsf, POOH. Bit at rotary table at 0615 h.		
335	25 Apr 2011	0615	1507.1	Make up cementing bit (Reed 517; no nozzles) to 2 stands of drill collars, RIH to 922 mbsf.	Reentry 43, Run 335-5, cementing (50 bbl)	0.90
335	25 Apr 2011	1715	1507.1	Install circulating head. Pressure test cement system.		
335	25 Apr 2011	1800	1507.1	Mix and pump 50 bbl of 15 ppg cement slurry.		
335	25 Apr 2011	1845	1507.1	Displace cement slurry with seawater.		
335	25 Apr 2011	1900	1507.1	Lay out circulating head and pull back in the hole to 720.5 mbsf.		
335	25 Apr 2011	1945	1507.1	Circulate and flush drill pipe with seawater (3 × volume).		
335	25 Apr 2011	2045	1507.1	POOH with the drill string to surface. Bit at rotary table at 0345 h.		

Table T4 (continued). (Continued on next page).

Leg	Date	Time	Depth (mbsf)	Comment	Brief run description	Time (days)
335	26 Apr 2011	0345	1507.1	Pick up 9-7/8 inch Atlas HP61 tricone with tandem boot baskets and 2 stands of drill collars. Run in hole to firm contact with cement at 882.0 mbsf.	Reentry 44, Run 335-6, drilling cement, washing and reaming	2.47
335	26 Apr 2011	1815	1507.1	Drill out cement with T/D 882.0–922.0 mbsf. Circulate 40 bbl gel sweep at 904.6 mbsf.		
335	26 Apr 2011	2230	1507.1	Attempt to drill through bridge with high erratic torque. Circulate 50 bbl gel sweep at 922 mbsf. Continue to wash/ream at 922.0 mbsf. Maximum T/D = 650 A.		
335	27 Apr 2011	0130	1507.1	Work stuck pipe at ~923 mbsf. Maximum T/D = 800 A with 120,000 lb overpull.		
335	27 Apr 2011	0230	1507.1	Resume washing/reaming ledge at 922 mbsf with high rotary speed, high pump, and lighter WOB. mid-morning progress was lost later in the day, which may indicate a shifting obstruction. Circulate multiple 50 bbl hi-vis gel sweeps at 922 mbsf. Continue to wash/ream obstruction at 921.6 mbsf (tide ± 0.5 m). Circulate 100 bbl hi-vis gel sweep at 922.0 mbsf.		
335	28 Apr 2011	0600	1507.1	POOH, clear seafloor at 0850 h and bit at rotary table at 1455 h. Bit in good condition with no appreciable shirttail wear, all teeth intact, and exhibiting very little wear.		
335	28 Apr 2011	1500	1507.1	Make up new Smith tricone bit, bit sub with float, and 4 stands of drill collars; RIH with drill string to 861.4 mbsf. RIH with T/D 861.4–921.9 mbsf.	Reentry 45, Run 335-7, washing and reaming, reached bottom	3.49
335	29 Apr 2011	0615	1507.1	Attempt to pass obstruction with pump and no rotation. No advance. Resume washing/reaming, drill through obstruction at 935.0 mbsf, and advance 921.9–941.5 mbsf. Circulate 100 bbl gel sweep at 931.0 mbsf.		
335	30 Apr 2011	0000	1507.1	Continue to wash/ream 941.5–1143.2 mbsf. High torque and pump pressure increase of 500 psi when picking off slips at last connection. Circulate 50 bbl hi-vis gel sweeps at 988.6 and 1113.6 mbsf. Work back to 1114.4 mbsf and work out excess pump pressure and torque.		
335	30 Apr 2011	1400	1507.1	Resume washing/reaming 1143.2–1162.4 mbsf. High torque and increase of 500 psi pump pressure when coming off slips on last connection.		
335	30 Apr 2011	1630	1507.1	Work stuck pipe free.		
335	30 Apr 2011	1830	1507.1	Wash/ream 1162.4–1507.1 mbsf. Circulate 50 bbl hi-vis gel sweeps at 1142.6 and 1253.6 mbsf. Find 6 m of hard fill. Circulate 100 bbl hi-vis gel sweep.		
335	1 May 2011	1030	1507.1	Pull back in the hole with T/D 1507.1–1265.0 mbsf.		
335	1 May 2011	1245	1507.1	Pull back in the hole with drill string 1265.0–890.5 mbsf.		
335	1 May 2011	1530	1507.1	RIH with drill string and T/D to 967.3 mbsf with no drag or overpull.		
335	1 May 2011	1630	1507.1	Break circulation; spot 60 bbl of 10.5 ppg mud at 967 mbsf. POOH; bit at rotary table at 0245 h.		
335	2 May 2011	0245	1507.1	Make up cement BHA with used Reed 9-7/8 inch bit (without jets) and RIH to 960.5 mbsf.	Reentry 46, Run 335-8, cementing	1.02
335	2 May 2011	1615	1507.1	Make up circulating head and pressure test to 2000 psi; mix and pump 60 bbl of 15 ppg cement slurry.		
335	2 May 2011	1715	1507.1	Displace cement with seawater.		
335	2 May 2011	1745	1507.1	Lay out circulating head and pull back in the hole to 605.5 mbsf.		
335	2 May 2011	1845	1507.1	Flush drill string with seawater (3 × volume).		
335	2 May 2011	1945	1507.1	POOH with the drill string. Bit at rotary table at 0315 h.		
335	3 May 2011	0315	1507.1	Lay out Reed tricone bit and pick up RCB assembly (coring Bit 1), RIH to tag contact (ledge or top of plug) at 924.0 mbsf.	Reentry 47, Run 335-9, coring Bit 24 (first of Expedition 335), cement coring (no recovery)	1.85
335	3 May 2011	1500	1507.1	Pull back in the hole 924.0–891.5 mbsf, pick up T/D.		
335	3 May 2011	1600	1507.1	Drop nonmagnetic core barrels. Establish SCR parameters.		
335	3 May 2011	1745	1507.1	Cut cement cores 924.0–971.3 mbsf (Cores 1G–5G: no recovery).		
335	4 May 2011	0600	1507.1	Pull back in the hole to 833.9 mbsf.		
335	4 May 2011	0845	1507.1	Drop wash barrel, RIH 833.9–971.3 mbsf.		
335	4 May 2011	1030	1507.1	Round trip wash barrel and core 971.3–980.9 mbsf (Core 6G).		
335	4 May 2011	1330	1507.1	Drop wash barrel and wash 980.9–1507.1 mbsf. Note tight hole at 1499.6–1501.1 mbsf. Pump 50-bbl hi-vis sweeps at 1154.6 and 1501.1 mbsf		
335	4 May 2011	2245	1507.1	Circulate 50-bbl hi-vis gel sweep.		
335	4 May 2011	2345	1507.1	Deploy sinker bars. Round trip wash barrel at 1497.0 mbsf. Drop fresh core barrel.	Cores 235R–236R (total 94 cm, undergauge pieces)	0.72
335	5 May 2011	0145	1507.1	RCB core 1507.1–1516.5 mbsf (Cores 235R–236R), using half-cores with no liners to improve recovery. All cores obtained with nonmagnetic core barrels.		

Table T4 (continued). (Continued on next page).

Leg	Date	Time	Depth (mbsf)	Comment	Brief run description	Time (days)
335	5 May 2011	1700	1516.5	Attempt to core 1516.5–1518.2 mbsf (Core 237R) with maximum overpull = 60,000 lb, maximum T/D = 800 A, WOB = 0. Circulate 50 and 100 bbl hi-vis gel sweeps at 1518.2 mbsf after retrieving Core 237R.	Core 237R	1.53
335	5 May 2011	2145	1520.2	Drop core barrel and attempt to core 1518.2–1520.2 mbsf (Core 238R; tide ± 0.8 m). Pump 50-bbl hi-vis sweep at 1520.2 mbsf. Average ROP for 5 May was 0.7 m/h. 3 cm × 20 cm rollers.	Core 238R (3 rollers)	
335	6 May 2011	1330	1520.2	Drop bit deplugger. Examine core catcher sub: ~0.5 inch abraded away, indicating downhole mechanical problem. Recover deplugger. Pump 70 bbl of 10.5 ppg mud.		
335	6 May 2011	1645	1520.2	Pull back in hole with drill string to 58.2 mbsf, flush with seawater to clean reentry cone.		
335	6 May 2011	2100	1520.2	POOH. Clear the rotary at 0545 h. Bit body honed to a smooth profile at the bottom and on the sides. Bit missing all 4 cones, 4 legs, and core guides. Bit spiral stabilizer blades and embedded TCI inserts absent. Bit totally unrecognizable.	Disintegrated coring bit!	
335	7 May 2011	0545	1520.2	Prepare and make up Bowen 9 inch fishing magnet with 2 boot baskets to 2 stands of drill collars and RIH to 3632 mbrf.	Reentry 48, Run 335-10, fishing (magnet + 2 junk baskets)	1.43
335	7 May 2011	1630	1520.2	Search and position vessel for reentry. Observe reentry cone clouded over with mud. Attempt reentry, miss cone, and pull back. Break circulation and reenter at 1815 h.		
335	7 May 2011	1815	1520.2	RIH with drill string to 1294.6 mbsf. Contact ledge that takes 10,000 lb.		
335	7 May 2011	2245	1520.2	RIH with T/D to 1434.2 mbsf. Tight hole at 1328.7 mbsf takes 10,000 lb. Excessive rotary current at 20 spm. Increase in pump pressure (2500 psi at 20 spm). Bleed off pressure at rig floor.		
335	8 May 2011	0145	1520.2	Pull back in the hole 1434.2–1395.8 mbsf; attempt to unplug drill string with high pressure. No joy.		
335	8 May 2011	0300	1520.2	POOH to 264.2 mbsf just inside casing shoe; attempt to circulate with circulating head. No Joy.		
335	8 May 2011	0715	1520.2	POOH from 264.2 mbsf and clear seafloor at 0755 hr. 4 m of fine cuttings plugging inside bit sub and 2 junk baskets. Magnet at the rotary table at 1555 h.		
335	8 May 2011	1600	1520.2	Make up Atlas tricone bit to dual set of junk baskets with 3 drill collar stands and deploy to 1356.1 mbsf, where bit contacts ledge. Pull back to 1324.3 mbsf.	Reentry 49, Run 335-11, tricone + 2 junk baskets	1.84
335	9 May 2011	0715	1520.2	Pickup T/D and obtain SCR parameters. Clean up ledge at 1356.1 mbsf and continue in the hole to 1442.5 mbsf. Circulate 100 bbl hi-vis gel sweep at 1442.5 mbsf.		
335	9 May 2011	1000	1520.2	RIH 1442.5–1520.3 mbsf. Clean up undergage areas of hole: maximum T/D = 500 A. Circulate 100 bbl hi-vis gel sweep at 1520.3 mbsf. Continue to circulate, work rathole at 1520.3 mbsf. Circulate 100 bbl hi-vis gel sweep and circulate seawater (3 × volume).		
335	9 May 2011	1615	1520.2	Pull back in the hole with T/D 1520.3–1363.0 mbsf. RIH and tag ledge at 1473 mbsf. Work through ledge with pumps and rotation. Observe excess pump pressure and torque off slips at 1477.5 mbsf. Unable to pump. Reestablish rotation and circulation.		
335	9 May 2011	1930	1520.2	Work pipe from 1477.5 back to 1459.0 mbsf. Clear excess pump pressure and torque. Maximum T/D = 700 A, maximum pump pressure = 3000 psi.		
335	9 May 2011	2015	1520.2	Ream 1477.6–1484.6 mbsf. Continue with T/D to 1518.2 mbsf, pump 150 bbl gel sweep.		
335	10 May 2011	1130	1520.2	POOH. Flush top of cone with seawater. Bit at rotary at 1130 h. Empty junk baskets.		
335	10 May 2011	1215	1520.2	Make up Bowen RCJB, 1 junk basket, and 2 stands of drill collars. RIH to 1327.5 mbsf; RIH with T/D to 1517.9 mbsf.	Reentry 50, Run 335-12, RCJB + EXJB	1.74
335	11 May 2011	0630	1520.2	Clean hole. Circulate at 150 spm with 1600 psi. Find 2.5 m of fill. Pump 100 bbl hi-vis sweep and chase with seawater (1.5 × volume).		
335	11 May 2011	0930	1520.2	Drop stainless steel ball at 0937 h and activate reverse circulation in Bowen junk basket.		
335	11 May 2011	1000	1520.2	Attempt to drill over junk at the bottom of the hole.		
335	11 May 2011	1030	1520.2	POOH. Clear top of cone at 1520 h. BHA drill collars up to T/D filled with fine cuttings (50 m, several hundred kg). Coarser gravel found in the head, crossover, and bit subs. ~20 kg of granoblastic dike rocks in Bowen RCJB.		

Table T4 (continued). (Continued on next page).

Leg	Date	Time	Depth (mbsf)	Comment	Brief run description	Time (days)
335	12 May 2011	0600	1520.2	Make up Bowen tool with 1 junk basket and 2 stands of drill collars; RIH to 1384.8 mbsf.	Reentry 51, Run 335-13, RCJB + EXJB	1.28
335	12 May 2011	1730	1520.2	RIH with T/D and rotation and circulation past a soft tag at 1465.0 mbsf and a hard tag at 1518.0 mbsf. Backflow on connections starting at 1470.0 mbsf.		
335	12 May 2011	2015	1520.2	Work drill string to 1518.0 mbsf and fail in an attempt to penetrate to 1520.2 mbsf with maximum WOB = 2000–4000 lb, and 160 spm at 1600 psi. Maximum T/D = 200–400 A. Circulate 100 bbl hi-vis sweep, and chase with seawater (2 × volume).		
335	12 May 2011	2215	1520.2	Drop stainless ball to activate reverse circulation. Apparently unable to shear pins in tool with pump pressure up to 3000 psi at 50 spm.		
335	12 May 2011	2300	1520.2	POOH, clear seafloor at 0340 h. Bowen RCJB at rotary table at 1100 h: contains large granoblastic dike rocks (up to 4.5 kg). RCJB was activated by the stainless ball. Loss of circulation probably due to clogged jets. Almost entire BHA filled with fine cuttings.		
335	13 May 2011	1245	1520.2	Pick up Homco 9-3/4 inch FTJB with bit sub junk basket and float, 2-stand BHA, and boot basket. RIH to 1517.2 mbsf. Pump 100 bbl sweep and continue to work down to top of fish at 1521.0 mbsf.	Reentry 52, Run 335-14, FTJB + BSJB	1.34
335	14 May 2011	0815	1520.2	Attempt to recover junk/fish. Circulate 50 bbl sweep at 1520.0 mbsf.		
335	14 May 2011	0945	1520.2	POOH. Rack back drill collars. HOMCO FTJB clears rotary at 2010 h. Empty FTJB of 2 rocks (combined weight = 3.2 kg). Lower set of junk catcher fingers completely torn out.		
335	14 May 2011	2100	1520.2	Make up new Smith hard formation 9-7/8 inch tricone bit with 1 junk basket to 3-stand BHA and RIH to 1371.8 mbsf.	Reentry 53, Run 335-15, tricone + junk basket	1.80
335	15 May 2011	1245	1520.2	Resume RIH with T/D from 1371.8 mbsf. Tag soft fill at 1510.0 mbsf and hard tag at 1518.8 mbsf.		
335	15 May 2011	1415	1520.2	Pick up 30 ft knobby and work bit with light WOB at 1518.5 mbsf and then to 1520.6 mbsf multiple times, attempting to stabilize bottom 2–3 m of the hole. Hole seems to pack off below 1518.0 mbsf and requires working back to bottom. Circulate multiple mud sweeps at 1520.6 mbsf (total = 400 bbl). Continue to work drill string 1518.5–1521.05 mbsf. Pump 200 bbl of sweeps. Pull drill string to inspect and change bit.		
335	16 May 2011	0615	1520.2	POOH, clear the seafloor at 1015 h. Bit clears rotary at 1545 h. Inspect bit and find bearings still tight with virtually no wear on teeth except for a single chipped tooth on the heel. The bit is undergage by 0.4 inch with some shirttail wear and minor junk damage on the body.		
335	16 May 2011	1615	1520.2	Make up new 9-7/8 inch Smith FH3VPS tricone to a 3-stand BHA and RIH to 1399.7 mbsf, and to 1516.5 with T/D.	Reentry 54, Run 335-16, tricone bit	1.76
335	17 May 2011	0815	1520.2	Wash/ream 1516.5–1519.7 mbsf. Circulate 60 bbl sweep at 1516.7 mbsf. Flush hole with 200 bbl of mud at 1519.6 mbsf.		
335	18 May 2011	0100	1520.2	POOH. Clear seafloor at 0340 h. Bit at rotary table at 0900 h. Tricone bit in gauge, minus 6 teeth on one cone.		
335	18 May 2011	1030	1520.2	Make up 9-5/8 inch flat-bottomed mill with EXJB and 3-stand BHA; RIH to 1429.9 mbrf. Continue to RIH with the T/D 1429.9–1520.0 mbsf.	Reentry 55, Run 335-17, milling tool	1.70
335	19 May 2011	0130	1520.2	Mill debris at 1520.0–1521.0 mbsf. Use junk basket pump sweeps. Pump 200 bbl sweep at 1520.0 mbsf.		
335	19 May 2011	1330	1520.2	Circulate 100 bbl sweep and chase same with seawater (2 × volume).		
335	19 May 2011	1445	1520.2	POOH, clear seafloor at 1920 h. Used mill at rotary table at 0315 h. Clean and lay out damaged junk basket. Mill heavily worn and undergage by ~0.5 inch.		
335	20 May 2011	0315	1520.2	Pick up new 9 inch flat mill with fresh junk basket and RIH to 1458.6 mbsf.	Reentry 56, Run 335-18, milling tool	1.40
335	20 May 2011	1845	1520.2	RIH with T/D and tag fill at 1518.9 mbsf. Advance with low pump and rotary speed and tag hard fill at 1520.4 mbsf.		
335	20 May 2011	1945	1520.2	Mill junk and work junk basket. Pump several sepiolite sweeps and circulate out.		
335	21 May 2011	0300	1520.2	POOH, clear the seafloor at 0645 h; milling tool at the drill floor at 1225 h. Abrasive surface of the milling tool eroded away; some external junk damage on the side of the tool and the crossover sub directly above the mill. In addition to the usual rock fragments and fine cuttings, some flakes of what appears to be freshly ground metal.		

Table T4 (continued). (Continued on next page).

Leg	Date	Time	Depth (mbsf)	Comment	Brief run description	Time (days)
335	21 May 2011	1245	1520.2	Make up RCJB with 3 EXJBs and deploy along with a 2-stand BHA. RIH to 1405.7 mbsf with drill pipe, and then to 1519.5 mbsf. Hard tag at 1519.5 mbsf.	Reentry 57, RCJB + 3 EXJB	1.22
335	22 May 2011	0315	1520.2	Work junk baskets. Pump 100 bbl sweep and chase with seawater (2 × volume).		
335	22 May 2011	0545	1520.2	Drop stainless steel activation ball in open pipe. Advance RCJB to 1520.5 mbsf with slow rotation and light WOB. Jog rotation attempting to catch debris.		
335	22 May 2011	0700	1520.2	POOH with the drill string and clear seafloor at 1015 h; RCJB at rotary table at 1645 h.		
335	22 May 2011	0730	1520.2	Rack T/D.		
335	22 May 2011	0800	1520.2	POOH with the drill string and clear seafloor at 1015 h. Rack back BHA. RCJB at rotary table at 1645 h. Empty RCJB of congealed sepiolite and 4 large rocks (total weight = 8.9 kg; largest rock = 3.9 kg). Unload 3 EXJBs of cuttings and a few small metal fragments.		
335	22 May 2011	1800	1520.2	Rebuild and make up RCJB and 3 EXJBs with a 2-stand BHA and RIH to 1793 mbrf.	Reentry 58, RCJB + 3 EXJB	1.46
335	23 May 2011	0000	1520.2	Repair pneumatic supply lines for drawworks high clutch.		
335	23 May 2011	0300	1520.2	Resume RIH 1793 mbrf–1519.0 mbsf (TP at 1462.9 mbsf).		
335	23 May 2011	1030	1520.2	Hard tag at 1519.5 mbsf (tide adjusted). Work EXJBs.		
335	23 May 2011	1045	1520.2	Pump 100 bbl sweep followed by seawater (2 × volume).		
335	23 May 2011	1230	1520.2	Drop ball and activate RCJB. Note increase in pressure of 600 psi. Unable to pass hard tag at 1519.0 mbsf with maximum WOB = 7000 lb with very slow rotation.		
335	23 May 2011	1315	1520.2	POOH. Clear seafloor at 1725 h. Slip and cut 115 ft of drilling line. Resume POOH. RCJB at the rotary table at 0215 h. RCJB contains 3 rocks (total weight = 5.0 kg). One rock (1.4 kg) is gabbro. Angularity of the rocks indicates that they were freshly deposited with a suspected origin somewhere in the bottom 7 m of the hole. EXJBs contain gravel sized cuttings to small pebbles.		
335	24 May 2011	0500	1520.2	Make up RCJB and 3 EXJBs with 2-stand BHA and RIH to 1434.4 mbsf (Reentry 21), and then with T/D and minimum pump/rotation. Tag soft fill at 1518.8 mbsf.	Reentry 59, RCJB + 3 EXJB	1.14
335	24 May 2011	1615	1520.2	Wash down to 1519.8 mbsf and work junk baskets.		
335	24 May 2011	1630	1520.2	Pump 100 bbl of sepiolite sweep mud and chase with seawater (2 × volume).		
335	24 May 2011	1800	1520.2	Drop ball, activate RCJB, and work same.		
335	24 May 2011	1845	1520.2	Displace lower portion of annulus with 200 bbl of drill water in preparation for logging.		
335	24 May 2011	1930	1520.2	POOH. Clear seafloor at 0100 h and rotary table at 0700 h. Disassemble and empty RCJB of 4 small cobbles. Empty 3 EXJBs and clean out the usual assortment of cuttings, etc.		
335	25 May 2011	0815	1520.2	Make up Bowen fishing magnet and 3 EXJBs and RIH to 1462.6 mbsf, and then with T/D to 1519 (tag fill). Wash down to 1520.0 mbsf. Work fishing magnet and junk baskets.	Reentry 60, Bowen fishing magnet + 3 EXJB	1.03
335	25 May 2011	2230	1520.2	Displace lower annulus with 200 bbl of drill water (preparing hole for logging).		
335	25 May 2011	2300	1520.2	POOH. Clear seafloor at 0230 h and rotary table at 0900 h. Disassemble and empty EXJBs. Fishing magnet contained very little metal debris, all of which was finely ground!??!		
335	26 May 2011	0900	1520.2	Make up and deploy logging bit and collars; RIH to 203.3 mbsf. Pick up 2 knobbies and set end of pipe at 218.9 mbsf. Rig up for logging.	Reentry 61, downhole measurements (triple combo, FMS, UBI)	1.08
335	26 May 2011	2030	1520.2	Make up Log 1 (triple combo-GR/APS/HLDS/HRLA/GPIT). Deploy Log 1 into the pipe at 2255 h. Reached the bottom of the hole at 1520.0 mbsf. Recover tool at 0700 h.		
335	26 May 2011	2300	1520.2	Deploy Log 1 into pipe at 2255 h.		
335	27 May 2011	0700	1520.2	Disassemble triple combo. Make up Log 2 (FMS-sonic); deploy into pipe at 1050 h.		
335	27 May 2011	1100	1520.2	Tool unable to exit pipe into hole. Recover FMS-sonic at 1410 h. Replace damaged lower centralizer spring and redeploy FMS-sonic at 1500 h. Tool appears to jam inside BHA with lower section (~20 m) of unit extending 20 m into the open hole. Attempt to pump tool clear without success.	FMS stuck in logging bit; end of logging	1.13
335	27 May 2011	1815	1520.2	Make up Kinley cutter assemblies. Drop crimper in pipe at 2135 h. Assemble Kinley severing tool and drop into pipe at 2315 h; drop hammer and logging cable at 0115 h.		
335	28 May 2011	0330	1520.2	Recover and tie back logging cable. POOH. Clear seafloor at 0425 h.		
335	28 May 2011	1200	1520.2	Release jammed FMS-sonic tool from landing saver sub in BHA. Tool is in good condition.		

Table T4 (continued).

Leg	Date	Time	Depth (mbsf)	Comment	Brief run description	Time (days)
335	28 May 2011	1400	1520.2	Make up RCB 3-stand BHA with new RCB C9 bit. Check core barrel space-out and RIH to 1430.5 mbsf. Recover VIT and coat line on the way out. RIH with T/D to 1520.2 mbsf. Circulate 100 bbl sweep at 1520.0 mbsf.	Reentry 62 (24 and last of Expedition 335), coring (RCB C9 bit), Core 239R (36% recovery; rollers)	0.97
335	29 May 2011	0515	1521.6	Drop fresh core barrel and rotary core 1520.2–1521.6 mbsf (Core 239R) at an average ROP = 0.6 m/h. Average recovery = 36%. No indication of metal in the core barrel. No symptoms of downhole junk in the coring process. Time for coring expires. Prepare for cementing. Circulate 50 bbl sweep at 1521.6 mbsf.		
335	29 May 2011	1015	1521.6	RIH with the coring line to 1510.6 mbsf and coat same on retrieval. Rack sinker bars and dress for layup period. Pull back in the hole with the T/D to 1487.8 mbsf.		
335	29 May 2011	1315	1521.6	Make up circulating head and pressure test. Position bit at 1518.6 mbsf.	Cementing BOH (10 m) and 910–940 mbsf interval to stabilize hole for Superfast 5	0.28
335	29 May 2011	1345	1521.6	Mix and pump 15 bbl of 15 ppg cement. Displace cement with seawater.		
335	29 May 2011	1445	1521.6	Lay out circulating head and pull back in the hole to 1372.6 mbsf. Flush drill string with seawater (2 × volume). Pull back with the drill string to 940.8 mbsf.		
335	29 May 2011	1715	1521.6	Mix and pump 58 bbl of 15 ppg cement slurry. Displace cement with seawater.		
335	29 May 2011	1845	1521.6	Pull back with the drill string to 739.3 mbsf. Flush drill string with seawater (2 × volume).		
335	29 May 2011	2000	1521.6	POOH with the drill string to 3295.4 mbsf. Clear top of cone at 2135 h.	POOH; end of Expedition 335	0.05
335	30 May 2011	0700	1521.6	Recover beacons and secure vessel for sea. Under way to Panama.	End of Expedition 335	
335					**Total:**	**40.56**
1256D					**Total:**	**155.69**

Gray = beginning and end of legs, casing operations; blue = downhole measurements; green = coring; red = hardware failure and hole remediation/stabilization. CADA = cam-actuated drill-ahead, BCR = bi-center reamer, BHA = bottom-hole assembly, TD = total depth, POOH = pull out of hole, WOW = waiting on weather, BGRM = Bundesanstalt für Geowissenschafen und Rohstoffe magnetometer, triple combo = triple combination, FMS = Formation MicroScanner, UBI = Ultrasonic Borehole Imager, WST = Well Seismic Tool, WSTP = water-sampling temperature probe, APCT = advanced piston corer temperature tool, RCB = rotary core barrel, VIT = vibration-isolated television, ROP = rate of penetration, VSI = Versatile Seismic Imager, TAP = Temperature/Acceleration/Pressure tool, DLL = Dual Laterolog, SGT = Scintillation Gamma Ray Tool, RIH = run in hole, T/D = top drive, WOB = weight on bit, SCR = slow circulation rates, TCI = tungsten carbide inserts, RCJB = reverse circulation junk basket, FTJB = flow-through junk basket, EXJB = external junk basket, TP = total penetration, GR = natural gamma ray logging tool, APS = Accelerator Porosity Sonde, HLDS = Hostile Environment Natural Gamma Ray Sonde, HRLA = High-Resolution Laterolog Array, GPIT = General Purpose Inclinometry Tool, BSJB = bit sub junk basket, BOH = bottom of hole. This table is available in **ASCII** and in Microsoft Excel format (see 104_T4.XLS in CHAPTER_104 in TABLES in **"Supplementary material"**).