Deep Crustal Drilling Engineering Working Group

16-18 October 2017

College Station, Texas

Final Report

Recent International Ocean Discovery Program (IODP) expeditions that focused on drilling into ocean crust had trouble reaching their target depths, thus limiting the science returns on these investments. At the request of the JOIDES Resolution Facility Board (JRFB) at their May 2017 meeting, a working group was formed and convened at the JOIDES Resolution Science Operator (JRSO) in College Station, Texas, to define strategies and engineering recommendations to optimize capabilities on the riserless *JOIDES Resolution* (JR) drilling vessel for deep drilling and coring (≥1.5 km) into hard rock.

The request from the JRFB included the following:

> *The JRFB recommends the immediate formation of a "Deep Crustal Drilling Engineering" working group at the JOIDES Resolution Science Operator (JRSO) with representatives of the JRFB and JRSO, Siem Offshore drilling engineers, and the principal proponents, in order to review the results of Expedition 360 "SW Indian Ridge Lower Crust and Moho, Leg 1" and Expedition 335 "Superfast Spreading Rate Crust, Leg 4" and make recommendations on how to successfully achieve drilling, coring, and logging deeper than 1.5 km into ocean crust hard rock environments. The JRFB will be represented by Clive Neal (chair), Mike Coffin, and Wolfgang Bach. The JRSO will be represented by Mitch Malone and Jay Miller. Other interested parties within IODP, such as engineers from JAMSTEC, will be invited.*

The goal of this working group was to define strategies for deep drilling and coring (≥1.5 km) into hard rock using the riserless *JOIDES Resolution* (JR) drilling vessel. This report is the product of the working group meeting. Attendees included

JRFB: Clive Neal (chair), Wolfgang Bach, Mike Coffin

JRSO: Jay Miller, Tobias Höfig, David Houpt, Peter Blum, Kevin Grigar, Steve Midgley (science staff and engineers)

Siem Offshore: Leon Holloway (management), Mark Robinson (drilling supervisor)

Principal proponents: Henry Dick (Expedition 360), Damon Teagle (Expedition 335)

CDEX/JAMSTEC: Eigo Miyazaki, Nori Sakurai, Yasuhiro Namba (drilling and technology departments)

Other deep ocean crust drilling programs: John Millett (offshore Faroe Islands), Don Thomas, Ron Fierbach (Hawaii Scientific Drilling Project)

Industry engineering developments: Ralf Duerholt (Baker Hughes—drill bits), Jack Setterberg (Weatherford—open hole clad), Graham Riley (Schlumberger—innovations and opportunities)

Hydraulics, well control, well remediation: Jerome Schubert, Sam Noynaert, Nobuo Morita (TAMU Petroleum Engineering)

IODP management: Jamie Austin (IODP Forum), Jamie Allan (NSF)

The conveners are grateful to the funding agencies that provided support for this workgroup and the active participation of all attendees. The review, advice, and recommendations provided are timely and valuable for planning future engineering development and improving JRSO's ability to successfully achieve drilling, coring, and logging deeper than 1.5 km into ocean crust hard rock environments.

Introduction

The working group comprised JRSO staff, JRFB members, proponents from Expeditions 335 and 360, as well as industry and vendor representatives. It was important to note for the industry and vendor representatives that the normal mode of operation for the JR is to operate self-sufficiently for approximately 2 months at a time—resupply from shore is usually not possible.

The first day of the workshop and part of the second was spent on presentations and discussion about the history of deep crustal drilling in the Program over its various incarnations, specific recent examples (Expeditions 335: "Superfast" and Expedition 360: "SloMo"), bit design challenges and solutions, hole management strategies, and examples of successful deep hard-rock drilling projects (Hawaiian Scientific Drilling Project, Faroe Islands, and North Atlantic). The presentations stimulated a plenary discussion regarding specific improvements that could make coring deeper than 1.5 km into ocean crust possible and how some of these new technologies could be tested during the engineering expedition scheduled in 2019 (Expedition 384). This discussion was followed by two breakout groups, one to examine the rig data from Expeditions 335 and 360 and one to discuss the implementation of "Project Coordination Teams" for complex drilling expeditions.

Working group discussion determined that the JRSO engineering section is seriously understaffed to the point that successful implementation of future complex drilling expeditions may not be possible. This led to what may be the most important recommendation from the working group:

Recommendation 1: Additional JRSO Engineering Staff. We recommend that the JRSO employ at least one, and preferably two, additional permanent engineers (FTEs) to ensure that complex drilling projects have the maximum potential for success.

Rationale: Drilling projects that push the boundaries of the JR's technological and engineering capabilities in most cases require more than one engineer to achieve the project's scientific objectives. Current JRSO engineering staffing levels preclude the possibility of involving more than one engineer in an expedition.

1. Project Coordination Team

The JRSO undertakes expeditions across a spectrum of scientific, technological, and engineering complexities. Whereas some expeditions do not challenge extant JR capabilities, others push the boundaries of scientific ocean drilling achievable on the platform. For the latter, the JRSO should establish Project Coordination Teams to determine feasibility and plan, monitor, and evaluate the scientific outcomes of each complex drilling project over its lifetime. These teams should include expertise external to the JRSO on an as-needed basis, science representation, and geotechnical and petrophysical expertise, as well as expertise from Siem and in-house JRSO personnel. Preparation for drilling such complex holes should include a "drilling well on paper" exercise to anticipate potential problems and devise implementable mitigation strategies. These preparations will reduce risk of drilling complex sites and maximize the science return from the program.

Recommendation 2: Project Coordination Teams. We recommend that the JRSO establishes a Project Coordination Team (PCT) for each proposal that presents challenges, as determined by the JRSO and/or JRFB, for existing drilling, coring, and/or logging capabilities aboard the JR. Each PCT should encompass requisite scientific, petrophysics, technological, and engineering expertise (including external when needed) to enable proposed complex drilling operations to develop into successful drilling projects. A PCT would typically be established when a proposal is forwarded from the SEP to the JRFB to consider a balance between scientific objectives and operational constraints, monitor the progress of an expedition, and evaluate the operational outcomes of an expedition. Each PCT will likely have different detailed responsibilities because each drilling project has different scientific objectives.

2. Technical Advisory Team

Some expeditions encounter technological and/or engineering challenges. To obtain lessons learned and to advance the scientific, technological, and engineering capabilities of the JR, a standing Technical Advisory Team (TAT; analogous to the current Laboratory Working Groups that the JRSO has already established) should be established to review, analyze, and evaluate operations during each challenging expedition, or review an operational plan before a particularly challenging expedition, as determined by the JRSO.

Recommendation 3: Technical Advisory Team. The JRSO should establish a permanent Technical Advisory Team that meets as needed to review, analyze, and evaluate operations for challenging expeditions and to make recommendations for improvements. Membership should encompass scientific, technological, and engineering expertise (including external as deemed appropriate). A report for each such expedition should be submitted in a timely fashion to the JRSO and JRFB.

3. Rig Instrumentation System

Drillers and other relevant Siem staff on the JR are only using parts of the existing rig instrumentation system (RIS) that are directly applicable to achieving the specific drilling goals of a given expedition. However, in order to have a meaningful forensic drilling analysis of complex drilling expeditions, the full capability of the RIS should be used. This will allow lessons learned from such complex drilling projects to be derived, so all relevant data from the rig instrumentation system need to be archived in an interpretable form. RIS data can then be used in the evaluation of these projects.

Recommendation 4: Rig Instrumentation System. We recommend that

- Drillers and other relevant Siem staff should be trained to utilize the full capabilities of the rig instrumentation system on the JR and apply this training during the execution of complex drilling projects.
- Relevant rig instrumentation data should be
  - archived in an interpretable form;
  - analyzed and evaluated post-expedition by the Technical Advisory Team, Siem Offshore Installation Manager (OIM), JRSO Operations Superintendent, and other Siem staff as necessary; and
  - open access.

4. Engineering Developments Needed to Drill ≥1.5 km into Hard Rock

This section is divided into two parts. Section A focuses on potential solutions that could be tested during the 2019 engineering expedition. Section B focuses on longer term solutions.

A. Engineering Expedition 384 in 2019

In 2019, engineering Expedition 384 is planned to be located in the area of Holes 1256D and 504B in the eastern Pacific Ocean in approximately 3,500 m water depth. The Working Group strongly recommends that the test site be located in shallower water to reduce pipe/core trip time and therefore maximize the results of this engineering expedition. In addition, this engineering expedition should employ a Project Coordination Team (including the "drilling on paper" exercise) to develop the protocol for application to complex drilling expeditions. From the presentations and discussion, a number of potential technologies were identified that could be tested during this engineering expedition, as itemized below.

Sensor Subs at the Drill Bit. Understanding the environment at the drill bit is critical for enhancing best drilling practices in hard rock formations. Information such as torque at the bit, pressure, and rate of penetration can be assessed with commercially available equipment, although the cost and diameter are not known and whether these can be used while coring still needs to be assessed.

Testing Different Bits (polycrystalline diamond compact [PDC], hybrid, etc.) for Drilling and Coring. Whereas different bit types are easy to test, the 2019 engineering expedition will represent only a single data point (sea conditions, depth, and lithology), so additional data points are needed in the future. The distinction between drilling and coring is highlighted because in some cases drilling a clean hole may be required before coring operations can begin. Additionally, bit testing should be done in conjunction with sensor subs in order to understand the environment at the bit. For example, selective use PDC/diamond core bits (no cones), and combining them with longer sections of drilling with application of specific drill bits (Tricone, Dynamus, TerrAdapt, Kymera) to test longevity, core recovery, etc. Technologies such as sidewall coring should be considered for additional samples in the drilled (but not recovered) sections.

Lined Core Barrels. These core barrels remove the need for core liner, which could be compromised under certain conditions. Whereas chrome-lined core barrels will be tested during the Brothers Arc Flux Expedition 376, core barrels lined with other materials should be tested during other opportunities.

Expandable Casing. Presentations and discussion also focused on improvements in casing technology for downhole stability. Expandable casing can be applied to entire holes or over individual problematic horizons to ensure hole stability. Examination and testing of this technology could improve the deep coring goals of Hole 1256D/Superfast.

Biodegradable Fiber Additives to Drilling Fluid. This new technology simply adds biodegradable fiber to the seawater used to wash out the hole to improve viscosity and cuttings removal. The fibers are biodegradable and dissolve in a few weeks, dependent upon temperature. There is also a compound called Alcomer 120L that is a vegetable derived polymer that adds viscosity (and lubrication) to the drilling fluids. It is also biodegradable and is approved for use in water well drilling (http://www.minex-intl.com/drilling-fluids.php). Another advantage is a little of this goes a long way and may prove to be less taxing on the JR's cargo capacity than high volumes of bentonite gel. Testing these additives could be done in conjunction with drill bit and sensor subs testing to understand how the additive changes the environment at the drill bit.

Recommendation 5: Engineering Expedition 2019. This engineering opportunity should be conducted in the shallowest water possible in the eastern Pacific region in order to minimize time for tripping pipe and retrieving core. This expedition should employ a Project Coordination Team to develop the protocol for application to complex drilling expeditions. Technologies to be tested that could dramatically improve deep crustal drilling and coring include:

- Sensor subs at the drill bit
- Different bits (PDC, hybrid, etc.) for drilling and coring
- Lined core barrels
- Expandable casing
- Biodegradable additives to drilling fluid

B. Engineering Development Beyond 2019

Future engineering testing should include the following technologies that will require long lead times to coordinate for comprehensive testing.

Seabed Hydraulic Pulldown System. This pulldown system could dramatically improve the constancy of weight on bit that in turn could increase core recovery, hole integrity, and rate of penetration.

Resonance Enhanced Drilling. This type of drilling could improve drilling efficiency. There is a potential for collaboration between IODP and the University of Aberdeen on this project, but coordination has not yet begun.

Mud Return System. Recirculating drilling mud would conserve resources but would require infrastructure upgrades (mud cleaning system, cuttings collection, etc.). However, these upgrades could improve drilling efficiency and hole integrity.

Recommendation 6. Future Engineering Testing. The following technologies that enhance deep drilling into hard rock (and others that may develop) should be tested using the JR in future engineering expeditions beyond 2019.

- Seabed hydraulic pulldown system
- Resonance enhanced drilling
- Mud return system

5. Current Complex Drilling Expedition Recommendations

Recommendation 7: Superfast (Site 1256). We recommend establishment of a Superfast-dedicated Project Coordination Team (PCT) to design and develop an efficient and effective technical plan to deepen ODP/IODP Hole 1256D significantly into cumulate gabbros (approximately 1000 m below the current depth of Hole 1256D, 1521 mbsf). The PCT should comprise JRSO operations and science personnel, Siem rig floor specialists, and selected scientists, as well as independent, experienced/recommended drilling engineers and technical consultants.

The PCT should develop a coring plan that includes (1) platform operational approaches; (2) procurement (or even design and manufacture) of ultra-hard-formation drill/coring bits; (3) hole stabilization strategies including casing and liner/patching strategies, including casing through the 23-in rathole and protection of critical intervals (e.g., 920–980 mbsf); (4) hole cleaning, mud approaches (including viscosifiers), reaming, fishing tools, and operations; and (5) cementing strategies.

The team should interrogate existing rig data and undertake hydraulic modeling based on current knowledge of Hole 1256D and the capabilities of the *JOIDES Resolution,* as well as gather and consider both existing and new geotechnical information on the formations to be encountered in Pacific Ocean crust formed at fast spreading rates.

See the "Expedition 335 Operations Review Task Force" report (Appendix A) and "Expedition 335 Lessons Learned" report (Appendix B).

Recommendation 8: SloMo – Atlantis Bank. The Working Group recommends moving the SloMo Phase I deep drill hole location from Site U1473 to Site 735 based on its review of the status of Hole U1473A and the deep penetration previously achieved at Hole 735B. The recommended drilling plan would begin with offsetting a minimum distance from Hole 735B and drilling without coring to 1500 m, logging the section, and setting casing as appropriate to hole conditions before coring ahead to the SloMo Phase I target depth of 3,000 m. Anticipating that hole conditions will be similar to Hole 735B, at least the uppermost 500 m of basement would be cased.

Drilling to 3 km at Site 735 can be accomplished with existing technology; however, potentially dramatic enhancements can be made based on the results of the Working Group review of newer technologies.

First there is a series of new bit designs that have allowed industry to demonstrate rapid penetration of basaltic rock to depths of several kilometers. These bits, though expensive, have the potential to dramatically increase penetration rates, and thus justify their costs. The JRSO should explore this option in full with industry. Second, having the option to deploy expandable casing to stabilize a local patch where a drilling bridge or problematic series of breakouts in the hole below 1500 m would provide additional insurance for success in reaching 3,000 m.

See the Appendix C for the rationale to this recommendation.

6. Future Developments

The following represents developments that would improve drilling and coring of deep holes into hard rocks as well as improve the efficiency of the platform. Many of these represent changes to the ship infrastructure and so are long-term suggestions for consideration by the JRSO and JRFB. A major consideration if and when a new platform is considered includes the self-sufficiency that the

JR affords, as it is a relatively simple platform that allows operation for 2 months at a time in remote locations without shore support. Any added complexity in drilling operations needs to be weighed carefully against the amount of shore-based support that will be necessary for optimal operation.

The following represents a list of issues that need to be investigated in order to improve coring and drilling as well as support more efficient ship operation.

- Improve weight on bit control
- Improve ability to clean holes
- Magnetic induction wireline to check bit competency without a pipe trip
- Larger laboratory space (to lay out more core, allow specialized equipment for specific expeditions, etc.)
- Maintain the ability to transit the Panama Canal
- More efficient/economical propulsion/higher transit speed (more operations time, less cost); for example, seal off moonpool/guide horn/thrusters to reduce drag

7. Final Thoughts

An issue that can positively impact complex drilling expeditions is organizational. A suggested scenario is if the JRFB were to accept a proposal from the SEP that justifies more than one expedition, once the first one is scheduled the proposal stays with the JRFB until the project is complete or the JRFB deems that a new proposal is necessary. This mechanism would allow flexibility of scheduling, minimize the time between expeditions to the same hole (thus reducing time for hole degradation), and protect the project from lack of corporate memory at the SEP when, as is the case now, each expedition requires a separate proposal. The result of the current situation is that science requiring multiple expeditions to the same hole is not set up to maximize success—rather the opposite is the case. The JRFB should discuss this potential change in proposal evaluation and operations.

In reading through the various summaries and reports provided, as well as the presentations of lessons learned from various drilling projects (both within IODP and outside), the following important take-home messages need to be highlighted regarding planning and executing drilling of deep holes into hard rock.

- Detailed planning prior to drilling can greatly reduce risk in a complex drilling project. Engineering support is critical during all stages of a project.
- Hole preservation strategies (casing, cleaning, etc.) need to be developed prior to drilling so the JR has the necessary equipment to allow successful drilling and coring.
- During drilling, knowing what is happening at the bit is necessary in order to take mitigating action earlier in a deteriorating hole.
- Effective communication between engineering and science is essential through all stages.
- Accurate acquisition and preservation of the drilling/rig data and archiving in a form that can be easily retrieved and used is essential for forensic analysis of a complex drilling project.
- Building a database of comprehensive post-drilling performance analyses can and will lead to improved future operational efficiency and problem mitigation.

APPENDIX A

IODP Operations Review Task Force Meeting
Expedition 335

Superfast Spreading Rate Crust 4

March 7th – 8th, 2011

Consortium for Ocean Leadership

Washington DC, USA

EXPEDITION 335 OPERATIONS REVIEW TASK FORCE (ORTF)

PARTICIPANTS

Damon Teagle	Co-Chief Scientist, University of Southampton, UK
Benoît Ildefonse	Co-Chief Scientist, University of Montpellier II, France
Keir Becker	External Reviewer, Miami University, USA
Dave Huey	External Reviewer, Stress Engineering, USA
Haruki Inooka	External Reviewer, JAPEX, Japan
Roy Estes	External Reviewer, Transcontential Supply, USA
Peter Blum	EPM, USIO, TAMU, USA
Mitch Malone	USIO, TAMU, USA
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Gilles Guèrin	USIO, LDEO, USA
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David McInroy	ESO, BGS, UK
Jamie Allan	NSF, USA
Thomas Janecek	NSF, USA
Yoshi Kawamura	IODP-MI
Issa Kagaya	IODP-MI

MEETING FORMAT

The IODP-MI Operations Review Task Force (ORTF) met on March 7th - 8th at the Consortium for Ocean Leadership (COL), Washington DC, to review operational aspects of Integrated Ocean Drilling Program (IODP) Expedition 335 Superfast Spreading Rate Crust 4. The review concentrated on "lessons learned" from the expedition with an emphasis on "what should be done differently in the future". The ORTF review was based upon confidential reports submitted by the U.S. Implementing Organization (USIO) and the Expedition 335 Co-Chief Scientists, as well as the expedition daily and weekly reports available on-line.

The meeting began with oral presentations by the Co-Chief Scientists (Damon Teagle, Benoît Ildefonse) and the Expedition Project Manager (EPM: Peter Blum), that summarized the Co-Chief Scientists' and USIO reports, respectively. The Co-Chief Scientists also presented their Co-chiefs' joint recommendations. Following the presentations, the external reviewers and IODP-MI personnel had an Executive Session to identify important issues related to this expedition and to formulate draft recommendations. On the second day of the meeting, the ORTF reviewed the draft recommendations from the Executive Session and finalized them. These recommendations are presented in this report.

EXPEDITION SUMMARY

Expedition 335: April 13th – June 3rd, 2011
Co-Chief Scientists: Damon Teagle, Benoît Ildefonse
Expedition Project Managers: Peter Blum
USIO Operations Superintendent (OSI): Ronald Grout

The Integrated Ocean Drilling Program (IODP) Expedition 335 was based on the IODP drilling proposal 522Full5 Superfast 4, and was officially scheduled on 25 January 2010 based on advice from IODP Science Advisory Structure (SAS). Expedition 335 was implemented to deepen ODP Hole 1256D a few hundred meters into the cumulate gabbros of the lower crust to test theoretical models of accretion of new crust at mid-ocean ridges.

ODP Hole 1256D was drilled through the 250m thick sediment layer and ~500m into the upper crust lavas, and cased to ~269m, during ODP Leg 206 (2002). The hole was deepened 500m through lavas and into the sheeted dike complex during IODP Expedition 309 (2005) and deepened an additional ~250m during Expedition 312 (2005). The lowermost ~100m drilled during the Expedition 312 penetrated into a complex dike–gabbro transition zone. At the end of Expedition 312, Hole 1256D had a total depth of 1507.1mbsf.

The main objective of drilling into the lower crust and recovering samples of cumulate gabbro was not achieved during Expedition 335. Hole 1256D was only deepened ~14.5m to a total depth of 1521.6mbsf. About 2m of core were recovered from this interval. However, two scientific achievements are noteworthy. First, Expedition 335 had shipped all core sections from the gabbro interval drilled during the Expedition 312 to the *JOIDES Resolution*, and the Expedition 335 scientists spent considerably more time describing those sections than was available to the Expedition 312 scientists. A coordinated sampling party was conducted at the end of the cruise to complement existing studies of those materials with new shore-based investigations. Second, hole cleaning operations using junk baskets returned a large number of rock samples. These samples consisted primarily of completely recrystallized granoblastic basalt with minor gabbroic and evolved plutonic rocks. Their size and quantity make them a unique sampling of the thermal boundary layer in the ocean crust; they reveal the intimate coupling between temporally and spatially intercalated intrusive, hydrothermal, contact-metamorphic, partial melting, and retrogressive processes. Shipboard scientists were enthusiastic about this bounty and committed to a significant post-cruise research program on both these new rocks as well as those recovered during previous expeditions.

See http://iodp.tamu.edu/scienceops/expeditions/superfast_rate_crust.html for more details regarding the background and objectives, the preliminary scientific results, and conclusions of the Expedition 335.

RECOMMENDATIONS OF THE EXPEDITION 335 ORTF

The Expedition 335 ORTF found that this expedition was one of the most difficult and technically challenging expeditions mounted by the USIO during IODP. Operational difficulties in Hole 1256D during Expedition 335 precluded progress towards the scientific objectives, and the hole was only deepened <15m . Hole 1256D now has a total depth of 1521.6mbsf. Scientists have yet to achieve the scientific objectives of the Proposal 522-Fu115 to recover samples of cumulate gabbros at the Hole 1256D. However, in a difficult context, all working teams on Expedition 335 performed remarkably well. The drilling crew of the *JOIDES Resolution* and the USIO staff did a truly exemplary job of opening, stabilizing and cleaning Hole 1256D, through a careful and prudent course of actions.

The ORTF also identified several areas for future *JOIDES Resolution* operational improvement, particularly pre-expedition planning/preparation and during-expedition operations. Specifically, the ORTF recognized that issues related to deep drilling operation in the fractured, hard formation zone of Hole 1256D were more problematic than those identified by the USIO during its operation planning. This is because the limited knowledge of Hole 1256D conditions by the USIO, a difficulty that is inherent to deep drilling in the ocean crust given the limited experience accumulated so far in very deep holes. The USIO needs a strategic planning approach for future deepening the Hole 1256D with better contingency planning to face any event, and a wide range of hard formation drilling equipment to deal with difficult conditions.

The Expedition 335 ORTF has formulated 10 recommendations and one acknowledgement. Although the primary focus of this review was on the USIO operations during the Expedition 335, many recommendations in this report are equally valuable for other IODP operators, the Science Advisory Structure (SAS), the IODP management, IODP scientists, and some of our recommendations are also directed to those groups.

Recommendation 335-01: Strategic Planning Approach for Future Drilling of the Hole 1256D

The ORTF suggests that downhole hardware best suited for drilling, reaming, hole opening and coring should be selected through the process of a formal engineering assessment using, where possible, hard rock drilling specialists from both inside and outside normal IODP domains. This assessment could be organized and directed either by IODP engineers, or by contracted outside consultants. Based on the results of that assessment, *JOIDES Resolution* should be equipped with a comprehensive inventory of hole cleaning, reaming, and drilling hardware, all selected for robust, difficult drilling conditions. However, adequate time, funding and strategic commitment is required. As a first step, the agency or agencies responsible for implementation of this plan must be determined by SIPCOM.

A similar set of recommendations also applies to improvements in tools and techniques for fishing, casing or liners, remedial cementing, and most effective use of mud.

If possible, the IODP-MI should share with the IOs any valuable outcome of an ongoing 2012 engineering assessment aimed at addressing similar drilling and coring issues for BEAM (Borehole into Earth's Mantle).

All of the above must include appropriate definition of required lead times and overall funding requirements and sources, and, of course, must be tempered with awareness of present day fiscal realities for IODP and the NSF.

Routing: USIO, IODP-MI, SIPCOM

Background: Drilling in Hole 1256D, IODP Expedition 335 encountered a significant thickness (>10x m) of extremely hard contact metamorphosed granoblastic basalts, and coring these rocks resulted in the absolute destruction of a C-9 RCB coring. This C-9 bit was ground to a smooth featureless stump after a maximum of only 15 hours coring/rotation. The external reviewers and Co-Chiefs pointed that if the hole was not completely clear of all junk or cavings from the hard / ultra-hard formation, a C-9 bit would have been rapidly damaged.

The Expedition 309/312 ORTF in 2006 discussed and recommended the investigation of finding ultra-hard formation drilling and coring bits but no progress has been made for the Expedition 335 planning.

The ORTF agreed with the request from Expedition 335 Co-Chiefs that future drilling operation in Hole 1256D must be prepared to battle hard/ultra-hard formations, including hard/ultra-hard formation high quality industrial tri-cone bits for hole opening, cleaning/reaming as well as a complete set of hard formation mills and junk baskets. Also the ORTF agreed with the importance of consulting with an experienced/recommended drilling engineer to evaluate the best coring plan, including the procurement (or even design and manufacture) of ultra-hard formation drill/coring bits, fishing tools and its operations, cementing strategies and casing strategies.

Recommendation 335-02: Appropriate Personnel Involvement on Expedition Planning

The ORTF recommends that the USIO should involve appropriate personnel in pre-expedition planning, especially to attend Expedition planning meetings. (Examples of such personnel might include previous Co-chief scientists, senior proponents and the *JOIDES Resolution*'s rig floor expertise.)

Routing: USIO

Background: During Expedition 335, Co-chiefs built an effective relationship with the drilling crew of the *JOIDES Resolution* and the USIO staff, and there was open and productive exchange of information. Also at the end of the Expedition 335 operations, the Co-chiefs organized a formal meeting (attended by Co-chiefs, past Co-chiefs and proponents, EPM, OS, OIM, Core Techs, Tool Pushers, and Driller) for an effective debrief and discussion of issues encountered during the expedition. A wide range of future operation options (casing, cementing, tools, coring, drilling bits, time on site) at the Hole 1256D was discussed, and a series of recommendations was made.

The ORTF agreed that it is very effective to have involvement of experts during the operation planning phase when specific operational difficulties may be anticipated, and different rig floor teams are used to deepen multi-expedition holes. This kind of approach should have been undertaken during the operations planning of Expedition 335.

Recommendation 335-03: Post-Operation Onboard Meeting

The ORTF considers the type of Post-Operation Onboard Meeting that the Expedition 335 had at the end of expedition has real merit and is an effective and efficient mechanism to reflect upon operational challenges during drilling expeditions. Although similar onboard meetings have taken place on some cruises (other USIO/*JOIDES Resolution* expeditions), POOMs should become standard practice and be formal, mandatory and have minutes recorded.

Routing: USIO

Background: The USIO is now holding the Post-Operation Onboard Meeting at the end of most expeditions, either during the return transit or after arrival in port (with attendees listed in Recommendation 335-02). The ORTF recognized that this meeting is very effective to review the operation and identify the issues while the issues on the expedition are still fresh in mind. Similar Post-Operation Onboard meetings have been held on other Expedition, but minutes have not been systematically recorded.

Recommendation 335-04: Ship Schedule Flexibility

The ORTF suggests that when clear progress is being made on a particularly difficult site near the end of expedition, serious consideration should be given to ship schedule flexibility whenever possible, including time extensions (especially where possible in conjunction with ship tie-up schedules, thereby avoiding schedule conflict with next expeditions science party and operation crew).

Routing: USIO, LAs
Background: The Expedition 335 had assigned 45 operation days, which was eventually not enough to achieve its scientific goal, because most of the scheduled time was spent on the remediation of Hole 1256D. Unfortunately, Expedition 335 had to leave Site 1256 only a few hours after coring resumed.
This problem of ship schedule flexibility was already identified in the Expedition 309/312 ORTF meeting in 2006 (Recommendation 309/312-03). However, there was no progress made on this area in the IODP. The external reviewers understand that difficult target with deep drilling expedition such as the Expedition 335 might needs mechanisms for allowing more flexibility, and revising expedition schedules so that drilling can continue in deep boreholes when progress is actually being made. This may require the movement of crew, scientists and supplies to and from the rig so that drilling and hole cleaning can continue, and the temporary postponement of the immediately following expeditions.
The ORTF understands that making the ship schedule more flexible is financially difficult in the current IODP system. However, a flexible ship schedule has considerable advantages over a rigid ship schedule, for achieving some long-standing, technically challenging scientific objectives.

Recommendation 335-05: Rubber Coated Centralizer Blades
ORTF recommends to modify the rubber coated bowsprings of the logging tool centralizers so that the tool can exit the BHA into the borehole for the *JOIDES Resolution* logging operations.

Routing: USIO
Background: Logging operations at Expedition 335 had some difficulty and several bowsprings on the centralizer damaged during the operation. The triple combo tool which was first deployed successfully reached the bottom of Hole 1256D but tool returned with three damaged bowsprings on the upper centralizer and had to replace them. Then FMS-sonic logging tool was deployed as second logging run but was unable to exit the BHA into the borehole because of some mechanical obstruction at the bit. Once the tool returned to the surface, again they found one damaged bowspring on centralizer but this time was in lower centralizer section. USIO tried third run after replacing the damaged bowspring but was also unable to exit the BHA.
The external reviewers pointed out that the problem of this type of centralizer blades causing tools to jam in the bit throat or while passing through a float valve is not new. Past practice to solve the problem was to cut off all rubber before running any logging tool with that type of coating on the stabilizers regardless of logging engineer preferences.

Recommendation 335-06: Hydrodynamic Characteristics and Flow Control Planning of the Hole 1256D

The ORTF recommends that hydrodynamic characteristics of Hole 1256D (and other problematic holes with potential scientific value by deepening) should be analyzed by a qualified drilling engineer / well planner using existing well caliper logs and downhole surveys. This should lead to recommendations for best drilling and coring procedures, predict pressure drops to be expected, and provide an estimation of how much deeper such holes can be drilled within the limits of available hydraulic horsepower on the *JOIDES Resolution*.

The USIO should re-examine the use of the quad-casing potential (include using short liner(s) and/or expandable casing) for remedial flow control of problem areas in Hole 1256D.

Routing: USIO

Background: The Expedition 335 found that Hole 1256D has very complex hydrodynamic characteristics because of several wide diameter sections of the hole (rat hole, washed out section). These sections greatly reduced pumping efficiencies for hole cleaning even when the *JOIDES Resolution* uses high viscosity muds.

A typical example section is located below the 16" casing section. Hole 1256D was equipped with 16" casing down to 269mbsf during the ODP Leg 206. The casing extends ~19m into basement. Below this casing section, there is a ~7m long ~23" diameter rat hole (down to 276 mbsf).

The ORTF recognized that the 23" rat hole below the 16" casing, and washed out section greatly reduced pumping efficiencies when deepening and cleaning the hole.

10-3/4" casing set in 16" casing to the bottom of the 23" rat hole, or setting short liner or expandable casing to cover existing open-hole section would improve the hydrodynamics of Hole 1256D and enable more efficient flow controlling and hole clearing

Recommendation 335-07: Coring Approaches in Hole 1256D

For deepening Hole 1256D, the ORTF recommends consideration of applying spot coring approaches or non-standard coring (conventional/non-wireline and/or thin kerf) techniques at some diameter slightly larger than 9-7/8" to penetrate the final section of the dike/gabbro transition zone, to reach underlying consistent gabbros where continuous coring could resume.

Routing: USIO, Superfast Scientists

Background: The Expedition 335 operation results showed that future deepening and coring operation in the dike/gabbro transition zone in Hole 1256D is feasible but remains challenging. The external reviewers advised that the USIO and the Hole 1256D Co-Chiefs should concentrate on deepening the hole to reach the scientific target depth by industrial type conventional drilling with a full-face bit (e.g. using a 9-7/8-inch tri-cone bit and adequate drill collars to present appropriate weight on bit for the specific type of bit selected). The external reviewers pointed out that using such techniques will preclude continuous coring in the difficult interval. After deepening the hole and reaching the main

scientific target, coring could resume with less operation difficulty.
Also one of external reviewer introduced that conventional/industry hard rock coring system would be an option to take cores from the dike/gabbro transition zone. This system has typically 15-30 feet long non wireline type core barrels and takes a large diameter core which is captured in a core barrel above the bit, but only removed when the entire drill string and BHA are recovered on deck. This type of system was already used in IODP on Expedition 331 by *CHIKYU*.

Recommendation 335-08: Hole Cleaning

The ORTF recommends continuing the practice of verifying and/or creating clean hole conditions on any return to Hole 1256D through a pre-planned and rigorous hole cleaning program before attempting to advance the hole with normal drill or core bits. Any debris or borehole obstructions that could damage the bits should be removed first by using appropriate tools which cause less damage to borehole wall than reverse circulation junk basket (RCJB).

Routing: USIO
Background: Exceedingly hard formation (granoblastic basalts) at the bottom of the hole caused the C-9 hard formation coring bit failure during Expedition 335. The USIO had to conduct number of fishing/milling operation (19 days, 13 reentries) to fish/mill junk of the destroyed C-9 bit from the bottom of hole, and to ream/clean the hole. The ORTF agreed that the USIO must ensure that the hole is completely clean of debris before attempting to deepen Hole 1256D in future.
The ORTF meeting for the Expedition 309/312 in 2006 also made similar recommendation to the USIO, to explore future applications of riserless hole cleaning and stabilization (Recommendation 309/312-12). Unfortunately there has been modest progress on these recommendations in the five years since the last ORTF.

Recommendation 335-09: State of the Proposal 522-Full5

As the Proposal 522-Full5 has already been strongly endorsed in the SAS proposal evaluation process and is now residing at the OTF, the ORTF recommends (1) that the status of the Proposal 522-Full5 be formally changed to a Multi-phase Drilling Project (MDP) without requiring new SAS review, and (2) that the appropriate IO/OTF operational planning process as outlined in the proceedings of Expedition 335 and in the ORTF recommendations be started as soon as possible.

Routing: SIPCOM
Background: While reviewing Expedition 335 during the ORTF meeting, the external reviewers recognized that the stated objectives of Proposal 522-Full5 and its most recent Addendum 5 submitted in July 2011 would best be achieved by a MDP drilling strategy. The external reviewers and the IODP-MI commented that, if the proposal science targets are not going to change, the SIPCOM should agree to change the Proposal 522-Full5 status to MDP without requiring new MDP proposal submission from the proponents.

Recommendation 335-10: Expedition Operation Report

The ORTF recommends that the operations reports generated during IODP expeditions be circulated in a timely manner to Co-chiefs. These reports may include the operations report written by the operations superintendent, operations information spreadsheets, core tech sheets, and any special reporting data specific to a given leg. This has happened for several expeditions already, but it could be done more consistently.

Routing: USIO

Background: On every USIO expedition, operation teams of the *JOIDES Resolution* archive all kind of operational related activity log into the Expedition Operation Report. However this report is an internal report in the USIO, and is not often circulated outside include Co-Chiefs. The ORTF found that operational information on this report might be highly efficient to Co-Chiefs for understanding current operational situation, and give them some answers to their questions regarding future operations.

Acknowledgement 335-01: Pre-planning Communication

The ORTF acknowledges that the simplified planning structure being put in place for the "new IODP" should minimize the unfortunate pre-planning communication issues highlighted by IODP Expedition 335 Co-Chiefs.

Routing: IODP-MI, IOs, LAs

Background: The IODP-MI held the ORTF meeting for the previous Superfast expeditions Expedition 309/312 in 2006 with the Co-Chiefs and the USIO. A wide range of issues were discussed and several recommendations were made for future Superfast expeditions. The outcomes and recommendations of that ORTF meeting were combined into a meeting report by IODP-MI and distributed to LAs, IOs, related SAS chairs and posted on IODP website. Following the Expedition 309/312 ORTF meeting, some progress on the issues and recommendations areas discussed was made by the USIO internally during planning phase of the Expedition 335. However, the Expedition 335 ORTF understands that progress was limited and not sufficient to achieve the objectives of Expedition 335. The ORTF recognized the importance of ensuring the communication and digestion of the ORTF reports among SAS, LAs, IOs, and IODP-MI. IODP-MI should follow the status of each ORTF recommendation and any actions taken by the organizations/groups to which ORTF reports are sent.

APPENDIX B

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

and

Recommendations from the IODP Expedition 335 Initial De-brief

Teagle, D.A.H., Ildefonse, B., Blum, P., and the Expedition 335 Scientists
Proceedings of the Integrated Ocean Drilling Program, Volume 335

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

Expedition 335 Scientists[2]

Chapter contents

[1]Expedition 335 Scientists, 2012. Deep drilling of intact ocean crust: harnessing past lessons to inform future endeavors. *In* Teagle, D.A.H., Ildefonse, B., Blum, P., and the Expedition 335 Scientists, *Proc. IODP,* 335: Tokyo (Integrated Ocean Drilling Program Management International, Inc.).
doi:10.2204/iodp.proc.335.104.2012
[2]Expedition 335 Scientists' addresses.

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 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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Publication: 3 June 2012
MS 335-104

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.

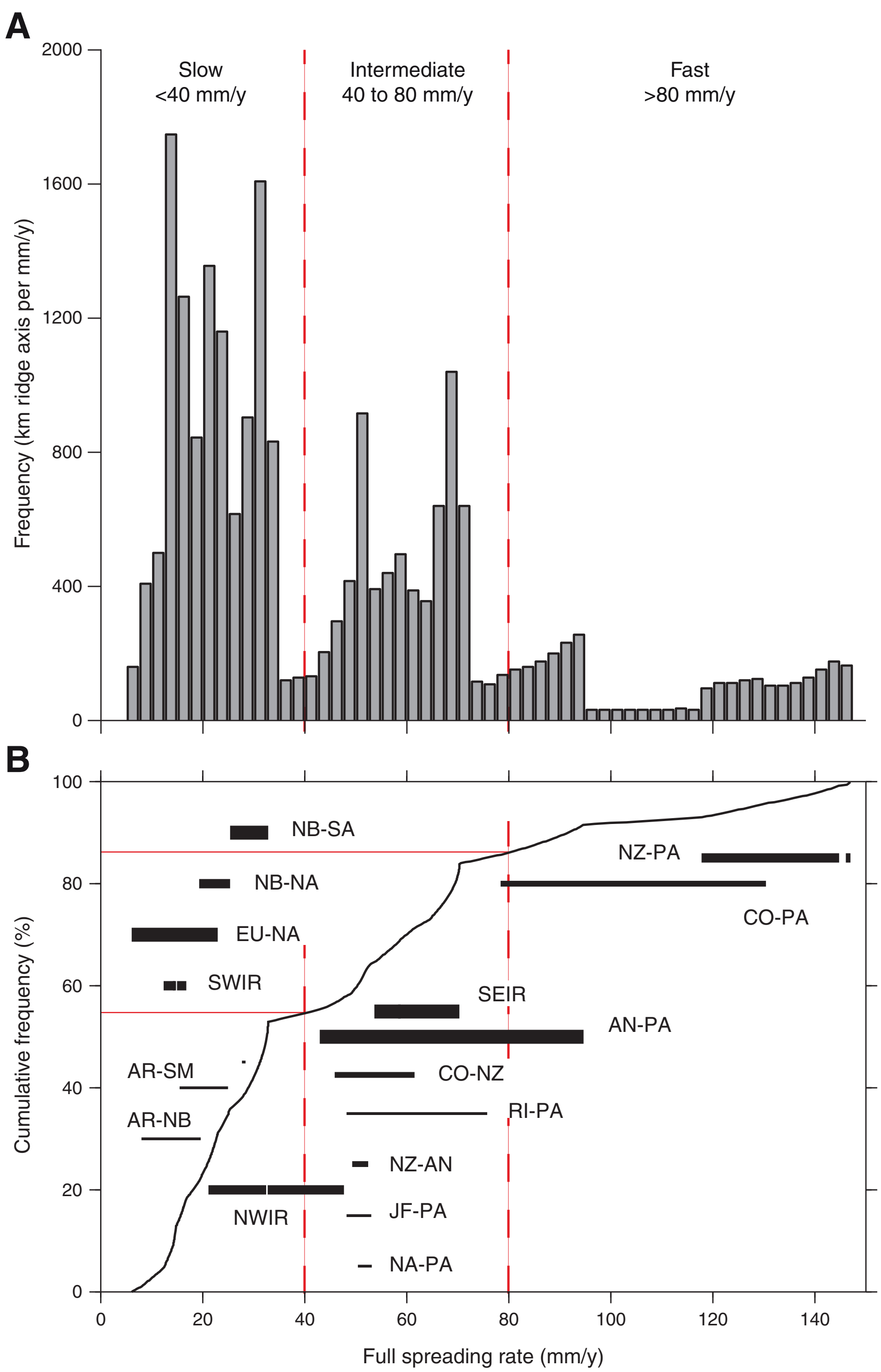

Figure F2. A. Global view of ocean crust colored by spreading rate at time of formation, based on age and spreading rate grids by Müller et al. (2008), revised version 3 (www.earthbyte.org/). **B.** Histogram comparing the proportions of the present-day ocean crust that formed at slow, intermediate, 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.

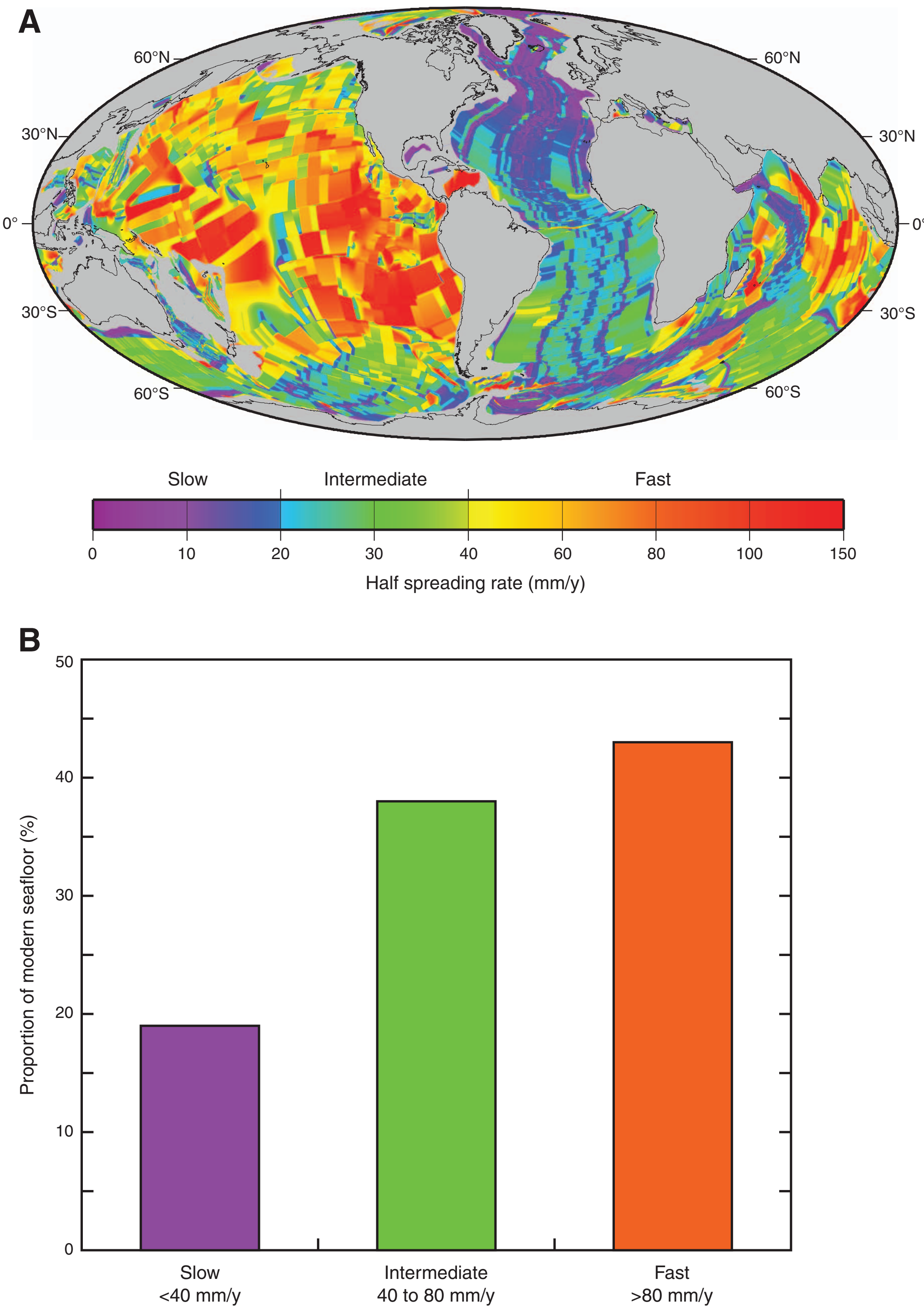

Figure F3. A. Contour map of seismic *P*-wave velocity at the top of basement in the Site 1256 area, based on tomographic inversion of seismic refraction data (A.J. Harding, pers. comm., 2005). The low-velocity area west of the center may reflect pillow lavas or other porous formation. The high-velocity 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.

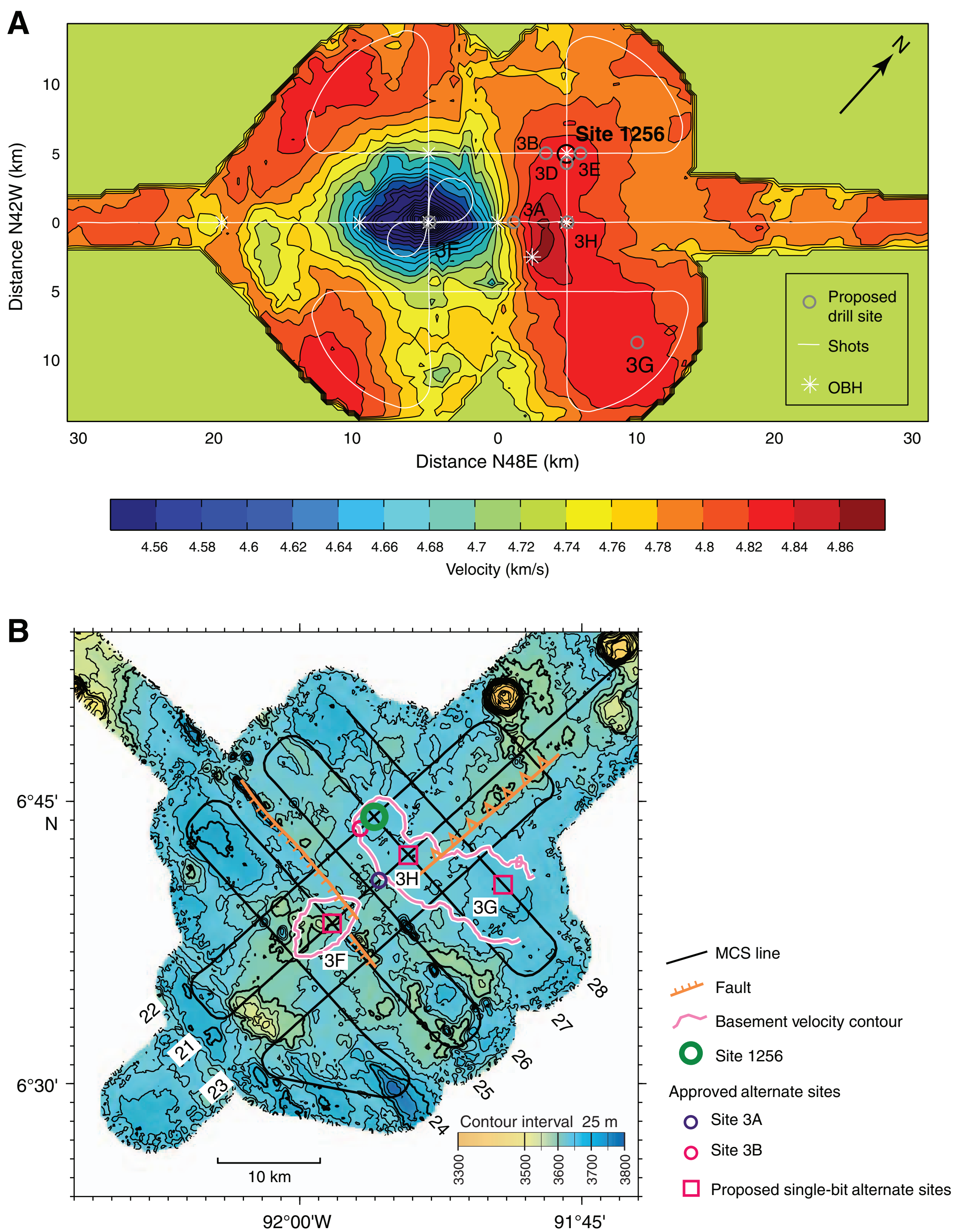

Figure F4. Schematic drawings of crustal accretion models (modified from Korenaga and Kelemen, 1997). Black arrows show the movement of the solid lower crust; blue arrows show the dominant zones where hydrothermal circulation will remove latent and sensible heat; red arrows show the movement of magma—this 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).

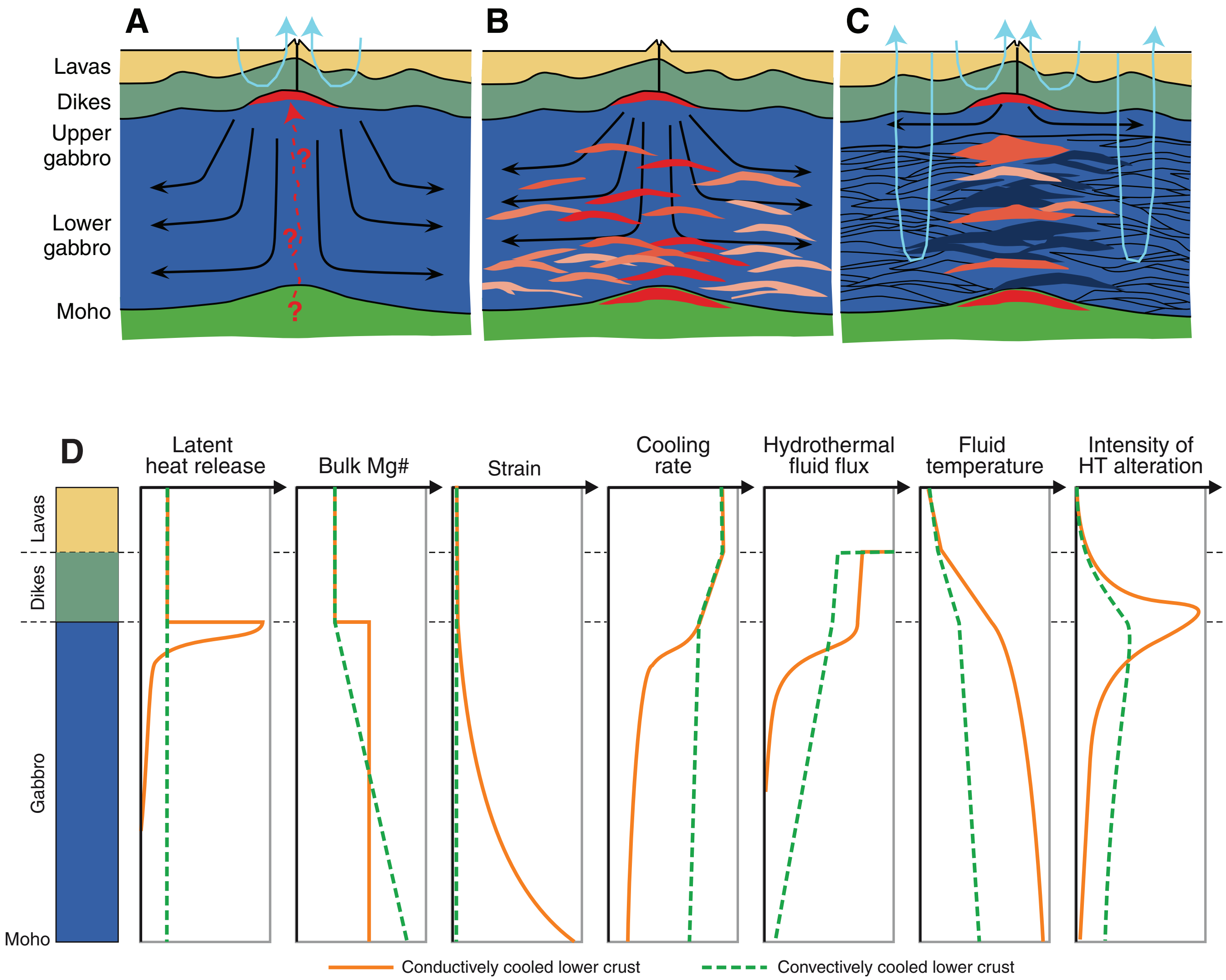

Figure F5. Map of ocean floor age, based on age grid by Müller et al. (2008), revised version 3 (www.earthbyte.org/). Symbols represent DSDP, ODP, and IODP holes drilled in ocean crust >100 mbsf from 1974 to 2011. Holes deeper than 500 m in intact and rifted oceanic crust are labeled. This map does not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

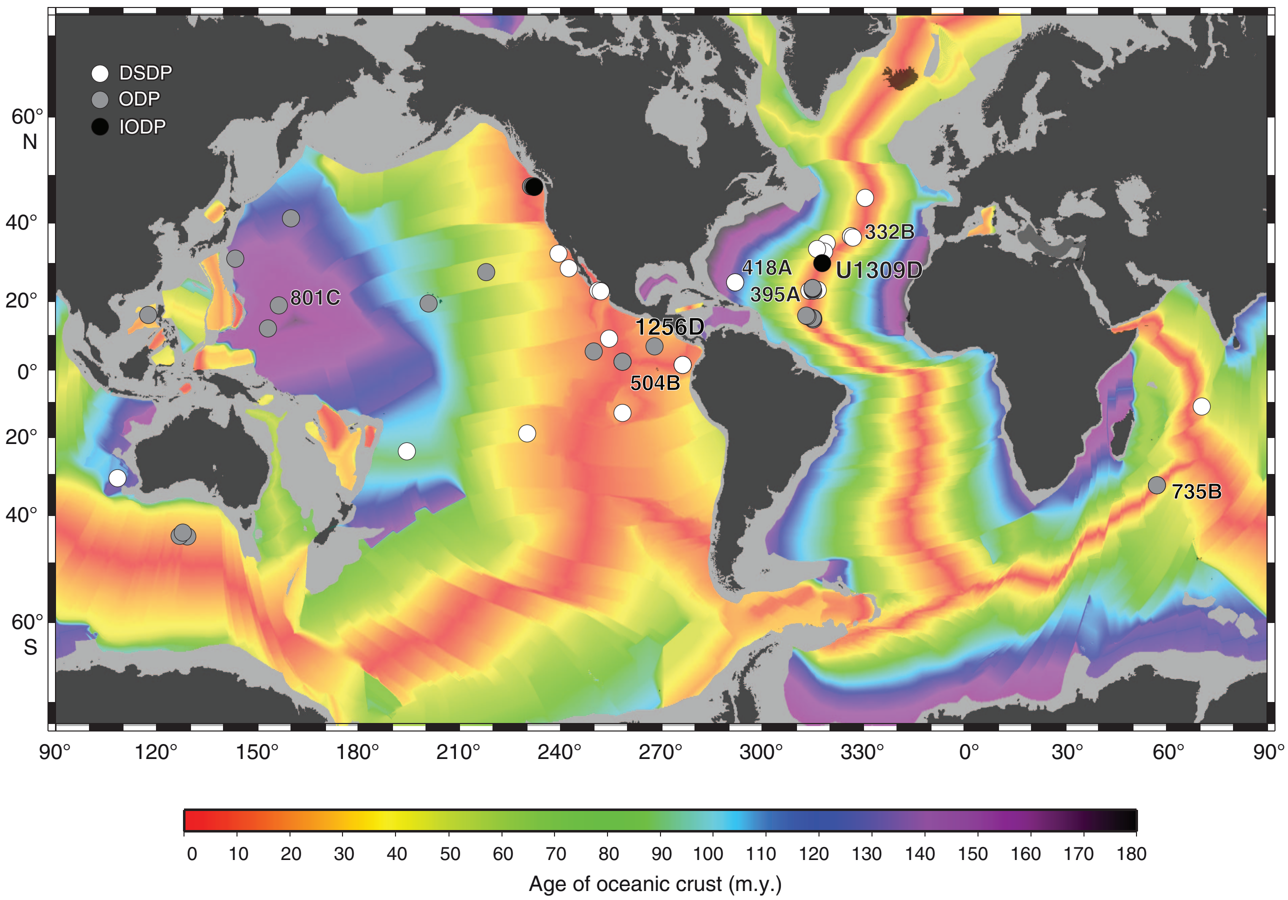

Figure F6. Compilation chart showing holes drilled >100 m in intact crust and tectonically exposed lower crust and upper mantle from 1974 to 2010 (drill hole locations in Fig. F5). For each hole are indicated the hole number and the recovery (in percent) for each lithology. This compilation does not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

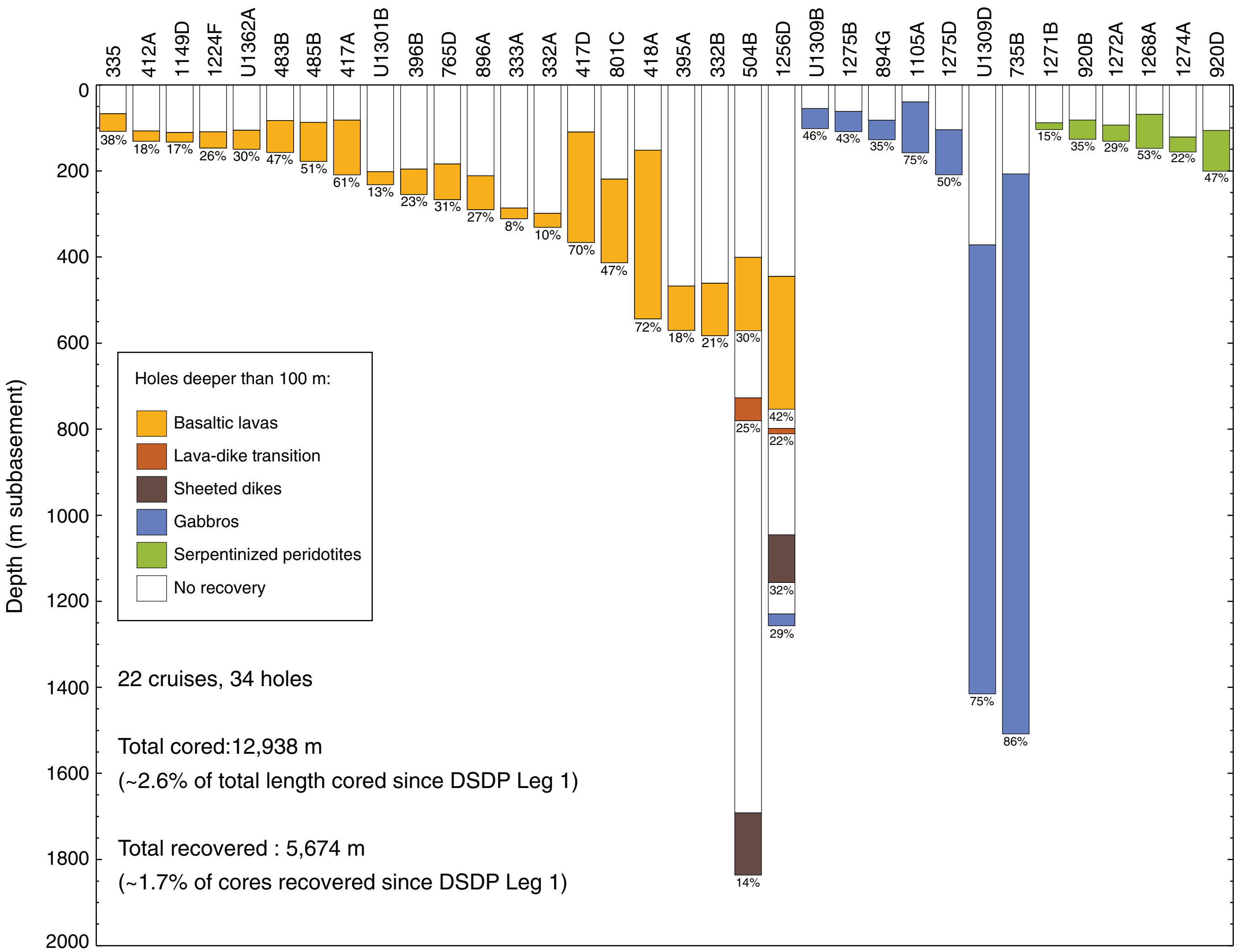

Figure F7. Age map of the Cocos plate and corresponding regions of the Pacific and Nazca plates. Isochrons at 5 m.y. intervals have been converted from magnetic anomaly identifications according to the timescale of Cande and Kent (1995). Selected DSDP and ODP sites that reached basement are indicated 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.

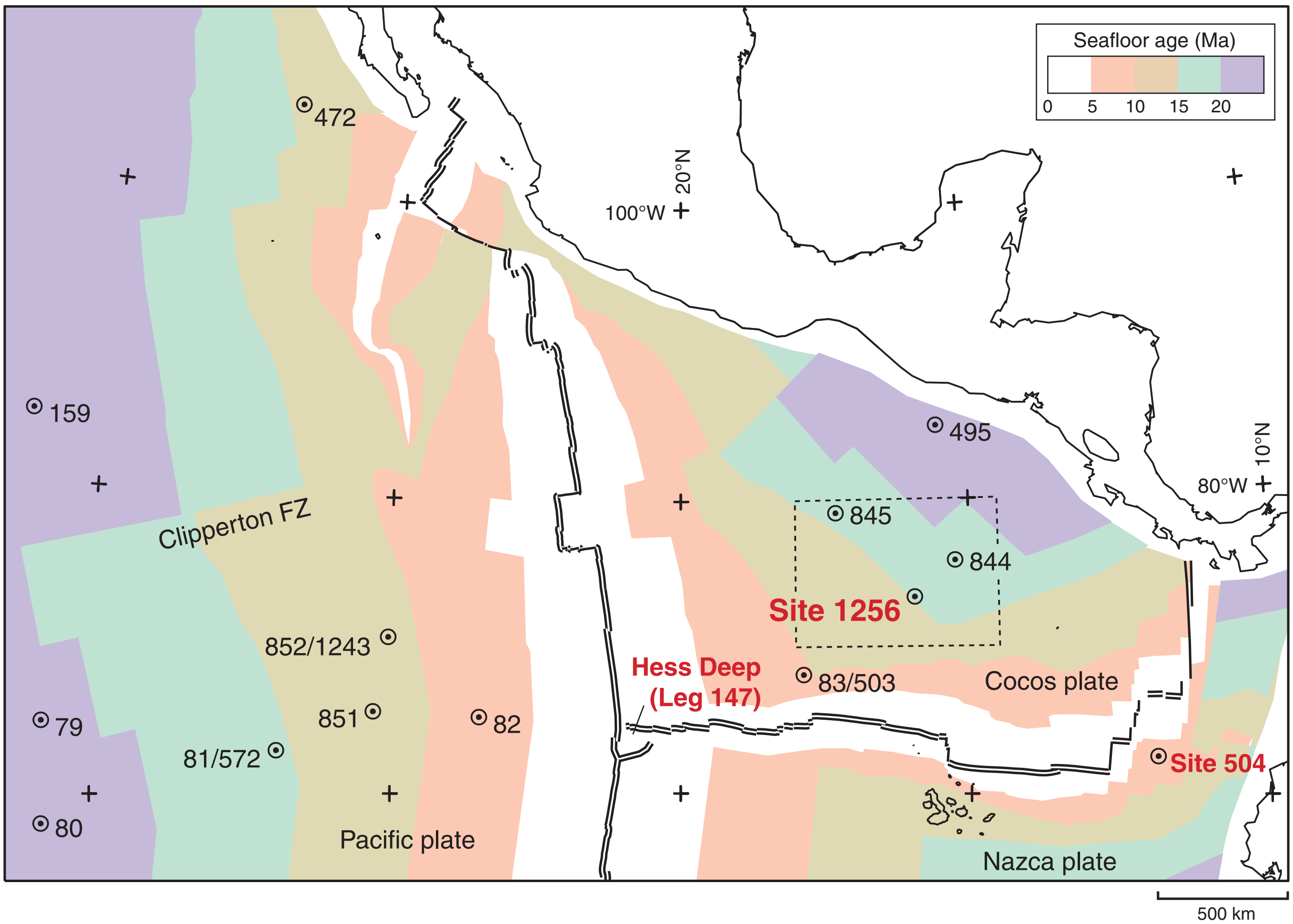

Figure F8. Time vs. depth plot for Hole 504B. Width of colored bars is proportional to the duration of DSDP and ODP legs. Major hardware failure and remediation events are reported at the depth to which they occurred. Pie charts indicate, at the end of each cruise, cumulative proportions of time spent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

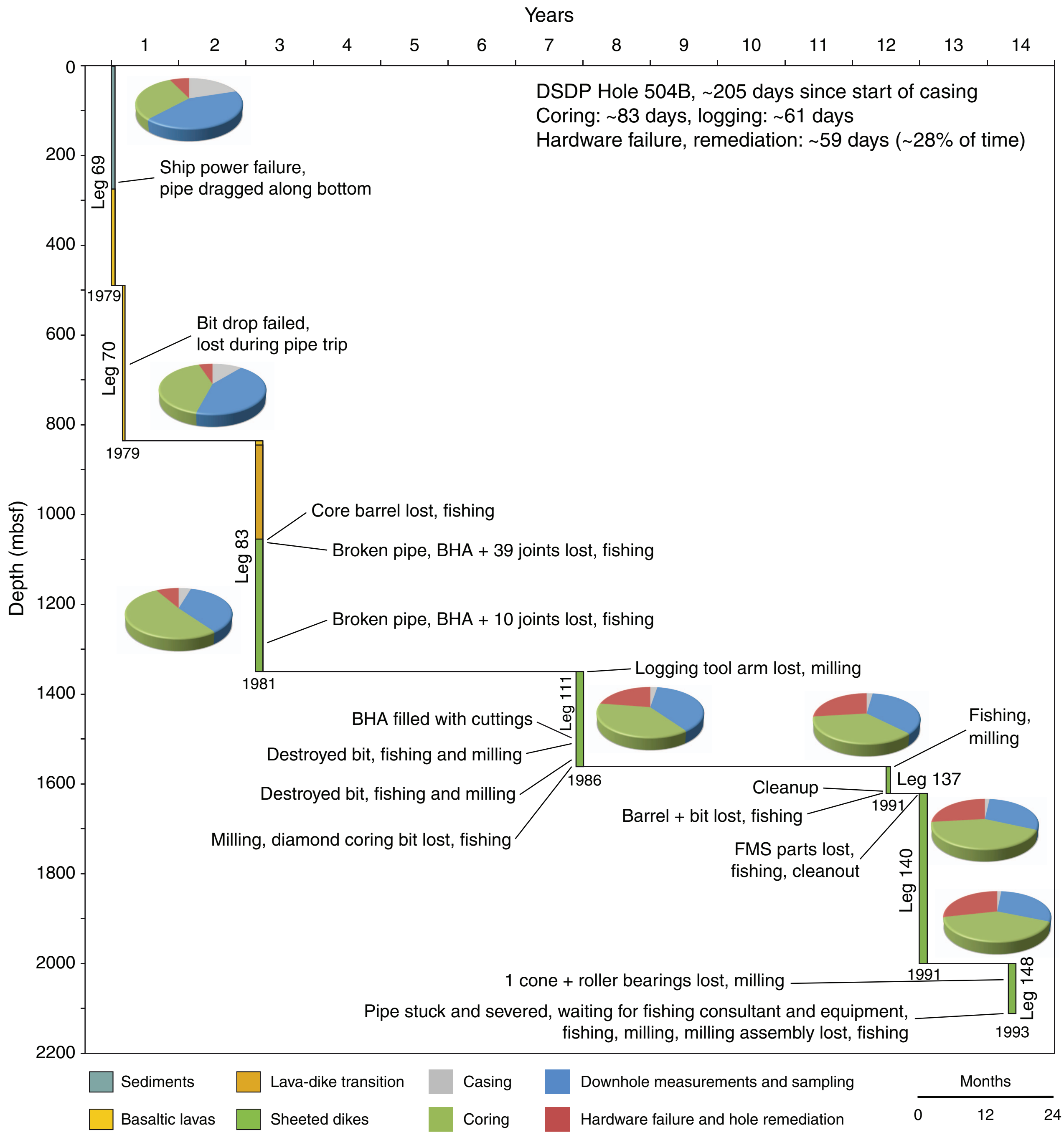

Figure F9. Time vs. depth plot for Hole 1256D. Width of colored bars is proportional to the duration of ODP legs and IODP expeditions. Major hardware failure and remediation events are reported at the depth to which they occurred. Pie charts indicate, at the end of each cruise, cumulative proportions 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.

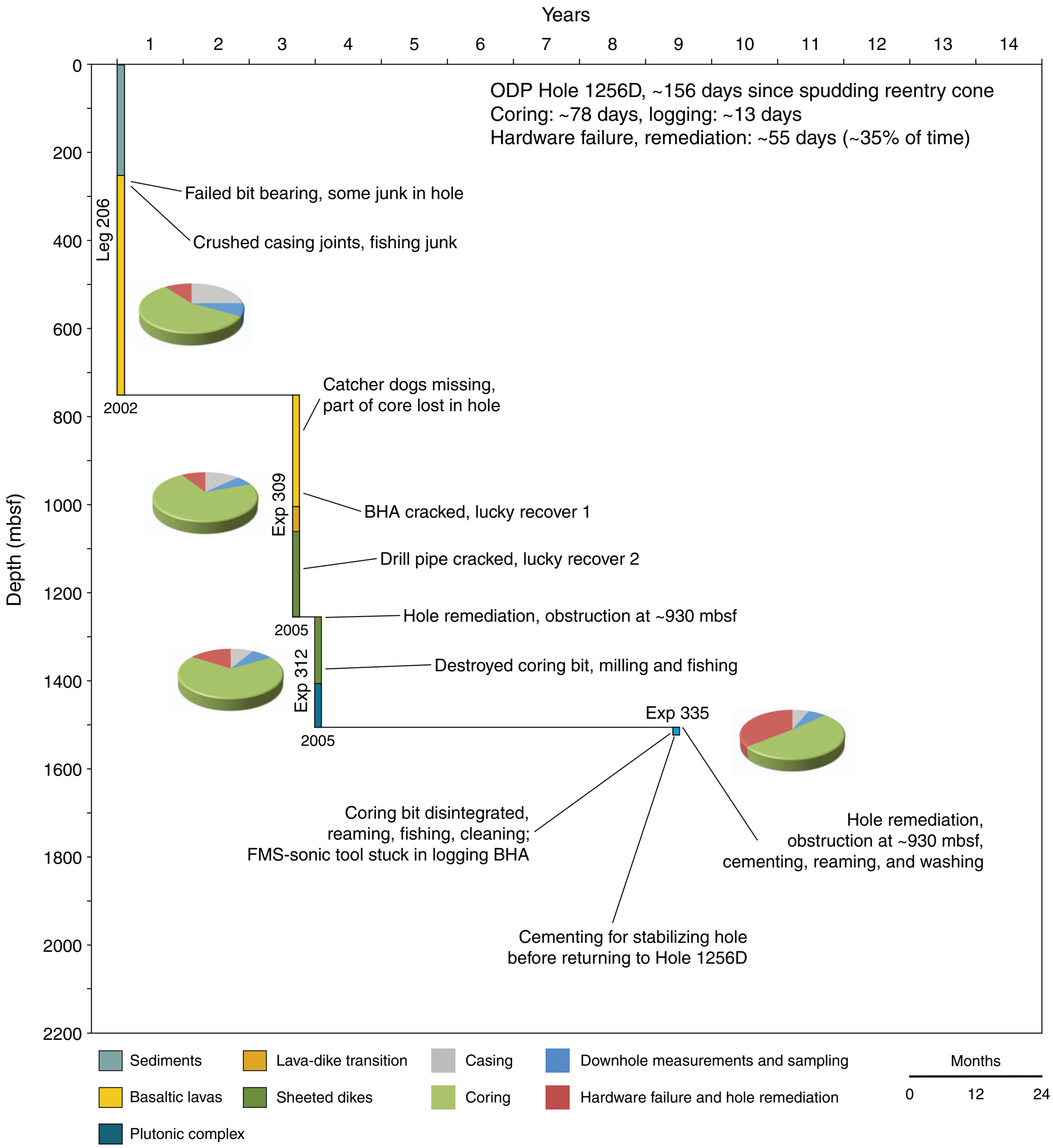

Figure F10. Plot showing the progressive deepening of Holes 504B and 1256D over eight and four scientific ocean drilling expeditions, respectively. Colored bars show the subdivision of time on site into casing, coring, downhole logging, and hole remediation activities.

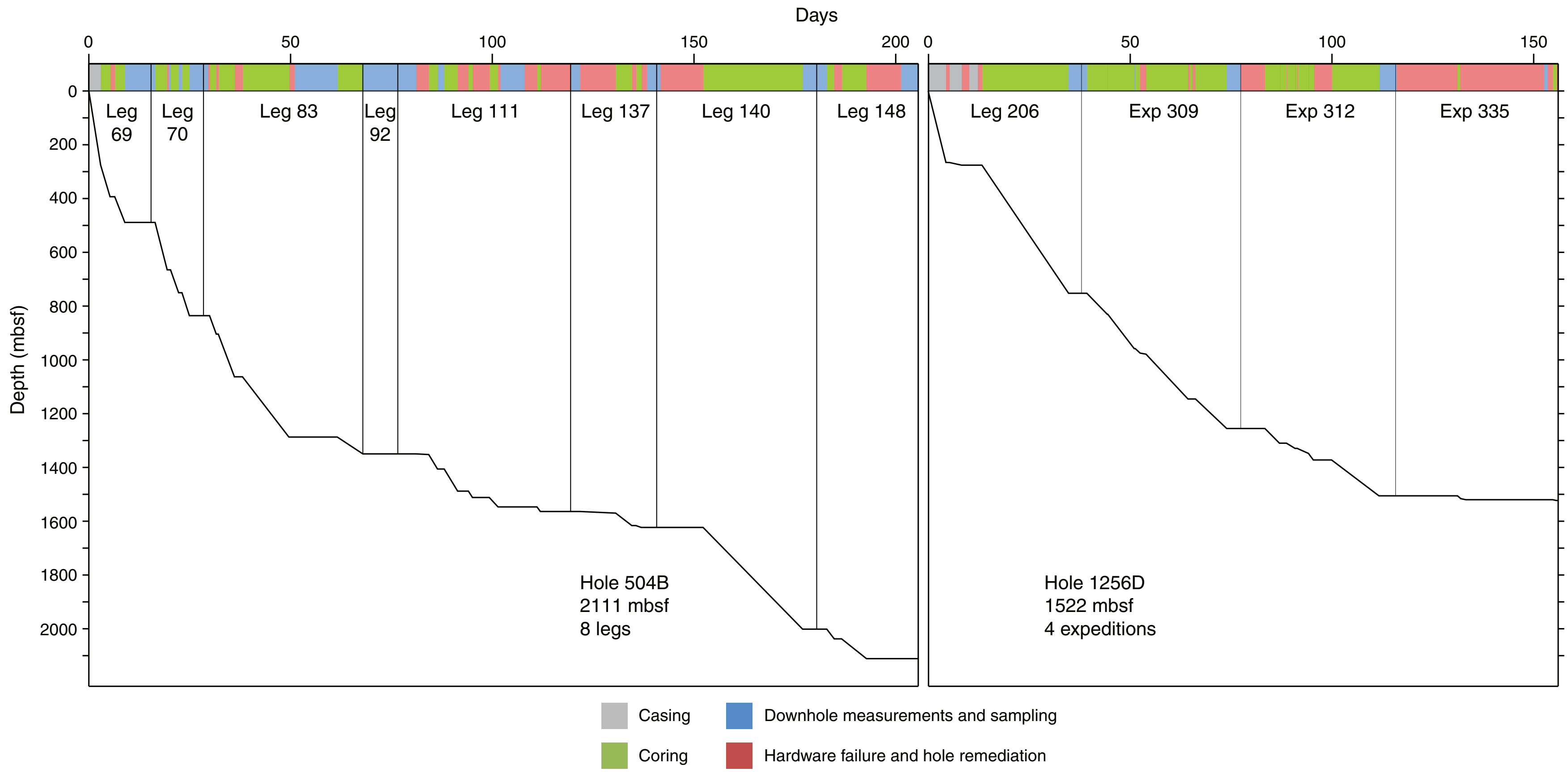

Table T1. Drill holes into oceanic basement in intact crust and tectonically exposed lower crust and upper mantle. (Continued on next two pages.)

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"**).

APPENDIX C

Rationale for SloMo Recommendation 8

Although Hole U1473A is open and can be deepened, an imbricate fault zone that extends from the top of the hole to 575 mbsf significantly compromises it for successful deep penetration to 3,000 m. The Expedition 360 Scientific Party identified five significant zones of faulting ranging from 75 to 80 m in vertical dimension based on examination of the cores and the caliper logs. There is also clear evidence from the temperature logs of open seawater circulation through the major fault zone at 415 m. Drilling conditions in the upper 575 m were poor, with 4 roller cones lost in the hole. Only two of these were successfully fished from the hole, and it is evident that there are two remaining cones in the wall of the fault rubble zones that remain a hazard for future drilling. While Hole U1473A was successfully cleaned and deepened during Remediation Expedition 362T, cementing operations were only partially successful. Thus, additional hole remediation is required before resuming coring, which would include both additional cementing and casing to a depth of ~600 m. There may be additional deeper faults.

The irregular diameter of Hole U1473A, if uncased, could be expected to worsen with continued operations and would increasingly inhibit successful removal of drill cuttings as the hole is deepened, even if additional debris from the unstable fault zone does not cause sticking of the bit. Although drilling conditions below 575 m to its present depth of 809.4 m are excellent, matching those found in Hole 735B, there is no guarantee that further imbrication of the fault zone may be found at depth. Thus, while it remains possible to continue SloMo Phase 1 operations in Hole U1473A, this is not recommended as the best possible option.

The major SloMo Expedition 1 scientific objectives, which provided the rationale for siting Hole U1473A at 3 km from Hole 735B, have been accomplished, with the exception of drilling through a reversed magnetic polarity interval. The results show that Hole U1473A, 1105A, and 735B stratigraphies all reflect the same process of dynamic accretion of the lower crust, with the same rock types in equivalent proportions. This continuity of process has been extended from the ~300,000 year time span of the drill holes to ~2.5 Myr by the site survey results which now, integrated with extensive mineral data, show that the massif is both laterally and vertically zoned with moderate to highly differentiated gabbros constituting its upper and distal portions. Despite 6 crossings of the crust/mantle boundary on the western wall of the Atlantis Bank gabbro massif, the gabbros in contact with or immediately overlying coarse granular mantle peridotite crystallized from melts that underwent >40%–50% fractional crystallization prior to intrusion. The overwhelming proportion of gabbros drilled or sampled from the seafloor had to have crystallized from melts more fractionated than even moderately differentiated mid-ocean-ridge basalt (MORB). Thus, the key cumulate rocks that form during the initial intrusion of magmas from the mantle and largely control the composition of the most abundant magma type on Earth, lie beneath the centerline of the gabbro massif parallel to the spreading direction. Based on this and the results of Hole U1473A, a single deep penetration to crust will be representative of the lower crust in combination with the site survey data.

As deep drilling at either location will pass through the magnetic reversal projected to lie beneath Hole U1473A, this objective can also be accomplished at Site 735. Moreover, recent modeling based on new zircon data from Holes U1473A and 735B suggests the paleo-geotherm indicators may turn near vertical with depth (Cheadle, personal communication) and hence drilling through a magnetic reversed polarity interval may not be possible at either site.

Moving the SloMo project to Site 735, in addition to providing ideal drilling conditions down to at least 1.5 km, has the additional major advantage of providing the opportunity to log the 1,000 m section cored during ODP Leg 176. Although Legs 118 and 176 extensively logged the upper 500 m, pipe failure blocked the lower 1,000 m of Hole 735B. While this would not provide the opportunity to reorient cores for structural studies, it would record all the other geophysical properties normally measured during logging. As the Hole 735B section is undisturbed by faulting, the logs would be more valuable than those to be gained by deepening Hole U1473A.

Moving the SloMo site to Site 735 would also follow the standard industry practice of first drilling test holes in preparation for deep penetration so that a proper drilling plan can be made. Thus, the drilling plan for the new hole would include casing the upper 500 m where there was a bridge in Hole 735B.

The Hole U1473A logs demonstrate that recovery is a direct function of the degree of fracturing in the formation. A sharp break in both the caliper and resistivity logs is located at the point at which drilling conditions dramatically improved. Average core recovery increased from ~50% to near 100%, and hole diameter steadily decreased as the drill string thus stabilized (Fig. A1). Therefore, based on the downhole recovery log for Hole 735B, which remained at a steady average of 87% from the point at which the drill collars entered the hole to 1508 m, with a steady penetration rate (Fig. A2), the ideal drilling conditions at the bottom of Hole U1473A exist throughout Hole 735B down to 1508 m.

An additional consideration is that the expedition to drill the uppermost 1,500 m could be sailed with a substantially reduced scientific party, as the principal objective of the first expedition would be downhole logging, while any additional coring would be modest, and could be logged by the oncoming scientific party for the following expedition.

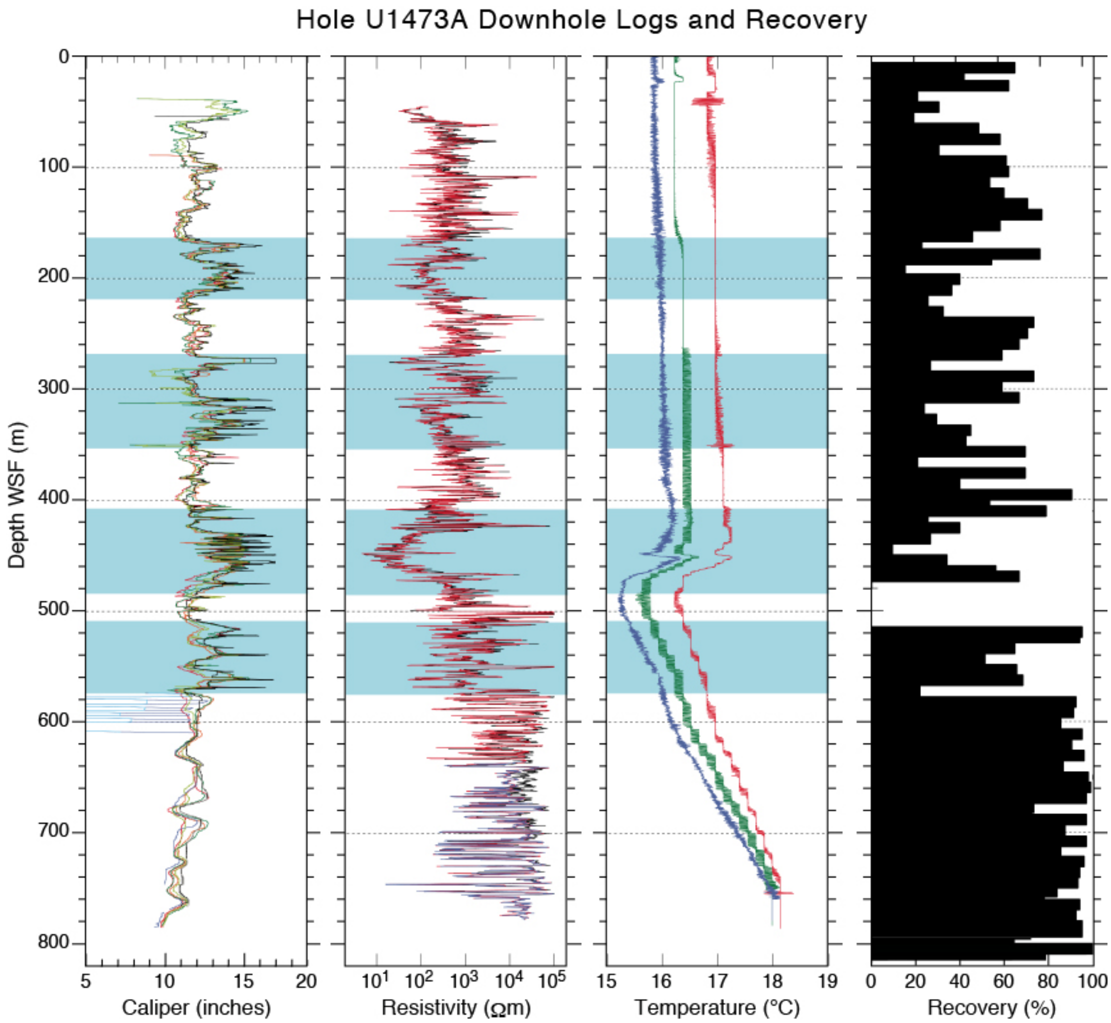

Figure A1. Downhole logs of Caliper, Resistivity, and Temperature, as well as Core Recovery %) for hole U1473A

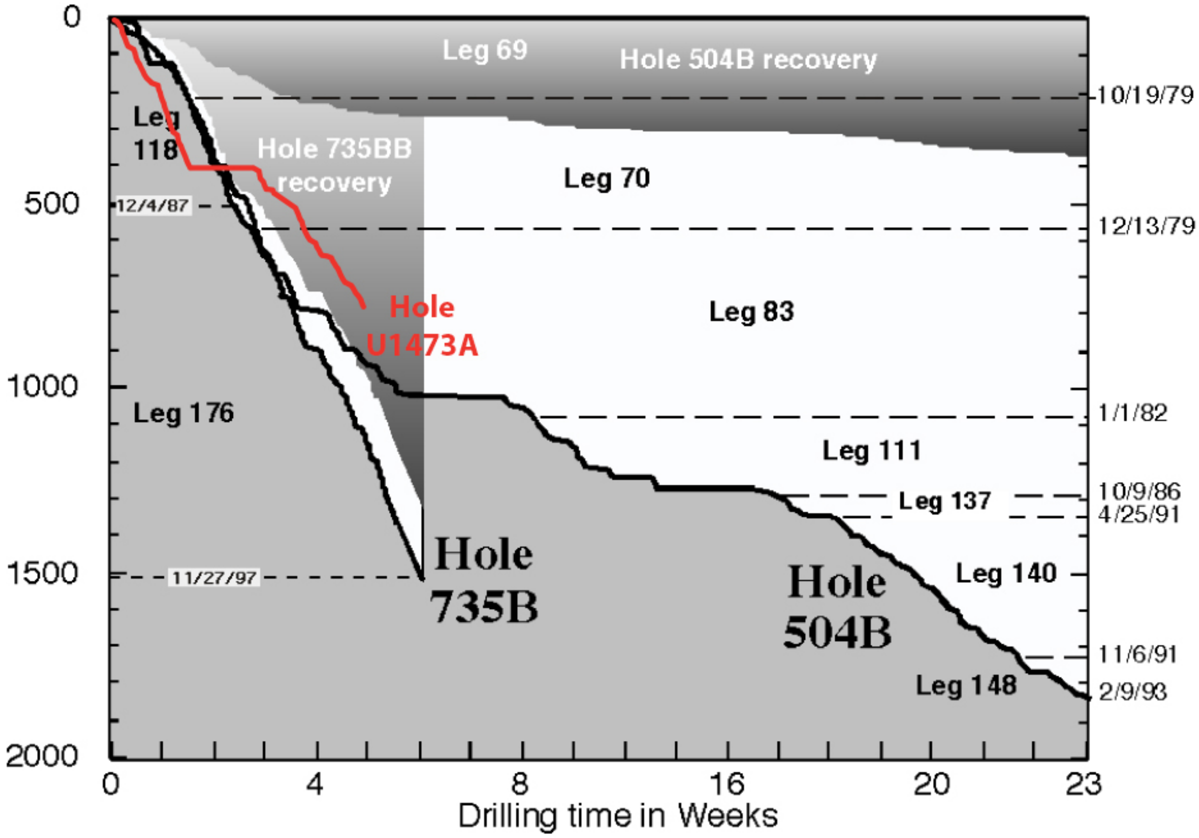

Figure A2: Comparison between deep crustal holes 504B, 735B, and U1473A.

Geological Setting and Scientific Goals of the Superfast Campaign

Drilling a deep hole through intact ocean crust formed at a fast spreading rate has been one of the prime motivations for scientific ocean drilling since its inception. IODP Expedition 335 (13th April – 3rd June, 2011) was the fourth scientific drilling cruise of the "Superfast" campaign (Wilson et al., 1999; ODP Proposal 522Full) and returned to ODP Hole 1256D (6°44.163'N, 91°56.061'W) to deepen this ocean crust reference penetration a significant distance into cumulate gabbros. Site 1256 was specifically located on oceanic crust that formed at a superfast spreading rate (>200 mm/yr) to exploit the observed relationship between spreading rate and depth to axial low velocity zones, thought to be magma chambers, seismically imaged at active mid-ocean ridges. This was a deliberate strategy to reduce the drilling distance to gabbroic rocks because thick sequences of lavas and dikes have proved difficult to penetrate in past. ODP Leg 206 (2002) initiated operations at Site 1256 including the installation in Hole 1256D of a re-entry cone with 16-in casing inserted through the 250 m-thick sedimentary cover and cemented into basement to facilitate deep drilling. The hole was then cored ~500 m into basement. IODP Expeditions 309 and 312 (2005) successfully completed the first sampling of an intact section of upper oceanic crust from lavas, through the sheeted dikes, and into the upper gabbros. Before IODP Expedition 335, Hole 1256D penetrated >1500 mbsf and >1250 m sub-basement and resided in the dike-gabbro transition zone. The first gabbroic rocks were encountered at 1407 mbsf. Below this lies a ~100 m-thick complex zone of fractionated gabbros intruded into contact metamorphosed granoblastic dikes.

Although only a shortened cruise was approved (~40 days on site), given good drilling conditions, an advance of 350 m was predicted that should push the hole through varitextured gabbros into foliated gabbros (following the stratigraphy of the Samail ophiolite, Oman).

The specific scientific questions to be addressed by deepening Hole 1256D a significant depth into cumulate gabbros include:

• What is the major mechanism of magmatic accretion in crust formed at fast spreading rates. Is the lower crust formed by gabbro glaciers or sheeted sills or some mixed or unknown mechanism?
• How is heat extracted from the lower oceanic crust?
• What is the geological significance of the seismic layer 2/3 boundary at Site 1256?
• What is the magnetic contribution of the gabbro layer? Can the magnetic polarity structure of the lower crust be used to constrain cooling rates?

Additionally, Hole 1256D was anticipated to cross the ~120°C "limit of life".

Operations:

The operational plan for IODP Expedition 335 was informed by previous experiences in Hole 1256D, the IODP-MI Operational Review Task Force Expedition 309/312 Report, and a USIO position paper that considered a number of strategies for deepening Hole 1256D. Followed the recommendations of the USIO technical review, the operational approach was to **"Resume RCB coring in Hole 1256D using large volume (100-150 bbl) high viscosity mud sweeps combined with frequent bit trips"**. Unfortunately, operational difficulties in Hole 1256D precluded progress towards the scientific objectives, with only <15 m of advance achieved. Hole 1256D now has a total depth of 1521.6 mbsf (1271.6 msb), but is open to its full depth apart from two intervals of protective cement at 920 to 960 mbsf and the bottom of the hole.

Operations on IODP Expedition 335 can be subdivided into 4 main phases:

1) Open the hole to full depth and stabilize (cement) the interval 920-960 mbsf – **15 days**
2) RCB coring – 4 cores pulled before the destruction of a C9 RCB bit – **2 days**
3) Fishing and Milling of Junk / reaming and cleaning hole – **19 days**
4) Wireline logging, 1 RCB core, cementing of critical intervals – **3.5 days**

JOIDES Resolution left Site 1256 immediately following cleaning of the hole for extended tie-up.

During the planning for IODP Expedition 335, concerns were raised about a potential bridge in Hole 1256D at 922 mbsf. Although this interval of lava flows had been drilled without remark on Expedition 309, less than 3 months later Expedition 312 had difficulty re-entering the hole because of an obstruction at this level and >5 days were spent opening the hole. On Expedition 335, a more stubborn obstruction at the same level was encountered and 16 days were spent opening the hole and stabilizing the interval with cement. This interval was secured at the end of Expedition 335 with 65 bbls of cement. RCB coring started after the opening of the hole but only 4 cores were pulled, some strongly under-gauge, before the complete destruction of a C9 hard formation coring bit.

This necessitated a further 19 days of fishing, milling, reaming and cleaning operations, but at the end of this process it was possible to get both a drill bit and wireline tools to the bottom of the hole. Much has been made of the extreme hardness of the metamorphosed granoblastic dikes encountered in the lower 170 m of Hole 1256D. However, triaxial compressive test measurements indicate, that although hard, these rocks are not *extremely* hard (Compressive strength <40 kpsi; Abe et al., 2012), and are within the parameters of industry hard formation bit design (>80 kpsi).

The clearing of cuttings from a >1500 m-deep uncased borehole appears to be the major impediment to deepening Hole 1256D. The upper 800 m of the basement comprises sheet and massive lava flows, and the very large number of bit trips has resulted in a ragged and irregular borehole wall, with numerous cavities and traps that preclude the effective flushing of the hole. Cleaning operations, using large mud sweeps and more mechanical approaches, eventually removed many 100s of kg of cuttings originating from all levels in the hole. The petrology of some cuttings suggest that they may have been re-circulating in the hole since they were drilled on Leg 206. Additionally, the ~270 m of 16-in casing extends only 17 m into basement (a major achievement of ocean drilling at the time) leaving a 7 m-high 23-in diameter rat-hole beneath the casing that further impedes the clearing of the hole. Casing across this interval with 10 ¾-in casing would probably increase the "hydraulic horsepower" and effectiveness of the mud sweeps.

Recommendations from the IODP Expedition 335 Initial De-brief:

Following the completion of Site operations, the Co-chiefs organized a formal meeting so that there was an effective debrief and discussion of issues encountered during Expedition 335 whilst these were still fresh in everyone's mind. This meeting was attended by the Co-Chief Scientists (Teagle and Ildefonse), past Co-chief scientists and senior proponents (Wilson and Alt), the EMP/SS (Peter Blum), the Operation Superintendent (Ron Grout), the Off-shore Installation Manager (Sam MacLelland), Core Techs/Tool Pushers (Wayne Malone / Mark Robinson), and one of the Drillers (Craig Prosser). We agreed upon the following observations and recommendations:

• Hole 1256D is now in good condition, clear of cuttings to its total depth (except for cement plugs), and can be deepened if the recommended steps below are followed through with.

• Cementing has proved effective at stabilizing unstable formations, but more technical advice is required on cementing options (accelerants, etc) and operations (e.g., packers to more effectively force cement into voids).

• Casing the complete out of gauge section (e.g., down to 1000 mbsf in Hole 1256D) of an existing open borehole is not technically feasible in oceanic basement.

• Casing through the 16-in casing to the bottom of the rat hole with 10 ¾-in casing would greatly improve the hydrodynamics of the hole and enhance the hole clearing efficiencies. This operation would be reasonably straightforward, and not require under-reaming or other technically challenging and untested operations in hard volcanic formations.

• Return visits to Hole 1256D must be fully armed with hard/ultra-hard formation, highly armored tricones for hole opening and cleaning/reaming, and hard/ultra-hard formation coring bits, as well as an armored suite of mills and junk baskets. The first operation upon return to Hole 1256D, and possibly deploying a 10 ¾ casing string to the bottom of the rat hole, will be to reenter with an armored tricone bit, drill the cement plugs and displace the cuttings, and ream and clean the bottom of the hole, before coring can resume.

• The program should investigate the feasibility of using synthetic polymer viscosifiers for the binding and lifting of cuttings from open/riserless holes (see also 309/312 Review Task Force).

• Consult with an experienced / recommended drilling engineer to evaluate the best future coring plan including: the procurement (or even design and manufacture) of ultra-hard formation drill/coring bits; fishing tools and operations; cementing strategies; and casing strategies.

• ODL/Transocean rig floor expertise should be directly involved in the planning of future deep drilling efforts at Hole 1256D, and other deep targets drilled by the JOIDES Resolution. Together with the Co-chief scientists they have built up considerable expertise and experience relevant to the achievement of deep drilling targets, and they should be kept engaged in the planning and implementation of future operations.

• Follow the recommendations of the IODP-MI Operations Review Task Force for Expeditions 309/312 (and 335), to investigate innovative cruise scheduling mechanisms to **maximize time on site** for the achievement of high priority objectives that require deep drilling (e.g., back to back cruises; at sea crew transfers).

More detailed information is available in:

Expedition 335 Scientists, 2012. Deep drilling of intact ocean crust: harnessing past lessons to inform future endeavors. In Teagle, D.A.H., Ildefonse, B., Blum, P., and the Expedition 335 Scientists, Proc. IODP, 335: Tokyo (Integrated Ocean Drilling Program Management International, Inc.). doi:10.2204/iodp.proc.335.101.2012

Expedition 335 Scientists, 2012. Expedition 335 Summary including Operations. In Teagle, D.A.H., Ildefonse, B., Blum, P., and the Expedition 335 Scientists, Proc. IODP, 335: Tokyo (Integrated Ocean Drilling Program Management International, Inc.). doi:10.2204/iodp.proc.335.104.2012

Report of IODP Operations Review Task Force Expedition 309/312, June 2006, (Washington DC)

Report of the IODP Operations Review Task Force Expedition 335 "Superfast Spreading Rate Crust 4" Meeting, March 2011 (Washington DC), Consortium for Ocean Leadership.

Teagle, D.A.H. & Ildefonse, B., Co-Chief Scientists' submission to the IODP Operations Review Task Force Expedition 335 "Superfast Spreading Rate Crust 4" meeting, March 2011.

USIO Position Paper – Operational Requirements for returning to Hole 1256D, Excerpted from the Mission Moho Workshop report, 2006 http:// http://www.iodp.org/mission-moho-workshop