IODP Expedition 384: Engineering Testing

Site U1555 Summary

Background and Objectives

The primary objective of International Ocean Discovery Program (IODP) Expedition 384, Engineering Testing, was to carry out engineering tests with the goal of improving the chances of success in deep (>1 km) drilling and coring in igneous ocean crust. The Deep Crustal Drilling Engineering Working Group (2017) laid out a wide range of tools and technologies for potential testing, largely based on reports from recent crustal drilling, Expedition 335 (Superfast Spreading Rate Crust 4) and Expedition 360 (SW Indian Ridge Lower Crust and Moho). The *JOIDES Resolution* Facility Board (JRFB) further prioritized the testing goals in 2018. The top priority of all recommendations was an evaluation of drilling and coring bits, because coring bit wear, tear, and failure is the prevalent issue in deep crustal drilling attempts, requiring an excessive amount of fishing and hole cleaning time.

The questions to be addressed by the tests were the following. (1) Can we acquire drill bits that drill holes faster than has been possible in the past, in preparation for logging and casing? (2) Can we acquire bits that last longer than in the past in harsh igneous rock formation? (3) Is it possible to ream an igneous rock hole for casing operations, using a different type of reamer than used in the past? (4) Should we take another look at polycrystalline diamond compact (PDC) coring bits for better recovery and, less likely, faster coring?

The test plan included drilling in basalt with three different types of drill bits: a tungsten carbide insert (TCI) tricone bit, a PDC, and a more novel PDC/TCI hybrid bit. These were all 12¼ inch diameter bits from the top two bit vendors worldwide because they are industry standard and readily available, and because they are suitable to drill holes for deep casing. In addition, a TCI bit was to be paired with an underreamer with expanding cutting blocks instead of extending arms. A mud motor was to be used in these drilling tests to increase the total rotational speed to at least 120 revolutions per minute (rpm). Finally, a type of rotary core barrel (RCB) PDC coring bit that had been acquired for the *JOIDES Resolution* several years ago but never deployed would also be given a test run. Depending on the outcome of these tests, additional deployments of the best performing drill bit and a regular C7 coring bit would be considered. The test holes were to be spaced ~20 m from each other to ensure comparable hole conditions. After washing through the ~200 m of sediment cover, which serves to stabilize the bottom-hole assembly (BHA), each drill bit was to penetrate up to ~100 m into basaltic basement, or as far as the lifetime of the bit allowed, whereas shorter runs with the underreamer and coring bits were planned. A small number of core samples would be made available to the drilling engineers analyzing the test results, and additional core samples would be made available to the Expedition 395 science team.

The test location was based on various factors, including the *JOIDES Resolution's* location at the time, our inability to obtain territorial clearance in a short period of time, and a suitable

combination of sediment and igneous rock for the coring operations. Expedition 395, which was postponed due to the COVID-19 pandemic, offered the best site candidates. In particular, proposed Site REYK-13A perfectly met the logistics, water depth, and sediment thickness requirements. Furthermore, the possibility existed to accomplish some work for the Expedition 395 project if time became available. A contingency plan of attempting to drill into the gabbro-dominated formation at Site U1309 was canceled soon after departure when the arrival port changed from Las Palmas, Gran Canaria, to Kristiansand, Norway, due to COVID-19 travel restrictions.

Operations

We arrived at Site U1555 (proposed Site REYK-13A) on 29 July 2020. The ship was positioned 50 m east of the coordinates for proposed Site REYK-13A, along the seismic survey line toward Site REYK-11A. Additional holes were planned at 20 m intervals along this same line. The water depth for Hole U1555A, calculated from precision depth recorder (PDR) readings, was 1516 m. This water depth was used for all drilling tests, for lack of better measurements with the drill pipe. A total of five holes were drilled and two holes were cored at Site U1555. Total time on site was 19.7 d.

Hole U1555A

For the first drilling test, a 12¼ TCI roller-cone bit and an 8 inch mud motor were made up with the BHA. The bit used for this test was similar to the TCI bits previously used on the *JOIDES Resolution*, but was a much more robust version. The motor used was the same high-torque model used previously when running casing. We drilled through the sediment, starting on 30 July, at a controlled rate of penetration (ROP) of ~40 m/h. Basement was encountered at ~185 m driller's depth below seafloor (DSF), marked by the slowing of the ROP to <5 m/h. The bit got stuck for the first time at 224 m DSF and difficult hole conditions had to be mitigated repeatedly with circulation of mud sweeps and reaming. When we had reached a basement penetration of 97.4 m, at 282.0 m DSF on 31 July, the drill string was retrieved, ending Hole U1555A operations. The average ROP was 4.2 m/h over 23.1 h of bit on bottom. We spent 2.5 d on Hole U1555A. Upon recovery, the bit cones, cutters, and bearings were in good condition and the bit was considered reusable for up to 40 h. However, the outer gauge was heavily worn.

Hole U1555B

The ship was offset ~20 m east of Hole U1555A in preparation for the second test with a 12¼ inch hybrid PDC/TCI bit and mud motor made up with the BHA. Due to heave in excess of 4 m and winds approaching 40 kt, operations were suspended until 1200 h on 2 August, with the bit suspended ~100 m above seafloor. Drilling in Hole U1555B began at 1400 h. The sediment was penetrated at the same controlled ROP of ~40 m/h as was done in the first test. Basement was encountered at 186.6 m DSF. At 1600 h on 3 August and a bit depth of 210.8 m DSF or 24.2 m into basement, we decided to terminate drilling in Hole U1555B based on the low ROP

of <1 m/h over 6 h. The average ROP was 1.3 m/h over 19.4 h of bit on bottom. We spent 2.8 d on Hole U1555B, of which we waited 1.1 d on weather. Upon recovery, the hybrid bit showed significant damage. Several of the PDC cutters were damaged and pieces of metal were missing from the PDC arms. The cone bearings appeared to be frozen. The outer diameter (gauge) was also significantly damaged. It was later noted that one of the carbide jet nozzles had come out, which was possibly the cause of the damage to the bit. This bit was not considered reusable.

Hole U1555C

For the third test, the rig floor crew made up a 12¼ inch TCI bit, a 12¼ to 14½ inch hydraulically expandable reamer with cutting blocks, and a mud motor with the BHA. The TCI bit was the same type of bit run during the first test. The mud motor was the same motor used on the previous tests. The ship was offset ~20 m to the east and the drill string was deployed in the early morning of 4 August. Drilling began with a low flow rate so as not to engage the underreamer until necessary. The pumping rate was increased to expand the cutting blocks of the reamer with the bit at 130.6 m DSF. The top of the basement was encountered at 186.6 m DSF. Drilling in Hole U1555C continued until 5 August, when the underreamer had reached 20 h of operation and the bit was at 225.8 m DSF, or 39.2 m into basement, and the drill string was retrieved. The average ROP was 1.8 m/h over 20.0 h of bit on bottom. We spent 1.8 d on Hole U1555C. Upon recovery, the underreamer had several PDC cutters damaged and the cutting blocks were still extended just over 1 inch.

Hole U1555D

For the fourth drilling test, the rig floor crew made up a 12¼ inch PDC bit and mud motor with the BHA. This was the first time this newer type of PDC bit with conical-shaped inserts was run on the *JOIDES Resolution*. The ship was offset ~20 m to the east, the drill string was deployed, and drilling in Hole U1555D began on 6 August. The top of the basement was encountered at 189.0 m DSF. Drilling continued until 7 August when failure of the mud motor was indicated by a pressure loss of >200 psi. The depth reached with the PDC bit was therefore limited to 222.9 m DSF, or 33.9 m basement penetration. The drill string was retrieved, ending Hole U1555D. The average ROP was 1.7 m/h over 20.3 h of bit on bottom. We spent 1.7 d on Hole U1555D. Once back on the rig floor, the cutters and outer gauge of the PDC bit were in good condition and the bit was ready for a follow-up test. The mud motor was flow-tested. Rotation started at a higher rate than after the previous run, and the motor appeared to be responding with an intermittent stall in its rotation. The rule of thumb for this type of motor is to perform up to 200 rotating hours under normal operating conditions. Although this motor had only ~125 rotating hours, these were in extreme conditions compared to general oil field use. The leased motor will be returned to the vendor for evaluation and refurbishment.

Hole U1555E

The fifth drilling test aimed at advancing the bit that had performed best so far to its performance limit. We altered the test plan slightly by using the 12¼ inch TCI bit used for the third test rather

than a third, brand new bit, but without a mud motor to preserve the second mud motor on board for upcoming operations. This would also provide information on running the TCI bit, with and without a mud motor. The 20.3 h of bit on bottom that this bit had accumulated during the third test would be extended by ~40 h rather than 20 h to account for the ~50% lower rotational speed with the top drive alone. The TCI bit and BHA were made up and deployed, and drilling in Hole U1555E began on 7 August. The top of the basement was encountered at 191.8 m DSF. Drilling continued until the maximum bit depth of 290.6 m DSF, or 98.8 m into basement, was reached on 9 August. The last two hours were spent working tight hole conditions, circulating high-viscosity mud sweeps, pulling the pipe 30 m off bottom, and attempting to get back to bottom without success. We terminated drilling and retrieved the drill pipe, ending operations in Hole U1555E. The bit hours added were 23.6 h rather than the intended 40 h. The average ROP was 4.1 m/h over the 23.6 h of bit on bottom. We spent 2.0 d on Hole U1555E. Upon recovery, the bit cones, cutters, and bearings were in generally good condition and considered to be reusable. However, the outer gauge showed clear signs of wear.

Hole U1555F

The next test was dedicated to the first deployment of one of the 9⅞ inch RCB PDC coring bits that were acquired several years ago but never used. The bit and BHA were made up and deployed and coring in Hole U1555F began on 9 August. Core U1555F-1R was an attempt at establishing the seafloor depth and recovered 2.5 m of sediment with a good indication of the mudline. This resulted in a calculated water depth of 1523 m, 7 m deeper than the PDR computed depth measured at Hole U1555A and used so far at this site. After the recovery of this first core we drilled ahead without recovery through the sediment section with a wash barrel until the basement was tagged at 176.3 m DSF. The wash barrel was retrieved and basement coring began. We retrieved the core barrel after average advances of just ~1 m because the rate of penetration was very low. We terminated coring on 11 August, at a total depth of 184.3 m DSF. Cores U1555F-3R through 9R advanced a total of just 8.1 m in basement over a period of ~26 h, with a recovery of 5.81 m (72%). The average ROP in basement was 0.4 m/h with 20.7 h of bit on bottom. We spent 2.0 d on Hole U1555F. Upon recovery, the PDC bit was heavily damaged, with most of the PDC cutters broken or missing. The cutter pedestals were severely worn, indicating that the bit face itself had been turning against the formation. The cutters in the throat of the bit, where the core trimming takes place, were still fairly intact, explaining the superior core quality compared with regular RCB coring bits.

Hole U1555G

The objective for the final hole was to core and log the 130 m basalt sequence specified as an Expedition 395 objective. This would provide a few more samples for the drilling test assessments as well as samples needed from this site for the Expedition 395 scientific work. A standard RCB C7 coring bit was made up with the BHA, including a mechanical bit release (MBR) so we could follow up with wireline logging. The drill string was deployed and drilling in Hole U1555G began on 11 August. We drilled ahead through the sediment section to 168.6 m DSF and deployed the first core barrel to recover the sediment/basement interface. Core

U1555G-2R advanced from 168.6 to 178.3 m DSF and recovered 0.66 m of sediment above a 5 cm long piece of basalt. We continued coring the basalt basement and reached the final depth of 309.5 m DSF on 14 August. Basement Cores U1555G-3R through 27R advanced 131.2 m and recovered a total of 59.6 m of basalt (45%) in 70 h of coring operations. The average ROP was 2.7 m/h over 48.3 h of bit on bottom.

In preparation for logging on 14 August, the hole was swept with 50 barrels of sepiolite mud and the coring bit was released to the bottom of the hole. The hole was then displaced with heavy mud (barite-weighted to 10.5 lb/gal) and the end of the drill pipe was raised to 202.4 m DSF (~24 m below the sediment/basalt interface). Three tool strings were deployed. The triple combo tool string measured electrical resistivity, density, porosity, magnetic susceptibility, and natural gamma radiation in the formation. The first of two logging passes with the tool string reached a maximum depth of 305.5 m wireline log depth below seafloor (WSF), where tight hole conditions were encountered. The second tool string included the Dipole Sonic Imager and Formation MicroScanner systems and was deployed to a maximum depth of 295.4 m WSF due to the problems during the first pass. The tool string encountered tight hole conditions at 270.4 m WSF, where the calipers had to be temporarily closed to make the tool pass. The third tool string included the Versatile Seismic Imager and was deployed while maintaining the appropriate marine mammal and protected species observation procedures. Successful recordings were achieved at two depth stations in the open basement hole.

The hole was displaced with heavy mud (10.5 lb/gal) and the end of pipe was raised to 85.4 m DSF in preparation for logging the sediment section. The triple combo wireline logging tool string was rigged up and was in the process of being deployed in the early hours of 16 August, when at 0500 h the logging line winch motor failed. The logging line had to be transferred over to the coring line winch, which was then used to recover the logging tools. At this point, drilling and coring operations had to be suspended for safety reasons because a functioning logging winch is required in case the drill pipe gets stuck and needs to be severed. The drill string was retrieved, ending operations in Hole U1555G. We spent 5.6 d on Hole U1555G.

End of Site U1555 Operations and Expedition 384

Shipboard engineers spent 17 August disconnecting and disassembling parts of the failed wireline logging winch motor to assess its condition. On 18 August the motor was found not to be repairable on board. This assessment added another 1.4 d to the total time on site, for a total of 19.7 d.

The ship switched from dynamic positioning to cruise mode and we left Site U1555 at 0812 h on 18 August for the 1174 nmi transit to Kristiansand, Norway. We arrived in Kristiansand on 24 August. The pilot came aboard at 0704 h and the first line ashore was at 0839 h, ending Expedition 384.

Principal Results

Drilling and coring in seven holes at Site U1555 met nearly all the test objectives laid out for Expedition 384. The following overview is a preliminary assessment and further analysis will be carried out by the bit vendors and IODP JRSO staff.

Drill Bits

The TCI bits deployed in Holes U1555A, U1555C, and U1555E were the best performers, with the highest ROP (~4 m/h) and the best durability. These bits reached the target depths and were considered reusable in all three cases. The rotational speed did not seem to be a significant factor, at least in basalt, based on the ROP comparison in Holes U1555A and U1555E, which were drilled with and without a mud motor, respectively.

The traditional (cylindrical) PDC cutters did not perform well. Not surprisingly, nearly all cylindrical cutters on the drill bit (Hole U1555B), the underreamer (Hole U1555C), and also the coring bit (Hole U1555F) returned damaged. The combination of igneous rock, varying weight on bit (WOB), layered formation (fresher massive basalt vs. more altered, vesicular or amygdaloidal basalt), and perhaps the limited rotational speed appears to present an insurmountable challenge for these cutters.

The conical PDC inserts on the PDC bit we used for the first time in Hole U1555D fared much better than the cylindrical ones and might point to a path to pursue. Although the run for that bit was cut short by the mud motor failure, the bit and its conical cutters returned in a ready to be rerun condition after 20.3 h on bottom.

The TCI/PCD hybrid bit (Hole U1555B) did not perform well. Drilling was terminated after only 24.2 m basalt penetration because the ROP remained at <1 m/h over several hours. In addition to the PDC cutters and arms, the cone bearings and the outer diameter showed severe damage. We cannot be certain at this time whether the carbide jet nozzle that came out contributed to the problem. However, the totality of the damage suggests that this TCI/PCD hybrid bit does not stand up to the demands of the formation we drilled.

Our preliminary assessment points to the gauge or outer diameter (OD) protection as a critical factor in the harsh igneous rock environment. This was true for the TCI bits that in general performed well and could be reused, as well as the TCI/PDC hybrid bit, which was severely damaged and returned unusable for further drilling. The time-limiting parameter monitored for drill bits is the hours spent on bottom, when the hole is being advanced. However, the OD of the bit is in constant contact with the formation while making connections, circulating off bottom, or performing a short wiper trip. A worn OD leads to a smaller, tapered hole, which puts additional stress on the bit and can lead to spectacular coring bit failure, as experienced on Expedition 335. An additional concern is material falling in from the hole above, landing around the top of the bit. For this reason, having a back-reaming capability is important as well.

Underreamer

The top-of-the-line underreamer with cutter blocks used in Hole U1555C arguably worked better than an arm-type underreamer would do in this formation. The penetration rate was a respectable ~2 m/h. However, the amount of damage and wear to the cutter blocks in 20 h does not render this as a viable option for continuous hole opening. A cutting block type reamer may prove capable of removing ledges in front of a casing string, however.

PDC Coring Bit

The test of our RCB PDC coring bit confirmed that PDC bits are capable of cutting high-quality core pieces, even in basalt. However, the ROP and longevity are unacceptably low in the hard basalt formation. The limited rotational speeds that can be achieved on the *JOIDES Resolution* may be a contributing factor.

Other Comments

Mud motors are likely too expensive for long-term use in deep holes, given the limited run time of ~125 h we got with the one motor used. The motor was primarily used to replicate the rotational speed of the latest generation of top drives (120–150+ rpm).

Adequate heave compensation is critical for bit ROP and durability. The TCI bits used were less affected by the ±50% range in WOB, whereas the WOB variations were likely the major detriment in the poor PDC bit performance.

Hole cleaning, or hydraulics, was purposely minimized as a contributing factor for this testing with the selection of shallow target depths. However, the importance of good hole cleaning was demonstrated by the difficulties, and eventual termination of drilling, in Holes U1555A and U1555E, the two deepest holes during testing.

The RigWatch drilling system is prone to drift and errors in the depth record for reasons not yet completely explained. The driller must reset the depth with every connection by up to 20 m, which creates large, vertical offsets in the depth data and makes post-drilling analysis and interpretation difficult. Postprocessing of the data is currently carried out “manually” and therefore is extremely time-consuming and prone to bias and errors. For example, the operational time spent on connections and wiper trips had to be removed from the record manually.

Support of Expedition 395 Objectives

The original objective of obtaining some core samples with a regular RCB coring bit was expanded to coring the entire 130 m basalt section targeted in the Expedition 395 *Scientific Prospectus* for Site U1555. This resulted in the recovery of 59.6 m of basalt from the 131.2 m cored section. After reserving a few samples for potential geotechnical testing, we worked with the Expedition 395 science party on shore in selecting pilot samples based on core images. Thin section and geochemistry samples were collected and processed on board by IODP JRSO staff. In addition, a complete set of wireline logs was acquired from ~70–100 m of the basalt section, to complement the incomplete core recovery.