International Ocean Discovery Program Expedition 384 Preliminary Report

Engineering Testing

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Abstract

The objective of International Ocean Discovery Program (IODP) Expedition 384 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. A wide range of tools and technologies for potential testing were proposed by the Deep Crustal Drilling Engineering Working Group in 2017 based on reports from recent crustal drilling expeditions. The *JOIDES Resolution* Facility Board further prioritized the testing opportunities in 2018. The top priority of all recommendations was an evaluation of drilling and coring bits because rate of penetration and bit wear and tear are the prevalent issue in deep crustal drilling attempts, and bit failures often require an excessive amount of fishing and hole cleaning time. The plan included drilling in basalt with three different types of drill bits: a tungsten carbide insert (TCI) tricone bit, a polycrystalline diamond compact (PDC) bit, and a more novel TCI/PDC hybrid bit. In addition, a TCI bit was to be paired with an underreamer with expanding cutter blocks instead of extending arms. Finally, a type of rotary core barrel (RCB) PDC coring bit that was acquired for the R/V *JOIDES Resolution* several years ago but never deployed would also be given a test run.

A second objective was added when additional operating time became available for Expedition 384 as a result of the latest schedule changes. This objective included the assessment and potential improvement of current procedures for advanced piston corer (APC) core orientation.

Expedition 384 began in Kristiansand, Norway, on 20 July 2020. The location for tests 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 drilling and coring operations. IODP Expedition 395, which was postponed due to the COVID-19 pandemic, had proposed sites that were suitable for our testing and offered the opportunity to carry out some serendipitous sampling, logging, and casing work for science.

We first spent 3 days triple coring the top 70 m of sediment at Site U1554 (Proposed Site REYK-6A) to obtain cores for evaluating potential problems with the magnetic core orientation tools and for assessing other potential sources of errors that might explain prior anomalous core orientation results. Comparison of the observed core orientation from magnetic orientation tools to the expected orientation based on the paleomagnetic directions recorded in the cores revealed an 180° misalignment in the assembly of one of the tools. This misalignment appears to have persisted over several years and could explain most of the problems previously noted. The assembly part was fixed, and this problem was eliminated for future expeditions.

We subsequently spent 20 days at Site U1555 (Proposed Site REYK-13A) to test the three types of drill bits, an underreamer, and a coring bit in six holes. The TCI bits were the best performers, the TCI/PDC hybrid bit did not stand up to the harsh formation, and the PDC bit did not get sufficient run time because of a mud motor failure. The cutter block underreamer is not considered able to perform major hole opening in basalt but could be useful for knocking out ledges. The PDC coring bit cut good quality basalt cores at an unacceptably low rate.

In the seventh and final hole (U1555G), we used a regular RCB coring bit to recover the entire 130 m basalt section specified in the Expedition 395 *Scientific Prospectus* and provided the project team with shipboard data and samples. The basalt section was successfully wireline logged before the logging winch motor failed, which precluded further operations for safety reasons. Additional operations plans in support of Expedition 395, including coring, logging, and casing at Site U1554, had to be canceled, and Expedition 384 ended prematurely on 24 August in Kristiansand.

Introduction

Challenges of crustal drilling

Advancing fundamental scientific objectives such as investigations of the evolution of oceanic crust, hydrothermal circulation and material exchanges between crust and seawater, and the nature and extent of the deep biosphere requires drilling and coring deep (>1 km) into oceanic crust. Deep crustal drilling using the R/V *JOIDES Resolution* continues to face significant challenges in achieving such deep holes. A major part of these challenges is related to the level of resources allocated to crustal drilling by the scientific community and funding agencies, including operational time, money for equipment, full-time personnel, and long-term planning. These types of challenges are outside the scope of what the *JOIDES Resolution* Science Operator (JRSO) can address and therefore outside the scope of this project. The other part of the challenges is related to the performance and operation of drilling, coring, and casing equipment. This includes primary performance metrics such as the rate of penetration (ROP) when coring or drilling, hole cleaning, casing, and so forth, as well as the risk of equipment failure, which requires extensive fishing and hole remediation time and is perhaps the most detrimental issue facing crustal drilling. The use of real-time data collected on the rig or at the bit to optimize drilling operations and analyze and troubleshoot problems presents an additional ongoing operational challenge. Some of these engineering and operational challenges can be addressed when engineering expeditions such as Expedition 384 are placed on the *JOIDES Resolution* schedule, test priorities are established, and adequate funding is allocated.

The two most recent *JOIDES Resolution* expeditions attempting to core deep holes into oceanic crust were Integrated Ocean Drilling Program Expedition 335, Superfast Spreading Rate Crust 4 (13 April–3 June 2011; Teagle, Ildefonse, Blum, and the Expedition 335 Scientists, 2012; see Expedition 335 Scientists [2012] for a detailed operational assessment), and International Ocean Discovery Program (IODP) Expedition 360, Southwest Indian Ridge Lower Crust and Moho (30 November 2015–30 January 2016; MacLeod, Dick, Blum, and the Expedition 360 Scientists, 2017; see Dick et al. [2016] for a detailed operational assessment). In May 2017, outcomes from these two expeditions motivated the *JOIDES Resolution* Facility Board (JRFB) to recommend that a Deep Crustal Drilling Engineering workshop be held (*JOIDES Resolution* Facility Board, 2017). That workshop was held in October 2017 (Deep Crustal Drilling Engineering Working Group, 2017), and the reports from Expeditions 335 and 360 were the main references for its deliberations and recommendations. The operational and technical challenges of these two expeditions are therefore briefly summarized here.

Expedition 335

Expedition 335 was the fourth occupation of Ocean Drilling Program (ODP) Hole 1256D (Guatemala Basin, Cocos plate). The objective was to advance the hole from 1507 meters below seafloor (mbsf) into lower crust gabbroic rocks by as much as several hundred meters. Only ~4% of the time was spent on coring, and Hole 1256D was advanced a mere 15 m from 1507 to 1522 mbsf in 4 weeks. Three major issues forced us to spend 93% of operational time with hole remediation and stabilization. First, we encountered an obstruction in the open hole at 920–950 mbsf, and it took a total of 16 days and eight reentries to attempt to drill through, cement the interval, drill a fresh hole through the cemented problem interval, and reach the bottom of the hole. After coring ~13 m in <30 h with a Rock Bit International (RBI) C9 hard formation coring bit, penetration came to a grinding halt and a problem was suspected at the bit. Upon recovery of the drill string, we found that the bit was ground and honed to a smooth stump with all four cones, four legs, and core guides gone. The following 19 days were spent cleaning (and reaming) the hole, primarily driven by the need to remove metal debris before coring could continue. In this process, we encountered a huge amount of rock debris from previous and current drilling and coring in Hole 1256D. The debris not only filled junk baskets deployed with fishing magnets, mill shoes, reverse circulation junk baskets (RCJBs) and flow-through junk baskets, but also bit subs and up to five drill collars (through the float valve). The junk recovery also included cobble-sized rocks from near the bottom of the hole, assumed to have been water-jetted from the borehole wall as a result of the intense cleaning action. After five fishing trips, we still had not reached the bottom of the hole by a few meters and decided to ream to the bottom with a tricone (roller cone) bit. Upon recovery of the bit, we found that it had virtually no wear but was under gauge, indicating that it had been squeezed into a smaller diameter hole. After reaming the lowermost ~3 m with another tricone bit, six more milling, fishing, and cleaning trips were conducted. After a logging run, the last of 24 reentries during Expedition 335 was dedicated to coring with a new Ulterra 9⅞ inch rotary core barrel (RCB) bit for the last ~6 h available and advanced the hole 1.4 m to a final depth of 1520.2 mbsf. Hole 1256D finally seemed clear and ready for further coring.

Expedition 360

Expedition 360 was the second return to Atlantis Bank, and the objective was to drill a third hole in the vicinity of existing ODP Holes 735B and 1105A with the ultimate multiexpedition goal to drill and core to the Mohorovicic seismic discontinuity (Moho) at ~3 km depth. Hole 735B was successfully cored to 1508 mbsf during two previous expeditions and was terminated only because the entire drill string failed at the rig and fell into the hole, obstructing it for good. Based on the advice of the scientific advisory panel, the new hole was to be located a few kilometers away from Hole 735B and cored from the top to learn about the lateral variability of the crustal architecture and evolution on Atlantis Bank. IODP Hole U1473A was established ~2 km away from Holes 735B and 1105A. The reentry system was installed efficiently and successfully into the bare rock seafloor in <2 days. This was followed by successful coring to 410 mbsf in ~11 days. Coring at this rate would have allowed us to reach a respectable 1200 mbsf in the remaining time. At this point, however, three of the four roller cones were lost in problematic hole conditions associated with faults. We deployed two fishing magnets followed by two RCJBs for 3 days without recovering any cones. To everyone's surprise, the last RCJB recovered an unprecedented 0.5 m (18 cm diameter) core, which made it extremely unlikely that we had roller cones at the bottom of the hole. During intermittent coring and hole remediation for 7 days, we advanced the hole a mere 72 m to 482 mbsf. Penetration rates while coring were high and recovery was low in a highly fractured formation, and we lost another roller cone. The second of two subsequent RCJB runs recovered one roller cone. We continued coring but soon came to a grinding halt. Upon recovery of the drill string, the bit showed damage clearly attributable to having been grinding on a lost cone. We deployed a fishing magnet and recovered a highly abraded roller cone. At that point, we decided to drill ahead without coring for a couple of days. We advanced the hole to 519 mbsf at a rate that was not significantly better than coring. The subsequent 10 days were spent coring with excellent recovery in less fractured gabbroic rock (similar to Hole 735B), reaching a total depth for Hole U1473A of 789 mbsf. With a week of operations left, we dropped the spent coring bit on the seafloor using a mechanical bit release (MBR) and conducted two successful logging runs. Our plan was to spend the remaining time coring; however, when the logging bit arrived back on the rig floor, a retainer sleeve was missing from the MBR and had to be assumed left in the hole. This situation was indirectly confirmed with a subsequent RCJB fishing run recovering two large gravel pieces with characteristic marks.

Half a year later (July 2016), during a transit from a tie-up period in Cape Town, South Africa, to Colombo, Sri Lanka, on a 33 day transit, *JOIDES Resolution* passed by Hole U1473A. The JRFB approved a plan in March 2016 to spend 9 days out of that transit to remediate Hole U1473A (Blum et al., 2017): (1) fish for the lost MBR retainer sleeve, (2) core up to 20 m to confirm the viability for future deepening of the hole, and (3) complete cementing the fault zones between 420 and 580 mbsf to stabilize the hole for future penetration (a lesson learned from Expedition 335). We quickly determined that the MBR sleeve was not in the hole; it must have been recovered with the last RCJB fishing trip during Expedition 360 and fallen to the seafloor when the bit was recovered without leaving any operational evidence. Subsequent coring successfully deepened Hole U1473A to 809.4 mbsf and cleared it for future deepening. The cement job to stabilize the hole was partially completed; the fault zone accommodated more cement than anticipated. Additional cementing attempts were limited by the quantity of cement on board that could be utilized for hole remediation.

Two types of challenges of deep crustal drilling

Based on the experiences with Expeditions 335 and 360, as well as other similar operations, the challenges of deep crustal drilling must be differentiated into those that can and those that cannot be addressed with an engineering expedition. The following are critical but nontechnical challenges:

- Deep crustal drilling takes time and patience and requires a substantial resource commitment by the scientific drilling community. Drilling a new frontier is guaranteed to face known and unknown operational problems. Both Holes 1256D and U1473A could have been deepened further with existing technology if more than 4–6 weeks of operations had been allocated.
- Principal investigators tend to expect immediate scientific return from any drilling or coring operations. That expectation may be in conflict with the need to spend time for proper engineering or conditioning of a top hole if deep penetration is the objective, as exemplified by the decision for Hole U1473A. Proper engineering with existing technology may include fast drilling (without coring) or reaming and subsequent casing of a hole, preferably close to an existing pilot hole such as Holes 1256D and 735B, so that deeper coring has a fair chance of success.
- IODP Expedition 362T was an example of how to use a cost-effective opportunity to remediate and condition a hole. Few or no scientists are required to be on board to execute such standard operational tasks. The few cores we recovered to establish via-

bility for future deepening were described and analyzed by a science team on shore.

The challenges that can be addressed with engineering projects such as Expedition 384 include the following:

- Coring bit failure is by far the biggest problem. It is hard to detect and requires time consuming fishing and milling operations. Better use of rig instrumentation data may (and has been demonstrated to) allow operators to detect bit failure earlier, but in most cases detection still happens after the failure has occurred. The complete destruction of the coring bit in the granoblastic dike formation at the bottom of Hole 1256D in hours may have been the result of a tight hole, or it may point to an absolute limit of what available coring bits are able to do. Bit failures in Hole U1473A were attributed to the more common problem of rubble in fault zones, both ahead of the bit and falling onto the bit from above. Unfortunately, coring bit research and development appear to be vanishing, and we do not know of the existence of suitable alternatives to our coring bits that would alleviate these problems.
- The tricone drilling bits commonly used on *JOIDES Resolution* are in general more robust than coring bits but have been shown to be "squeezed" in Hole 1256D in an interval previously cored under gauge. Drilling bits are mainly deployed to open (and potentially case) a hole in the vicinity of a pilot hole that was previously cored in preparation for deep drilling or to remediate various types of problems such as hole collapse (and potential cementing of the interval), coring bit failure follow-up, undergauge intervals, and so forth. Drilling bit alternatives do exist on the market, and an engineering expedition is a good opportunity to evaluate some in a systematic fashion. Identification of better drill bit technology may eventually lead to the development of more robust coring bits.
- Casing a hole is one principal way to stabilize a hole and minimize the risk of coring bit failure. If Hole 1256D had been cased to 1000 mbsf instead of 263 mbsf (sediment section only), the 2 weeks spent to get past the ledge at 920–950 mbsf during Expedition 335 might have been avoided. We have successfully deployed casing strings from *JOIDES Resolution* up to 1100 m long in sedimentary systems. Deploying casing is expensive and time consuming and bears its own operational risk, but it's a reasonable if not unavoidable trade off for successful deep drilling and coring. Importantly, casing will also improve the hydraulic conditions for hole cleaning.
- Cleaning debris from the hole will be an increasingly challenging issue the deeper a hole is advanced. The sepiolite and attapulgite used safely in open hole drilling appears to be an adequate agent; however, large quantities are required, and the necessary time must be invested so as not to leave an overwhelming amount of debris for a future expedition (see Expedition 335). Failure to keep up with rigorous hole cleaning will compromise a hole. Casing as much as possible of the top hole is the best way to ensure effective hole cleaning, especially if challenging hole conditions are encountered (e.g., Hole U1473A) at borehole depths where casing can be deployed. Hole cleaning after a problem has already occurred may also have side effects. During Expedition 335, the intense, high-powered cleaning of the lowermost portion of Hole 1256D resulted in water-jetted cobble-sized rocks that had to be fished, ground, and flushed with a large investment of time. The enlarged hole resulting from this operation may compromise future operations in Hole 1256D.

Expedition 384 objectives

Scoping of Expedition 384 engineering test objectives

At their May 2017 meeting, the JRFB made the following recommendation (*JOIDES Resolution* Facility Board, 2017):

"**Consensus 7:** The JRFB recommends the immediate formation of a 'Deep Crustal Drilling Engineering' workgroup 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 355 '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 Deep Crustal Drilling Engineering Working Group workshop was subsequently held on 16–18 October 2017 and recommended the following testing opportunities for Expedition 384, which at that time was still scheduled for 2019 (Deep Crustal Drilling Engineering Working Group, 2017):

"**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"

The workshop recommendation was further prioritized by the JRFB at their May 2018 meeting (*JOIDES Resolution* Facility Board, 2018) in light of the available time frame and budget:

"**Consensus 6:** The JRFB recommends the following engineering tests to be carried out during Expedition 384 by the JRSO in order of priority:

1. New drilling bits for improved advancement, opening and remediation of drill holes in hard rock formations.
2. New underreamers for opening up holes in hard rock formations.
3. New coring bits for coring in hard rock formations.
4. New biodegradable drilling fluid additives for improved hole cleaning.
5. New bottom-driven XCB based on current Chikyu XCB designs.
6. Continued testing of the Turbine Driven Coring System (TDC) depending on the outcome of first tests during Expedition 376 and discussions with CDEX.
7. [Motion Decoupled Hydraulic Delivery System] MDHDS testing in conjunction with the T2P system."

Based on the JRFB guidance, the JRSO project team developed a plan that addressed Recommendations 1 (drilling bits), 2 (underreamers), and to the degree possible, 3 (coring bits) (*JOIDES Resolution* Facility Board, 2018) (Table **T1**).

Recommendation 3 (coring bit design) was addressed with an existing polycrystalline diamond compact (PDC) bit, with low expectations. Potential design of a new coring bit specifically suited for basaltic rocks must be postponed. Our hope was that the experience with the drill bits during Expedition 384 might point to a design approach. Recommendation 4 (drilling mud alternatives) was considered, but the leading biodegradable mud enhancer, recommended during the deep crustal workshop, is no longer being manufactured. Also, the shallow depths for this expedition would not be an adequate test for drilling mud alternatives. Recommendation 6 (Japan Agency for Marine-Earth Science and Technology's turbine-driven coring system) figured in an earlier version of the plan but ultimately could not be added because of the travel and shipping complications associated with multiple expedition rescheduling. Recommendation 5 (bottom-drive extended core barrel [XCB]) was dropped because of time considerations and because the tool could likely be tested during the course of normal operations or during a transit. Recommendation 7 (MDHDS) was dropped because the tool will be replaced by the probe deployment tool (PDT) currently under development, and to be tested, by the same third party team that developed the MDHDS.

Primary objectives

The following questions were to be addressed by the tests:

- Can we acquire drill bits that drill holes faster than has been possible in the past, in preparation for logging and casing?
- Can we acquire bits that last longer in harsh igneous rock formation than in the past?
- Is it possible to ream an igneous rock hole for casing operations using a different type of reamer than used in the past?
- Should we take another look at PDC coring bits for better recovery and, less likely, faster coring?

Drilling bits

The first primary objective was to test and compare the performance of three types of drill bits: (1) the conventional tungsten carbide insert (TCI) tricone bit, but a more robust model than previously used on *JOIDES Resolution*; (2) a ruggedized PDC bit with some "harder rock" success according to the vendor, using a new, more robust cutter shape; and (3) a TCI/PDC hybrid bit that combines roller cone crushing efficiency with fixed cutter elements. We decided to focus on one size (12¼ inches) for bits because they are industry standard and readily available and because they are suitable to drill holes for deep casing.

A mud motor was to be used in these drilling tests to increase the total rotational speed to at least 120 rpm. 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, and 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 results, and additional core samples would be made available to the IODP Expedition 395 science team.

Underreamer

Our second primary objective was to conduct performance tests on an underreamer that could open the 12¼ inch hole to 14½ inches. Vendors and JRSO engineers agreed that the chances of success were minimal; however, one vendor was willing to provide a newer type of underreamer with expanding cutter blocks instead of the extending arms used by the JRSO in the past. The underreamer was to be made up with the same type of TCI bit and mud motor used in the drill bit tests.

PDC coring bit

The third primary objective was to deploy one or more of the four standard PDC-cutter coring bits available on *JOIDES Resolution*, which were built for our RCB coring BHA for a project with another operator several years ago. These bits have never been used, and we were planning to test them during Expedition 384. Depending on the outcome of these tests, deployment of a regular C7 coring bit would be considered to obtain the desired samples.

Site selection

The locations for the tests were selected based on various factors, including the *JOIDES Resolution's* location at the time, our inability to obtain territorial clearance in a short period time, and a suitable combination of sediment and igneous rock for the coring operations. Expedition 395, which was postponed because of the COVID-19 pandemic, included proposed sites that were suitable for our testing and offered the opportunity to carry out some serendipitous sampling, logging, and casing work for science (Figures **F1**, **F2**, **F3**, **F4**). In particular, Proposed Site REYK-13A perfectly met the logistics, water depth, and sediment thickness requirements (Figure **F3**). A contingency plan of attempting to drill into the gabbro-dominated formation at Integrated Ocean Drilling Program Site U1309 was canceled soon after Expedition 384 departed from Kristiansand, Norway, when the arrival port changed from Las Palmas, Gran Canaria, to Kristiansand because of COVID-19 travel restrictions.

Secondary objectives

The main objective of Expedition 384 was to test drilling, reaming, and coring equipment in igneous ocean crust. Operational schedule changes related to some major *JOIDES Resolution* repairs as well as travel restrictions imposed by the COVID-19 pandemic provided an opportunity to conduct other operations. Given the short notice and preparation time, the JRSO decided to insert an assessment of the advanced piston corer (APC) core orientation tools and procedures during Expedition 384.

Azimuthal orientation of APC cores using magnetic orientation tools (MOTs) has been routinely performed for many years. The tool currently used is the Icefield MI-5 core orientation tool; the FlexIT tool was used in the past and is also available. However, recent experience has shown that these measurements are unreliable, working consistently during some expeditions and failing repeatedly during others. The objective during Expedition 384 was to investigate the origin of the problem by assessing the procedures and equipment used for orienting the cores under more controlled conditions than is typically possible during expeditions when the focus is on maximizing core recovery. We planned to recover APC cores in three adjacent holes to 70 mbsf to obtain a sufficient number of orientation measurements that could be compared with the paleomagnetic measurements in the stratigraphically correlated cores.

The site chosen for the primary engineering objective, Proposed Site REYK-13A, happened to have a companion site <100 km away, Proposed Site REYK-6A, that had the requisite young sediments expected to be good paleomagnetic recorders based on results from nearby drift sediments cored ~150 km to the northeast during ODP Leg 162 (Sites 983 and 984; Figure **F2**) (Jansen, Raymo, Blum, P., et al., 1996; Channel 1999). The paleomagnetic declination for these Brunhes age sediments were expected to average to approximately due north, providing the reference declination against which the orientation tools could be tested.

Site summaries

Site U1554

Operations

Operations at Site U1554 (Proposed Site REYK-6A) began after the 1100 nmi transit from Kristiansand, Norway, which ended at 0629 h on 27 July 2020 when we established dynamic positioning. The average speed of the transit was 11.6 kt.

An 11⁷⁄₁₆ inch APC/XCB bit was made up with a 136.8 m long BHA, and the drill string was deployed at 1445 h. The pipe stands were measured and cleared of rust during deployment. Hole U1554A was started at 2300 h with a 5.7 m long mudline core. The calculated water depth was 1870 m. We completed APC coring in Hole U1554A at 0625 h on 28 July with Core 8H to 72.2 m drilling depth below seafloor (DSF) with a recovery of 74.7 m (103%). The ship was offset 20 m east, and Hole U1554B was completed at 1515 h with Core 8H to 76.0 m DSF with a recovery of 76.8 m (101%). The ship was offset 20 m south, and we completed Hole U1554C at 2330 h with Core 8H to 75.0 m DSF with a recovery of 77.0 m (103%). Core orientation was measured on all cores in each hole. On 29 July, the ship was offset once more, this time 20 m west of Hole U1554C, and coring in Hole U1554D began at 0045 h. Here, we drilled to 14 m DSF and cored a single core (2H) from 14 to 23.5 m DSF with a recovery of 9.72 m (102%). This core was taken for future training and testing purposes on the ship. In total, 25 cores were recovered at Site U1554 (Table **T2**). The drill string was retrieved and cleared the rig floor at 0715 h, ending operations at Site U1554. The rig floor was secured, and the ship began the transit to Site U1555 (Proposed Site REYK-13A) at 0900 h. Total time spent at Site U1554 was 2.0 days.

Preliminary results

Stratigraphic characterization

Core logging and stratigraphic correlation. The core orientation tests required a set of stratigraphically correlated cores characterized with the standard set of shipboard measurements and observations. To that end, all cores from Holes U1554A–U1554D were first measured for magnetic susceptibility (MS) and gamma ray attenuation (GRA) on the Special Task Multisensor Logger (STMSL). The STMSL was configured to perform these measurements as rapidly as possible to allow for real-time feedback to the driller to ensure that all coring gaps in a hole were covered by cores in at least one of the adjacent holes. Our coring gaps in Hole U1554A were perfectly covered in cores from both Holes U1554B and U1554C using that method. We constructed a composite depth scale to 83.3 m core composite depth below seafloor (CCSF) and a splice representative of the complete stratigraphic section (Tables **T2**, **T3**; Figure **F5**). All cores from Holes U1554A and U1554B were used except for Core 384-U1554B-5H, which was more disturbed by the coring process than all other cores. We replaced it with Core 384-U1554C-5H for the splice.

Higher resolution measurements of MS and GRA were made on the Whole-Round Multisensor Logger (WRMSL), which included *P*-wave velocity measurements, and all whole-round core sections were also measured on the Natural Gamma Radiation Logger (NGRL). All cores were subsequently split and imaged with both visual light and X-ray. Color reflectance and MS measurements were made using the Section Half Multisensor Logger (SHMSL). A small set of discrete samples were taken from the working-half sections for moisture and density and magnetic property measurements. Magnetic remanence was measured on all archive-half sections using the superconducting rock magnetometer (SRM).

Paleomagnetic chronostratigraphy. The sediments proved to be high-fidelity recorders of the Brunhes normal polarity geomagnetic field, with the exception of Core 384-U1554B-5H, which suffered drilling disturbance throughout (Figures **F6**, **F7**). Furthermore, the MS and relative paleomagnetic intensity records can be correlated with a high degree of confidence to the equivalent records from nearby Sites 983 and 984, where the records were dated with the help of oxygen stable isotopes (Channel, 1999). Based on this correlation, we infer that the sediments in the top 83 m CCSF at Site U1554 represent the last ~0.6 Ma, yielding an average sedimentation rate of ~14 cm/ky.

Lithostratigraphy. The sediment section recovered at Site U1554 is a fine-grained mixture of clay- to silt-sized siliciclastics and ash. The fine-grained texture is uniform throughout, with the exception of two pebbles observed and interpreted to be dropstones. The color transitions between shades of greenish gray and gray in intervals on the order of a few centimeters to meters. The color transitions are generally gradual over a few centimeters and only sharp in a few cases where a dark greenish gray ash-dominated layer overlies a light greenish gray or gray layer. The sediment constituents are dominated by silt-sized particles and/or ash in the greenish gray layers based on smear slide observations and as expected for a drift deposit in a volcanic province. In gray intervals, calcareous nannofossils are abundant or dominant. The silt fraction in these sediments may largely represent broken down volcaniclastic particles rather than siliciclastic grains. Clay and siliceous microfossils (mainly sponge spicules and diatoms), as well as calcareous nannofossils in the darker greenish gray layers, are subordinate constituents. The ash is mostly dispersed and mixed with the other constituents and is more concentrated in thin, darker greenish gray layers. The sediment is intensely bioturbated, as indicated by discrete burrows, particularly at interval boundaries with strong color contrast, by ash pods representing remnants of ash layers, and by pervasive mottling. The greenish gray sediments can be referred to as silty ash or tuffaceous silt with nannofossils and siliceous microfossils, and the light gray layers can be referred to as tuffaceous nannofossil ooze. Note that this differs from the Leg 162 descriptions at nearby Sites 983 and 984, which characterize the sediment as terrigenous silty clay, clay, clayey nannofossil mixed sediment, and clay with variable amounts of nannofossils and silt (Jansen, Raymo, Blum, P., et al., 1996). We didn't observe that dominance of clay at Site U1554 using smear slide observations and primitive settling and remolding tests.

Core orientation tests

Core orientation tests were initiated mainly because multiple previous expeditions had reported suspect orientation results, with large scatter and anomalous core orientation estimates. Thus, our study aimed to monitor all steps in the orientation process for a suite of cores to document where orientation errors might be introduced and provide estimates about the size of the errors associated with core orientation. We also planned to assess multiple MOTs to determine if the apparent aberrant results originated from one or more of the tools.

To assess whether the core orientation tools were functioning accurately, different MOTs were deployed while acquiring the 25 cores in Holes U1554A–U1554D. Eight cores were collected with FlexIT Tool 0937, and the remaining 17 cores were collected with three Icefield tools (2007, 2043, and 2052). These tools give an angle, referred to as the magnetic tool face (MTF) angle, that can be used to determine the azimuthal orientation of the core. The azimuthal orientation that is determined from the MTF angle will be referred to as the observed orientation.

The FlexIT and Icefield tools have essentially the same capabilities, but the Icefield tools are newer tools and have more memory than the FlexIT tools, which are no longer produced. These MOTs have three orthogonal fluxgate magnetometers, three orthogonal accelerometers, and a thermistor. The output includes measurement number/time, MTF angle, total magnetic field strength, horizontal and vertical magnetic field components, dip of the hole and its azimuth, three accelerometer components, and the temperature (Table **T4**).

Paleomagnetic data from APC cores provide an independent estimate of the azimuthal orientation of the cores. Based on the geocentric axial dipole (GAD) hypothesis, the mean declination of the geomagnetic field when averaged over several tens of thousands of years will be 0°. The instantaneous or short-term field differs from a GAD field, but those differences or variations, referred to as paleosecular variation, are averaged out over time. In other words, the average paleomagnetic declination computed from sediments deposited over time will point toward Earth's spin axis or North Pole if the sediments were deposited during a normal polarity interval. Site U1554 was selected because the normal polarity Brunhes age (<780 ka) sediments in the Bjorn drift were known to be excellent paleomagnetic recorders (Channell, 1999), allowing the mean paleomagnetic declination of each core to be accurately determined. The deviation of the in situ core mean declination from 0° provides an estimate of the azimuthal orientation of the core. This paleomagnetic orientation, therefore, provides very tight constraints on what will be referred to as the expected orientation. Comparison of the MOT observed orientation to the GAD expected orientation provides the basis for determining the accuracy and precision of the MOTs (Table **T4**).

We used the paleomagnetic data from archive-half sections, except for the one core collected from Hole U1554D, for which we used data only from whole-round Section 384-U1554D-2H-7. The split-core sections were measured every 1 cm using progressive alternating field (AF) demagnetization up to 25 mT (Figure **F6**), typically with 7 steps (0, 2, 6, 10, 15, 20, and 25 mT). Selected sections were progressively demagnetized in more detail using 13 steps (0–22 mT at 2 mT steps and a 25 mT step). Section 2H-7 was measured every 1 cm using detailed progressive AF demagnetization (0–80 mT at 5 mT steps) (Figure **F6C**). Demagnetization to 25 mT proved more than sufficient to resolve the characteristic remanent magnetization (ChRM) very accurately while also retaining enough magnetization for other postexpedition studies.

The ChRM directions for each hole are plotted in Figure **F7**. The declinations are shown in sample coordinates prior to reorientation, after being corrected using the MOT reorientation angles, and after being corrected using the paleomagnetic data assuming a GAD field. It is clear visually that the MOTs corrected the declinations close to the expected values.

The accuracy of the MOTs can be assessed in detail by comparing the observed reorientation angles measured by the MOTs (R_{MOT}) to the expected reorientation angles determined from paleomagnetic measurements assuming the geomagnetic field corresponds to a GAD (R_{GAD}) (Table **T4**). These are computed using the following equations:

$$R_{MOT} = A_{MTF} + D_{IGRF}, \text{ and}$$

$$R_{GAD} = -D_P = 360° - D_P,$$

where

A_{MTF} = MTF angle from the MOT,
D_{IGRF} = present-day magnetic declination at the site determined from the International Geomagnetic Reference Field (IGRF) model (−13.6°), and
D_P = core mean declination determined from the paleomagnetic measurements.

The difference between the expected and observed declinations is given by

$$\Delta R = R_{MOT} - R_{GAD}.$$

The initially determined ΔR values for 20 of the 25 cores differed by <28°. One core (384-U1554B-5H) had significant coring disturbance throughout, as was evident in the X-ray images, and was not used in the assessment. The paleomagnetic directions were clearly disturbed in this core, and likewise ΔR was somewhat larger (34.8°) than observed for the undisturbed cores. The four results obtained with Icefield Tool 2043 were all anomalous, with ΔR values of 155.3°, 183.6°, 192.4, and 189.0°. The average of these happens to be 180.1°, which indicated that some component in the tool had likely been inverted.

We determined these anomalous results were caused by a misaligned internal key for the end seal of the pressure barrel used with Icefield Tool 2043, which had been inverted (i.e., it was rotated by 180° from its proper position) (Figure **F8**). This internal key locks into the T-slot keyhole of the MOT. It must be aligned with the external key of the end seal. The external key is inserted into the muleshoe keyhole in the sinker bars, thus aligning the MOT with the core barrel and liner. We suspect that this had been inverted for several years, had been used with other MOTs, and was the primary reason for the anomalous orientations reported in the past, which had sometimes noted orientations that were roughly 180° off. We also noted that the internal key for the end seal of the pressure barrel used with FlexIT Tool 0936 was misaligned by about 5°, which would have resulted in orientations about 5° smaller than they should have been for that tool. All internal keys were checked, and only minor adjustments of a few degrees were made as needed.

After correcting the R_{MOT} values by 180° for Icefield Tool 2043, the ΔR values were <28° for 24 of the 25 cores (Table **T4**; Figure **F9**). Disturbed Core 384-U1554B-5H is the exception and was excluded from further consideration. For the valid 24 determinations, the mean ΔR is 9.1° and the standard deviation (STDEV) is 13.2° for all tools. The mean ΔR is 3.9° and STDEV is 11.8° for the 16 Icefield tool orientations, and the mean ΔR is 19.4° and STDEV is 9.7° for the 8 FlexIT tool orientations. The 95% confidence limits for the Icefield tool orientations are

$$\pm(4.49)^{½}(13.2°)/(16)^{½} = \pm6.2°.$$

The 95% confidence limits for the FlexIT tool orientations are

$$\pm(5.32)^{½}(9.7°)/(8)^{½} = \pm7.9°.$$

Thus, the Icefield tools accurately measured core orientations within their uncertainty. FlexIT Tool 0937, however, has a relatively large bias, with reorientation angles that were on average at least 11.5° smaller than expected. It is possible that FlexIT Tool 0937 needs to be recalibrated, some other systematic error occurs that has yet to be identified, or the bias is related to the fairly small sample size. More measurements would help resolve this issue. Given that the FlexIT tools have been superseded by the Icefield tools and the vendor no longer is in business, recalibration or even the opportunity to gather additional data during an upcoming IODP expedition with these tools is not planned.

Natural questions to ask from the above analysis are why was the internal key for an Icefield tool misaligned by 180° and why was this misalignment not noticed and fixed. The alignment of the internal key is adjusted by loosening a jam nut, turning the key to the desired position, and then tightening the jam nut while holding the key in its proper position. If one is unfamiliar with the importance of the alignment of the keys or how the jam nut functions, it would be easy to overlook aligning the keys in a specific orientation or to misalign them when loosening or tightening the jam nut. Furthermore, the key is very similar looking in the proper orientation and when rotated 180°, with the only difference being a small pin on one side of the key (Figure **F8**). Finally, the internal key is not visible when the tool is in the pressure barrel, which means for most of the time the tool is handled, no one would be able to note any misalignment of the internal key.

It was clear from looking at the service records for the Icefield tools that the tools had been sent back to the vendor multiple times for recalibration because of the anomalous reorientation values the tools were giving. However, the tools were sent to the vendor without their pressure barrels and end seals, so the vendor could not resolve the problem. They would have noted the tools were functioning as intended and done whatever minor recalibrations were needed before sending them back to IODP. After this, one of these properly functioning tools (not just Icefield Tool 2043) were likely used with the end seal with the misaligned internal key, resulting in the recurring anomalous core orientations.

Although it might seem that the problem was obvious and would have been easy to catch, multiple paleomagnetists and technicians had conducted tests with the tools over the past several years without ever noting the inverted internal key. Given that four of the five internal keys were aligned reasonably accurately and all five tools were functioning properly when not in their pressure barrels, catching the misalignment of one internal key proved deceptively difficult. Even in this study, which had the advantage of having sediments ideal for determining the expected core orientation, it took many tests on the dock with the tools in and out of their pressure barrels before we noted the one misaligned internal key. In the future, the alignment of the keys will be checked regularly, and each Icefield tool will preferably be used with a specific pressure barrel and end seal, all of which will be documented in the data files uploaded into the Laboratory Information Management System (LIMS) database.

In summary, we concluded that a misaligned internal key on one of the end seals for an Icefield tool pressure barrel was the probable source of the anomalous core orientation results obtained during prior expeditions. When that misalignment is accounted for, the Icefield tools give accurate reorientation angles to within about ±12° (standard deviation) of the expected value for a single core orientation estimate. Given that we only had time to orient 17 cores with the Icefield tools, both the accuracy and precision of the tools should be further evaluated on many more cores from regions with paleomagnetic records comparable to the Bjorn drift. Upcoming Expedition 395 presents an excellent opportunity to enlarge the sample size by an order of magnitude.

Site U1555

Operations

We arrived at Site U1555 at 1541 h on 29 July 2020 after switching to dynamic positioning mode. The ship was positioned 50 m east of the coordinates for Proposed Site REYK-13A along the seismic survey line toward Proposed Site REYK-11A. Additional holes were planned at 20 m intervals along this same line. The goal for Hole U1555A and subsequent holes was to penetrate ~210 m of sediment, as estimated from geophysical site survey data, and then deepen the hole ~100 m into the basaltic basement or drill for ~40 h, whichever came first. 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. A complete set of wireline logs was acquired in Hole U1555G. Total time on site was 19.7 days.

Hole U1555A

For the first drilling test, a Gemini 12¼ inch TCI roller cone bit from Schlumberger/Smith Bits was made up with a Baker Hughes 8 inch Ultra XL/VS mud motor. The bit used for this test was similar to the TCI bits previously used on *JOIDES Resolution* but was a much more robust version (IADC Grade 647Y). The motor used was the same high-torque model used previously on *JOIDES Resolution* when running casing. The bit and motor assembly was flow tested before deployment.

Deployment of the drill string was completed at 0015 h on 30 July, and we began drilling Hole U1555A. The seafloor was barely felt with the drill string at approximately the depth determined by the PDR. Sediment penetration proceeded at a controlled ROP of ~40 m/h. At 0545 h, with the bit at ~185 m DSF, the formation stiffened and the ROP slowed by an order of magnitude to typically <5 m/h. At 1930 h, the bit got stuck at 224 m DSF, and time was spent trying to free the drill string, including offsetting the ship to be able to set the slips and remove a joint of pipe, circulating mud sweeps, and working the pipe free. The bit was raised to 212.6 m DSF for further mud circulation and hole cleaning. On 31 July, the driller had to pull the bit back two more times by ~30 m for hole cleaning with additional mud sweeps at 242.6 m DSF (0415 h) and 252.6 m DSF (0915 h). When the bit reached 262.6 m DSF (1045 h), the hole was reamed up to 242.6 m DSF before the final 20 m of advancement. We reached the target basement penetration of ~100 m (97.4 m exactly) at 2000 h on 31 July at 282.0 m DSF. The drill string was retrieved, and the bit cleared the rig floor at 0245 h on 1 August, ending Hole U1555A. The average ROP was 4.2 m/h over 23.1 h of bit on bottom. We spent 2.5 days 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 (Figure **F10A, F10B**).

Hole U1555B

The ship was offset ~20 m east of Hole U1555A in preparation for the second test. The second test bit, a 12¼ inch hybrid TCI/PDC "Kymera" bit from Baker Hughes, was made up to the bottom of the mud motor and flow tested. The motor started rotating at 5 strokes/min, compared to 30 strokes/min before, indicating that the bearing assembly was now broken in, but the flow across the motor seals was still normal. The BHA was made up, and the drill string was deployed. Because of heave in excess of 4 m and winds approaching 40 kt, the decision was made to suspend operations with the bit suspended at 1435 m below the rig floor or ~100 m above the seafloor.

At 1200 h on 2 August, the heave became safe for operations to resume. Deployment of the drill string was completed, and drilling in Hole U1555B began at 1400 h. The sediment was penetrated at the same controlled ROP of ~40 m/h used in the first test with the TCI bit. At 2030 h, we encountered the hard basement formation at 186.6 m DSF, where the ROP dropped by an order of magnitude. At 1600 h on 3 August, at a bit depth of 210.8 m DSF (24.2 m into basement), we decided to terminate drilling based on the low ROP of <1 m/h over 6 h. The drill string was retrieved, and the bit cleared the rig floor at 2225 h, ending Hole U1555B operations. The average ROP was 1.3 m/h over 19.4 h of bit on bottom. We spent 2.8 days on Hole U1555B, of which 1.1 days we spent waiting 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 (Figure **F10C, F10D**). The cone bearings appeared to be frozen. The outer diameter (OD; 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 Schlumberger 12¼ inch Gemini IAD 647Y (SN RK4875) TCI bit, a Schlumberger Rhino XS 11625 Series 12¼ to 14½ inch hydraulically expandable reamer with StingBlock blades, the mud motor, and the BHA. The TCI bit was the same type of bit run during the first test. The mud motor was the same motor used in the previous tests. The bearing play on the motor was checked and fell well within the acceptable range. The assembly was flow tested at the rig floor. The activation ball was placed on the seat in the underreamer because a ball-drop activation once the reamer is downhole is impossible with a motor above the reamer. The underreamer cutter blocks shifted at ~600 psi. The cutter blocks opened at ~45 strokes/min and were fully open at 50 strokes/min, corresponding to the design parameters of 220–245 gal/min, respectively. The drill string was deployed in the early morning of 4 August, and drilling in Hole U1555C began at 0650 h using as low a flow rate as possible so as not to engage the underreamer until necessary. At 1000 h, the pumping rate was increased to 60 strokes/min to expand the cutter blocks of the reamer with the bit at 130.6 m DSF. At 1225 h, we reached the top of the basement at 186.6 m DSF. Drilling in Hole U1555C continued until 1045 h on 5 August when the underreamer reached 20 h of operation and the bit was at 225.8 m DSF (39.2 m into basement). The drill string was retrieved, and the bit cleared the rig floor at 1745 h, ending the third drilling test and operations in Hole U1555C. The average ROP was 1.8 m/h over 20.0 h of bit on bottom. We spent 1.8 days on Hole U1555C.

Upon recovery, the underreamer had several PDC cutters damaged and the cutter blocks were still extended just over 1 inch (Figure **F11A, F11B**).

Hole U1555D

For the fourth drilling test, the rig floor crew made up a Smith Bits/Schlumberger StingBlade (SN 1678) 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 *JOIDES Resolution*. The mud motor bearings were confirmed to be still in good condition. The ship was offset ~20 m east, the drill string was deployed, and drilling in Hole U1555D began at 0245 h on 6 August. The top of the basement was encountered at 0800 h with the bit at 189.0 m DSF. Drilling continued until 0545 h on 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 (33.9 m into basement). The drill string was retrieved, and the bit cleared the rig floor at 1040 h, ending Hole U1555D. The average ROP was 1.7 m/h over 20.3 h of bit on bottom. We spent 1.7 days on Hole U1555D.

Once back on the rig floor, the cutters and outer gauge of the PDC bit were found to be in good condition, and the bit was ready for a follow-up test (Figure **F10E, F10F**). 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 oilfield 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 plan slightly by using the Schlumberger Gemini 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 at 1650 h on 7 August. The top of the basement was encountered at 2330 h with the bit at 191.8 m DSF. Drilling continued until the maximum bit depth of 290.6 m DSF (98.8 m into basement) was reached at 0300 h on 9 August. The subsequent 2 h 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. At 0500 h, we terminated drilling and retrieved the drill pipe. The bit cleared the rig floor at 1020 h, ending operations in Hole U1555E. The bit hours added were ~24 h rather than the intended 40 h. The average ROP was 4.1 m/h over 23.6 h of bit on bottom. We spent 2.0 days 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. The drilling line was slipped and cut from 1715 to 1915 h, and coring in Hole U1555F began at 2200 h on 9 August. Core 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 for 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 0415 h on 10 August with the bit 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 ROP was very low. We terminated RCB coring with the PDC bit at 0600 h on 11 August at a total depth of 184.3 m DSF. Although the basalt cores we recovered in Hole U1555F were better trimmed than the typical RCB cores cut with our regular bits, the ROP became unacceptably low. We retrieved the drill string, and the bit cleared the rig floor at 0935 h, ending operations in Hole U1555F. Cores 3R–9R advanced a total of 8.1 m in basement over a period of ~26 h with a total recovery of 5.81 m (72%) (Table **T5**). The average ROP in basement was 0.4 m/h with 20.7 m h of bit on bottom. We spent 2.0 days on Hole U1555F.

Upon recovery, the PDC bit was heavily damaged, with most of the PDC cutters broken or missing (Figure **F11C, F11D**). 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 all the 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 MBR so we could follow up with wireline logging. The drill string was deployed, and drilling in Hole U1555G began at 1620 h 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 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 in Hole U1555G and reached the final depth of 309.5 m DSF at 2000 h on 14 August. Basement Cores 3R–27R advanced 131.2 m and recovered a total of 59.6 m of basalt (45%) in 70 h of coring operations (Table **T5**; Figure **F12**). The average ROP was 2.7 m/h over 48.3 h of bit on bottom.

In preparation for logging, the hole was first swept with 50 bbl of sepiolite mud. At 2230 h, the coring bit was released to the bottom of the hole using the release shifting tool to trigger the MBR. 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).

The triple combo tool string was rigged and deployed from 0300 to 1000 h on 15 August. This tool string measured electrical resistivity, density, porosity, MS, 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, including the Dipole Sonic Imager and Formation MicroScanner (FMS) systems, was deployed from 1000 to 1545 h. This second tool string was deployed to a maximum depth of 295.4 m WSF because of 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. It was deployed from 1545 to 2245 h 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 being deployed in the early hours of 16 August when at 0500 h the logging line winch motor failed. Initial troubleshooting indicated that the failure was with one of the motor bearings. The logging line was pulled up using two T-bar clamps until ~200 m of line were available to be transferred over to the coring line winch, which was then used to recover the logging tools by 1330 h.

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 and cleared the rig floor at 2300 h, ending operations in Hole U1555G. We spent 5.6 days 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 days to the total time on site for a total of 19.7 days.

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 on board at 0704 h, and the first line ashore was at 0839 h, ending Expedition 384.

Preliminary results

Engineering tests

Drilling and coring in seven holes at Site U1555 met nearly all the objectives planned for Expedition 384. The following overview is a preliminary assessment, and further analysis will be carried out by the bit vendors and 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 after each of the three deployments. 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 bits (Holes U1555B and U1555D; Figure **F10D, F10F**, respectively), the underreamer (Hole U1555C; Figure **F11B**), and also the coring bit (Hole U1555F; Figure **F11D**) 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 (Figure **F10F**). 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/PDC hybrid bit (Hole U1555B; Figure **F10C, F10D**) did not perform well. Drilling was terminated after only 24.2 m of 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 OD 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/PDC hybrid bit does not stand up to the demands of the formation we drilled.

Our preliminary assessment points to the gauge or 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 cause coring bit failure, as experienced during 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 (Figure **F11A, F11B**). A cutter 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 *JOIDES Resolution* may be a contribution 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.

RigWatch, the software that monitors drilling parameters, is prone to drift producing 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 postdrilling 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

Coring and sampling. The original coring objective at Site U1555 was to obtain a small number of core samples with a regular RCB coring bit if sampling with the PDC coring bit did not yield any useful recovery. With significant time becoming available, this objective was expanded to include 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 (Table **T5**; Figure **F12**).

The cores consist of massive, (very) fine to medium grained, mostly aphyric, nonvesicular to (sparsely) vesicular or amygdaloidal basalt. Black glassy selvedge on the order of 1 cm thick are present on many rock pieces, likely representing flow unit boundaries. Some intervals are massive and appear fresh, likely representing the interiors of flow units. Veins and mineralized fracture surfaces are among the indicators of alteration, typically in the finer grained and more vesicular intervals.

Whole-round and section half images of all cores were sent to the Expedition 395 science party representatives on shore, who marked up selected pilot samples for thin section and chemical analysis. JRSO personnel cut the samples and made thin sections on board for distribution to the scientists after the expedition. We reserved a few massive and relatively fresh basalt whole-round samples for potential geotechnical testing.

Logging. A complete set of wireline logs of the basalt section was acquired to complement the incomplete core recovery (Figure **F12**). The logs do not cover the entire basalt section; the top of the section is missing because the pipe had to be placed within the basalt for operational safety, and the bottom of the section is missing because of the length of the tool strings as well as obstructions encountered near the bottom of the hole. However, the logs provide an invaluable contiguous record of ~70–90 m of basalt section. Preliminary observations indicate that correlations between borehole diameter based on caliper signals, resistivity, bulk density, *P*-wave velocity, and porosity exist. Detailed investigations may find that this signature corresponds to particular rock textures, degree of alteration, and deformation.

Note that the operations report refers to WSF depth, whereas Figure **F12**, which is based on the data set processed at the Lamont-Doherty Earth Observatory Borehole Research Group (LDEO-BRG), uses the wireline log matched depth below seafloor (WMSF) depth scale. The WMSF scale is based on modest depth shifts applied to multiple runs from a tool string. The final WMSF scales for the triple combo and FMS-sonic tool strings appear to be offset by ~2 m relative to one another (Figure **F12**).

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Table T1. Expedition 384 objectives relative to *JOIDES Resolution* Facility Board (JRFB) recommendations. PDC = polycrystalline diamond compact, XCB = extended core barrel, TDCS = Turbine Driven Coring System, MarE3 = Institute for Marine-Earth Exploration and Engineering, MDHDS = Motion Decoupled Hydraulic Delivery System, T2P = temperature dual pressure probe.

Priority	JRFB recommendations	Objective	Expedition 384 plan
1	New drilling bits for improved advancement, opening, and remediation of drill holes in hard rock formations.	1	As recommended.
2	New underreamers for opening up holes in hard rock formations.	2	As recommended.
3	New coring bits for coring in hard rock formations.		Although this is arguably the most important issue to the IODP community, the market for coring is problematical. We plan to test an existing PDC coring bit for the first time, though.
4	New biodegradable drilling fluid additives for improved hole cleaning.		Low priority, sepiolite and attapulgite work fine, hard to find other product that is safe for open hole drilling.
5	New bottom-driven XCB based on current D/V *Chikyu* XCB designs.	(3)	Low priority based on preliminary experience.
6	Continued testing of the TDCS depending on the outcome of first tests during IODP Expedition 376 and discussions with MarE3.	(3)	We were planning on this in a previous expedition schedule—the unusual circumstances this year did not allow for the required shipping and staffing.
7	MDHDS testing in conjunction with the T2P system.		Not urgent at this time.

Table T2. Core summary, Site U1554. Core composite depth below seafloor (CCSF) established by correlating cores from Holes U1554A, U1554B, and U1554C. CSF-A = core depth below seafloor, Method A. Core type: H = advanced piston corer.

	Standard CSF-A assignment						CCSF construction				
Core	Top depth CSF-A (m)	Bottom depth CSF-A (m)	Advanced (m)	Recovered and curated length (m)	Recovery (%)	Time on deck (UTC; h)	Cumulative offset for correlation (m)	Top depth CCSF (m)	Bottom depth CCSF (m)	Core gaps in hole (m)	Depth scale growth rate CCSF/CSF-A
384-U1554A-											
1H	0.0	5.74	5.7	5.74	101	27 Jul 2020 2215	0.00	0.000	5.740		
2H	5.7	15.54	9.5	9.84	104	27 Jul 2020 2325	−0.02	5.684	15.524	−0.06	1.00
3H	15.2	25.00	9.5	9.80	103	28 Jul 2020 0020	0.53	15.731	25.531	0.21	1.03
4H	24.7	34.48	9.5	9.78	103	28 Jul 2020 0130	0.87	25.574	35.354	0.04	1.04
5H	34.2	44.01	9.5	9.81	103	28 Jul 2020 0220	2.82	37.015	46.825	1.66	1.08
6H	43.7	53.63	9.5	9.93	105	28 Jul 2020 0300	3.82	47.515	57.445	0.69	1.09
7H	53.2	63.03	9.5	9.83	103	28 Jul 2020 0350	4.96	58.164	67.994	0.72	1.09
8H	62.7	72.68	9.5	9.98	105	28 Jul 2020 0435	6.39	69.091	79.071	1.10	1.10
384-U1554B-											
1H	0.0	9.72	9.5	9.72	102	28 Jul 2020 0650	2.75	2.749	12.469	2.75	
2H	9.5	18.91	9.5	9.41	99	28 Jul 2020 0745	2.89	12.387	21.797	−0.08	1.30
3H	19.0	28.70	9.5	9.70	102	28 Jul 2020 0830	3.01	22.005	31.705	0.21	1.16
4H	28.5	38.31	9.5	9.81	103	28 Jul 2020 0915	4.10	32.604	42.414	0.90	1.14
5H	38.0	47.20	9.5	9.20	97	28 Jul 2020 1000	4.84	42.845	52.045	0.43	1.13
6H	47.5	56.60	9.5	9.10	96	28 Jul 2020 1045	5.47	52.972	62.072	0.93	1.12
7H	57.0	66.86	9.5	9.86	104	28 Jul 2020 1140	6.24	63.245	73.105	1.17	1.11
8H	66.5	76.45	9.5	9.95	105	28 Jul 2020 1240	7.16	73.663	83.613	0.56	1.11
384-U1554C-											
1H	0.0	8.52	8.5	8.52	100	28 Jul 2020 1525	0.14	0.137	8.657	0.14	
2H	8.5	17.99	9.5	9.49	100	28 Jul 2020 1630	0.14	8.638	18.128	−0.02	1.02
3H	18.0	27.85	9.5	9.85	104	28 Jul 2020 1720	1.10	19.097	28.947	0.97	1.06
4H	27.5	37.35	9.5	9.85	104	28 Jul 2020 1810	2.87	30.367	40.217	1.42	1.10
5H	37.0	46.96	9.5	9.96	105	28 Jul 2020 1925	3.74	40.742	50.702	0.52	1.10
6H	46.5	56.33	9.5	9.83	103	28 Jul 2020 2020	4.60	51.104	60.934	0.40	1.10
7H	56.0	65.79	9.5	9.79	103	28 Jul 2020 2105	5.29	61.292	71.082	0.36	1.09
8H	65.5	75.24	9.5	9.74	103	28 Jul 2020 2155	5.89	71.394	81.134	0.31	1.09
384-U1554D-											
Drilled	0.0	14.00	14.0			29 Jul 2020 0000					
2H	14.0	23.72	9.5	9.72	102	29 Jul 2020 0040					

Table T3. Splice intervals, Site U1554.

Interval	Hole, core	Top section	Top offset (cm)	Top depth CSF-A (m)	Top depth CCSF (m)	Bottom section	Bottom offset (cm)	Bottom depth CSF-A (m)	Bottom depth CCSF (m)
	384-								
1	U1554A-1H	1	0.0	0.000	0.000	4	10.5	4.605	4.605
2	U1554B-1H	2	35.6	1.856	4.605	4	75.8	5.258	8.007
3	U1554A-2H	2	81.3	8.023	8.007	5	94.9	12.679	12.663
4	U1554B-2H	1	27.6	9.776	12.663	4	76.9	14.769	17.656
5	U1554A-3H	2	42.5	17.125	17.656	6	51.2	23.242	23.773
6	U1554B-3H	2	26.8	20.768	23.773	4	89.8	24.408	27.413
7	U1554A-4H	2	32.9	26.539	27.413	6	52.9	32.759	33.633
8	U1554B-4H	1	102.9	29.529	33.633	4	144.7	34.457	38.561
9	U1554A-5H	2	4.6	35.746	38.561	4	115.3	39.853	42.668
10	U1554C-5H	2	42.6	38.926	42.668	6	128.1	45.781	49.523
11	U1554A-6H	2	50.8	45.708	49.523	5	124.1	50.951	54.766
12	U1554B-6H	2	29.4	49.294	54.766	5	98.0	54.500	59.972
13	U1554A-7H	2	30.8	55.008	59.972	5	110.0	60.300	65.264
14	U1554B-7H	2	50.9	59.019	65.264	6	43.8	64.958	71.203
15	U1554A-8H	2	61.2	64.812	71.203	5	43.2	69.142	75.533
16	U1554B-8H	2	37.0	68.370	75.533	7	69.0	76.230	83.393

Table T4. Core orientation results, Site U1554. * = magnetic tool face (MTF) results from Icefield Tool 2043 are rotated 180° to account for misaligned internal key of end seal (see text), † = 384-U1554B-5H results are biased because of coring deformation as noted in X-ray images. A_{MTF} = MTF angle, azimuth of double lines on core liner when core is collected; R_{MOT} = magnetic orientation tool (MOT) reorientation angle; D_{IGRF} = International Geomagnetic Reference Field (IGRF) angle for Site U1554 (−13.6°); instrument = specific MOT used to orient a core; N = number of paleomagnetic directions used to compute Fisherian mean direction for each core; Fisherian R value = resultant vector length from summing the N sample vectors; K = precision parameter from Fisher statistical calculations; α_{95} = 95% confidence circle for the mean direction; R_{GAD} = geocentric axial dipole (GAD) angle, expected rotation needed to return a core into its geographical coordinates ($-D_P$; 360° − D_P); ΔR = difference in R_{MOT} observed and R_{GAD} expected orientations ($R_{MOT} - R_{GAD}$). Tool temperatures measured during core orientation varied between 4.0° and 8.0°C. Total magnetic field measured varied from 65.8 to 85.4 T. Hole dip angles varied from 88.9° to 89.8°. Core measurement outliers occurred within geomagnetic excursions and/or were more than 2 standard deviations from the mean.

Hole, core	Mean core depth CSF-A (m)	Core orientation tool data			
		Magnetic dip (°)	A_{MTF} (°)	$R_{MOT} = A_{MTF} + D_{IGRF}$ (°)	Instrument
384-					
U1554A-1H	2.80	−78.6	178.4	164.8	Icefield 2007
U1554A-2H	10.91	−79.0	208.5	194.9	Icefield 2007
U1554A-3H	20.12	−78.5	182.5	168.9	Icefield 2007
U1554A-4H	29.97	−78.7	294.0	280.4	Icefield 2007
U1554A-5H	39.21	76.7	143.3	129.7	FlexIT 0937
U1554A-6H	48.86	76.4	195.2	181.6	FlexIT 0937
U1554A-7H	58.06	76.5	121.6	108.0	FlexIT 0937
U1554A-8H	67.57	76.3	173.6	160.0	FlexIT 0937
U1554B-1H	4.85	−78.9	290.7	277.1	Icefield 2043*
U1554B-2H	14.20	−79.1	331.8	318.2	Icefield 2043*
U1554B-3H	23.68	−78.6	123.0	109.4	Icefield 2043*
U1554B-4H	33.38	−78.8	4.7	−8.9	Icefield 2043*
U1554B-5H†	43.05	−79.3	170.8	157.2	Icefield 2052
U1554B-6H	52.00	−79.4	46.7	33.1	Icefield 2052
U1554B-7H	61.87	−77.4	309.2	295.6	Icefield 2052
U1554B-8H	71.38	−79.9	132.3	118.7	Icefield 2052
U1554C-1H	4.24	77.0	192.1	178.5	FlexIT 0937
U1554C-2H	13.31	76.9	114.5	100.9	FlexIT 0937
U1554C-3H	22.84	76.2	328.9	315.3	FlexIT 0937
U1554C-4H	32.52	76.8	137.2	123.6	FlexIT 0937
U1554C-5H	42.01	−78.2	346.6	333.0	Icefield 2007
U1554C-6H	51.40	−78.4	136.1	122.5	Icefield 2007
U1554C-7H	60.97	−78.0	35.5	21.9	Icefield 2007
U1554C-8H	70.38	−78.6	200.4	186.8	Icefield 2007
U1554D-2H	23.27	−78.2	15.6	2.0	Icefield 2007

Hole, core	Paleomagnetic core orientation data													Orientation comparison
	All measurements						Outliers removed							
	N	Mean inclination (°)	Mean declination D_P (°)	Fisherian R value	K	α_{95}	N	Mean inclination (°)	Mean declination D_P (°)	Fisherian R value	K	α_{95}	R_{GAD} (°)	ΔR
384-														
U1554A-1H	470	71.5	182.6	466	125.4	0.6	448	71.0	181.1	445	156.2	0.5	178.9	−14.1
U1554A-2H	770	66.1	152.0	761	86.5	0.5	744	66.4	153.4	737	105.8	0.5	206.6	−11.7
U1554A-3H	846	69.1	185.4	839	121.8	0.4	829	69.3	184.8	823	134.9	0.4	175.2	−6.3
U1554A-4H	761	72.6	96.3	744	43.5	0.8	727	72.0	97.6	718	77.4	0.6	262.4	18.0
U1554A-5H	825	71.4	204.5	809	52.8	0.7	783	71.6	207.1	772	74.1	0.6	152.9	−23.2
U1554A-6H	828	71.5	150.0	813	53.7	0.7	809	71.2	151.1	795	58.8	0.6	208.9	−27.3
U1554A-7H	854	70.9	226.7	846	102.0	0.5	829	71.3	226.3	822	114.2	0.5	133.7	−25.7
U1554A-8H	876	72.3	174.7	861	57.6	0.6	830	72.1	172.8	820	81.3	0.5	187.2	−27.2
U1554B-1H	835	71.1	107.9	823	69.0	0.6	800	71.0	107.6	790	83.4	0.5	252.4	24.7
U1554B-2H	814	73.6	39.0	807	122.4	0.4	795	73.9	38.2	789	142.3	0.4	321.8	−3.6
U1554B-3H	773	70.8	238.3	762	68.8	0.6	751	70.5	238.2	743	95.5	0.5	121.8	−12.4
U1554B-4H	845	74.0	356.9	827	46.8	0.7	810	73.7	359.9	797	61.7	0.6	0.1	−9.0
U1554B-5H†	747	65.9	168.3	739	92.8	0.5	713	65.5	168.0	707	122.7	0.5	192.0	−34.8
U1554B-6H	808	72.3	318.7	791	48.1	0.7	779	71.3	320.2	766	62.2	0.6	39.8	−6.7
U1554B-7H	849	72.4	64.4	838	79.7	0.5	834	72.4	63.4	824	87.1	0.5	296.6	−1.0
U1554B-8H	872	72.5	232.7	855	51.6	0.7	831	72.9	233.9	818	65.1	0.6	126.1	−7.4
U1554C-1H	756	68.7	181.9	748	90.2	0.5	718	68.7	182.7	713	136.3	0.5	177.3	1.2
U1554C-2H	806	72.9	236.1	798	103.7	0.5	771	73.0	236.3	765	134.2	0.4	123.7	−22.8
U1554C-3H	864	74.6	30.0	852	73.0	0.6	852	74.6	29.0	841	76.9	0.6	331.0	−15.7
U1554C-4H	835	73.0	220.9	827	103.5	0.5	810	73.0	222.0	804	130.5	0.4	138.0	−14.4
U1554C-5H	855	73.1	38.0	841	60.6	0.6	852	73.1	38.0	838	61.3	0.6	322.0	11.0
U1554C-6H	854	70.6	221.9	837	50.3	0.7	812	70.2	222.6	799	63.7	0.6	137.4	−14.9
U1554C-7H	827	72.6	323.6	812	56.4	0.7	802	72.3	323.8	791	73.1	0.6	36.2	−14.3
U1554C-8H	817	72.1	165.2	803	58.7	0.6	766	71.9	164.4	757	84.6	0.6	195.6	−8.8
U1554D-2H	37	76.6	352.1	37	1731.9	0.6	37	76.6	352.1	37	1731.9	0.6	7.9	−5.9

Table T5. Core summary, Site U1555. CSF-A = core depth below seafloor, Method A. Core type: R = rotary core barrel.

Core	Top depth CSF-A (m)	Bottom depth CSF-A (m)	Advanced (m)	Recovered length (m)	Curated length (m)	Recovery (%)	Time on deck (UTC; h)
384-U1555F-							
1R	0.0	2.53	2.5	2.53	2.53	101	9 Aug 2020 2120
Drilled	2.5	176.20	173.7				10 Aug 2020 0350
3R	176.2	177.50	2.0	1.07	1.30	54	10 Aug 2020 0540
4R	178.2	180.26	3.5	1.98	2.06	57	10 Aug 2020 0930
5R	181.7	182.94	0.8	1.09	1.24	136	10 Aug 2020 1315
6R	182.5	183.32	0.7	0.68	0.82	97	10 Aug 2020 1710
7R	183.2	183.55	0.4	0.35	0.35	88	10 Aug 2020 2100
8R	183.6	184.00	0.4	0.34	0.40	85	11 Aug 2020 0055
9R	184.0	184.33	0.3	0.30	0.33	100	11 Aug 2020 0500
384-U1555G-							
Drilled	0.0	168.60	168.6				11 Aug 2020 2030
2R	168.6	169.32	9.7	0.72	0.72	7	11 Aug 2020 2135
3R	178.3	184.16	9.7	4.57	5.86	47	12 Aug 2020 0145
4R	188.0	192.30	8.7	3.26	4.30	37	12 Aug 2020 0615
5R	196.7	199.86	5.3	2.53	3.16	48	12 Aug 2020 0900
6R	202.0	204.96	5.5	2.28	2.96	41	12 Aug 2020 1150
7R	207.5	209.90	4.7	1.86	2.40	40	12 Aug 2020 1440
8R	212.2	214.57	5.0	1.88	2.37	38	12 Aug 2020 1650
9R	217.2	222.38	4.7	4.60	5.18	98	12 Aug 2020 2000
10R	221.9	224.36	5.0	2.28	2.46	46	12 Aug 2020 2225
11R	226.9	229.42	4.8	1.93	2.52	40	13 Aug 2020 0100
12R	231.7	235.84	5.0	3.47	4.14	69	13 Aug 2020 0515
13R	236.7	239.39	4.7	2.10	2.69	45	13 Aug 2020 0755
14R	241.4	244.05	5.0	2.16	2.65	43	13 Aug 2020 1035
15R	246.4	249.65	4.7	2.63	3.25	56	13 Aug 2020 1345
16R	251.1	255.77	5.0	3.86	4.67	77	13 Aug 2020 1745
17R	256.1	257.86	4.7	1.50	1.76	32	13 Aug 2020 2020
18R	260.8	262.30	5.2	1.03	1.50	20	13 Aug 2020 2215
19R	266.0	266.98	4.6	0.81	0.98	18	13 Aug 2020 2345
20R	270.6	273.23	5.0	1.87	2.63	37	14 Aug 2020 0220
21R	275.6	279.02	4.7	2.60	3.42	55	14 Aug 2020 0500
22R	280.3	283.48	5.0	2.55	3.18	51	14 Aug 2020 0725
23R	285.3	287.57	4.7	1.73	2.27	37	14 Aug 2020 0920
24R	290.0	292.57	5.0	1.83	2.57	37	14 Aug 2020 1120
25R	295.0	296.56	4.8	1.16	1.56	24	14 Aug 2020 1330
26R	299.8	302.59	5.0	2.22	2.79	44	14 Aug 2020 1630
27R	304.8	308.42	4.7	2.87	3.62	61	14 Aug 2020 2005

Figure F1. Site locations, Expedition 384.

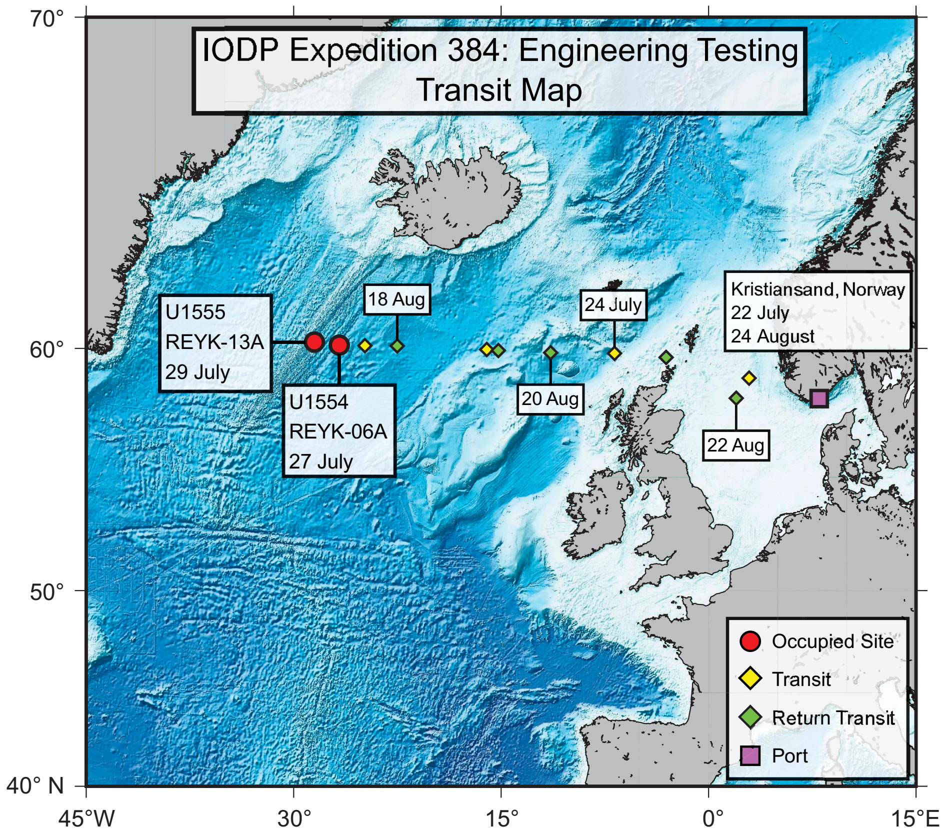

Figure F2. Sites U1554 and U1555 (Proposed Sites REYK-6A and REYK-13A, respectively) on site map for postponed Expedition 395 (from Parnell-Turner et al., 2020). A. Bathymetry. Box = location of B. Yellow circles = proposed drill sites, black circles = Ocean Drilling Program/Deep Sea Drilling Project boreholes. Solid black lines = seismic reflection profiles, gray lines = magnetic polarity chrons. Red star = Iceland plume center, red dashed line = Mid-Atlantic Ridge, dotted black lines = deepwater currents. WBUC = Western Boundary Undercurrent, DSOW = Denmark Strait Overflow Water, ISOW = Iceland-Scotland Overflow Water, DS = Denmark Strait, IFR = Iceland-Faroe Ridge, BFZ = Bight Fracture Zone. B. Satellite free-air gravity anomaly map. Dashed line = Reykjanes Ridge (RR), VSR = V-shaped ridge, VST = V-shaped trough, open circles/triangles = dredged basalt samples.

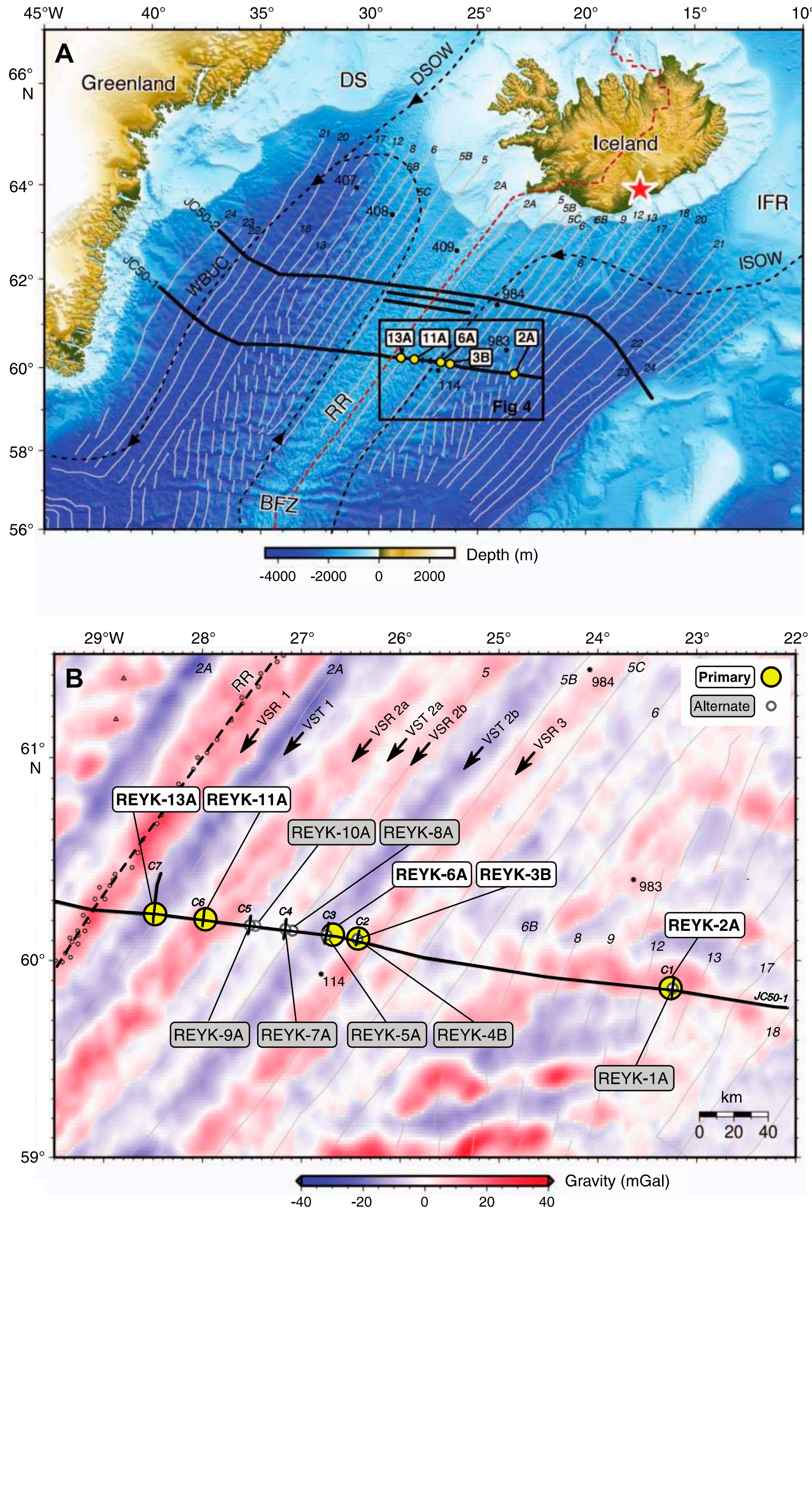

Figure F3. Detailed location and seismic imaging, Site U1555 (Proposed Site REYK-13A; from Parnell-Turner et al., 2020). CMP = common midpoint, TWT = two-way traveltime.

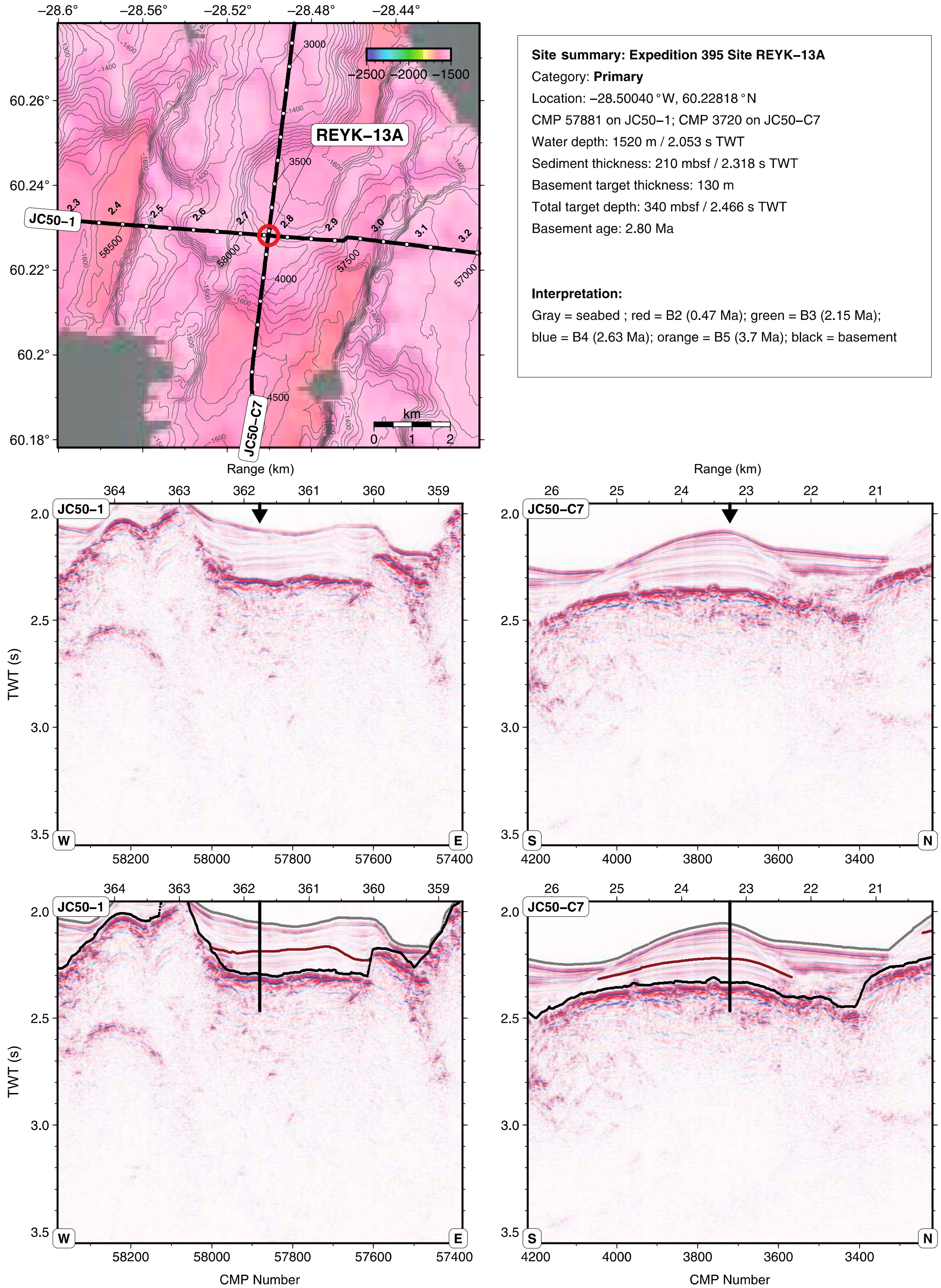

Figure F4. Detailed location and seismic imaging, Site U1554 (Proposed Site REYK-6A; from Parnell-Turner et al., 2020). CMP = common midpoint, TWT = two-way traveltime.

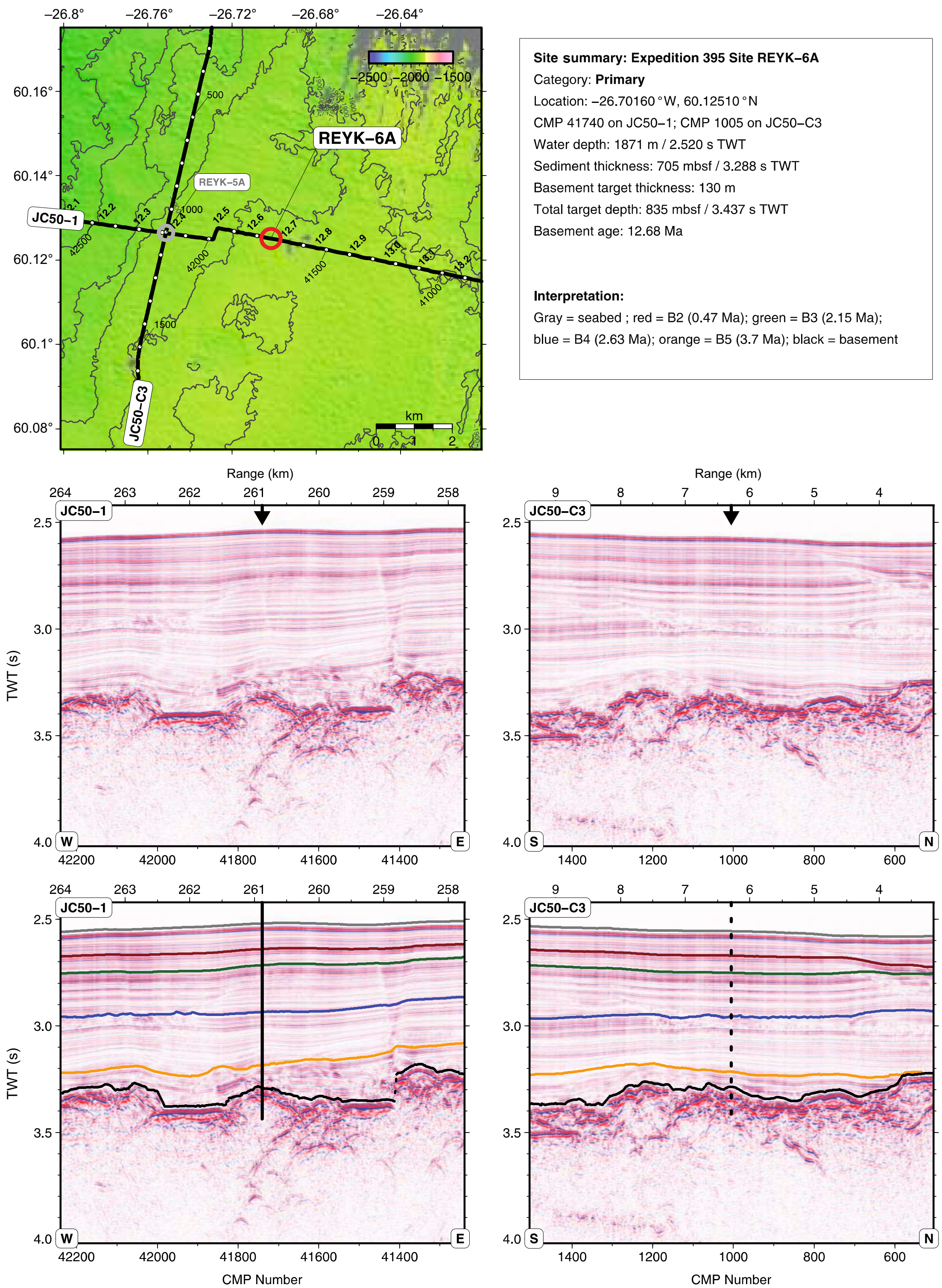

Figure F5. Stratigraphic splice for whole-round magnetic susceptibility (MS) data, which were the primary data used for correlating between holes, Site U1554. Splice intervals used from each hole are bounded by vertical lines. Splice interval labels (A1, B1, etc.) refer to hole and core the spliced data originate from (e.g., A1 = 384-U1554A-1H).

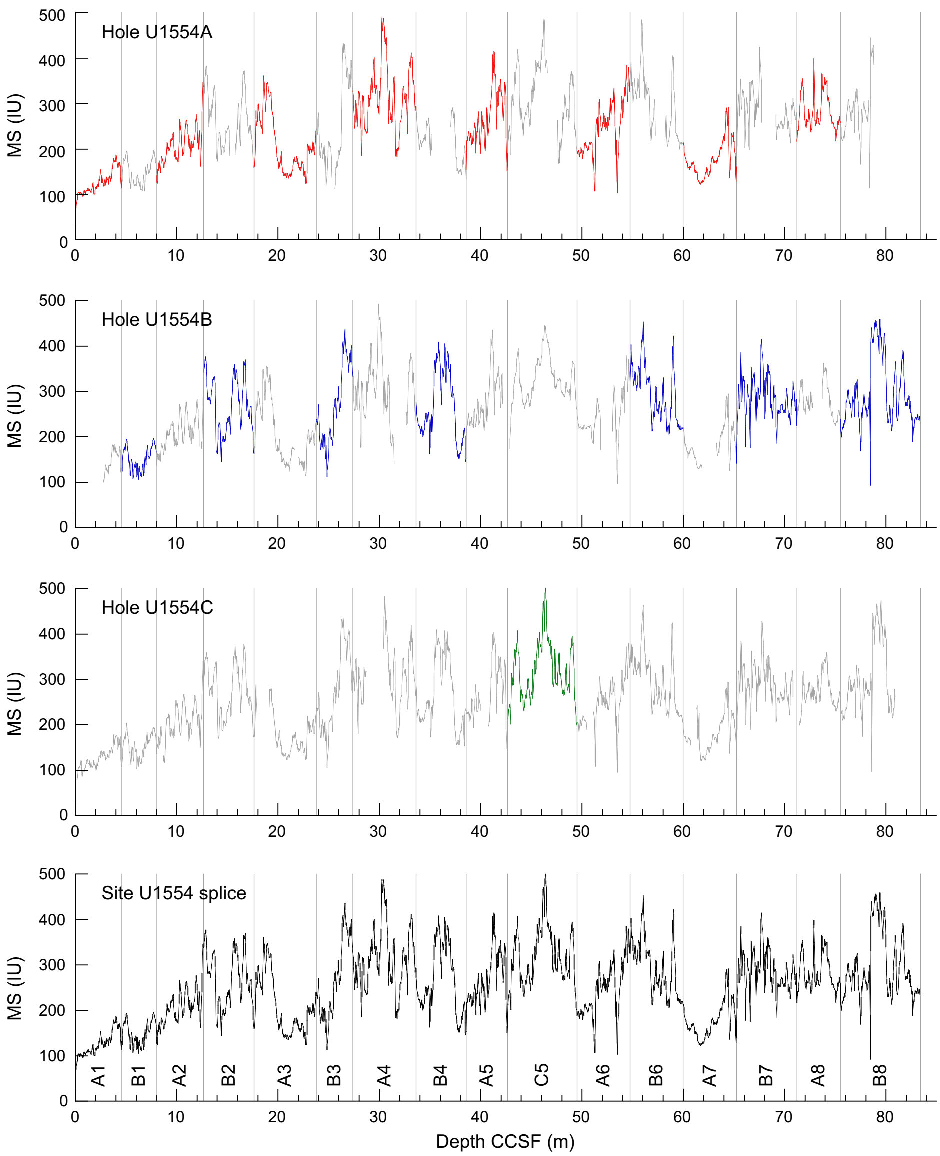

Figure F6. Alternating field demagnetization results. A. 384-U1554A-1H-2, 100 cm (2.50 m core depth below seafloor [CSF-A]). B. 384-U1554A-5H-3, 40 cm (37.59 m CSF-A). C. 384-U1554D-2H-7, 38 cm (23.40 m CSF-A). Left: Vector endpoints of paleomagnetic directions on vector demagnetization diagrams or modified Zijderveld plots. Right: Intensity variation with progressive demagnetization. Data indicate the removal of a steep downward drilling overprint from 0 to 6 mT. Above about 8 mT demagnetization, a stable component is observed, interpreted to be the characteristic remanent magnetization. Best-fit lines from principal component analysis (PCA) are shown only through inclination data (FRE = free-fitting PCA option, ANC = anchored PCA option, SEP = stable end points). Stable end points are computed from Fisherian average of highest 3 steps used in fitting the PCA lines. Black outlines = data used in PCA. Declination data are plotted in sample coordinates (i.e., not orientation corrected). NRM = natural remanent magnetization.

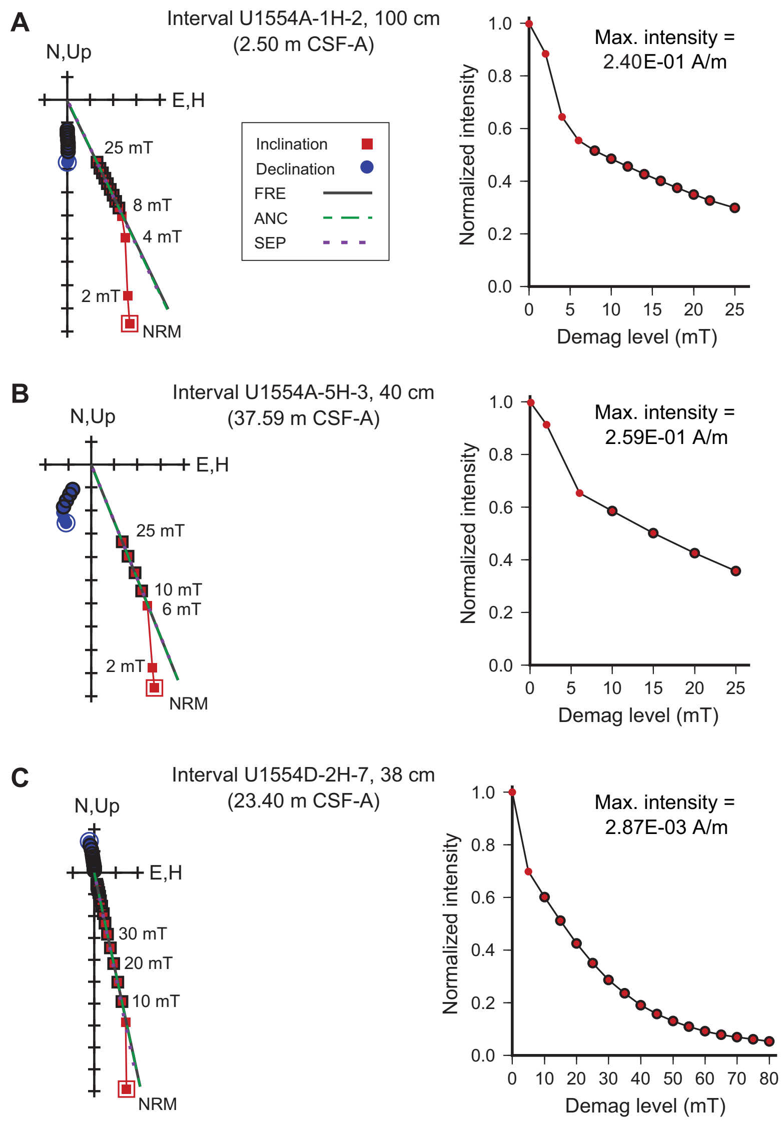

Figure F7. Paleomagnetic results. Declinations are shown in sample coordinates (uncorrected), corrected using magnetic orientation tool (MOT) reorientation angles, and corrected using paleomagnetic data assuming a geocentric axial dipole (GAD) field. A. Hole U1554A. (Continued on next 2 pages.)

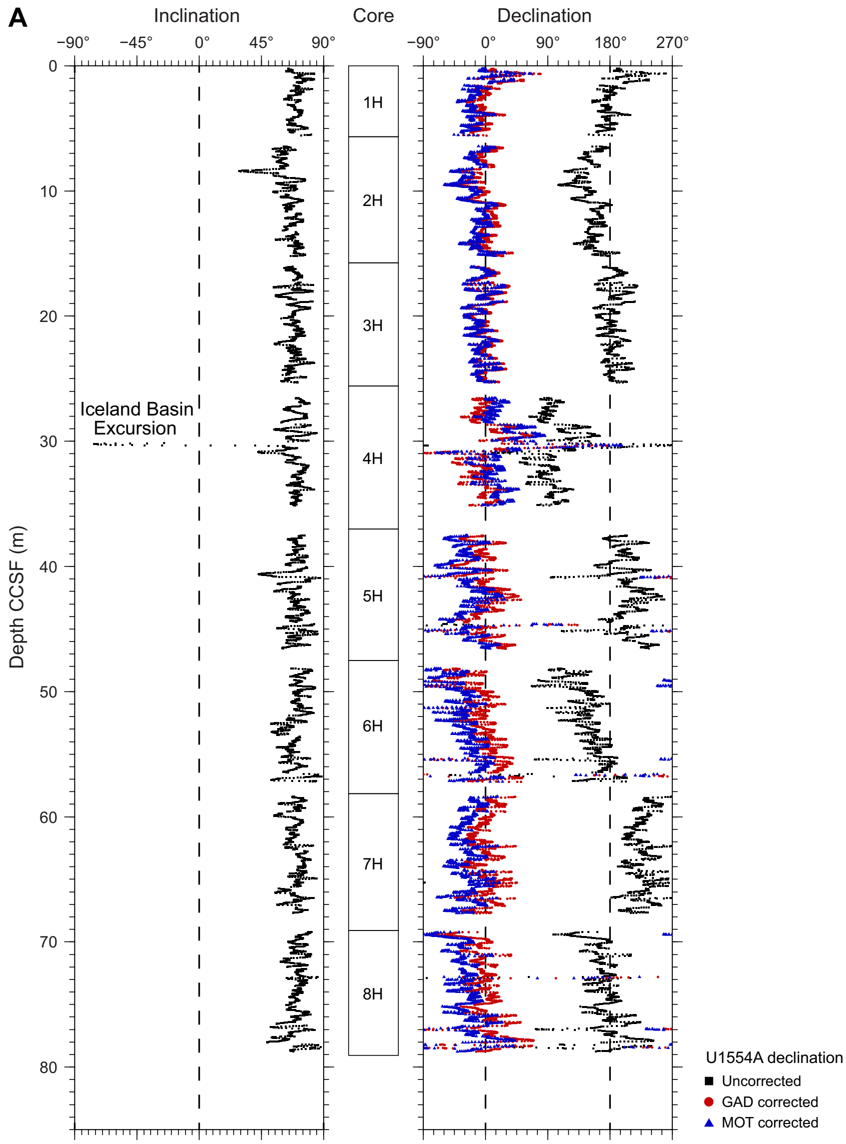

Figure F7 (continued). B. Hole U1554B. (Continued on next page.)

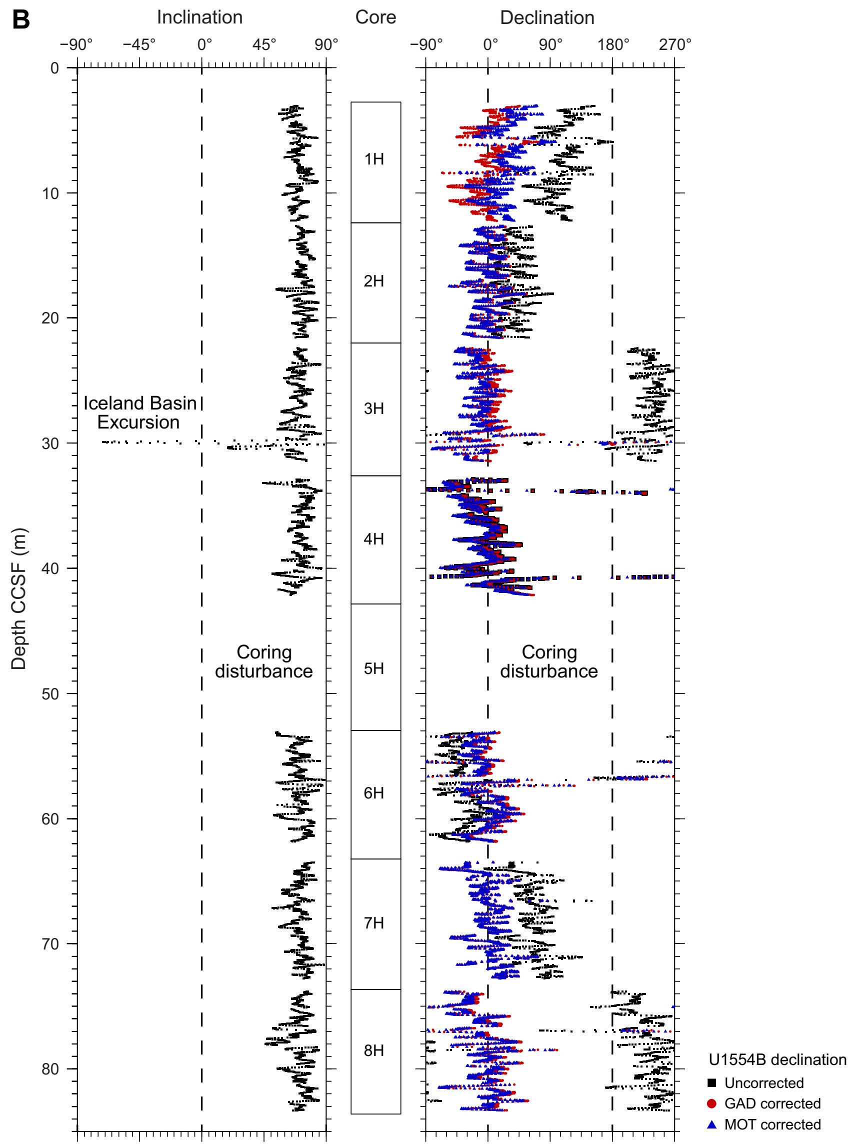

Figure F7 (continued). C. Hole U1554C. D. Hole U1554D.

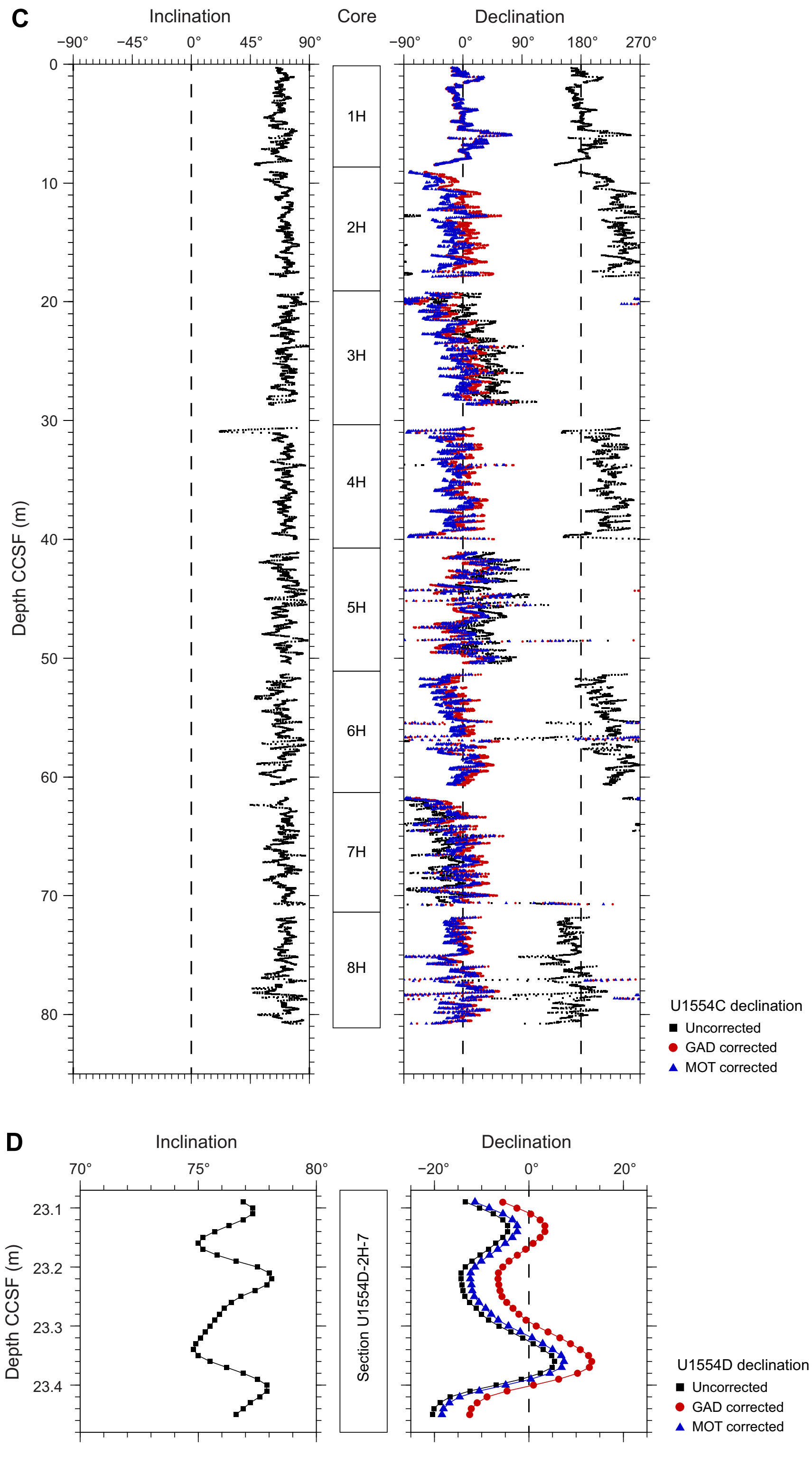

Figure F8. Components of Icefield core orientation tools.

Figure F9. Histograms of differences between reorientation angles observed by magnetic orientation tools and expected reorientation angles, Site U1554. Histogram bin widths chosen to be comparable to standard deviation of a typical FlexIT or Icefield core orientation measurement. Left: Combined FlexIT and Icefield tool results. Right: Icefield tool results.

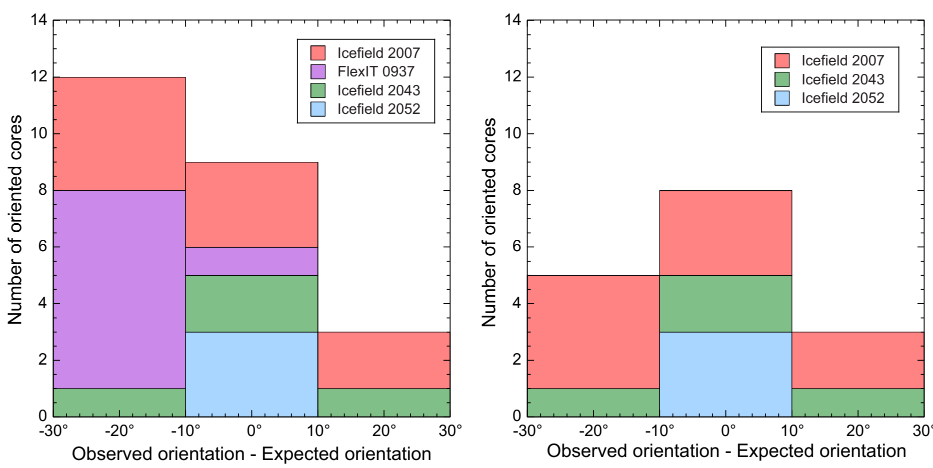

Figure F10. Drilling bits tested at Site U1555 (A, C, E) before and (B, D, F) after deployment.

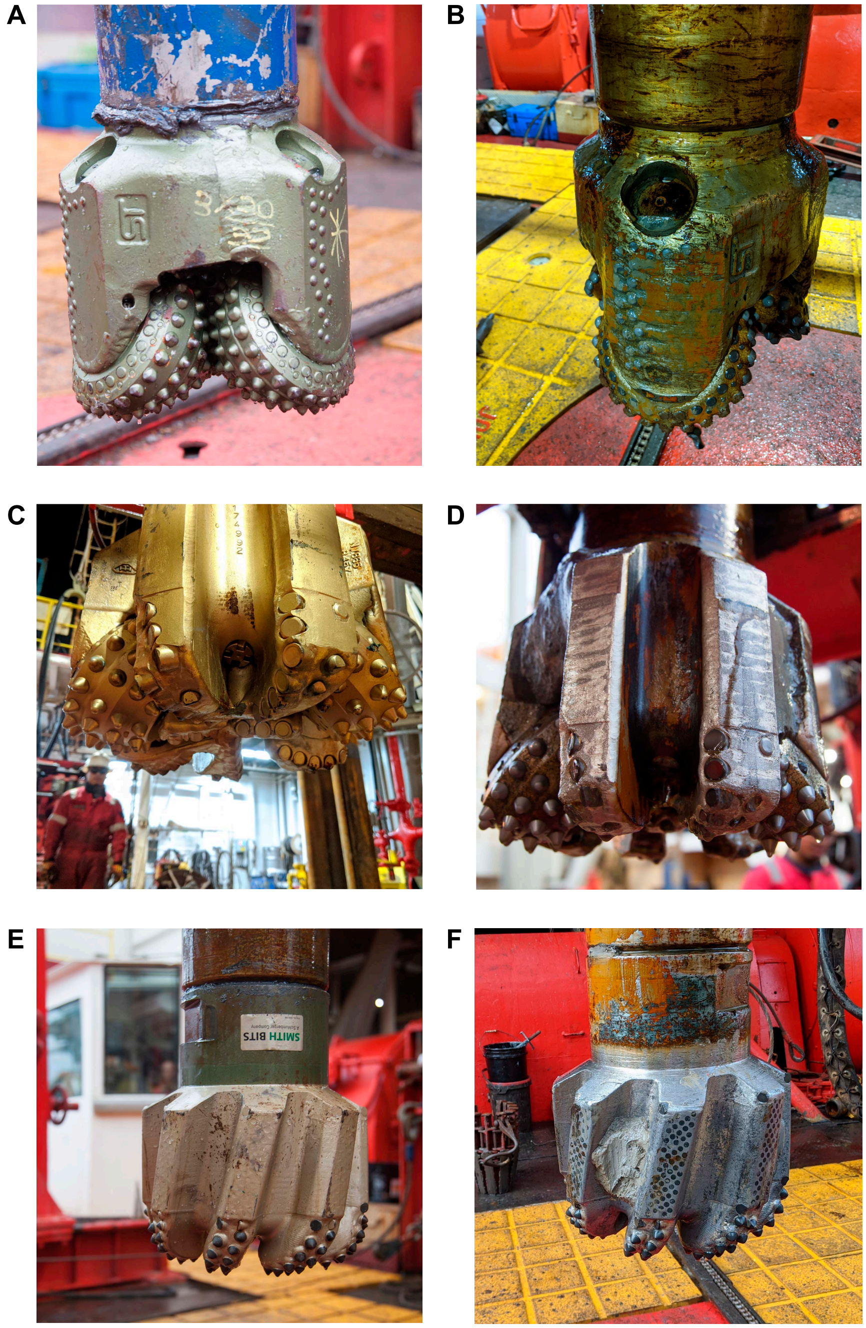

Figure F11. (A, B) Underreamer and (C, D) polycrystalline diamond compact coring bit tested in Holes U1555C and U1555F, respectively.

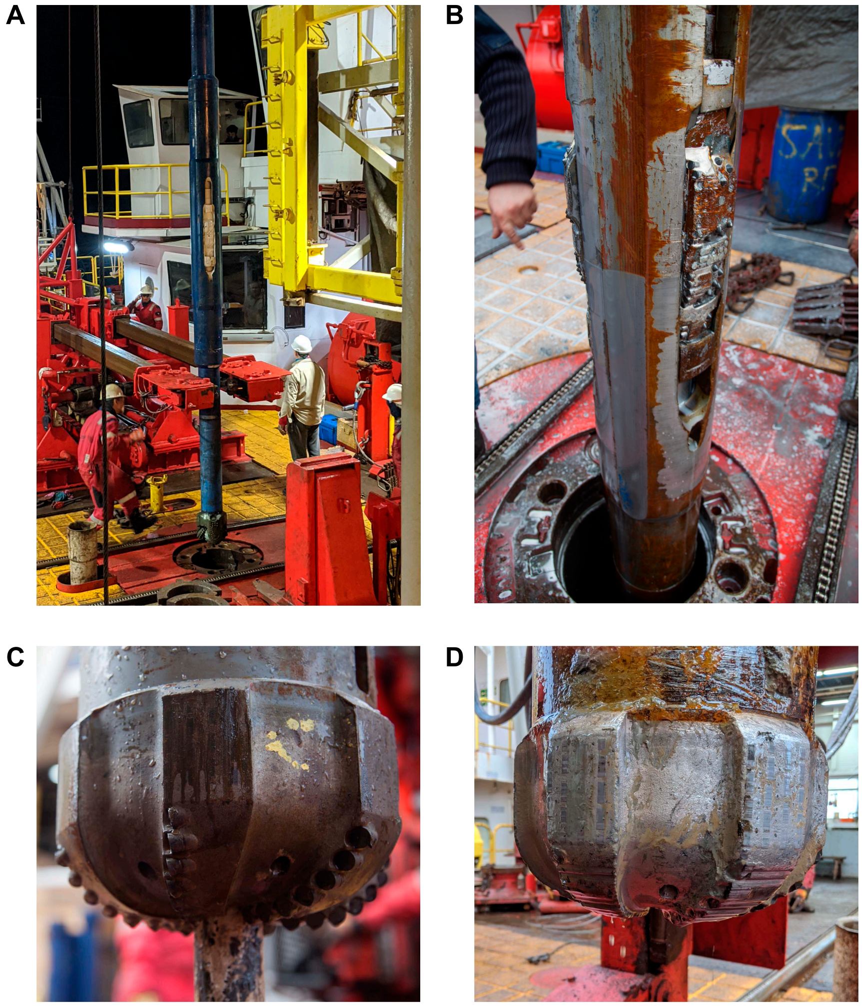

Figure F12. Coring and logging data overview, Hole U1555G. Caliper and *P*-wave logs are from second tool string (Formation MicroScanner-sonic). Resistivity, density, and porosity are from first tool string (triple combo). Based on log signals, a depth offset of ~2 m appears to exist between data from the two tool strings (red and blue rectangles).