OCEAN DRILLING PROGRAM

LEG 179 PRELIMINARY REPORT

HAMMER DRILLING and NERO

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SCIENTIFIC REPORT

ABSTRACT

Ocean Drilling Program Leg 179 set out with two primary objectives. These objectives were (1) testing the recently developed hammer drill-in casing system on the Atlantis Bank, Southwest Indian Ridge, and (2) drilling a cased reentry hole into basaltic basement on the Ninetyeast Ridge to allow future installation of an ocean floor geophysical observatory, the Ninetyeast Ridge Observatory (NERO). Both these objectives were accomplished during Leg 179. Because of contingencies developed during the leg, certain ancillary objectives were not accomplished, but one contingency drilling site was cored on the Atlantis Bank, Southwest Indian Ridge.

Hammer drill testing was completed at Sites 1104 and 1106 (virtually coincident locations but positioned from different beacons after a hiatus in testing while waiting for resupply). These tests provide a wealth of information regarding the viability of the system as a new tool for investigating the solid Earth. Although the testing was not completed as planned, design changes as a result of tests we were able to complete are already under way. We are confident, based on the results of the first sea trial of the hammer drill-in casing system, that continued development will soon allow us to sample the deep ocean crust in environments where, with rare exceptions, we have historically been unable to operate.

Hole 1105A penetrated to a depth of 158 m and cored an interval of 143 m starting 15 mbsf on the Atlantis Bank. We recovered 118.43 m of gabbroic rock representing 82.8% of the cored section. Gabbro, olivine gabbro, oxide gabbro, and felsic rocks were recovered. Together with logging results that included Formation MicroScanner images of the borehole, this recovery provides a rather complete coverage of the rock types and a comprehensive view of pseudostratigraphy in the gabbroic section that appears related to nearby Hole 735B, 1.3 km away. This is the first example of two offset holes (Holes 735B and 1105A) in an oceanic gabbroic section in which shipboard results indicate a high probability that specific units, structures, and/or geophysical characteristics may indeed be correlated.

Our second primary objective specifically included drilling a single hole as deep as possible into basement, and installing a reentry cone and casing beyond basement to prepare the Ninetyeast Ridge site as an ocean-bottom observatory. The observatory will be installed at a later date and will be part of the future network of seafloor observatories proposed in the International Ocean Network program. Drilling reached a depth of 493.8 mbsf, which was sufficient to create an acceptable borehole below casing for the downhole seismometer installation. The total penetration into basement was 122 m, and total penetration below casing reached 79.4 m. This significant depth of penetration below the casing, as well as the firm attachment to basement should isolate the instrument from noise reported from other ocean floor seismometer installations.

INTRODUCTION

Leg 179 of the Ocean Drilling Program (ODP) represents an endeavor aimed at two longstanding gaps in our understanding of the nature of the solid earth. First, we set out to test a new drilling technology that might enable deeper drilling and eventually higher recovery from the deep ocean crust than ever before possible. Our second goal was to prepare a site where researchers can establish a long-term geophysical ocean-bottom observatory as part of the International Ocean Network (ION) program. Both of these primary objectives were accomplished. Initial tests of the hammer drill-in casing system yielded data that will allow future development and implementation of this technology on a regular basis. A nearly 500-m-deep borehole—cased to basement, cemented into the hard rock basement, and left with a reentry cone—was established at the Ninetyeast Ridge. Installation of a downhole observatory at this location will fill one of the six major gaps in global seismic monitoring coverage. Given potential delays in port because of repairs to the drillship, the advisory structure of ODP prioritized the supplementary objectives for Leg 179. The highest priority for these objectives was given to the two-ship offset seismic experiment in coordination with the *Sonne*. Unfortunately, time constraints prevented completion of these supplementary objectives.

HAMMER DRILLING SYSTEM (HDS) ENGINEERING

Drilling the igneous foundation of the ocean crust has always been a challenging undertaking. Since the inception of the Deep Sea Drilling Project (DSDP) and its successor, ODP, one of the principal objectives of the science community has been to penetrate an entire section of the ocean crust and to reach the boundary between the Earth’s crust and mantle. Attempts at accomplishing this objective have been limited by drilling technology originally designed for recovering sediments by the oil industry but adapted by ODP for sampling igneous basement. There have been spectacular successes in this endeavor, witness Holes 504B and 735B, but challenges confronted in establishing, maintaining, and reentering boreholes in fractured, hard rock have been more common.

In response to these challenges, the Ocean Drilling Program has embarked on the development of a new technology, the hammer drill-in casing system, which will allow us to initiate a hole, then simultaneously deepen that hole and stabilize its walls with casing. This system is an adaptation of pneumatically driven drilling systems that have successfully drilled in environments not unlike those that present our greatest challenge. Owing to the water depths in which we operate, however, pneumatic power is not an option. This innovative design employs a hydraulically actuated hammer, which drives a drill bit into the ocean floor. Following the bit is a string of casing to stabilize the borehole walls and improve our ability to clean drill cuttings from the hole. The bit design allows it to be withdrawn through the casing system, after deployment of a reentry funnel, such that most of the documented problems associated with drilling hard rock in the ocean’s basin are alleviated. This new technology not only solves the technological problems, but it also reduces our dependency on site specific surveys, because the hammer can initiate a hole without regard to local topographic variability, thin sediment cover, debris, or rubble lying on the surface.

HDS testing was undertaken adjacent to the Atlantis II Fracture Zone along the Southwest Indian Ridge on an uplifted platform where two other ODP legs had successfully cored in hard rock using conventional drilling technology (see Robinson, Von Herzen, et al., 1989, Dick, Natland, Miller, et al., in press). We hoped that the shallow but variable water depth and locally flat but regionally rugged topography would both adequately emulate other environments where the HDS might be employed and test the limits of the system. By choosing this location, we also had a proven record of our best performance in hard rock penetration rate and recovery for comparison.

NINETYEAST RIDGE OBSERVATORY (NERO)

Geophysical observatories currently operating worldwide share a common attribute and shortcoming in that these stations are only emplaced on continents or islands. Inasmuch as the world’s oceans cover more than two-thirds of the planet’s surface, the sporadic coverage allowed by observatories on oceanic islands is woefully incomplete. There are six major gaps in global seismic coverage, defined by vast expanses of sea without a land surface on which to establish an observatory. During Leg 179, ODP engaged in preparation of the first deep ocean global seismic observatory in one of these gaps, along the Ninetyeast Ridge in the east Indian Ocean.

Over the past decade, our understanding of deep Earth processes has improved owing to the development of new generations of global monitoring networks. Although the quantity and quality of data have radically increased, these new data have revealed large departures from lateral homogeneity at every level within the Earth from surface to core. Additionally, absolute plate motions cannot be accurately determined without precise geodetic measurements that are conventionally monitored on land. Extrapolating the Earth’s magnetic field to the core/mantle boundary is challenged by gaps in coverage, particularly in the Indian and Pacific Oceans. Images of the velocity heterogeneity of the interior of the Earth, related to thermal and chemical convection, are aliased by the lack of control in observation sites. As the technology to deploy observatories to monitor these types of phenomena is under development, a borehole cased and firmly attached to basement at the Ninetyeast Ridge will provide an ideal deployment structure.

LEG OBJECTIVES

There were two primary and several ancillary objectives outlined in the scientific prospectus for Leg 179. The two primary objectives can be summarized as (1) engineering tests of the hammer drill-in casing system, and (2) establishing a borehole, cased and cemented to basement and deepened as far as possible for future deployment of an ocean-bottom observatory.

Supplementary objectives included deepening a hole through a hammered-in casing, a proof-of-concept test for acquiring seismic data while drilling, and a conventional vertical seismic profile to complement an offset seismic profile experiment in conjunction with the Sonne. We had also hoped to attempt deployment of a test borehole strainmeter in preparation for Leg 186.

As a result of an extended delay in port because of ship repairs and loss of equipment in shipment, 17 of the 26 operational days scheduled for primary and ancillary objectives were lost. Although 2 additional days were added early in the leg to ensure completion of as many primary and ancillary objectives as possible, both of these days were lost to longer than expected transits. Consequently, in terms of primary objectives, the hammer test was incomplete as envisioned in the scientific prospectus, but still a success in that a detailed evaluation of the tests we were able to manage will result in modifications to various components of the system. As with most engineering endeavors, our test of the hammer drill-in casing system was a proof-of-concept experiment, and based on the results of these tests we remain confident in the viability of the system. In contrast, despite the abbreviated operations schedule, our second primary objective, establishing a borehole for the ION program, was wholly a success.

One consequence of the reduction in drilling time was less success in achieving supplementary objectives. We were, however, able to collect seismic-while-drilling (SWD) data at both the hammer drill test site and at NERO. These data await shore-based processing to develop a plan for future deployments of this technology. Regrettably, we were unable to complete the conventional vertical seismic profile experiment, the two-ship offset seismic experiment, logging and coring of the NERO hole, or the test deployment on the borehole seismometer. An unanticipated but overwhelmingly successful additional contingency program resulted from the delay we suffered waiting on a ship-to-ship transfer of hammer drilling supplies. We chose to invest this time in bare rock drilling at the hammer drill test site. What resulted was superb recovery from 158 m penetration in the gabbroic massif at the Atlantis II platform at a distance far enough from previous drilling to potentially allow correlation on a scale yet unfathomed in marine research. Additionally, a full suite of downhole logs was collected, which will surely aid in that endeavor.

Hammer Drill-in Casing Test Results

Hammer drill testing was carried out on the Atlantis II Bank, located east of the Atlantis II Fracture Zone which offsets the Southwest Indian Ridge between latitude 31°50’S and longitude 33°40’S at 57°E (Fig. 1). The platform is a flat-topped bench, ~9 km long and 4 km wide. This massif was successfully cored Legs 118 and 176 to a depth in excess of 1500 mbsf. This location was chosen primarily as an area of opportunity, to coincide with a point in the hammer drill development when sea trials were in order. As an additional benefit, the shallow water was envisioned to facilitate efficiency in our early operations. The flanks of the massif offered additional targets at greater depth and with topographic slopes, should the engineering tests advance beyond the initial objectives.

Site 1104

Site 1104 is located at a water depth of 731 m on the east rim of the Atlantis II Fracture Zone, ~200 m northwest of Hole 735B (latitude 32°43.32’S, longitude 57°15.85’E; Fig. 2). This site was selected based on a video survey beginning at Hole 735B, by which we sought to find a reasonably flat, large outcrop to initiate the first spud tests of the hammer drill. During the transit from Cape Town, the water hammer was successfully deck-tested. The initial assembly of the drill string including just the SDS hammer and a concentric arm bit to test the spudding capability of the system. A frequency analyzer for monitoring hammer operations was built and installed during the transit.

After a 4-hr video survey starting at the Hole 735B guide base, we selected a location with extensive, relatively flat-appearing outcrop and set the bit down on the outcrop to see how the hammer functioned without rotation. Several spud tests indicated the hammer was performing as expected, so we decided to pull the vibration-isolated television (VIT) frame and begin hammer drilling Hole 1104A. After ~45 min, it appeared from rig floor observation that we had made ~1.5 m of penetration, so we ran in the VIT to inspect the hole. We had also noted excessive vibration of the stand pipe and derrick during hammer operations. A clean, circular hole was apparent on the video image, so we pulled the camera and initiated a second test hole (Hole 1104B). After a couple of hours rotation, we had made ~2 m of penetration but also noted increasing torque and slower rate of penetration (ROP). Another camera trip revealed a second clean, circular hole, but some apparent obliquity indicated the hole had been initiated on a small local slope. We pulled the camera and attempted to spud a third hole, but the hammer would not fire, so it was pulled to the surface.

Inspection of the concentric arm bit indicated the reaming arms were damaged, and a valve had cracked in the hammer. The hammer was rebuilt, a new concentric arm bit installed, and we ran the assembly back to the seafloor. After a short video survey to inspect the site, we pulled the camera and spudded Hole 1104C. In less than two hours, although we noted ~2 m of penetration, there was also indication of high erratic torque and ROP effectively ceased. We attempted to initiate another hole (Hole 1104D) but made no advancement and experienced high and erratic torque, so this hammer test was terminated and we pulled the drill string. During the pipe trip we deployed the two United States Geological Survey (USGS) ocean-bottom seismometers (OBS), 100 and 300 m, respectively, from our drill site to monitor the noise transmitted through the outcrop which was generated by the hammer.

When inspection of the second concentric arm bit indicated once again that the underreamer arms had experienced excessive wear, a bit was modified by trimming the concentric arms to match the outside diameter of the pilot bit. After this modification, however, the bit did not appear robust enough to cut through the hard rock so this modification was abandoned. A second modification removed the concentric arms, cut the bit shank, and welded the interval where the arms had been closed. We had hoped to test the drilling capability of the bit without the added challenge of attempting to ream out the hole. Unfortunately, during the modification of the bit, a crack developed and the bit was set aside. We then modified a third bit by welding the concentric arms closed. This bit was tripped to the seafloor and we initiated Hole 1104E. After about an hour we had made ~1.5 m of penetration, but the bit stuck in the hole. We were able to free the bit with left-hand rotation, indicating that the arms had broken free and were causing the bit to stick. Having exhausted all the bits we had on board for hammer testing, and with the promise of delivery of a different bit design in a few days from a supply vessel, we chose to commit to conventional rotary coring while we waited for the equipment transfer. The OBS and positioning beacons were recovered, thus ending operations at Site 1104.

Site 1106

After delivery of the new bits from the supply vessel, we returned to the location of Site 1104 in anticipation of continued hammer testing. Despite the same coordinates as Site 1104 (latitude 32°43.32’S, longitude 57°15.85’E, Fig. 2), because a new beacon was deployed and we wanted the record to indicate the next phase of hammer testing, this location was assigned as Site 1106. The hammer was tested on the deck in preparation for deployment, but the continued deterioration of sea state prevented any further transfer from the supply vessel.

The hammer was run, and after a brief seafloor survey, Hole 1106A was initiated. After ~2 m of penetration, the hammer ceased activity, and we tripped it back to the surface. Once again a valve had broken in the hammer, potentially because of excessive heave during the continuing poor sea state. Hole 1106B was initiated on the ensuing pipe trip, which included the second of the three bits that we acquired on the transfer (coincidentally the last bit capable of drilling an overgauge hole) because the first bit was worn after Hole 1106A. Only about one-half a meter of penetration was realized before the hammer ceased activity again, necessitating another pipe trip. Again the bit was worn, so it was replaced with the last of the bit configurations we had available, a flat-faced drilling bit. Our decision to run this bit was based on the assumption that if we could demonstrate the ability to make a hole, we could use this information in future bit design.

Hole 1106C was spudded and we drilled ~1 m in less than an hour before the hammer stalled again. On the ensuing pipe trip, the piston in the hammer was replaced and the flat-faced bit was run back to the seafloor. Hole 1106D was attempted, but the hammer would not start, so it was pulled and rebuilt once again. Hole 1106E was initiated, and the hammer drill system performed admirably, cutting an 8-m-deep hole in less than 2 hr. The pressure transducer on the stand pipe chose this time to give way, so the pumps had to be shut down for repairs. Once the repair was completed, the driller noted no pressure buildup and was able to slowly lower the drill string to the total depth (TD) of the hole + 4 m, indicating that we had lost some of the bottom-hole assembly. The subsequent VIT trip indicated that the bit and hammer were indeed missing, and because we could not see them on the seafloor, we assume they are still in Hole 1106E. Weather conditions had still not improved, and we did not have a clear idea which of the several holes within a few meters radius was Hole 1106E, so a fishing attempt was unrealistic. Given that we had exhausted all the bits and hammer spare parts, we declared the hammer test for Leg 179 complete, and got under way for Ninetyeast Ridge.

In summary, although a detailed summation of all the data relevant to the hammer testing awaits postcruise development, we do have some preliminary impressions. We are encouraged by the performance of the hammer and will be able to use this series of tests for optimal design improvements. Despite the less than desired performance of the bits, again we are optimistic, particularly based on the last test where we made 8 m of penetration in less than 2 hr, that bit design improvements will yield improved performance in the future. Finally, as with all our operations, sea state appears to be a primary control if not on the success of an operation, at least on its duration and ease of completion.

Site 1105

Because of delays in the resupply ship that inhibited resumption of hammer tests near Hole 735B, Hole 1105A was drilled on Leg 179 for a period of 6 days. The hole was located ~1.3 km east-northeast of Site 735 on the Atlantis platform along the eastern transverse ridge of the Atlantis II Transform (latitude 32°43.13’S, longitude 57°16.65’E; Fig. 2). The site is along a ridge-axial trend with respect to Hole 735B, but more distal from the north-south trending Atlantis II Transform that lies to the west. The site was chosen to avoid a duplication of Hole 735B efforts that might occur by drilling at proximal Site 1104. At the same time, we wanted to utilize Hole 735B as a reference section to attempt lateral correlation of large-scale igneous units, structural features, and geophysical characteristics over the broader distance represented by the offset in holes in the direction approximately parallel to the former ridge axis. In addition, the site was chosen to help constrain the overall structure of the massif exposed on the platform. If successful, the correlation experiment could yield a minimum measure of the dimensions of subaxial magma chambers and continuity of structure and processes along strike of the ridge axis at a very slow-spreading center. If correlations are unsuccessful we can limit the dimensions of igneous units, former magma chambers, or structures to be smaller than the scale of the experiment. Correlation will be attempted on the basis of detailed and integrated data sets including core descriptions and subsequent shore-based laboratory analyses to establish cryptic chemical and mineralogical variations, and the alteration and structural framework in the core. A full and highly successful logging program that was completed after the cessation of drilling will aid in the correlation attempts.

The hole penetrated to a depth of 158 m, and the cored interval measured 143 m, starting 15 m below the seafloor. Core recovery included 118.43 m of gabbroic rock for a total recovery of 82.8%. Together with logging results, this recovery provides complete coverage of the rock types and a comprehensive view of pseudostratigraphy in the gabbroic section cored (Fig. 3). Shipboard results now indicate a high probability that specific units, structures, and/or geophysical characteristics from Holes 735B and 1105A may indeed be correlated.

The cores recovered record a wide variety of rock types ranging from gabbro (Fig. 4), oxide gabbro with up to 20–25 modal percent Fe-Ti oxides (Fig. 5), and olivine gabbro (Fig. 6) to scarcer troctolitic gabbro, gabbronorite, and felsic rocks such as trondjhemite. Described within the core are 141 intervals that have been defined on the basis of distinct changes in mode, modal proportions, grain size, and/or texture. Well-defined igneous layer contacts or structural boundaries to these intervals are preserved in many sections of the core (Fig. 7). The highly layered nature of the gabbroic rocks documented within the core is supported by high-quality continuous Formation MicroScanner (FMS) logs of the borehole (Fig. 8), as well as other logs and whole-core magnetic susceptibility measurements (Fig. 9). The scale of the layering in the core varies from a few centimeters to meters. On a broader scale, the intervals define four basic units from top to bottom consisting of (1) a gabbroic unit characterized by more primitive rock types and by a scarcity or lack of oxide gabbro, (2) a gabbroic unit characterized by a high abundance of oxide gabbro and oxide-bearing gabbro, (3) a gabbroic unit characterized more primitive rock types and a lack of oxide gabbros, and finally (4) another unit rich in oxide gabbro and oxide-bearing gabbro. Rocks are crosscut by millimeter- to decimeter-sized veins of leucocratic gabbro, quartz diorite, trondhjemite, and irregular pegmatitic gabbro intrusions. Irregular veins and bands of oxide minerals have also been observed.

Thin sections indicate typical cumulate textures in the majority of samples that range from adcumulate to orthocumulate and show variable amounts of core-to-rim zoning in plagioclase. Poikilitic textures are also common with pyroxene as the oikocryst phase and plagioclase as the chadocryst phase (Fig. 10). Igneous laminations were observed in several samples but are generally scarce or may be overprinted by crystal-plastic fabrics. Preliminary bulk rock geochemical results show a wide range in the chemistry of gabbroic rocks with Mg numbers varying from ~0.80–0.23, Fe_2O_3 from ~3.5–24.0 wt%, P_2O_5 from ~0.01–4.1 wt%, Y from 7–192 ppm, Nb from 1–10 ppm, and Cr from 1–1066 ppm.

Alteration of the primary igneous mineralogy in the core is generally low, but varies on the scale of a thin section to meters. Alteration of olivine to chlorite, tremolite-actinolite, and talc is the most common manifestation of alteration, whereas plagioclase and clinopyroxene tend to be less altered. It is common for clinopyroxene, where altered, to be partially replaced by patchy brown amphibole, but alteration generally does not exceed 1%–2%. A portion of this brown amphibole is likely to be of magmatic origin. Where alteration is extensive, clinopyroxene is replaced by assemblages of actinolite and chlorite. Plagioclase is generally fresh. Actinolite and chlorite are also the most common vein assemblages, although scarce high-temperature brown amphibole and low-temperature smectite and carbonate veins have also been observed.

The structure of the core is complex, and structural styles and intensities range from brittle to ductile. Most of the gabbroic samples cored possess igneous textures, but there are several parts of the core that display crystal-plastic fabrics. Mylonitic zones characterized by high oxide-mineral content were observed at ~53 and 71 mbsf (Fig. 11). Coarser grained centimeter- to decimeter-thick zones of ductile shear are present in the upper 90 m of core, whereas thicker zones of ductile deformation with weak to strong crystal-plastic fabrics become more prevalent at depths in excess of 90 mbsf. Intervals of penetrative ductile deformation in the lower portion of the core locally exceed 2 m in thickness. Zones of ductile deformation are commonly oxide rich, as are the contact regions between undeformed and ductily deformed rocks. Oxide-gabbro rich zones tend to be strain localizers because many, but not all, of the crystal-plastic shear zones are rich in oxide minerals. Inclination of the ductile foliations vary from ~18° to 75° in the cored intervals and averages ~30°–35°. Thin sections show a range of textures from strictly igneous to slightly deformed igneous to dynamically recrystallized metamorphic textures with crystal-plastic fabrics. As deformation intensity increases, the effect can be most easily observed in plagioclase, where a progression from strain-free plagioclase to plagioclase with deformation twins, undulose extinction, kink bands, and dynamic recrystallization to neoblasts along grain margins progresses to porphyroclastic textures with small neoblasts of plagioclase and highly strained and kinked plagioclase, pyroxene, or olivine porphyroclasts. Olivine appears to have recrystallized to neoblast grain sizes because pyroxene, which tends to be preserved as the dominant porphyroclastic phase unless the intensity of deformation is most severe. Brittle fractures are generally filled with vein material such as actinolite and chlorite, but no large faults zones were recovered in the core. There were several regions of low recovery that could correspond to fault zones based on temperature, sonic, resistivity, and porosity logs. These regions of poor recovery generally sampled little intact core, although gabbroic rocks that were recovered were altered to smectite and contained carbonate veins.

Preliminary analysis of the downhole geophysical measurements from core and logging data yields a wide variety of information. Magnetic data indicate that the core possesses a single coherent magnetic direction with an average inclination of ~67°. This is compared with an inclination of –52° expected for the site. As in Hole 735B, these results indicate a consistently reversed polarity for the section and may indicate a significant block rotation of the massif similar in magnitude to rotations interpreted from Hole 735B (15°–20°). The consistency of the magnetic inclination downhole suggests that any relative rotations along ductile shear zone in the section must have occurred before cooling below the blocking temperature and are necessarily high temperature in nature. Magnetic susceptibility measurements clearly define zones of oxide gabbro and oxide-bearing gabbro documented in the core. Likewise, it provides a direct downhole comparison for the FMS logs, which measure resistivity. Oxide-rich zones are conductive whereas oxide-free zones have high resistivity. Magnetic intensity on split cores ranges from ~0.2–5 A/m.

Lastly, an SWD experiment was conducted at Hole 1105A using two USGS OBS. These data, together with accelerometer data from the drill rig, will be employed to test the feasibility of SWD during drilling operations of the *JOIDES Resolution*.

NERO Site

After an 8-day transit, we arrived at Site 1107. The specific NERO site was selected based on seismic data collected in support of Leg 121, investigating the geology and paleoclimatic history of Ninetyeast Ridge. We selected Site 757 as our target, because, while meeting the criteria for emplacement of a borehole observatory in the Indian Ocean, it was also in our most direct line of transit between the hammer drill test site and our end of cruise port call in Darwin, Australia. Hole 1107A is located in 1650 m of water at 17°1.42'S latitude, 88°10.85'E longitude (Fig. 12). There was an ambitious program outlined in our prospectus, including establishing a borehole for future installation of a subseafloor observatory, conventional logging and vertical seismic profile experiments, deployment of a test installation of the strainmeter module in preparation for Leg 186, and the NERO offset seismic experiment (NOSE) in conjunction with the continuing expedition of the Seismic Investigation at Ninetyeast Ridge using the *Sonne* and the *JOIDES Resolution* (SINUS) during Leg 179. We had originally scheduled 11 days to complete these objectives. However, our extended port call, lost shipment, and extended transit times all worked to shorten our operational schedule, paring away 17 of our original 26 days of total operational time and reducing our time on location at NERO from 11 days to less than 6 days. Our optimistic estimate indicated that even given this radical reduction, if all went extraordinarily well we could still complete the borehole (although to significantly less depth of penetration than our original target of 100–200 m into basement) and have some time remaining for the two-ship experiment. Our restricted schedule, however, required that we allocate no time for the many other operations we had hoped to complete at NERO.

After we arrived on site, we deployed a beacon and ran to seafloor with 48.82 m of 16-in casing fixed to a reentry cone. This assembly was washed in, and subsequently we reentered the hole with a 14-3/4-in tricone bit to drill a large borehole to allow deployment of 10-3/4-in casing some 30–40 m into basement. We also deployed the ocean-bottom seismometers and installed the Lamont-Doherty Earth Observatory sensor sub on the drill string to conduct our second SWD experiment. Based on Leg 121 statistics, we had hoped to drill to basement in 12 or so hours, and to drill at least 30–40 m into basement over the next 10 hr. Drilling the sediment column took longer than we expected, probably because of the size of the hole we were drilling and resistive layers of volcanic breccia and tuff overlying basement as were reported in the Leg 121 Initial Reports volume (Pierce, Weissel, et al., 1989). Basement drilling also proceeded somewhat slower then we expected, although penetration rates were quite variable in the subaerially emplaced lava flows. At ~410 mbsf, we encountered a relatively hard layer, and ROP slowed to less than 2 m/hr. In light of the fact the drilling in basement had up to this point proceeded reasonably quickly, we envisioned this hard layer as an ideal position to anchor the bottom of the casing with cement. After drilling to 422 mbsf to ensure that any material wiped off the walls of the borehole during emplacement of the casing would have a place to go and would not impede casing operations, we terminated deepening Hole 1107A because we had reached our target depth for casing of ~40 m into basement.

In our optimistic schedule developed after recognizing that we only had 5.5 days of operational time, we had hoped to set aside ~48 hr of ship time for the two-ship experiment. This time included pipe trips, set up and rig down time, and preparation to get under way (as this was to be our last operation), which resulted in an estimated 29 hours of shooting time for the two-ship experiment. Any additional time was to be allocated to deepening the hole. At this point in our operations, however, individually minor but collectively significant delays because of handling pipe in heavy seas, slowed ROP, and mechanical difficulties had pared more than 25 hr from our already drastically reduced timetable.

By the time our last casing operation was completed (10-3/4-in casing set to 414 mbsf), we recognized there would not be sufficient time to clean out the cement shoe in the bottom of the casing, drill through the cement, clean out the rathole underneath, make 10 m of new hole below the casing string, and still have time remaining for a two-ship experiment. A 10-m penetration below the casing string was the absolute minimum envisioned as necessary for establishing a borehole for the observatory emplacement. In our estimation, completing the borehole and allowing time for even a short two-ship experiment would have resulted in a 24-hr delay in our arrival at Darwin. This was not possible given the program’s tight operational schedule and that the leg had already been extended 2 days beyond the original schedule.

Even with the disappointment we all felt regarding cancellation of the two-ship experiment, we recognized that although we did not have sufficient time to prepare for and rig down after a two-ship experiment (at least 20–24 hr), because we already had a drilling bit in the bottom of the hole, we did have enough operational time to deepen the borehole. We had elected to use a tricone bit rather than a coring bit to ensure that we could penetrate through the casing shoe without delay. This bit, although not allowing coring of the material drilled, did allow rapid penetration through the formation in the few hours we had remaining. We continued drilling to a depth of 493.8 mbsf, which is just over 120 m into basement and almost 80 m below the casing shoe (Fig. 13). We hope this depth will allow a successful installation of the Ninetyeast Ridge Observatory. During drilling through the sediment column and into basement, we again collected SWD data via OBS and the shipboard accelerometer. Postcruise processing is required to interpret these data, however our initial inspection of the data indicates this will be possible.

SUMMARY

The two primary objectives, which consisted of (1) testing the hammer-in casing system recently developed by ODP on the Atlantis Bank, Southwest Indian Ridge, and (2) drilling a cased reentry hole into basaltic basement on the Ninetyeast Ridge to allow future installation of an ocean floor geophysical observatory, the Ninetyeast Ridge Observatory, were accomplished during Leg 179. Because of delays during the leg caused by a late departure from Cape Town resulting from a lengthy repair to the ship's guide horn, slower than expected transits, and an errant shipment of hammer drill supplies requiring a resupply effort at sea, certain ancillary objectives were not accomplished and one unexpected contingency drilling site was cored on the Atlantis Bank, Southwest Indian Ridge.

The hammer testing at Sites 1104 and 1106 on the Atlantis Bank supplied the engineers with the enough data to suggest that the hammer is viable for the purpose of initiating hard rock holes on gentle or steep bare rock slopes. At the same time, modification to the bit design, in particular the underreaming arms originally developed for use on land, will be required to accommodate the significant heave conditions the ship experiences during drilling. A conventional simplified hammer bit design without underreaming capabilities was also tested and performed admirably with the hammer penetrating 8 m in 2 hr with the same strong heave conditions. This indicated that the underreaming bit design and its response to significant heave is the most serious problem and not the hammer's basic ability to spud and rapidly penetrate hard rock on the seafloor. In general, sea states were uncooperative during the entire hammer testing, and this inhibited completion of the tests and shortened their duration. A new generation of the active heave compensator may also help to improve bit operational tolerances. The ODP engineers are now quite convinced that the hammer system with a modified or alternate bit design will be the answer to the significant problem of spudding and maintaining stable holes in a range of bare rock environments and will be one of the most significant engineering developments for future hard rock drilling by the Ocean Drilling Program.

Contingency drilling at Site 1105 was highly successful and drilling penetrated 158 mbsf over a 6-day period. This resulted in 118 m of core from a large gabbroic massif exposed along the transverse ridge of the Atlantis II Transform. The site was ~1.3 km from the highly successful Hole 735B, which was cored to 1508 mbsf. The core included gabbro, olivine gabbro, and abundant oxide gabbro, and preliminary investigation indicates that part of the pseuodstratigraphy may be similar to that recovered in Hole 735B. We also acquired an extensive suite of logging data including high-quality FMS borehole image data. Because the core and logging data provide a comprehensive data set, cross-hole correlations between two high recovery offset holes (Holes 1105A and 735B) drilled into the plutonic foundations of the oceanic crust will be possible for the first time. The data will also allow us to conduct high-resolution structural and igneous studies and gain understanding into the geometry of igneous layering and ductile shear zones in the cumulate sequences sampled. The drilling of Hole 1105A demonstrated the versatility of the *JOIDES*

Resolution in a hard rock environment in the face of unplanned contingencies and the general ability to easily establish quality holes with good recovery on the Atlantis platform.

The primary objective of the NERO portion of Leg 179 was to prepare a seafloor borehole for future establishment of Geophysical Ocean-Bottom Observatory (GOBO). This objective specifically included drilling a single hole as deep as possible into basement, as well as installing a reentry cone and casing beyond the sediment\basement interface to prepare this site for an ocean-bottom observatory. The GOBO will be installed at a later time by submersible or surface ship and will be part of the future network of seafloor observatories proposed in the ION program. Hole 1107A was drilled in a water depth of 1648 m on the Ninetyeast Ridge. The sediment cover above the basaltic basement was drilled to ~372 mbsf; however, the drilling rates suggested that firm basement was not reached until 404 mbsf. Drilling reached a depth of 493.8 mbsf which was sufficient to create a 9-7/8-in borehole below casing for the downhole seismometer installation. The acceptable region of the borehole in basement for emplacement of a seismometer is the lower 71.8 m. The total penetration into basement was 122 m, and total penetration below casing reached 79.4 m. The hole is regarded as a success for a number of reasons. These include the excellent stability of the hole, the fact that the hole was cased to 43.4 m into basement as planned, and because a significant depth of the borehole below the casing was achieved, which otherwise have might been a source of potential noise as experienced at other ocean-floor seismometer installations.

Lastly, Leg 179 accomplished basic testing of the SWD concept at Sites 1104, 1105, and 1107 that should allow the feasibility of the concept to be evaluated. Other supplementary objectives of the leg, including coring and logging of the NERO hole, the offset seismic experiment, a VSP, and a strainmeter test could not be achieved because of the unfortunate and considerable amount of operational time lost.

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Dick, H.J.B., Schouten, H., Meyer, P.S., Gallo, D.G., Bergh, H., Tyce, R., Patriat, P., Johnson, K.T.M., Snow, J., and Fisher, A., 1991. Bathymetric map of the Atlantis II Fracture Zone, Southwest Indian Ridge. *In* Von Herzen, R.P., Robinson, P.T., et al., Proc. ODP, Sci. Results, 118: College Station, TX (Ocean Drilling Program) back pocket.

Dick, H.J.B., Natland, J.H., Miller, D.J., et. al., in press. *Proc. ODP, Init. Repts.,* 176: College Station, TX (Ocean Drilling Program).

Pierce, J., Weissel, J., et al., 1989. Proc. ODP, Init. Repts., 121: College Station, TX (Ocean Drilling Program).

Robinson, P.T.,Von Herzen, R., et al., 1989. Proc. ODP, Init. Repts., 118: College Station, TX, (Ocean Drilling Program).

FIGURE CAPTIONS

Figure 1. Bathymetry of the Atlantis II Transform Fault (data from Dick et al., 1991) displaying the transform valley, transverse ridges, median tectonic ridge and the northern and southern ridge-transform intersection (RTI). Solid circles marks the position of Hole 735B atop the Atlantis Bank.

Figure 2. Three-dimensional shaded-relief image of the Atlantis Bank (looking northeast) along the wall of the Atlantis II Transform Fault (data from Dick et al., 1991). The image shows Sites 1104, 1105A, and 1106 drilled on Leg 179 and Hole 735B drilled on Legs 118 and 176. Image shows the transform valley, transverse ridges with the Atlantis Bank (highest region), and the termination of the median tectonic in the axis of the transform valley.

Figure 3. Summary of visually defined lithologic intervals and syntheses units of Hole 1105A. Only the main lithologic rock types are illustrated.

Figure 4. Close-up core photograph showing a planar interface between layers of massive medium-grained gabbro and massive coarse-grained gabbro.

Figure 5. Close-up core photograph showing an interval with high concentration of Fe-Ti oxide minerals in coarse-grained gabbro.

Figure 6. Digital photomicrograph of medium-grained olivine gabbro with adcumulate texture. Field of view is 2.75 mm (plane-polarized light).

Figure 7. Photomicrograph of contact between fine-grained olivine gabbro with granular texture and a medium-grained olivine gabbro. Field of view 23 mm (plane-polarized light).

Figure 8. FMS image over the depth interval 93 to 100 mbsf in Hole 1105A with correlated lithologic units and oriented dips. Conductive areas appear in dark shades, whereas light shades are attributed to resistive zones.

Figure 9. Filtered whole-core magnetic susceptibility measurements. All measurements of pieces smaller than the sensing interval of the susceptibility loop, as well as all measurements within 5 cm of the end of a piece have been removed. A simplified graphic lithology column, highlighting only those intervals where Fe-Ti oxide have been reported is plotted to the left. Lithologic unit boundaries are also shown adjacent to the graphic lithology plot and embedded in the magnetic susceptibility plot. The dashed line represents a weighted moving average through the magnetic susceptibility data. Lithologic unit average magnetic susceptibilities are Unit I, 828 SI; Unit IIA, 3406 SI; Unit IIB, 3010 SI; Unit III, 780 SI; Unit IV, 3472 SI.

Figure 10. Poikilitic clinopyroxene enclosing anhedral plagioclase grains in medium-grained olivine gabbro. Field of view = 5.5 mm (cross-polarized light).

Figure 11. Highly strained ribbon grains of plagioclase in mylonitic fine-grained matrix. Field of view = 5.5 mm (cross-polarized light).

Figure 12. Site map in the eastern Indian Ocean showing the location of Ninetyeast Ridge and NERO Site 1107 and other ODP sites in the region (from Pierce, Weissel, et al., 1989). Contour is 3000 mbsl.

Figure 13. Schematic illustration of cased borehole configuration at Hole 1107A.

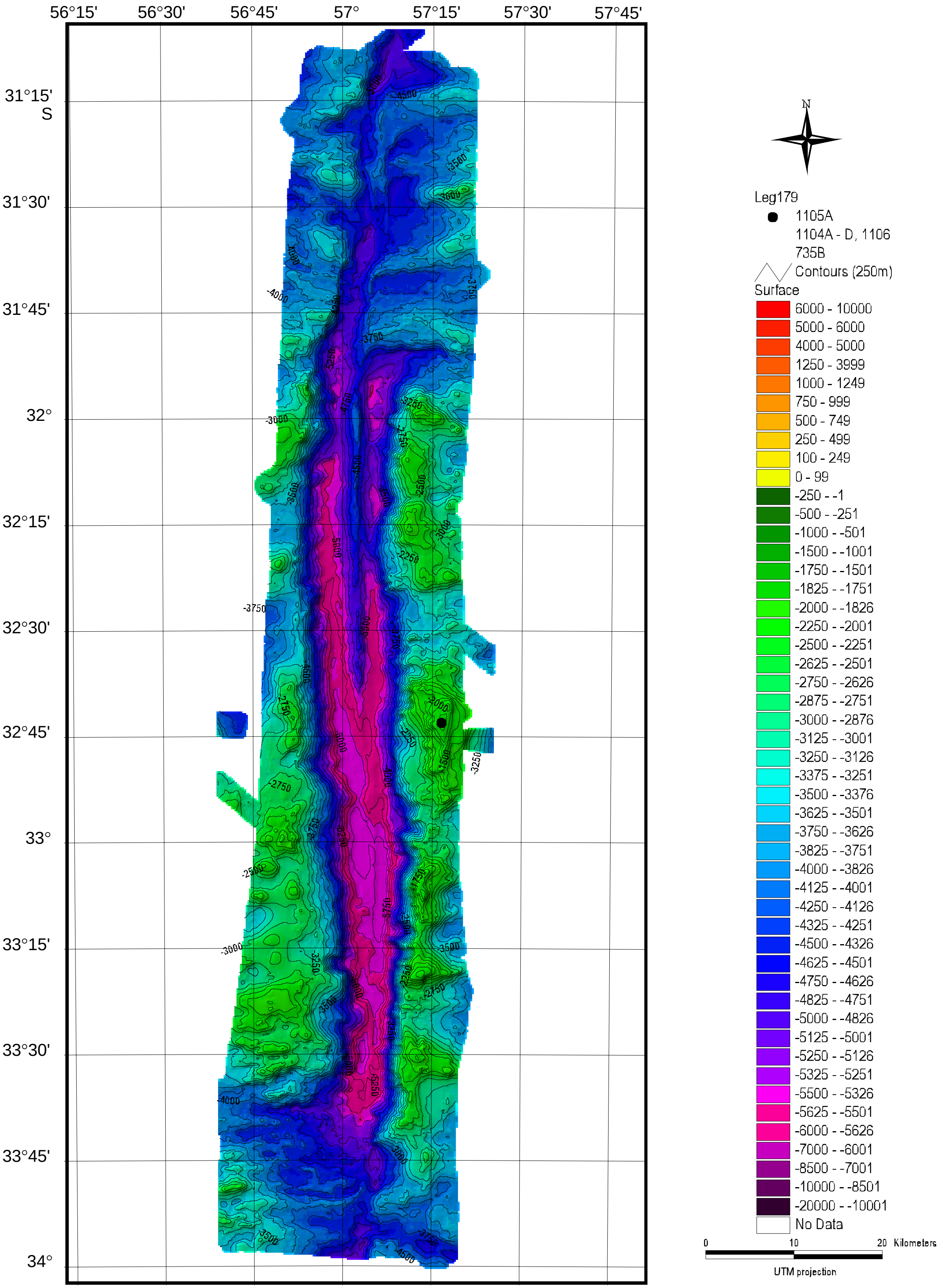

56°15'
56°30'
56°45'
57°
57°15'
57°30'
57°45'
31°15' S
31°30'
31°45'
32°
32°15'
32°30'
32°45'
33°
33°15'
33°30'
33°45'
34°
56°15'E
56°30'
56°45'
57°
57°15'
57°30'
57°45'
N
Leg179
1105A
1104A - D, 1106
735B
Contours (250m)
Surface
6000 - 10000
5000 - 6000
4000 - 5000
1250 - 3999
1000 - 1249
750 - 999
500 - 749
250 - 499
100 - 249
0 - 99
-250 - -1
-500 - -251
-1000 - -501
-1500 - -1001
-1750 - -1501
-1825 - -1751
-2000 - -1826
-2250 - -2001
-2500 - -2251
-2625 - -2501
-2750 - -2626
-2875 - -2751
-3000 - -2876
-3125 - -3001
-3250 - -3126
-3375 - -3251
-3500 - -3376
-3625 - -3501
-3750 - -3626
-3825 - -3751
-4000 - -3826
-4125 - -4001
-4250 - -4126
-4325 - -4251
-4500 - -4326
-4625 - -4501
-4750 - -4626
-4825 - -4751
-5000 - -4826
-5125 - -5001
-5250 - -5126
-5325 - -5251
-5500 - -5326
-5625 - -5501
-6000 - -5626
-7000 - -6001
-8500 - -7001
-10000 - -8501
-20000 - -10001
No Data
0
10
20 Kilometers
UTM projection

Figure 1

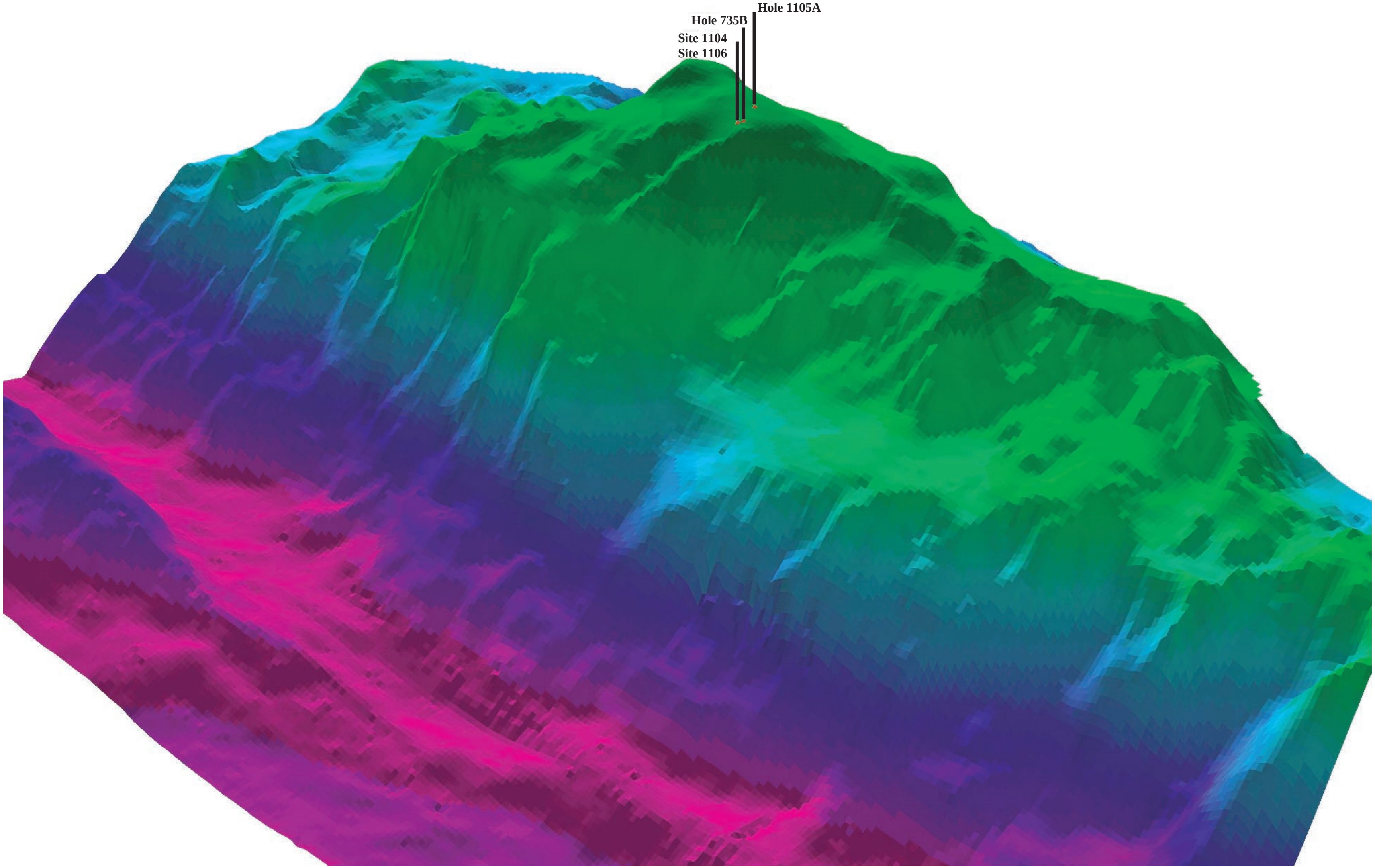


Fig. 2

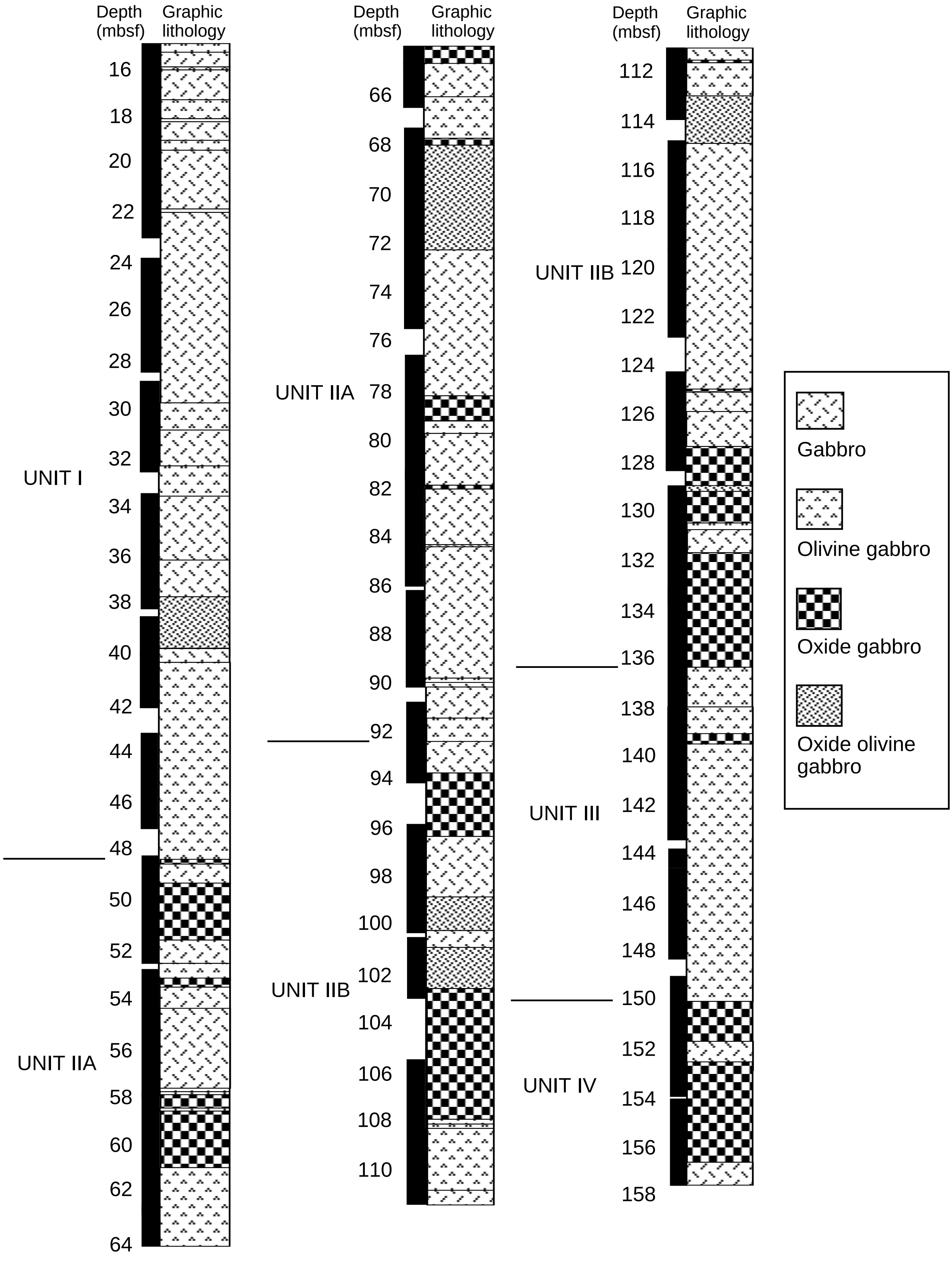

Depth (mbsf)
Graphic lithology
16
18
20
22
24
26
28
30
32
34
36
38
40
42
44
46
48
50
52
54
56
58
60
62
64
UNIT I
UNIT IIA
66
68
70
72
74
76
78
80
82
84
86
88
90
92
94
96
98
100
102
104
106
108
110
UNIT IIA
UNIT IIB
112
114
116
118
120
122
124
126
128
130
132
134
136
138
140
142
144
146
148
150
152
154
156
158
UNIT IIB
UNIT III
UNIT IV
Gabbro
Olivine gabbro
Oxide gabbro
Oxide olivine gabbro

Figure 3

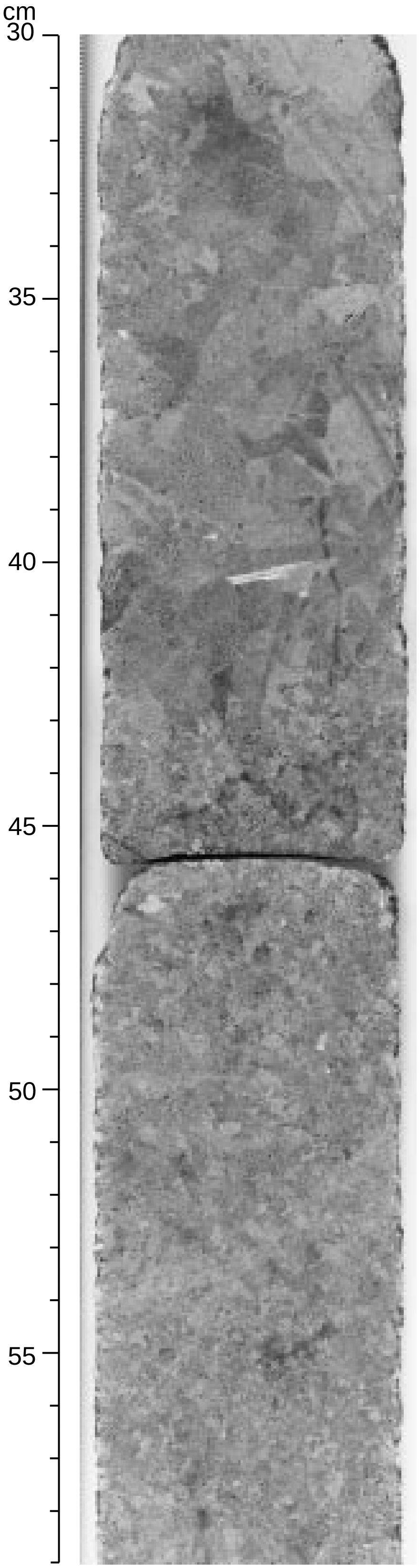
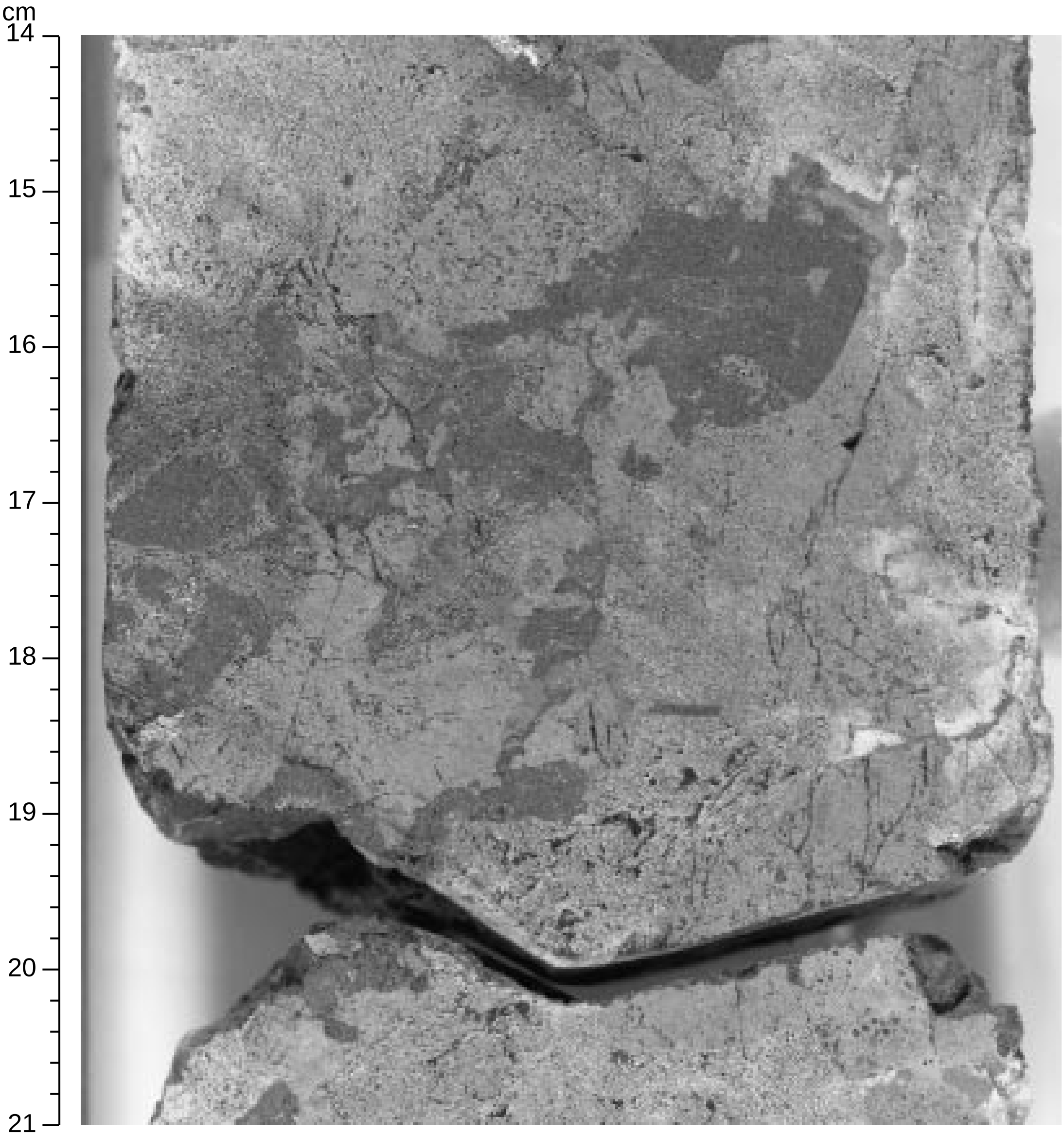


Figure 4



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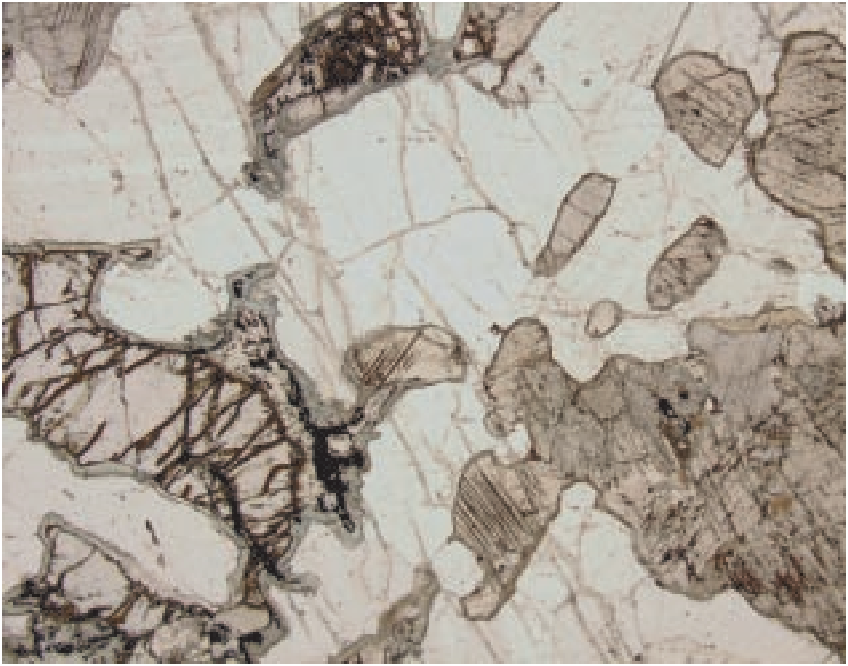

Figure 6

Figure 7

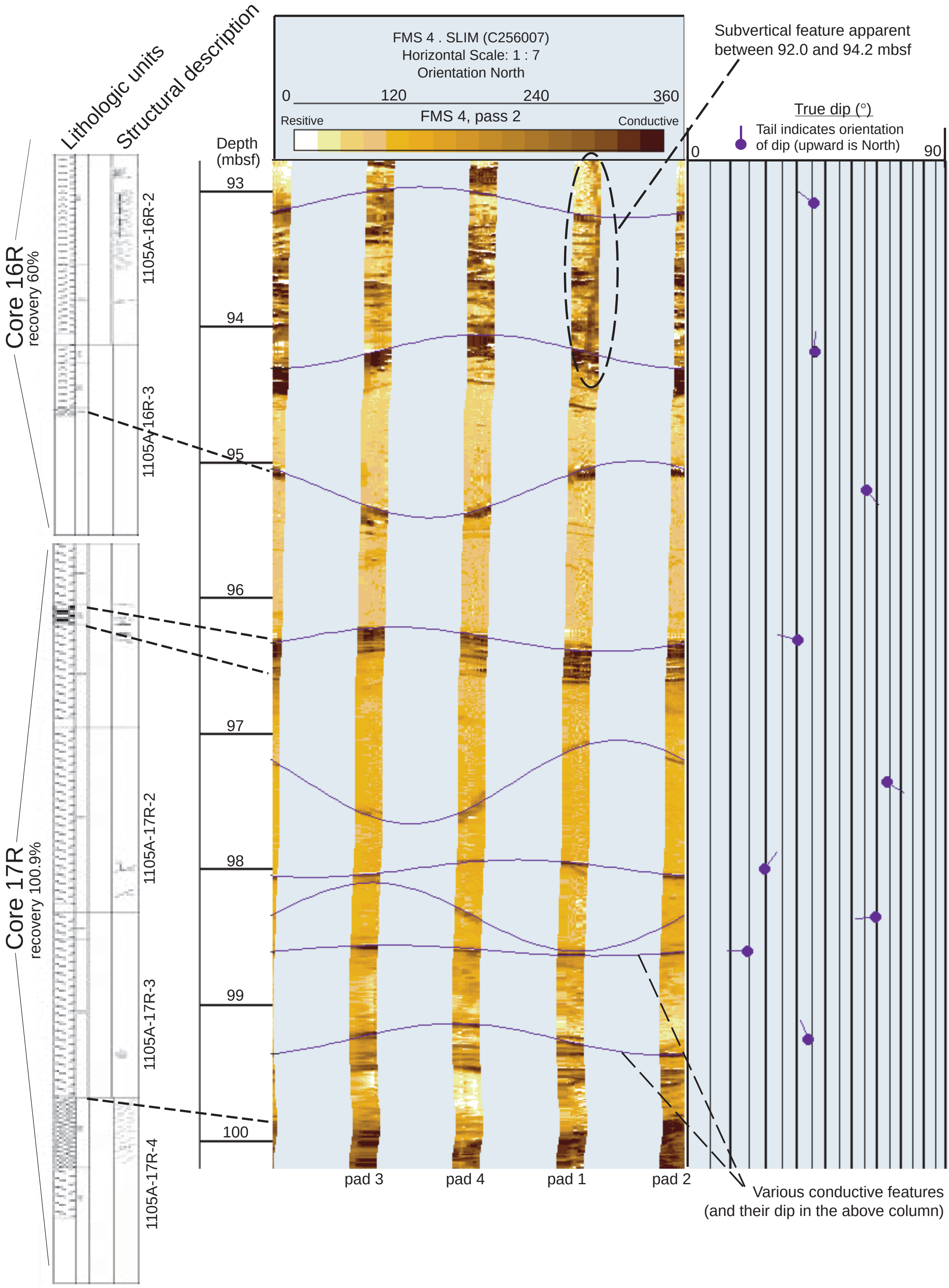
Lithologic units
Structural description
Core 16R
recovery 60%
Core 17R
recovery 100.9%
1105A-16R-2
1105A-16R-3
1105A-17R-2
1105A-17R-3
1105A-17R-4
Depth
(mbsf)
93
94
95
96
97
98
99
100
FMS 4 . SLIM (C256007)
Horizontal Scale: 1 : 7
Orientation North
0
120
240
360
FMS 4, pass 2
Resitive
Conductive
pad 3
pad 4
pad 1
pad 2
Subvertical feature apparent
between 92.0 and 94.2 mbsf
True dip (°)
Tail indicates orientation
of dip (upward is North)
0
90
Various conductive features
(and their dip in the above column)

Figure 8

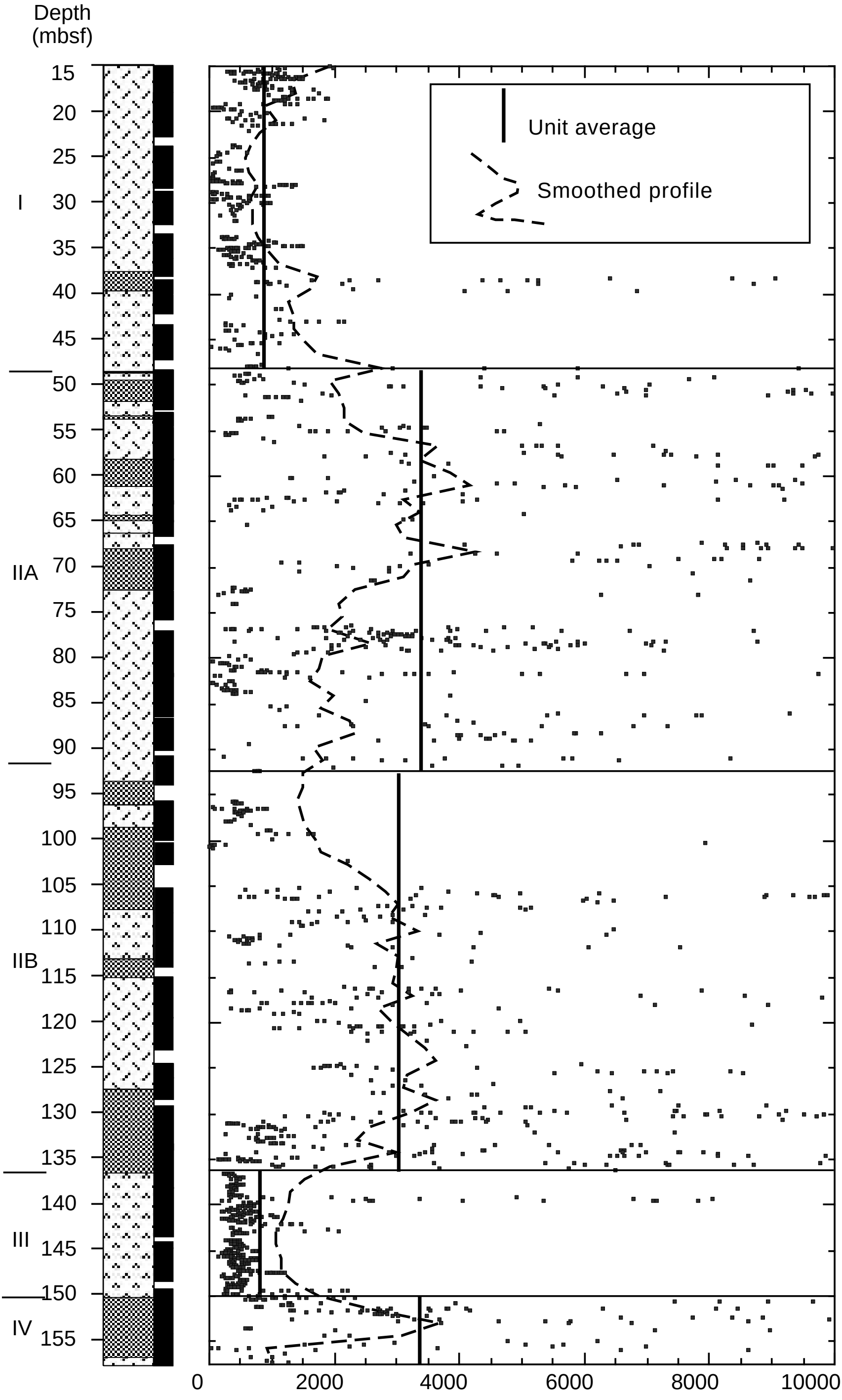
Depth
(mbsf)
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
100
105
110
115
120
125
130
135
140
145
150
155
I
IIA
IIB
III
IV
Unit average
Smoothed profile
0
2000
4000
6000
8000
10000
Magnetic susceptibility (SI)

Figure 9

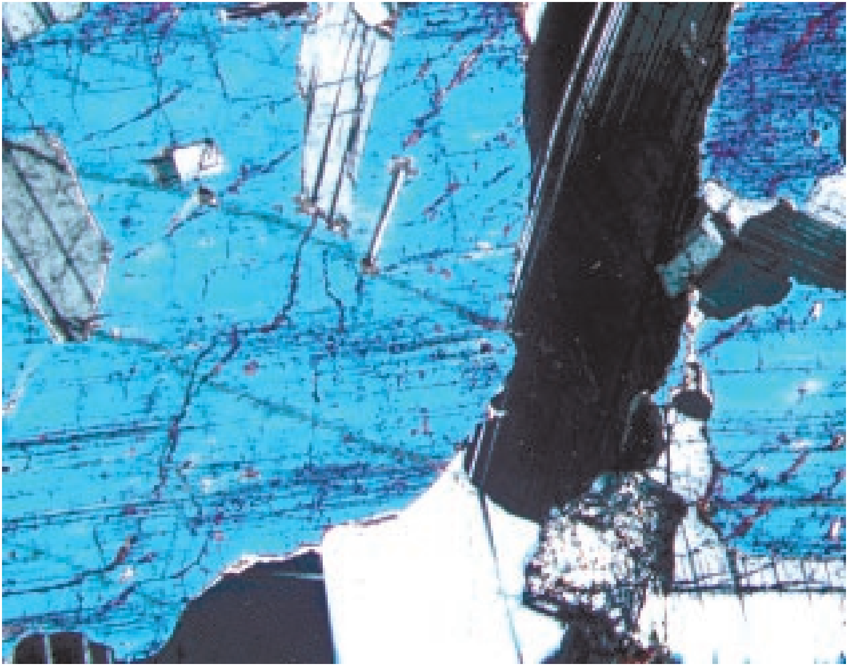

Figure 10

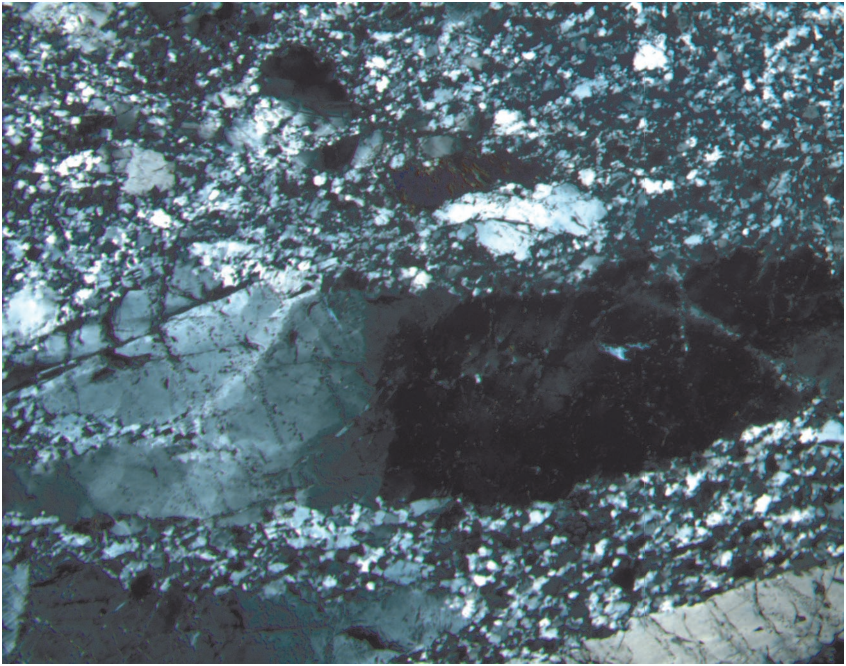

Fig. 11

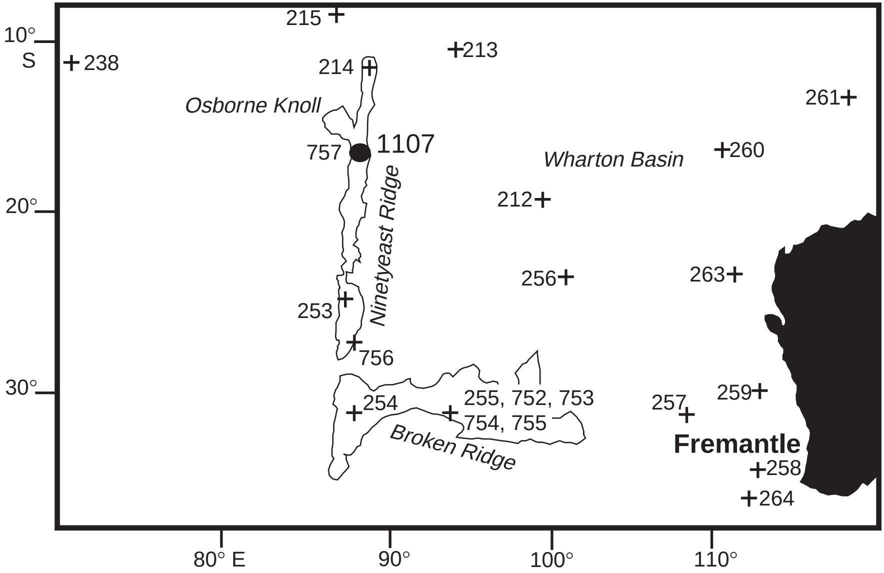
215
10°
S
238
213
214
Osborne Knoll
261
757
1107
Wharton Basin
260
20°
212
Ninetyeast Ridge
256
263
253
756
30°
254
255, 752, 753
754, 755
257
259
Fremantle
Broken Ridge
258
264
80° E
90°
100°
110°

Figure 12

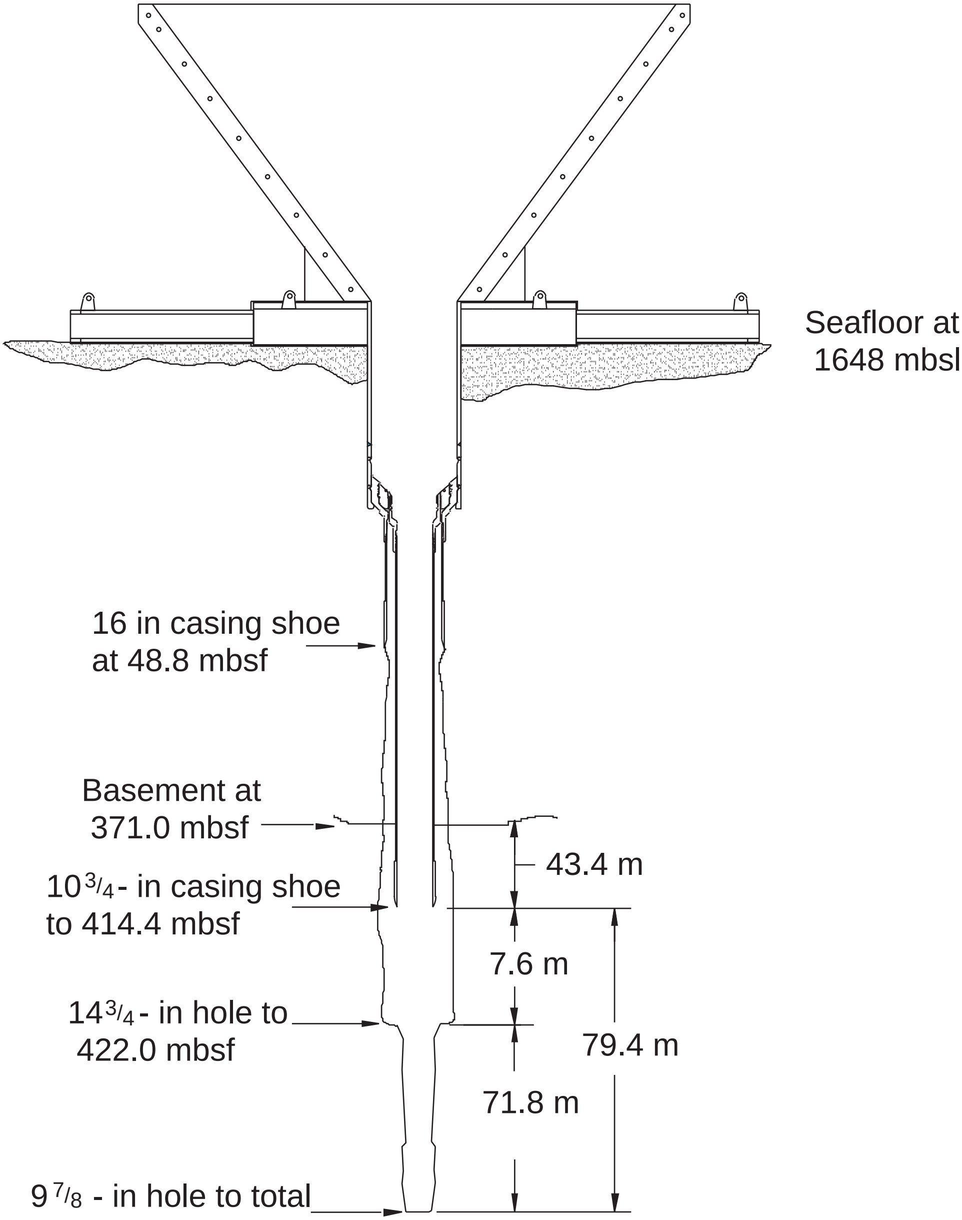
Seafloor at
1648 mbsl
16 in casing shoe
at 48.8 mbsf
Basement at
371.0 mbsf
43.4 m
10 3/4 - in casing shoe
to 414.4 mbsf
7.6 m
14 3/4 - in hole to
422.0 mbsf
79.4 m
71.8 m
9 7/8 - in hole to total
depth of 493.8 mbsf

Figure 13

OPERATIONS SYNOPSIS

The operations and engineering personnel aboard the *JOIDES Resolution* for Leg 179 were

Operations Manager and Chief Engineer	Tom Pettigrew
Development Engineer	Leon Holloway
SDS Consulting Engineer	Taras Olijnyk
SDS Consulting Engineer	Paul Speight

INTRODUCTION TO THE HAMMER DRILL-IN CASING SYSTEM

Drilling and coring operations in fractured hard rock must overcome many challenges not confronted in piston coring operations. These can be summarized as initiating the borehole, stabilizing the borehole, and establishing reentry capability. Until a drilling/coring bit can gain purchase, because it is not stabilized by sediment, it tends to chatter across the surface of a hard-rock outcrop. Difficulty initiating a hole is exacerbated if the drilling target is on a slope. Rubble from the seafloor, drill cuttings, and material dislodged from the borehole wall must continually be removed; however the size and density of this material complicates this task. Because of bit wear in hard rock, deep penetration (beyond a few tens of meters) absolutely requires the ability to perform multiple entries into a borehole. The ideal system for drilling in hard-rock environments would disregard local topographic variation, seafloor slope, and thickness of sediment cover or talus accumulation. Such a system should initiate a hole, then simultaneously deepen the hole and stabilize the upper part of the hole with casing. This requires the bit to cut a hole with a greater diameter than the casing, and then to be withdrawn through the casing string. The casing in turn would facilitate hole-cleaning operations by elevating the annular velocity of the drilling fluid and would ease reentry operations by eliminating the possibility of offsets in the borehole wall (ledges or bridges). Finally, this ideal system would leave behind a structure to simplify the required multiple reentries.

The hammer drill-in casing system is composed of a hydraulically actuated percussion hammer drill, a casing string or multiple casing strings, a free-fall deployable reentry funnel, and a casing hammer. Once the casing string has been drilled into place and the reentry funnel installed, the drilling assembly is unlatched from the casing string and removed. The borehole is left with casing and a reentry funnel in place. If required, the casing string may be cemented in place and multiple casing strings may be installed in the same borehole.

This type of hammer drilling system (HDS) is currently being used in Iceland to install large diameter 18-5/8-in casing more than 100 m deep in fractured basalt. Unfortunately, the Icelandic system is pneumatically driven and, thus, is not suited for use in deep water. However, a hydraulically actuated hammer drill, suitable for use by the Ocean Drilling Program (ODP), is currently under development in Australia. ODP is assisting in the development of this hammer drill and has incorporated it into the HDS.

A viable HDS would (1) eliminate the need for any form of independent seafloor structure such as the hard-rock base, (2) allow spudding boreholes on much steeper slopes than can be achieved using an independent seafloor structure, (3) reduce sensitivity to thin sediment cover, debris, or rubble lying on the spudding surface, and (4) reduce dependency on precise site surveys.

ODP initiated its HDS project in 1994 with a worldwide industry survey of the available hammer-drill technology, techniques, and equipment. In July 1996, ODP was invited to visit an Iceland Drilling

Company drill site where 11-3/4-in casing was being drilled into fractured basalt using a pneumatic hammer drill. It was determined that similar techniques could be employed by ODP. However, because of the water depths typically associated with ODP legs, the pneumatic hammer drill would have to be replaced with a hydraulic, or water, powered hammer drill. Further industry surveys resulted in locating SDS Digger Tools, Canning Vale, Western Australia, which had a 6-in prototype water-powered hammer drill that was ready for commercialization. Discussions with SDS Digger Tools resulted in an agreement between the company and ODP to work together to scale up the existing 6-in water hammer to a size suitable for drilling in 16-in casing.

To test the general concept, in August 1996, a field test of the existing SDS Digger Tools 6-in water hammer was carried out. The field test was successful in drilling 7-in casing into black granite in a quarry. Since SDS Digger Tools was not in the business of making underreaming hammer drill bits, in September 1996 the decision was made to use underreaming hammer drill bits manufactured by Holte Manufacturing, Eugene, Oregon, U.S.A. Holte Manufacturing has been in the business of drilling in casing into hard fractured rock for many years, in many locations around the world, using pneumatic hammer drills.

In October 1996, SDS Digger Tools presented the option to ODP of using an existing prototype 12-1/4-in water hammer. The 12-1/4-in water hammer could be used to drill 13-3/8-in casing and would cost less to complete development than developing an entirely new hammer capable of drilling in 16-in casing. Therefore, the decision was made to change the prototype HDS from 16-in casing to 13-3/8-in casing and to employ the SDS Digger Tools prototype 12-1/4-in water hammer. In January 1997, ODP engineers traveled to Perth, Australia, to witness bench testing of the prototype SDS 12-1/4-in water hammer. The bench test was successful, and the project was continued based on the 12-1/4-in water hammer drill.

The 12-1/4-in water hammer was field tested in black granite in April 1997. Although the field tests, from a drilling stand point, were successful, it was determined that the hammer closing forces were too high for safe operation from the drillship. A redesign of the 12-1/4-in water hammer was undertaken by SDS to lower the closing forces. A second round of field tests was carried out with a modified 12-1/4-in water hammer in September 1997 at Rogaland Research Center, Stavanger, Norway. The results of the second field test indicated that the closing forces were now in an acceptable range for use by ODP.

During development of the 12-1/4-in water hammer drill by SDS Digger Tools, ODP/TAMU (Texas A&M University) developed the supporting hardware required for the HDS system. This hardware included a hydraulically actuated casing running tool, a modified 13-3/8-in casing hanger, a bearing assembly between the modified casing hanger and casing string, and a free-fall reentry cone. The bearing assembly between the modified casing hanger and casing string was added to allow the drilling assembly to rotate independently of the casing string. The free-fall reentry cone was designed to be assembled around the drill pipe and dropped to the seafloor, coming to rest on the modified 13-3/8-in casing hanger. Besides making reentry easier, the free-fall reentry cone locks out the bearing between the casing hanger and casing string. Locking out the bearing is required for installation of other casing strings using conventional ODP casing running tools which must be rotated to latch and release. The HDS running tool, hanger bearing, and free fall-reentry cone were assembled and fit tested at ODP/TAMU in March 1998. All of the HDS equipment was shipped to Cape Town, South Africa, in April 1998, for testing at sea during Leg 179.

Hammer Drill System Components

The HDS tested on Leg 179 was a concept assembly comprised of seven basic components: (1) underreaming bit, (2) water hammer, (3) jet sub, (4) running tool, (5) hanger bearing assembly, (6) reentry cone, and (7) the casing string (Fig. 14). The overall HDS is an adaptation of similar hammer drill systems used on land, in particular by the geothermal industry. However, some fundamental aspects of the HDS had to be changed, or added, for deployment at sea.

Hammer Drill Underreaming Bits

Hammer drill bits drill by crushing rock under extremely high point loads using hemispherical tungsten carbide inserts (TCIs) as the cutters. The cutters are driven into the rock with each impact of the hammer, thus chipping a small portion of the rock with each blow. The bits are rotated slowly, ~20 rpm, to index the cutters between impacts of the hammer. Underreaming bits are required to open the borehole large enough for the casing to follow behind the drill bit as the hole is being drilled. The underreaming bits are designed to collapse to a small enough overall outside diameter to be pulled up through the casing string once the casing has been emplaced.

There were two basic designs of underreaming bits used during Leg 179. Both types were direct adaptations of land-based hammer drill underreaming bits currently used in industry. The first type is called a concentric underreaming bit (CUB; Fig. 15) and is a relatively new development in the hammer drill industry. The CUB has a pilot bit, ~12-1/4 in in diameter, sized such that it will pass through a 13-3/8-in casing string. Immediately above the pilot bit are three underreaming arms that are retracted and expanded by rotating the drill string left or right, respectively. When retracted, the underreamer arms close to the same outside diameter as the pilot bit (12-1/4-in). When expanded, the underreaming arms open to an effective diameter of 14-3/4-in, thus creating a large enough borehole for 13-3/8-in casing to pass through. The advantage of the CUB is that the underreaming arms ream ~84% of the borehole circumference with each stroke of the hammer. Based on data collected from land-based operations, the CUB has proven to drill faster and last longer than conventional eccentric underreaming bits.

The second type of underreaming bit used during Leg 179 is called an eccentric underreaming bit (EUB, Fig. 15). In the EUB the underreamer and the pilot bit are one piece. The EUB is built such that when it is in the closed position, the pilot bit is off axis to the drill string and the overall effective diameter (12-1/4-in) of the bit is small enough to be pulled up through 13-3/8-in casing. When opened, the pilot bit moves on axis with the drill string and the eccentric is moved outward to perform the underreaming. Thus, when open, the EUB has an effective diameter of 15 in, capable of creating a borehole large enough for 13-

3/8-in casing to pass through. As with the CUB, the EUB is retracted and expanded by rotating the drill string left or right, respectively. The EUB has been used for years in the land-based hammer drilling industry. The disadvantage to the EUB is that the eccentric only reams ~38% of the borehole circumference with each stoke of the hammer. Thus, the EUB drills slower and does not last as long as the CUB.

Water-Powered Hammer Drill

The heart of the HDS is the water-powered hammer drill (Fig. 16). As the name implies, the water-powered hammer drill is driven by pumping water through the hammer. The basic operating mechanism is an internal reciprocating piston. On the up stroke, the piston is slowed and stopped by compressing water. On the down stroke, high-pressure water drives the piston down until it impacts the top of the bit. The high-energy impact is transmitted through the bit body to the TCIs, thus creating extremely high, virtually point, impact loads on the rock.

Another feature of the hammer drill is a bypass mechanism that allows the driller to flush the borehole with high-viscosity mud without activating the hammer. When weight is applied to the hammer with the bit set on bottom, the bit shank moves upward closing the bypass and diverting all flow through the hammering mechanism. When the bit is pulled clear of bottom, the bit shank is allowed to move downward, opening the bypass and diverting all of the flow around the hammering mechanism so that the hammer stops operating when not in contact with bottom.

The water hammer used during the testing during Leg 179 is a proprietary product of SDS Digger Tools, Pty., Ltd., 49 Vulcan Road, Canning Vale, Western Australia 6155 (telephone (09) 455 4433; fax (09) 455 4399). Specific operational parameters of the water hammer can be obtained by contacting SDS Digger Tools.

Jet Sub

A special jet sub (Fig. 16) replaced the conventional water hammer top sub. The jet sub has receptacles for three nozzles capable of diverting part of the flow down the drill string and up the outside of the drill string at high velocities. When assembled in the complete HDS, the jet sub is placed ~2 m up inside the casing. While drilling in casing with the HDS, the cuttings are brought up the inside of the casing through the annular space formed by the casing inside diameter and the drilling assembly outside diameter. The jet sub is used to increase the velocity of the cuttings-laden water moving up the casing and out of the hole for more efficient hole cleaning.

Running Tool

When casing is conventionally drilled in with hammer drills on land, individual joints of casing are added to the overall casing string at the surface as the casing string is being drilled in. Unlike the conventional land-based hammer drill-in casing systems, the HDS, because it is to be deployed in deep water, requires that the entire casing string be made up as a single assembly with the HDS and lowered to the seafloor. Thus a special running tool, which becomes an integral part of the drilling assembly, is required to support the casing string as it is lowered to the seafloor and drilled into place. The running tool must also be able to unlatch from the casing string and be removed with the drilling assembly, thus leaving the drilled in casing fully open for reentry.

The HDS running tool employs a triangular cross section body (Fig. 17). The flats of the triangle provide flow paths for the cuttings to be circulated out of the hole while drilling. At each of the points of the triangle are latch dogs that, when extended, lock into mating grooves in the casing hanger. The latch dogs are held out, in the locked position, by a shifting sleeve inside the running tool body. To unlatch the running tool from the hanger bearing latch body, the shifting sleeve must be moved downward, out from underneath the latch dogs, thus allowing them to retract into the running tool body.

A special tool called a go-devil (Fig. 18) is used to move the running tool shifting sleeve. At the time when the running tool is unlatched from the casing hanger, the drill-string heave compensator is in operation and thus it is not safe to access to the drill-string bore to insert the go-devil. To get around this problem, there is a hydraulically actuated ball valve, on top of the top drive, which is normally opened and closed when retrieving core barrels during routine coring operations. When the HDS is deployed, the go-devil is placed on top of the ball valve, with the ball valve closed. To deploy the go-devil, the driller opens the ball valve, from the safety of the drillers shack, allowing the go-devil to fall into the drill string. Once the go-devil is inside the drill string, it is pumped down the drill string until it comes to rest on top of the running tool shifting sleeve. After the go-devil has landed on the shifting sleeve, the drill string pressure is increased to ~600 psi until the shifting sleeve overcomes a snap ring and moves downward, releasing the latch dogs. After confirming the running tool has been unlatched from the casing hanger, the driller increases the drill string pressure to ~1800 psi, shear releasing another sleeve inside the go-devil, which also moves downward and opens a circulation path to the hammer and borehole once again.

Hanger Bearing Assembly

A hanger bearing design was incorporated into the casing hanger to allow the drilling assembly and integral running tool to rotate relative to the casing string while supporting the weight of the casing string (Fig. 19). During the drilling in process, as the casing enters the borehole, the bearing assembly enables the casing to stop rotating, even though the drilling assembly is still being rotated. By doing so the total torque required to drill the casing in is reduced. Also, whatever torque is produced is a direct response from the bit, thus giving the driller direct feedback regarding torque on bit.

Casing String

As mentioned previously, unlike conventional land-based hammer drill in casing techniques where the individual joints of casing are added to the sting as it is being drilled in, the entire HDS casing string must be made up as part of the overall HDS assembly. The top of the HDS casing string must be compatible with other standard ODP casing tools and hangers. So, a standard ODP casing hanger is slightly modified by adding a hanger bearing assembly and shortening the casing pup joint for the HDS. For added protection at the bottom of the casing string, a hardened casing shoe is welded to the end, or shoe joint. The hardened casing shoe is more collapse- and abrasion-resistant than the casing itself.

Reentry Cone

A reentry cone was added to the HDS assembly to aid in reentering the borehole and to defeat the hanger bearing assembly (Fig. 20). The vibration-isolated television (VIT) camera is used to locate specific spud targets when spudding with the HDS. Because the HDS uses the drill string as a guide and must pass over the HDS assembly, the reentry cone can not be in place, on top of the HDS, while drilling in. Therefore, the HDS reentry cone was designed to be deployed after the casing has been drilled into place. The reentry cone is split into two halves and is attached around the drill string, while the drill string is still attached to the casing string, and free fall deployed. The falling reentry cone comes to rest on top of the HDS casing hanger. As the reentry cone is falling, a guide on top of the HDS running tool centers the reentry cone with respect to the drill-string axis so that the body of the reentry cone passes over the outside of the casing hanger and extends down to the hanger bearing assembly housing. Special lugs inside the reentry cone body, near the top, land on top of the casing hanger thus preventing the reentry cone from dropping below the casing hanger.

The standard ODP casing tools latch and unlatch by rotating the drill sting left and right respectively. Because the HDS hanger bearing allows the casing hanger to rotate relative to the casing string it must be locked out for standard ODP casing tools to be used during subsequent operations at an HDS installation. The HDS reentry cone also provides a mechanism for locking out the hanger bearing assembly. The special lugs that land on top of the casing hanger also lock into the bypass flow grooves in the body of the casing hanger, thus preventing rotation between the casing hanger and the reentry cone. There is another set of lugs inside the reentry cone, near the bottom, that engage lugs on the outside of the hanger bearing housing, thus preventing rotation of the reentry cone with respect to the hanger bearing housing. Therefore, rotation of the hanger relative to the casing string is prevented.

SUMMARY OF LEG 179 ENGINEERING AND DRILLING OPERATIONS

Port Call, Cape Town, South Africa

While in port, we learned that the surface freight that contained many parts of the hammer drill system shipment would not arrive before the ship got under way. A quick inventory of HDS equipment already on board was made. The following HDS items were identified as being in the delayed surface shipment:

1. Three double-pin crossover sub OG0709 (NC 70 x NC 70). One crossover sub OG0725 (NC 70 pin x 6-5/8-in full hole modified [FHM] box) was modified into one double-pin crossover sub OG0709 (NC 70 x NC 70) at a local machine shop in port.

2. Two HDS hanger bearing lower body OJ5010. There was one HDS hanger bearing lower body on board. It was not possible to fabricate replacement HDS hanger bearing lower bodies in port or on board ship.

3. Three HDS hanger bearing cap OJ5012. One HDS hanger bearing cap was fabricated at a local machine shop in port.

4. Two complete HDS reentry cone assemblies OJ5014. It was not possible to fabricate a complete HDS reentry cone assembly in port or on board ship.

5. One HDS reentry cone OJ5015. One drill-in casing reentry funnel OJ4852 was modified into one HDS reentry cone. With one HDS reentry cone body OJ5016 on board, one complete HDS reentry cone assembly OJ5014 was fabricated on board ship.

6. Two 13-3/8-in ST-L flush joint casing lift sub OH5159. Two 13-3/8-in ST-L flush joint pin connections were cut off of two damaged joints of 13-3/8-in ST-L flush joint casing and modified into two 13-3/8-in ST-L flush joint casing lift subs. Note: these are not certified lift subs and were destroyed after completion of the hammer drill testing.

7. Three 13-3/8-in buttress casing collar. The 13-3/8-in buttress casing collar is used to cross over from the HDS hanger bearing lower body to the 13-3/8-in ST-L flush joint casing string via a double-pin casing crossover sub (13-3/8-in buttress x 13-3/8-in ST-L). There were no 13-3/8-in buttress casing collars on board or available in port. The buttress pin connection was cut off the only HDS hanger bearing lower body on board. One double-pin casing crossover sub was cut in half and the 13-3/8-in ST-L pin connection welded onto the HDS hanger bearing lower body, thus eliminating the need for the 13-3/8-in buttress casing collar.

8. Four 9-1/2-in drill collar lift sub OD0208. The 9-1/2-in drill collar lift sub was replaced by one crossover sub OG0725 (NC 70 pin x 6-5/8-in FHM box) and one 8-1/4-in drill collar lift sub OD0200 which were on board. There were only Two crossover subs OG0725 on board after one was modified into a double-pin sub OG0709. So, only two 9-1/2-in drill collar lift subs were available.

9. Two 9-1/2-in drill collar bail-type lift nubbin OG0245. Fortunately the 9-1/2-in drill collars came with cast steel thread protectors of the bail type so they could be used in place of the lift nubbin. Note: the cast steel thread protectors are not certified and should not be used routinely as lift nubbins.

10. Three 13-3/8-in Holte hardened casing shoes. The 13-3/8-in hardened casing shoes could not be fabricated in port or on board ship.

11. Two 13-3/8-in HDS modified casing hangers. The 13-3/8-in HDS modified casing hangers could not be fabricated in port or on board ship. One 13-3/8-in HDS modified casing hanger was on board, allowing for one casing deployment.

12. Two HDS hanger bearing latch body OJ5009. The HDS hanger bearing latch body could not be fabricated in port or on board ship. One HDS hanger bearing latch body was on board, allowing for one casing deployment.

TRANSIT CAPE TOWN TO SITE 1104

During the transit from Cape Town to Site 1104, the SDS water hammer drill was picked up and deck tested on 28 April. The test assembly consisted of an SDS concentric underreaming bit, SDS 12-1/4-in water hammer, SDS jet sub, with three blank nozzles installed, and the required crossover subs to the top drive. After making up the assembly, the bit breaker was placed on top of some dunnage and rubber matting on the rig floor. The bit was then lowered into the bit breaker and 5000 lb applied to the bit via the top drive. The mud pump was engaged, and the flow rate slowly increased to 75 gpm at 700 psi, when the hammer first began to cycle. As the flow rate was increased the hammer cycled intermittently and erratically. The flow rate was increased to 375 gpm at 1770 psi, and the hammer began to cycle more evenly. The flow rate was increased to 400 gpm at 1900 psi and the hammer cycled smoothly. The hammer was cycled for several minutes before the flow rate was reduced to 240 gpm at 900 psi. The hammer was then cycled for a few minutes more before shutting down the pump.

It was theorized that the initial erratic behavior of the hammer was caused by air in the pumping system and excess grease left in the hammer from assembly. To test the theory the mud pump was once again engaged and the flow rate slowly increased to 75 gpm at 270 psi, and the hammer began cycling very smoothly. To create a base line pressure vs. flow rate curve, the flow rate was increased in 50-gpm steps and the corresponding pressure recorded as follows:

Flow rate (gpm)	Pressure (psi)	Comments
75	270	Hammer begins cycling smoothly
150	360	Hammer cycling smoothly at higher frequency
200	560	Hammer cycling smoothly at higher frequency
250	820	Hammer cycling smoothly at higher frequency
300	1125	Hammer cycling smoothly at higher frequency

Large vibrations were noted in the stand pipe and derrick, presumably from pressure pulse reflections from the hammer traveling back to the pump.

Also during the transit, a frequency analyzer was assembled on board to monitor the hammer-induced pulsation frequency in the stand pipe as an aid in determining when the hammer was cycling. Although the initial frequency spectrum recorded was not a clear indication of when the hammer was operating, the voltage output spectrum from the pressure transducer installed in the stand pipe gave a good indication of when the hammer was cycling.

It is interesting to note that later in the hammer drill tests, additional filtering that made the frequency spectrum more prominent was added to the frequency analyzer. The frequency spectrum indicated a notable peak at ~30 Hz, the known operating frequency of the hammer. However, there was an even more prominent peak at ~60 Hz that was believed to be an indication of the power stoke of the hammer at 30 Hz, plus the return pulse as the hammer piston moved upward at 30 Hz and 180° out of phase, essentially doubling the frequency to 60 Hz. The increased amplitude of the 60 Hz signal may indicate that more energy is transmitted up the stand pipe by the hammer piston up stroke than is reflected by the power stroke when the piston moves downward. This further supported the theory that the stand pipe vibrations were indeed caused by hammer-induced pressure pulse reflections traveling back to the pump.

SITE 1104

A positioning beacon was deployed at 1925 hr 29 April, establishing Site 1104. The hammer drill was prepared for deployment for the first series of spudding and drilling tests without casing. The bottom-hole assembly (BHA) used for the HDS testing was made up of SDS concentric bit #1, hammer drill, jet sub, crossover sub (OG0726), four 9-1/2-in drill collars (OG0244), crossover sub (OG0725), one 8-1/4-in drill collar (OL1040), one tapered drill collar (OG0300), six joints of 5-1/2-in drill pipe (OG0052), and a crossover sub (OG1010) to 5-in drill pipe.

The BHA was tripped to the seafloor and the VIT camera deployed for a seafloor survey. The point of reference for the survey was the hard rock guide base at Hole 735B. Once Hole 735B was located, the ship was offset ~75 m west to the primary HDS testing site. Massive, sediment-free outcrop was observed at the primary test site. However, based on the most recent survey information received from H.J.B. Dick aboard the *James Clark Ross* (pers. comm., 1998), a second test site was explored ~200 m northwest of Hole 735B. Massive, sediment-free outcrop was also observed at the second site, and the decision was made to begin the hammer drill testing at the second site. For better positioning of the ship, a second positioning beacon was deployed at 0224 hr 30 April.

Site 1104 Spud Test

Water depth was determined to be 740 meters below rig floor (mbrf) by drill pipe measurement. With the VIT camera deployed and no rotation of the drill string, several spud tests were conducted. The hammer performed well during the spud tests, and the decision was made to recover the VIT and move on to the drilling tests.

Hole 1104A

Hole 1104A was spudded at 0620 hr 30 April, with an SDS underreaming bit. The pointed pilot bit did not skid as the hole was initiated. However, it is suspected that the bit heaved off bottom occasionally, thus starting a new hole. Only enough weight on bit (WOB), ~8000 to 10,000 lb, was applied to the hammer to keep the bit on bottom and the hammer bypass closed. It appeared that once the pilot bit was below the seafloor, the hammer performed better. Heave constantly caused the hammer bypass to open, causing the hammer to stop cycling and then restart. After ~1 m penetration the torque increased and became erratic. Excessive vibration in the stand pipe and derrick was noted.

After ~45 min of hammering and 1.5 m penetration, the bit was pulled clear of the seafloor with a slight overpull of 10,000 to 15,000 lbs. The VIT camera was deployed to observe the borehole, which was found to be a clean symmetrical circle in the rock outcrop. The bit was set back on the seafloor, and while maintaining WOB, the VIT camera was retrieved in preparation for another drilling test.

Hole 1104B

With the VIT camera back on board, Hole 1104B was spudded at 0830 hr 30 April. The water depth was determined to be 739 mbrf by drill pipe measurement. The hammer began cycling smoothly as the flow rate was slowly increased with no rotation of the drill string. After a few minutes of spudding, the top drive was engaged to begin rotation of the drill string. Excessive vibration in the stand pipe and derrick were once again noted. At 0900 hr 30 April, the rig air pop-off valve failed and drilling had to be stopped, while the bit remained in the hole. The pop-off valve was soon isolated and drilling resumed. Torque soon increased and became erratic. The hammer bypass was constantly opened, presumably by heave, causing the hammer to stop cycling and then restart. At 1130 hr 30 April, after hammering for ~2 -1/2 hr with 1.5 m penetration, the bit became stuck. The bit was freed at 1150 hr 30 April, and kept on bottom as the VIT camera was deployed to observe the bit and borehole. The bit was pulled clear of the seafloor at 1230 hr 30 April, and appeared to be intact. The borehole was somewhat oval shaped, presumably from being spudded on a slope.

The bit was set back on the seafloor and while WOB was maintained, the VIT camera was retrieved in preparation for spudding Hole 1104C. With the VIT camera back on board, the pump was engaged, and the flow rate slowly increased, but the hammer would not cycle. The hammer was pulled clear of the seafloor to open the bypass and be flushed. However, similar results occurred when the bit was set back on the seafloor, closing the bypass. The standby pump (#1) was engaged to make sure a problem with the pumps did not exist. The same pressure drops vs. flow rates were recorded, and the hammer did not cycle. The hammer and bit were retrieved for inspection.

Once back on board, the hammer was disassembled and it was determined that the hammer valve had cracked, allowing fluid to bypass it and thus preventing the hammer from cycling. It is theorized that the pressure transients across the valve created by the constant opening and closing of the hammer bypass may have been the cause of the cracking. A new valve was installed in the hammer, and the hammer was deck tested. The hammer was cycled for ~6 min at 100 gpm and 330 psi and at 200 gpm and 560 psi, with no problems. The pressure vs. flow rate curve was the same as for the new hammer, possibly indicating that no appreciable wear had occurred on the piston or other internal parts of the hammer during the two previous runs. The SDS CUB was not reusable. The TCIs on all three of the underreaming arms were sheared or broken off, except for the last one on each of the trailing edges (Fig. 21). Heavy abrasion was also observed on the gage surfaces of all the underreaming arms. The pilot bit was in good shape, except for one chipped TCI.

Hole 1104C

With a new bit (SDS CUB #2) installed on the refurbished hammer, the BHA was tripped back to the seafloor. The VIT camera was deployed and a spudding location chosen. The bit was set on the seafloor and, while maintaining WOB, the VIT was retrieved. Once the VIT was back on board, Hole 1104C was spudded at 0105 hr 1 May. The water depth was established at 739 mbrf by drill pipe measurement. The pump was engaged and the flow rate increased slowly with 5 to 10 rpm drill string rotation. After ~10 min of drilling and 0.5 m penetration, there was a pressure loss observed, presumably from the hammer bypass opening, and the flow rate was slowed. The flow rate was once again increased with normal pressure versus flow rate correlation and the hammer restarted smoothly.

After ~30 min of drilling with 0.5 m penetration, the bit heaved off bottom, causing the hammer to stop, and the flow rate was reduced. It was thought that the bit may have heaved out of the hole and a new hole started as the flow rate was increased and the hammer restarted. Almost immediately the torque increased and became erratic. The drill string rotation was erratic, from 10 to 50 rpm, as a result of slip stick. The hammer had to be stopped and restarted several times because of high torque buildup resulting in top-drive stalling.

At 0225 hr 1 May, a 2-in nipple on the stand pipe manifold failed because of the vibration in the stand pipe. Drilling had to be stopped so that the pump could be shut down for manifold repair. The bit remained in the borehole while the manifold was repaired, and the VIT camera was deployed. Near the hole with the bit in it, three other holes were observed, confirming that the bit had indeed heaved out of the hole and started new holes. The bit appeared to be 0.5 m below the seafloor. The VIT was retrieved and, with the stand pipe manifold repaired, drilling resumed at 0334 hr 1 May.

The flow rate was slowly increased and the hammer began to cycle. Torque was low and erratic, but increasing. Drill string rotation was going through slip stick. The top drive stalled on several occasions, and the hammer was stopped and the torque released. Each time the hammer restarted without any problems. At 0410 hr 1 May, the bit became stuck and may have heaved out of the hole as it was freed. Drilling resumed until 0425 hr 1 May, when the stand pipe transducer failed because of stand pipe vibration. Because the pumps had to be shut down to remove the pressure transducer from the stand pipe for repair, the bit was pulled clear of the seafloor.

Hole 1104D

The stand pipe pressure transducer nipple was blanked and Hole 1104D was spudded at 0445 hr 1 May. The water depth was determined to be 739 mbrf by drill pipe measurement. The pump was engaged, and the flow rate slowly increased. The bit heaved off the seafloor several times, causing the hammer to stop and restart. The torque soon increased and became erratic, eventually stalling the top drive. At 0510 hr 1 May, drilling was halted and the VIT camera was deployed while the bit remained on the seafloor. It appeared that several new holes had been spudded because of the bit heaving out of the hole during spudding. At 0615 hr 1 May, the bit was pulled clear of the seafloor and the VIT camera retrieved. The bit was also retrieved for inspection because of a lack of penetration.

Once on deck the bit was inspected revealing the leading two TCIs on each of the underreamer arms were sheared or broken off (Fig. 22). The gauge surfaces of the SDS bit #2 underreamer arms were not as heavily abraded as those on the SDS bit #1. Except for the pilot bit nose TCI having been sheared or broken off, the rest of the pilot bit appeared to be in good shape. The pilot bit nose TCI was probably damaged as the bit was heaved off the seafloor during spudding.

Hole 1104E

It appeared that the underreaming arms were preventing the hammer drill from advancing the borehole. To test this theory, parts of the underreaming bits used during the previous tests were converted into a drilling bit.

Bit Modification 1

Using a torch, the underreaming arms of SDS bit 1 were trimmed such that when opened, they would not extend past the outside diameter of the pilot bit and driver. Upon reassembly of the bit, the modified underreamer arms, when opened, did not appear to be strong enough to withstand drilling in hard rock. Therefore, bit modification 1 was abandoned.

Bit Modification 2

The second attempt at modifying an underreamer bit into a drill bit involved removing the underreamer arms and pilot bit from SDS bit 1. The pilot bit shank was shortened such that when installed in the driver, the underreamer arm gap was closed. The pilot bit was then installed and welded directly to the driver. Unfortunately, the pilot bit cracked during the welding process, and the bit could not be deployed.

Bit Modification 3

The third attempt at modifying an underreamer bit into a drill bit involved replacing the pilot bit with the broken nose TCI on SDS bit 2 with a new pilot bit. The original, damaged underreaming arms from SDS bit 2 were left in place. However, the underreaming arms were welded in place in the closed position. Since the underreaming bit was fixed in the closed configuration, new waterways had to be cut through the toes of the underreaming arms, using a torch and grinder.

The modified SDS bit was made up to the hammer drill BHA and tripped to the seafloor. The VIT camera was then deployed to locate a spud target. The modified bit was place on the seafloor ~1 m from Holes 1104C and 1104D. Maintaining WOB, the VIT was retrieved and Hole 1104E was spudded at 0140 hr 2 May. Water depth was established at 740 mbrf by drill pipe measurement. The weather had began to deteriorate, and the rig floor was experiencing 1 to 2 m heave resulting in the WOB having to be increased to 10,000 to 12,000 lb to keep the bit on bottom and the hammer bypass closed.

The pump was engaged, and the flow rate slowly increased. The hammer cycled smoothly but there appeared to be ~100 psi less pressure at any give flow rate than in past tests. There was also a noticeable reduction in the vibration in the stand pipe and derrick. At ~0155 hr 2 May, the hammer heaved off bottom, opening the bypass, and thus the hammer quit cycling and had to be restarted. The flow rate was increased slowly once again, and once again the hammer began to cycle.

After ~1 m penetration the torque began to increase and become erratic. Heave at the rig floor had increased to 3-m. The top drive stalled at 24,000 ft/lb. An overpull of 40,000 lb was applied to the bit without freeing it. The BHA was lowered to close the hammer bypass. The hammer was restarted and cycled at 400 gpm at 1720 psi. The pipe was worked again with up to 40,000 lb overpull, and still the bit could not be freed. Finally the drill string was rotated left, the direction one would normally rotate to close the underreaming arms, and the bit came free. It was assumed that the welds had failed allowing the underreaming arms to open, so the bit was pulled clear of the seafloor and the VIT camera deployed to verify. Once the VIT had reached the end of the pipe, the underreamer arms could be seen clearly in the open position. The VIT and BHA were retrieved for inspection. Once on deck, it was observed that every weld on the modified bit had failed, allowing the underreaming arms to open. Also, ~2 in of the leading edge of all three of the underreaming arms was broken off (Fig. 23). The pilot bit looked to be in good condition.

HDS TESTING HIATUS

With no other hammer drill bits on board other than SDS concentric underreaming bits, the decision was made to suspend further HDS testing pending the arrival of a supply vessel, the La Curieuse, from Reunion Island. The lost surface shipment had been located and critical items were diverted to Reunion Island for delivery to the drillship via the *La Curieuse*. Also, a flat-faced standard hammer drill bit was sent to Reunion Island by SDS for delivery to the drillship via the *La Curieuse*. While waiting for the arrival of the *La Curieuse*, the drillship was moved ~1 km northeast of Site 1104 where Site 1105 was established. Hole 1105A was drilled to a depth of 15 mbsf using a 14-3/4-in tricone drill bit. The hole was then cored to a depth of 158 mbsf with 82.8% recovery, using the rotary core barrel. After logging Hole 1105A, the drillship was moved back to Site 1104 in anticipation of the arrival of the La Curieuse and the resumption of hammer drill testing. A new beacon was dropped at Site 1104 at 1938 hr 10 May, establishing Site 1106.

The La Curieuse arrived on location at 2045 hr 10 May, and requested that the offloading of cargo and personnel wait until daylight. Rough seas and high winds prevented the offloading from taking place the following day, 12 May. The La Curieuse remained on location until 13 May. The sea state and winds had deteriorated further and the forecast for the following 48 hr showed no signs of improvement. There were three hammer drill bits on board the La Curieuse that were critical to completion of the hammer drill tests, one Holte CUB, one Holte EUB, and one SDS flat-face drill bit.

The hammer drill bits were successfully transferred from the La Curieuse to the drillship by tying buoys onto the drill bits and dropping them over the side. The drillship was then maneuvered to catch the buoys and the ships crane was used to hoist the drill bits on board. Because it was too rough to attempt offloading any other cargo or personnel, the La Curieuse was released to return to Reunion Island at 1000 hr 13 May.

Hole 1106A

A Holte CUB was made up to the SDS hammer drill, and using the same HDS BHA configuration as previously used, the assembly was lowered to the seafloor. The VIT camera was deployed for a seafloor survey. The Site 1104 holes were quickly located. So as not to confuse the Site 1104 holes with the Site 1106 holes, the ship was offset ~20 m to the north on the same outcrop. It was theorized that the nose TCI damaged on the previous bit may have resulted from the bit heaving off the seafloor as we attempted to keep the bit in place on the seafloor during retrieval of the VIT. The decision was made to spud Hole 1106A with the bit off bottom. Thus the VIT camera was retrieved with the bit clear of the seafloor.

Once the VIT was back on board, the pump was engaged and a flow rate of 200 gpm established. Circulation was maintained for several minutes to flush any air out of the system. While maintaining a 200 gpm flow rate, and no rotation of the drill string, at 1600 hr 12 May, the bit was lowered to the seafloor and

Hole 1106A was spudded. The water depth was determined to be 740 mbrf by drill pipe measurement. The hammer began to cycle immediately and the flow rate was slowly increased. The heave at the rig floor was estimated to be 2 to 3 m and, as a result, the bit was heaved off bottom several times, causing the hammer to stop and restart. After ~10 min of drilling, penetration began to be made and the hammer operation settled out somewhat. Heave was still a major problem and, because of a cross swell, roll factored into the difficulties as well.

The drill bit had penetrated ~0.5 m when the torque began to increase and become erratic. The weather was deteriorating, and heave at the rig floor resulted in constant stop-start problems with the hammer. Several yellow (2%) automatic station keeping (ASK) system alerts occurred, indicating the dynamic positioning (DP) system was having a hard time holding the ship on station in the increasing wind. The DP operators also reported that the noise from the hammer was occasionally interfering with the acoustics of the ASK system. After ~3 hr drilling and 2 m penetration, 1000 psi was lost and the hammer quit running. The pump was stopped and the backup pump (#1) was engaged with similar results, indicating the problem was downhole. Drilling operations were suspended and the hammer retrieved for inspection.

With the hammer and bit on deck at 2230 hr 12 May, an inspection was carried out. The Holte CUB had suffered much the same damage as did the SDS bits (Fig. 24). All of the TCIs on the underreaming arms, except for the last one on the trailing edges, were broken off. Also, four TCIs near the shoulder of the pilot bit were broken off as well. Disassembly of the hammer revealed the valve was cracked similarly to the first cracked valve. The other internal parts of the hammer appeared to be in good shape.

Hole 1106B

A new valve was installed in the hammer, and a Holte eccentric underreaming bit was attached to the SDS hammer. The hammer and bit assembly was then deck tested. The hammer cycled immediately and was cycled for 6 min. The hammer and eccentric bit were made up to the HDS BHA and tripped to the seafloor. The VIT camera was deployed to locate a spud site. After locating the spud site and with the bit off bottom, the VIT was retrieved. The pump was engaged, and a flow rate of 150 gpm was established. At 0640 hr 13 May, the bit was lowered to the seafloor and Hole 1106B was spudded. The water depth was determined to be 741 mbrf by drill pipe measurement. After tagging bottom, the flow rate was slowly increased. It appeared as though the bit may have skidded downhill ~0.5 m during spudding. The hammer began to cycle smoothly and penetration was being made when the bit appeared to heave out of the hole and skid downhill ~1 m. The torque immediately increased and became erratic, causing the top drive to stall. Heave continuously opened the hammer bypass. After 1 hr of drilling with virtually no penetration, we stopped drilling and retrieved the bit for inspection.

Inspection of the Holte EUB revealed similar wear patterns as observed on the concentric bits (Fig. 25). The outer edge of the eccentric was severely abraded and most of the TCIs on the outer edged of the eccentric were broken. Several TCIs on the pilot bit shoulder were also broken. The EUB was determined not to be usable.

Hole 1106C

The SDS flat-face drill bit (Fig. 26) was the last hammer drill bit on board to test. Although the aim of the HDS is to drill in casing, which requires an underreamer bit, the drill bit was deployed in an effort to prove that (1) the hammer drill could drill hard rock and (2) it was the premature deterioration of the underreamer arms that was preventing deep penetration. In anticipation of a long drilling run, the hammer drill was disassembled and a new cartridge installed. The drill bit was attached to the refurbished hammer drill and the assembly deck tested. The hammer cycled perfectly and was run for ~2 min. We reduced the flow rate to 130 gpm and picked up the hammer to check the bypass, which opened as expected.

The drill bit and hammer drill were made up to the same HDS BHA and tripped to the seafloor. The VIT camera was deployed to locate a specific spud site for Hole 1106C. After retrieving the VIT camera, the pump was engaged at 150 gpm to flush air out of the system. While we maintained flow rate, the drill bit was set on the seafloor at 1840 hr 13 May, and Hole 1106C was spudded. Water depth was determined to be 742.5 mbrf by drill pipe measurement.

After ~25 min of drilling and 1 m penetration, the pressure began to increase and the hammer began to cycle intermittently. The bit was raised off bottom to open the bypass and flush the hammer. When the bit was set back on bottom, the pressure again began to rise and the hammer still cycled intermittently. The back-up pump (#1) was engaged and similar events occurred, indicating the problem was probably downhole. So, the hammer was retrieved for inspection. While the hammer was retrieved, the drill string stayed full of water. This was an indication that the hammer check valve was not allowing the water inside the drill string to drain out as it was retrieved.

Once on deck, the hammer was disassembled for inspection. The initial cartridge was removed, and the coating on the piston appeared to have chipped off, probably by cavitation erosion. The piston was found to have galled to the lower bushing and was stuck in the full up position. With the piston being stuck in the full up position, the check valve was prevented from opening and the water could not drain from the drill string. The piston sticking was also thought to be the cause of the high operating pressure and intermittent cycling. The drill bit was found to be in good condition and reusable.

Hole 1106D

The hammer was refurbished with another complete cartridge and the same flat-faced drill bit installed. The assembly was then deck tested, and the hammer performed as expected. The hammer and bit were then made up to the same HDS BHA and tripped to the seafloor. The bit was set on the seafloor and at 0340 hr 14 May, Hole 1106D was spudded with 2 m heave at the rig floor. The flow rate was slowly increased, and the hammer cycled normally.

After ~4 min of drilling, the pressure began to rise and the hammer began to cycle intermittently. The flow rate was reduced to stop the hammer and then increased slowly to restart the hammer. As before, the pressure continued to rise and the hammer cycled intermittently. The bit was raised off the seafloor to open the bypass and flush the hammer. When restarted, the hammer once again operated intermittently at higher than normal pressure. It was assumed that the piston and lower bushing had galled again, so the hammer was retrieved for inspection.

Once on deck, the hammer was disassembled for inspection. The initial cartridge was removed and the coating on the piston once again appeared to have chipped off, probably by cavitation erosion. The piston was found to have galled to the lower bushing and was stuck in the full up position. The extent of the galling did not appear to be as bad as that observed in the cartridge used in Hole 1106C. Once again, with the piston being stuck in the full up position, the check valve was prevented from opening, and the drill string had to be pulled full of water. The drill bit, however, was found to be in good condition and reusable.

Hole 1106E

The hammer was rebuilt with the same piston and valve. However, the lower bushing used in Hole 1106C had been repaired in the ship’s machine shop, and it was assembled in the hammer. The drill bit was still in good condition, so the hammer and drill bit were made up and deck tested. The hammer was cycled for 2 min at 200 gpm and 650 psi, which are nominal readings. A noticeable reduction in the stand pipe and derrick vibrations was observed, even though the flow rates and corresponding pressures were consistent with those of a new hammer.

The bit and hammer were tripped to the seafloor with the same HDS BHA configuration. The pump was engaged at a low flow rate of 150 gpm to flush out any air in the system. After a few minutes of flushing, the bit was lowered to the seafloor and Hole 1106E was spudded at 1140 hr 14 May. The drilling depth was determined to be 741 mbrf by drill pipe measurement. During this time, the average heave at the rig floor was estimated to be 3 to 4 m, with occasional 5-m heaves.

After ~15 min of drilling, the hammer drill began to make significant penetration. Despite constant opening of the hammer bypass caused by heave, the hammer drill continued to advance the borehole. Torque was slightly erratic, ranging from 2500 to 5000 ft/lb for most of the drilling. Occasionally the top drive would stall. However, when this happened, the hammer was allowed to keep cycling, and it soon drilled itself off, allowing the drill string rotation to resume.

After ~1 hr and 40 min and 8 m penetration, the stand pipe pressure transducer nipple failed because of stand pipe vibration, and the pump had to be stopped to repair it. The bit was pulled 4.5 m off the bottom of the hole, with a momentary 20,000 lb overpull. Slow rotation of the drill string was maintained as the pump was shut down. The stand pipe bull plug containing the pressure transducer was removed and a blank bull plug was installed in its place. The repairs took ~5 min.

When the pump was engaged, little or no pressure was observed, consistent with pumping through open-ended drill pipe. The back-up pump (#1) was engaged with similar results, indicating the problem was downhole. The drill string was then lowered in anticipation of tagging the bottom of the hole. After the end of the pipe had been lowered 4.5 m below the last TD of Hole 1106E, we decided to pull the bit clear of the seafloor and deploy the VIT camera for observation.

Once the VIT camera had reached the end of the pipe, it appeared as though all of the drill collars were still intact, and the crossover sub between the drill collars and the jet sub on top of the hammer could be seen. However, the jet sub, hammer, and bit could not be seen. The end of the pipe and the VIT camera were lowered to survey the seafloor. Several boreholes were observed. One of the boreholes appeared to have something in it, but it could not be confirmed as being the hammer. The sea state at the time of the survey caused the view of the seafloor to move in and out of focus. A further survey of the seafloor did not reveal the hammer, so either the hammer was still in the hole, out of sight, or had dropped onto the seafloor and rolled down slope. The VIT camera and drill string were then retrieved.

When the end of the drill string was retrieved, all of the drill collars and the crossover sub between the drill collars and the jet sub were recovered. The jet sub, hammer drill, and bit were missing. The pin connection on the bottom of the crossover sub showed signs of having pulled out of the box connection on top of the jet sub. Two theories have been put forth as to when the failure may have occurred. The first theory is that the jet sub box connection had been weakened or even split by the pounding the bit was taking as a result of the excessive heave during spudding. When the bit was pulled off bottom and the momentary 20,000 lb overpull was observed, the bit may have hung up on the borehole wall and the crossover sub pin may have pulled out of the weakened jet sub box. The second theory is that while waiting on the stand pipe to be repaired with the hammer heaving in the borehole, the BHA may have leaned over, causing the jet sub box to fail. By pulling the bit 4.5 m off the bottom of the hole, the jet sub was positioned at, or near, the seafloor, compounding the bending problem.

Although enough spare parts were on board to assemble a second hammer drill, the decision was made to halt the hammer drill testing because there were no more hammer drill bits available to be tested that would have increased the hammer drill test data base. Also, because of the weather conditions, lack of reentry hardware, time constraints, and high probability of loss of the fishing equipment, it was not thought prudent to attempt to fish for the lost hammer. The 9-1/2-in drill collars used in the HDS BHA were inspected, with no cracks found, and laid down. The drillship was secured for sea and at 2312 hr 14 May, the JOIDES Resolution got under way for the next site.

ENGINEERING RESULTS AND ACCOMPLISHMENTS FOR LEG 179

Although the complete HDS test plan could not be conducted because of the premature failure of the underreaming bits, a great deal of data was collected and a much better understanding of the HDS as deployed at sea was gained. Of primary concern was the performance of the hammer. Considering the sea state during most of the test, the hammer performed quite well. It must be noted that the hammer used for the tests was designed for drilling a 12-1/4-in borehole and that during the testing it was used to drill a 14-3/4-in borehole, an ~45% larger hole, thus reducing the efficiency of the hammer. The water hammer was also designed to work at maximum efficiency with a 2250-psi pressure drop across the piston. Because of the excessive vibrations in the pumps and stand pipe, the maximum continuous pressure drop across the hammer piston that could be maintained was ~1750 psi, which further reduced the hammer's efficiency. However, in spite of the low hammer efficiency, a rate of penetration of 4.8 m/hr was achieved in Hole 1106E in massive gabbro, using a 12-1/4-in standard hammer drill drilling bit.

Further analysis of the underreaming bits is required. However, first impressions are that the BHA was leaning over during spudding during the early stages of drilling. Being composed of 9-1/2-in drill collars, the BHA was very stiff and so, as the BHA leaned over from being placed in compression, it caused the underreaming bits to be rotated about the horizontal axis (perpendicular to the drill string axis). This rocking of the underreaming bit in the hole during drilling probably caused extremely high loads to be placed on the low side of the bit underreaming arms. The high loads resulted in shearing off the TCIs and severely abrading the underreaming arms themselves. Once the TCIs were broken off of the underreaming arms, the arms acted much like a bearing, preventing further penetration by the bit.

It is encouraging to note that the pilot portion of all the underreaming bits came out of the hole in good condition, further indicating that the hammer drill can penetrate subsea hard rock formations and that the premature failure of the underreamer arms is what prevented deep penetration by the bit. The standard hammer drill drilling bit used in Holes 1106C and 1106D showed no signs of wear when retrieved plus the excellent penetration rate observed in Hole 1106E further indicate that the overloading of the underreaming arms was the cause of lack of penetration with the underreaming bits.

There were three primary problems associated with the hammer drill during the tests. Twice during the testing, the hammer internal control valve cracked, thus allowing pressure to escape past the valve, preventing the piston from cycling. Failure of the valve appears to have been from two causes. First, the valve has some ports in a highly stressed area, causing a definite stress riser in the valve body. Second, the hammer was constantly opened and closed because of heave. When this occurred, the pump could not be stopped in time to prevent the pressure drop across the valve from dropping to near zero and then almost instantaneously increasing to ~1750 psi. The combination of the stress riser and the pressure cycling probably caused the cracking to occur in the valves.

The second problem that occurred with the hammer drill during the tests was that on two separate occasions the piston began galling to the lower bushing. A hard coating had been applied to the piston where it passes through the lower bushing. A close tolerance fit is used in place of a dynamic seal between the piston and lower bushing. It appears that the hard coating may have been spalling as a result of cavitation erosion. The small flakes of the hard coating appeared to be wedging between the piston and the lower bushing, causing the galling to occur. This theory will have to be studied further in a metallurgical laboratory. In any case, the galling resulted in sluggish and erratic operation of the hammer; and thus, the hammer had to be retrieved and the piston and lower bushing had to be replaced each time the galling occurred.

The third problem with the hammer drill during testing was associated with the stroke length, 40 mm, to open the bypass, thereby stopping the hammer from cycling. This stroke may be too short for deployment of the hammer drill from a floating vessel. Adding to the problem is a piston effect on the bit caused by the pressure drop across the hammer acting on the bit shank cross section area. This piston effect causes the bit to be pumped downward, thus opening the bypass, as the hammer drill indrills off in or is raised off bottom. Once the bypass opens, the power fluid is diverted around the piston, preventing the hammer from cycling. Thus whenever a large heave occurs that the heave compensator can not completely adjust for in the drill string motion, the hammer bypass is opened and the hammer stops cycling. None of the seafloor hardware or casing running tools was deployed during the testing, so no data on the performance of this equipment was obtained. However, this equipment was assembled and fit tested without problem.

CONCLUSIONS

The Leg 179 HDS tests were designed to be a test of the overall HDS concept in actual sea conditions. As such, the tests provided a wealth of data that, with further study, should provide a clear indication as to the direction in which the HDS development should proceed. The hammer drill itself shows great promise of being able to penetrate subsea hard-rock environments. Although the hammer drill performed well considering the sea state during the testing, a dialogue with the manufacturer will be established to address issues such as the short stroke length to open and close the bypass, the valve cracking problem, and galling of the piston and lower bushing.

It is evident that the underreaming bits designed for conventional land-based hammer drill operations, such as those used during Leg 179, are not suitable for drilling in casing in offshore deep water with an unsupported BHA. Ideas for new design underreaming bits are already being formulated. The HDS casing running tools and reentry cone were not deployed during Leg 179. However, they were land tested before Leg 179, and no problems were encountered. So, at this time, no redesign of these tools is planned. In general, confidence remains high with the overall HDS. The benefits of the HDS to ODP and the science community as a whole are well worth continuing with the HDS development.

TRANSIT TO SITE 1107

The 1930-nmi transit from Site 1106 to Site 1107 was accomplished in 7.8 days at an average speed of 10.2 kt. During the transit, preparations were made for deploying a reentry cone and casing. The reentry cone was assembled and moved onto the moonpool doors. The 16-in casing string was strapped, and a casing shoe was installed on the end of the 16-in shoe joint. The 16-in casing string was laid out on top of the riser hatch for immediate deployment upon arrival. The 10-3/4-in casing string was strapped and rabbited in the riser hold, where it remained until time for deployment. The 16-in and 10-3/4-in casing hangers and running tools were moved to the rig floor and fit tested. The 10-3/4-in cementing equipment, including the cementing head, kelly cock valve, and subsea release (SSR) plug, were also moved to the rig floor. The vessel arrived in the immediate area of the proposed site at 2012 hr 22 May, to be greeted by the *Sonne*. A positioning beacon was deployed at 2024 hr 22 May, on the Global Positional System coordinates for the proposed site, officially establishing Site 1107.

Hole 1107A

The reentry cone was positioned in the center of the moonpool doors. The 48.8-m 16-in casing string was made up and latched into the reentry cone in ~5 hr. Making up the 16-in casing was slowed by excessive roll caused by two large cross swells affecting vessel stability. The jetting BHA was made up of a 14-3/4-in bit, bit sub, five 8-1/4-in drill collars, 16-in Dril-Quip CADA casing running tool, two 8-1/4-in drill collars, tapered drill collar and two stands of 5-1/2-in drill pipe. The jetting BHA was latched into the 16-in casing hanger and the reentry cone/16-in casing string assembly was lowered to the seafloor. The VIT was also deployed to observe the position of the reentry cone after jetting in, and to observe release of the 16-in casing running tool.

No pilot hole or jet test was performed prior to jetting in the 16-in casing at Hole 1107A. The location of Hole 1107A was positioned between Holes 757B and 757C which are 200 m apart and were drilled on Leg 121. The length of 16-in casing to be jetted-in at Hole 1107A was determined based on advanced hydraulic piston corer data from Leg 121. Also, the seafloor depth established during Leg 121 was used for starting the jetting in process for Hole 1107A. However, the official water depth of 1659 mbrf was determined by tagging the seafloor with the end of the 16-in casing, which was determined to occur at the first noticeable pressure change while initiating the jetting in process.

Jetting in of the 16-in casing began at 1455 hr 23 May, establishing Hole 1107A. Jetting in the 48.8-m of 16-in casing was accomplished in 2 hr and 21 min. The VIT was used to determine that the reentry cone mud mat was positioned properly, sitting on the seafloor. The 16-in casing running tool was unlatched and retrieved with no difficulties. During the trip out of the hole, two Woods Hole Oceanographic Institution (WHOI) ocean-bottom seismometers (OBSs) were deployed and surveyed relative to Hole 1107A as part of a seismic-while-drilling (SWD) experiment. A ship-to-ship transfer from the *Sonne* of blasting caps and a ranging transducer was also completed.

Once back on deck, the 16-in casing running tool was removed and an additional 8-1/4-in drill collar was added to make up the 14-3/4-in drilling BHA. The 14-3/4-in drilling BHA was tripped to the seafloor and the reentry cone reentered at 0543 hr 24 May. The hole was drilled ahead to a depth of 2081 mbrf (422 mbsf) with mud sweeps as follows; 1 x 25 bbl at 1810.4 mbrf (151.4 mbsf), 1 x 25 bbl at 1897 mbrf (238.1 mbsf), 1 x 30 bbl at 2081 mbrf (422 mbsf). As soon as the BHA was below the seafloor the Lamont-Doherty Earth Observatory (LDEO) sensor sub, part of the SWD experiment, was installed. The sediment portion of the hole drilled slower than anticipated with rates of penetration (ROPs) as low as 4 m/hr. However, the hole remained stable with little if any fill at connections.

Contact with basement was made at a depth of ~2030 mbrf (371 mbsf). Unlike the sediments, the basement initially drilled faster than anticipated with ROPs as high as 8 m/hr. The original drilling plan called for ending the 14-3/4-in hole at a depth of 2069 mbsf (410 mbsf). However, firm basement was not encountered until a depth of 2063 mbrf (404 mbsf) had been reached. Therefore, the decision was made to continue drilling ahead until at least one full joint of casing could be positioned below the hard basement contact.

A wiper trip was made to a depth of 1692 mbrf (33 mbsf, inside the 16-in casing) with a maximum overpull of 10,000 lb. The LDEO sensor sub was removed during the wiper trip in preparation of running the 10-3/4-in casing string. The hole was allowed to stabilize for one hour, and then the bit was slowly tripped back to bottom. A moderate drag of 20,000 lb was observed near the sediment/basement contact at a depth of 2035 mbrf (376 mbsf). The top drive was picked up, and the hole was washed and reamed through the sediment/basement contact area. Once the bit was back on bottom, the hole was swept with a 30-bbl mud pill and then displaced with 346 bbl of sepiolite mud. The bit was then retrieved in preparation for deploying the 10-3/4-in casing string.

A 413.2-m-long string of 10-3/4-in casing, including the remaining 23 joints of 10-3/4-in standard coupling casing on board, was made up in ~5 hr. A cementing BHA consisting of a 10-3/4-in SSR cementing plug, a 10-3/4-in Dril-Quip casing running tool, five 8-1/4-in drill collars, a tapered drill collar, and two stands of 5-1/2-in drill pipe was made up and latched into the 10-3/4-in in casing string. The 10-3/4-in casing string was then tripped to the seafloor, and Hole 1107A was reentered at 1515 hr 26 May.

The casing was run to depth when the top drive, kelly cock valve (used to prevent cement from flowing up into the top drive), and cementing head were picked up. The drill string was then spaced out to land the 10-3/4-in casing hanger inside the 16-in casing hanger. After landing the 10-3/4-in casing hanger, latch-in was confirmed with a 10,000-lb overpull. From reentry to latch-in confirmation took ~2 hr, with no difficulties encountered.

The 10-3/4-in casing was successfully cemented in place with 238 sacks (48.8 bbl) of blended 15.8 lb/gal cement. While displacing the cement, the SSR plug dart was dropped on top of the cement slug and chased with a 10-bbl fresh water spacer and then seawater. Landing of the SSR plug dart was confirmed with an increase in drill string pressure. While we pressured up the drill string to release the SSR plug, the cementing hose burst at ~2000 psi, requiring the pump to be shut down immediately. Fortunately, at that time the cement slug was contained within the casing below the SSR plug (with latched in dart) and the casing shoe.

Using a tugger, the driller was raised in the derrick to the heaving cementing head, where he broke off the cementing hose and replaced it with a blanking plug. Once this had been accomplished, the driller also had to manually open the kelly cock valve above the cementing head, so a circulation path through the top drive could be established. After the driller was safely back on the rig floor, the pump was re-engaged and the drill string pressured up immediately, indicating the SSR plug and dart had remained in place. The drill string pressure was increased to ~2800 psi when the SSR plug released and was pumped to the casing shoe. Upon landing of the SSR plug in the casing shoe, a solid 600-psi pressure was held for a few minutes. The stand pipe bleed-off valve was then opened and no flow back was observed, indicating the casing shoe valve was holding. The only task remaining was to release the casing running tool. It required ~45 min of working the 10-3/4-in casing running tool before it finally was released and the drill string could be retrieved.

The original drilling plan called for coring Hole 1107A to a depth of ~200-m into basement. However, with the lost time in port rebuilding the lower guide horn, there was not time to core at all, let alone hope of reaching a depth of 200 m into basement. The decision was made to deploy a 9-7/8-in tricone drill bit and drill as deep into basement as the remaining operational time allowed in the hope of leaving an acceptable hole for installation of an ION seismometer in the future. A 9-7/8-in drilling BHA was made up consisting of a 9-7/8-in tricone bit, bit sub, eight 8-1/4-in drill collars, a tapered drill collar, and two stands of 5-1/2-in drill pipe. The 9-7/8-in drilling BHA was tripped to the seafloor, and Hole 1107A was reentered at 0738 hr 27 May.

The 10-3/4-in casing shoe was drilled out in 43 min. The rathole below the 10-3/4-in casing shoe was cleaned out, and then a 9-7/8-in diameter hole was drilled into basement to a total depth (TD) of 2152.8 mbrf (493.8 mbsf, 122.8 m into basement, 79.8 m below the 10-3/4-in casing shoe). A schematic drawing of the NERO borehole installation is shown in Figure 27. A single 25-bbl mud sweep was pumped at 2107.4 mbrf (448.4 mbsf). At TD the hole was flushed clean and a 30-bbl mud sweep was circulated. With the hole cleaned up as much as possible, and with operations time expiring, the bit was retrieved. The bit cleared the rotary table at 0640 hr 28 May, ending Hole 1107A. During the trip out of the hole, the two WHOI OBSs were recovered. The vessel was secured for sea and the transit to Darwin, Australia, began at 0730 hr 28 May.

FIGURE CAPTIONS

Figure 14. Schematic diagram of water hammer drill-in casing system deployment. **A.** Initial deployment. **B.** Spud hole and drill ahead. **C.** Disengage hydraulic hammer and circulate fluid. **D.** Install free-fall reentry funnel. **E.** Retract bit and release casing running tool. **F.** Recover hammer drill and leave a cased reentry hole on the seafloor.

Figure 15. Schematic drawings of concentric and eccentric hammer drill underreamer bits.

Figure 16. Schematic drawing of the SDS water hammer drill (courtesy of SDS Digger Tools, Pty., Ltd.)

Figure 17. Schematic drawing of the HDS running tool.

Figure 18. Schematic drawing of the HDS go-devil.

Figure 19. Schematic drawing of the HDS hanger bearing assembly.

Figure 20. Schematic drawing of the HDS reentry cone assembly.

Figure 21. SDS concentric underreamer bit 1.

Figure 22. SDS concentric underreamer bit 2.

Figure 23. SDS concentric underreamer bit modification 3.

Figure 24. Holte concentric underreamer bit.

Figure 25. Holte eccentric underreamer bit.

Figure 26. SDS drilling bit.

Figure 27. Schematic illustration of cased borehole configuration at Hole 1107A.

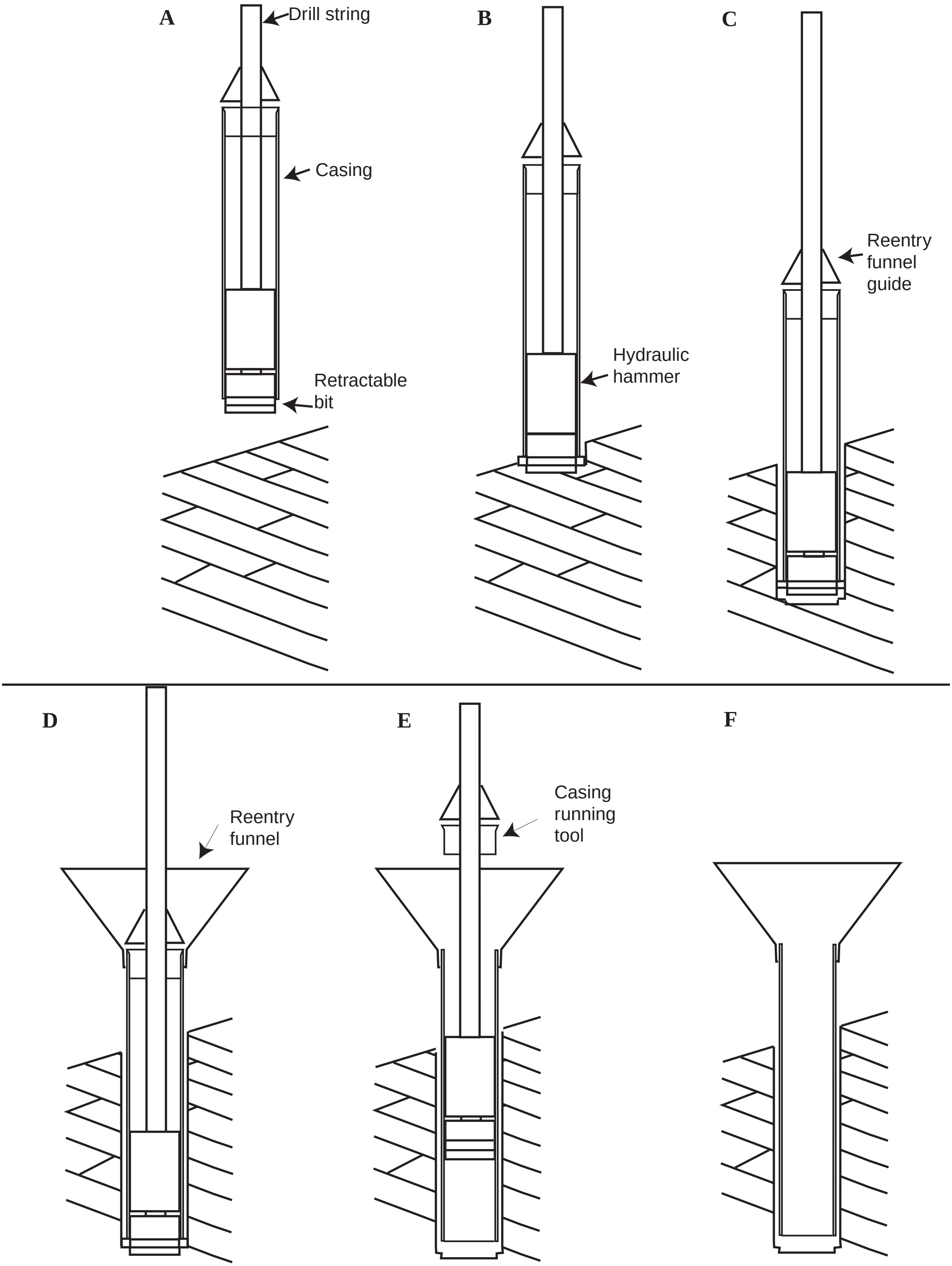
A
Drill string
Casing
Retractable bit
B
Hydraulic hammer
C
Reentry funnel guide
D
Reentry funnel
E
Casing running tool
F

Figure 14

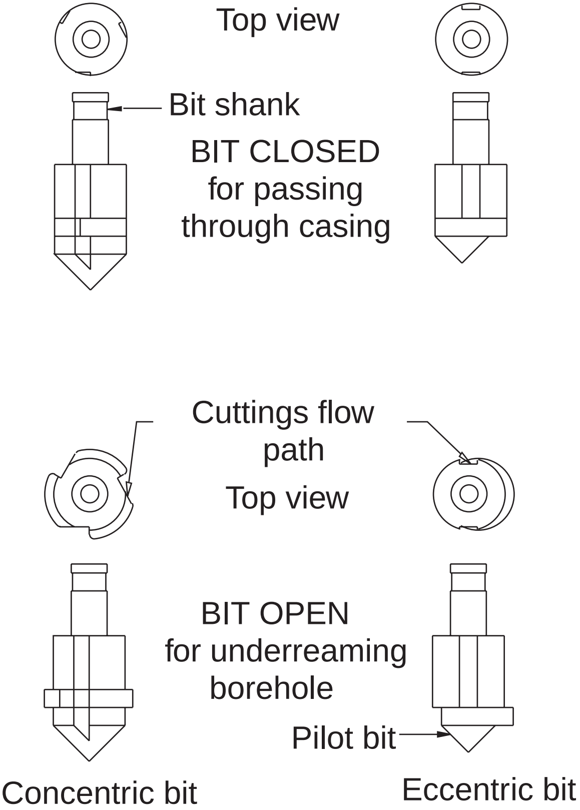
Top view
Bit shank
BIT CLOSED
for passing
through casing
Cuttings flow
path
Top view
BIT OPEN
for underreaming
borehole
Pilot bit
Concentric bit
Eccentric bit

Figure 15

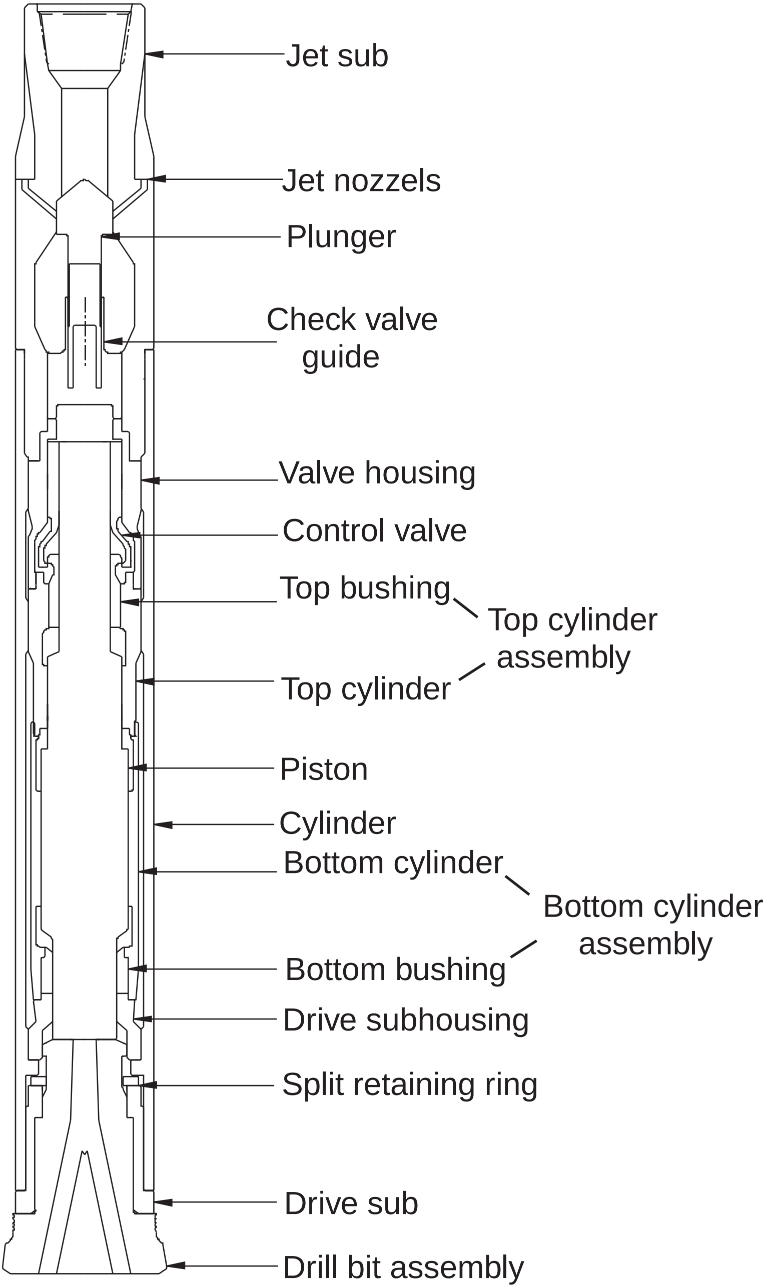
Jet sub
Jet nozzels
Plunger
Check valve guide
Valve housing
Control valve
Top bushing
Top cylinder assembly
Top cylinder
Piston
Cylinder
Bottom cylinder
Bottom cylinder assembly
Bottom bushing
Drive subhousing
Split retaining ring
Drive sub
Drill bit assembly

Figure 16

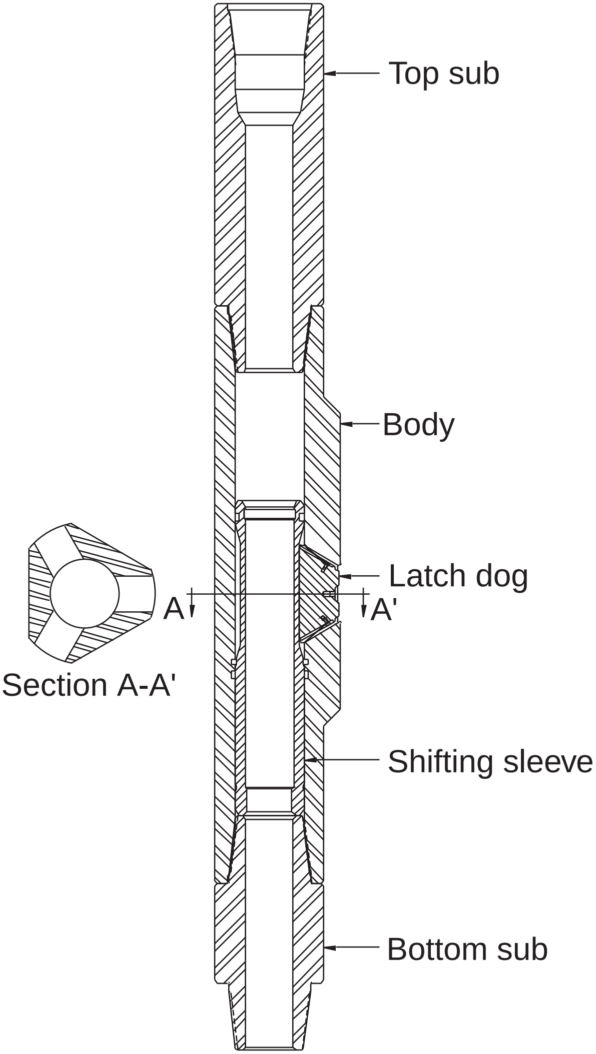
Top sub
Body
Latch dog
A
A'
Section A-A'
Shifting sleeve
Bottom sub

Figure 17

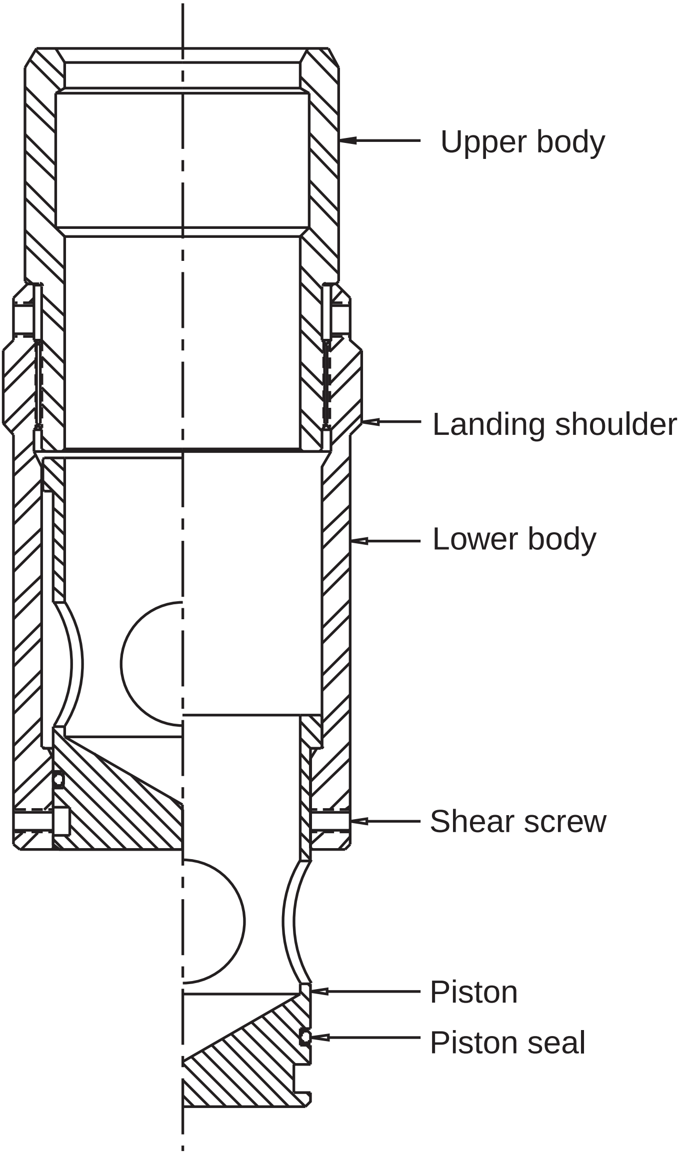
Upper body
Landing shoulder
Lower body
Shear screw
Piston
Piston seal

Figure 18

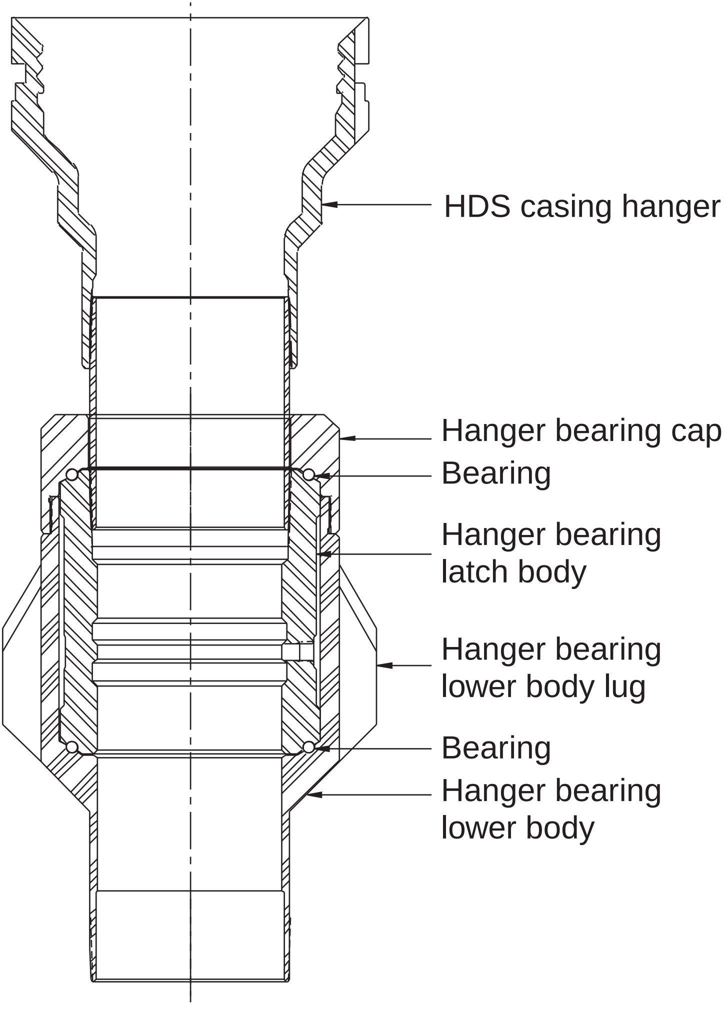
HDS casing hanger
Hanger bearing cap
Bearing
Hanger bearing latch body
Hanger bearing lower body lug
Bearing
Hanger bearing lower body

Figure 19

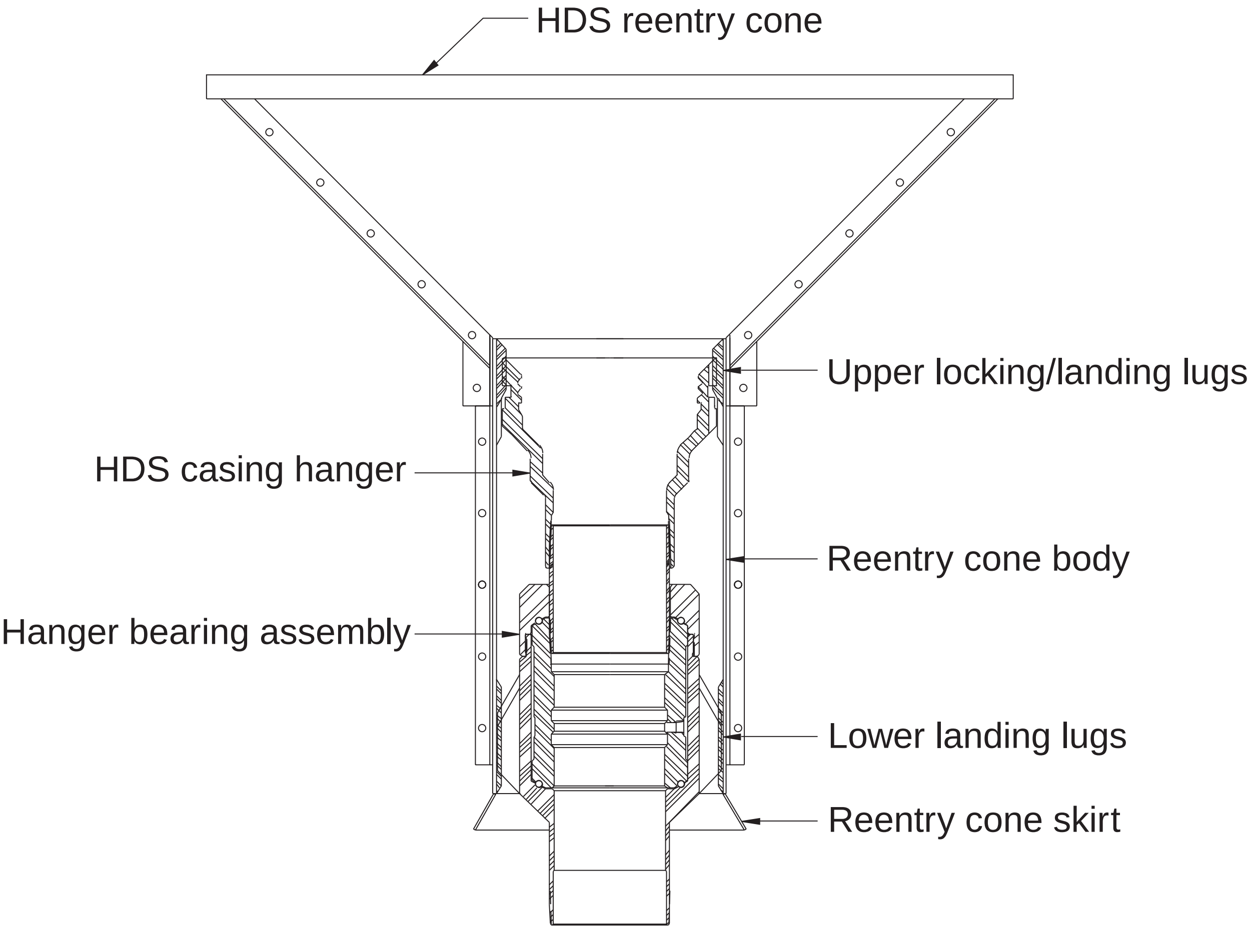
HDS reentry cone
Upper locking/landing lugs
HDS casing hanger
Reentry cone body
Hanger bearing assembly
Lower landing lugs
Reentry cone skirt

Figure 20

Figure 21

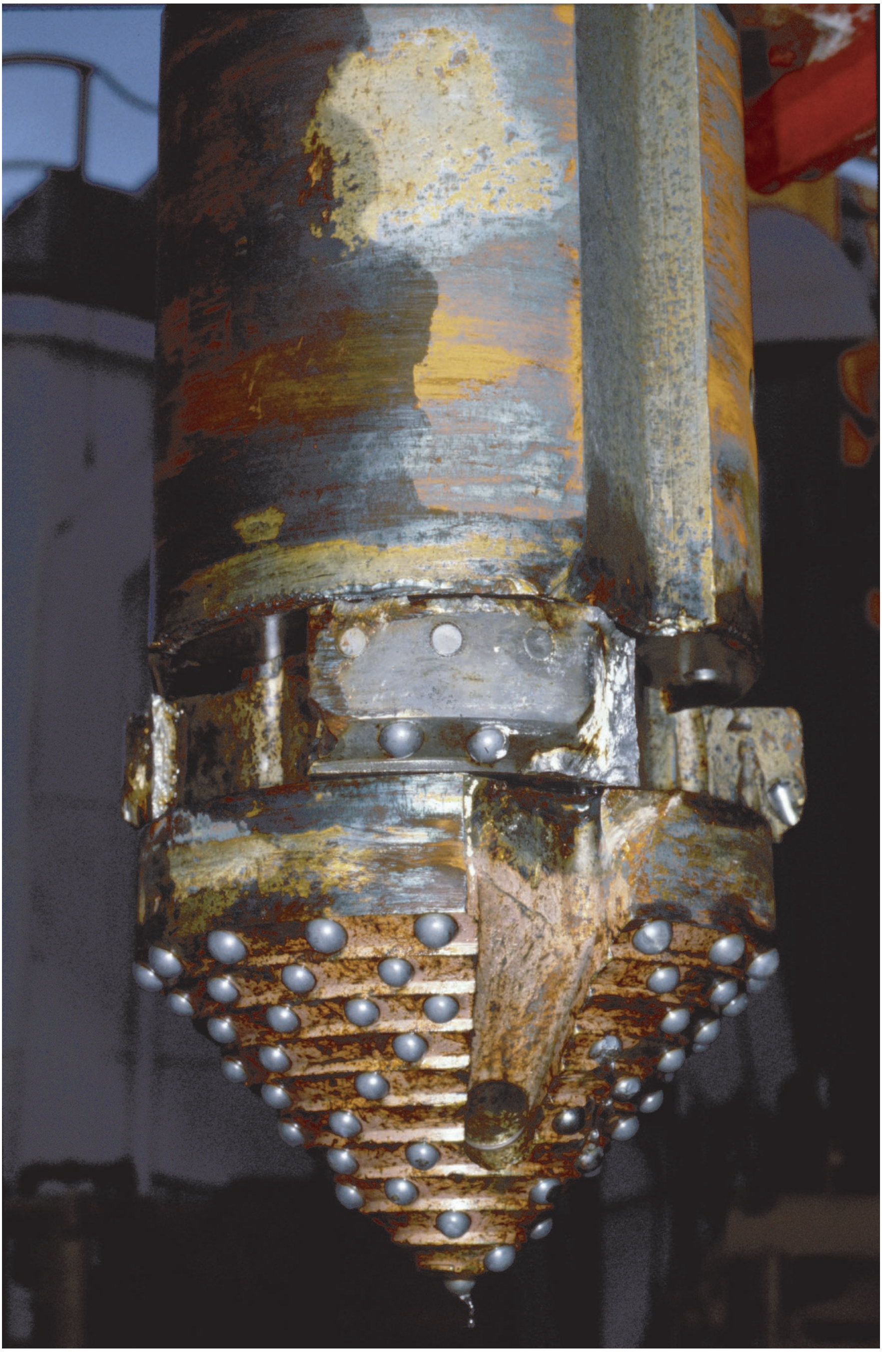

Figure 22

Figure 23

Figure 24

Figure 25

Figure 26

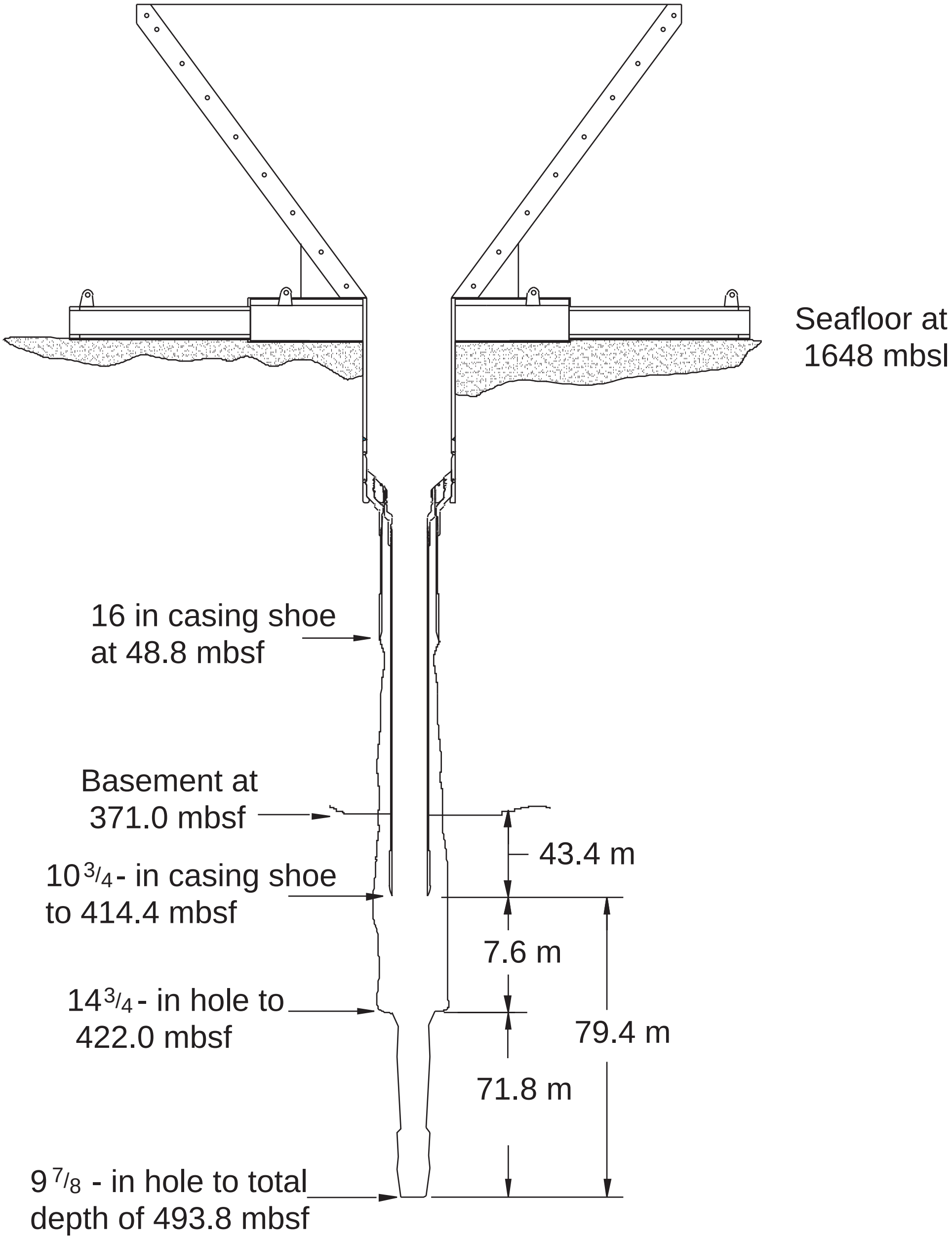
Seafloor at
1648 mbsl
16 in casing shoe
at 48.8 mbsf
Basement at
371.0 mbsf
43.4 m
10 3/4- in casing shoe
to 414.4 mbsf
7.6 m
14 3/4- in hole to
422.0 mbsf
79.4 m
71.8 m
9 7/8 - in hole to total
depth of 493.8 mbsf

Figure 27

OCEAN DRILLING PROGRAM
SITE SUMMARY
LEG 179

Site Summary Table

Hole	Latitude	Longtitude	Water depth (mbrf)	Number of cores	Interval cored (m)	Core recovered (m)	Recovery (%)	Length drilled (m)	Total penetration (m)	Time on hole (hr)	Time on site (days)
1104A	32 43.32' S	57 15.85' E	740.0	0	0.00	0.00	0.0%	1.5	1.50	11.58	0.5
1104B	32 43.32' S	57 15.85' E	739.0	0	0.00	0.00	0.0%	2.0	2.00	9.50	0.4
1104C	32 43.32' S	57 15.85' E	739.0	0	0.00	0.00	0.0%	2.0	2.00	12.00	0.5
1104D	32 43.32' S	57 15.85' E	740.0	0	0.00	0.00	0.0%	0.5	0.50	4.58	0.2
1104E	32 43.32' S	57 15.85' E	740.0	0	0.00	0.00	0.0%	1.5	1.50	21.92	0.9
1104 site totals:				**0**	**0.00**	**0.00**	**0.0%**	**7.5**	**7.50**	**59.58**	**2.5**
1105A	32 43.134' S	57 16.6517' E	714.0	30	143.00	118.43	82.8%	15.0	158.00	201.58	8.4
1105 site totals:				**30**	**143.00**	**118.43**	**82.8%**	**15.0**	**158.00**	**201.58**	**8.4**
1106A	32 43.32' S	57 15.86' E	740.0	0	0.00	0.00	0.0%	2.0	2.00	26.62	1.1
WOW	32 43.32' S	57 15.86' E	740.0	0	0.00	0.00	0.0%	0.0	0.00	24.25	1.0
1106B	32 43.32' S	57 15.86' E	741.0	0	0.00	0.00	0.0%	0.5	0.50	12.67	0.5
1106C	32 43.32' S	57 15.86' E	742.5	0	0.00	0.00	0.0%	1.0	1.00	11.08	0.5
1106D	32 43.32' S	57 15.86' E	742.5	0	0.00	0.00	0.0%	0.0	0.00	8.92	0.4
1106E	32 43.32' S	57 15.86' E	741.0	0	0.00	0.00	0.0%	8.0	8.00	16.03	0.7
1106 site totals:				**0**	**0.00**	**0.00**	**0.0%**	**11.5**	**11.50**	**99.57**	**4.1**
1107A	17 01.42'S	88 10.85'E	1659.0	0	0.00	0.00	0.0%	445.0	493.80	172.67	7.2
1107 site totals:				**0**	**0.00**	**0.00**	**0.0%**	**445.0**	**493.80**	**172.67**	**7.2**
Leg 179 totals:				**30**	**143.00**	**118.43**	**82.8%**	**479.00**	**670.80**	**533.40**	**22.2**

OCEAN DRILLING PROGRAM
OPERATIONS RESUME
LEG 179

Operations resume table

Total days (9 April 1998 to 8 June 1998)	59.63
Total days in port	12.52
Total days under way	26.49
Total days on site	21.21

	Days
Drilling	3.30
Other	0.31
Tripping time	5.59
Stuck pipe/hole trouble	0.19
Logging/downhole science	0.46
Mechanical repair time (contractor)	0.05
Reentry time	1.83
W.O.W.	1.34
Coring	5.18

Total distance traveled (nautical miles)	0.0
Average speed transit (knots):	0.0
Number of sites	4.0
Number of holes	12.0
Number of cores attempted	30.0
Total interval cored (m)	143.0
Total core recovery (m)	118.4
Core recovery (%)	82.82
Total interval drilled (m)	479.0
Total penetration	670.8
Maximum penetration (m)	493.8
Minimum penetration (m)	0.0
Maximum water depth (m from drilling datum)	1659.0
Minimum water depth (m from drilling datum)	739.0