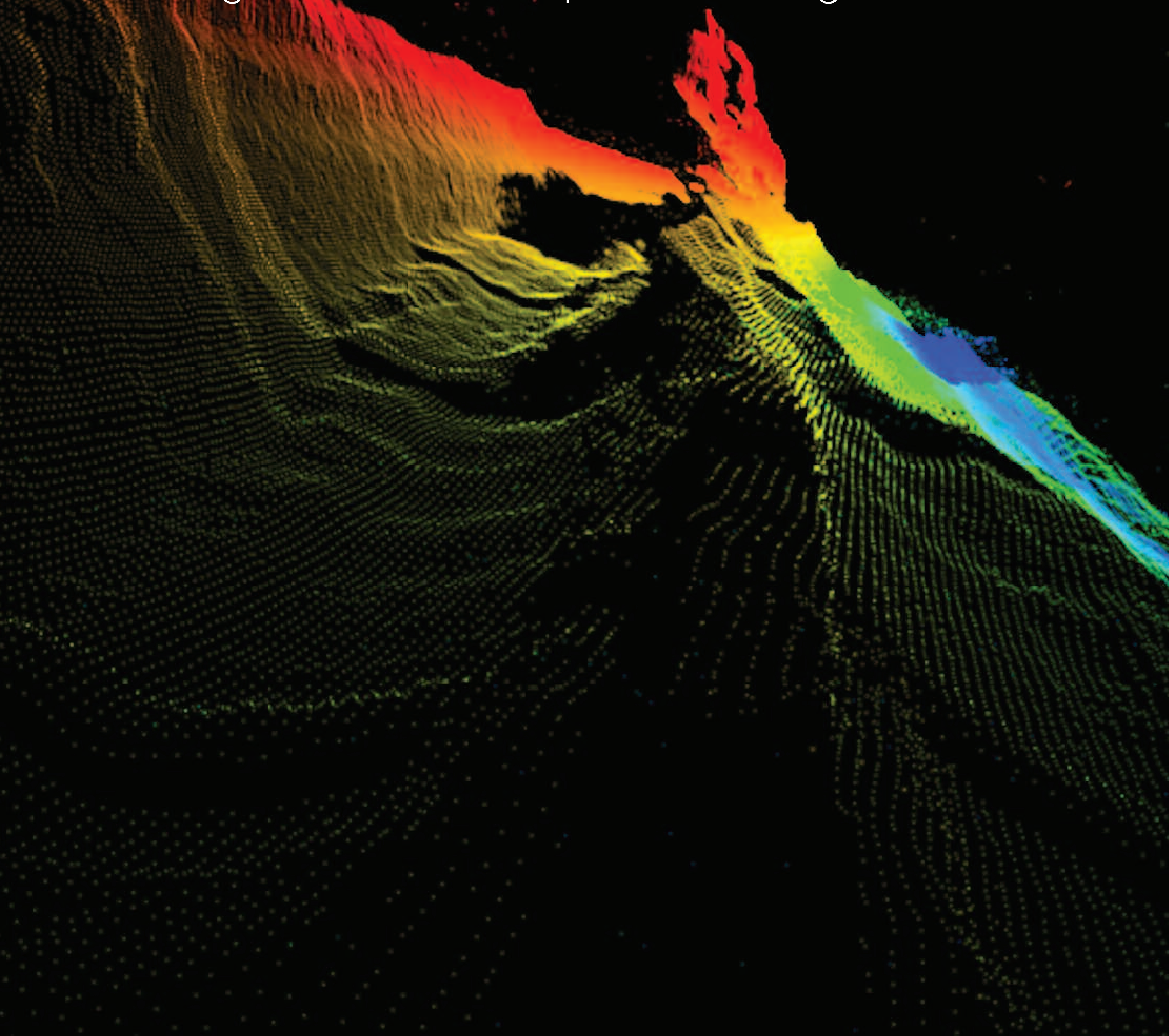
InterRidge News

Promoting international cooperation in ridge-crest studies



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DEADLINE FOR INTERRIDGE NEWS VOL. 21 CONTRIBUTIONS
3 SEPTEMBER 2012

Battling through the thermal boundary layer: Deep sampling in ODP Hole 1256D during IODP Expedition 335

*Damon A.H. Teagle, Benoit Ildefonse, Peter Blum and the IODP Expedition 335 Shipboard Scientists**

Table 1: Summary of operations on IODP Expedition 335.

Phase 1	Open hole to full depth, cement to stabilize hole (920-960 mbsf)	15 days (9 reentries)
Phase 2	Core (4 cores, 8% recovery); Coring bit destroyed	~ 2 day (1 reentry)
Phase 3	Fish/mill junk, ream/clean hole	19 days (13 reentries)
Phase 4	Logging	~ 2 day (1 reentry)
Phase 5	Core (1 core, 35% recovery), cement to stabilize hole (BOH to 1510, 940-910 mbsf)	~ 1.5 days (1 reentry)
• 24 reentries, ~150 miles (~240 km) of pipe trip		
• 920-940 mbsf zone: stabilized (15 trips through after cementing end of Phase 1 without any trouble)		
• Hole: clean and clear of cuttings, no metal junk left at bottom		
• Cone: clear		
• "Fieldwork" samples from ocean crust thermal boundary layer		

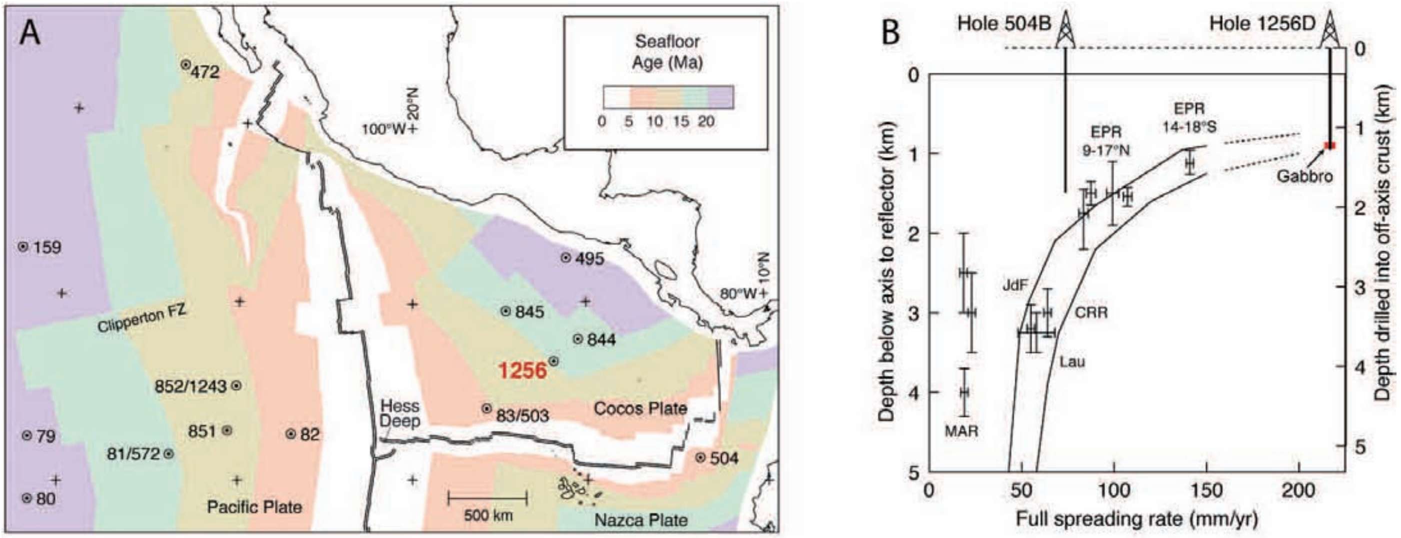

Figure 1 – A. Age map of the Cocos plate and corresponding regions of the Pacific and Nazca plates. Isochrons at 5 m.y. intervals have been converted from magnetic anomaly identifications according to the timescale of Cande and Kent (1995). Selected DSDP and ODP sites that reached basement are indicated by circles. The wide spacing of the 10 to 10 m.y. isochrons to the south reflects the extremely fast (200–220 mm/y) full spreading rate. FZ = fracture zone. **B.** Depth to axial low-velocity zone plotted against spreading rate (Purdy et al., 1992; Carbotte et al., 1997). B. Depth versus spreading rate predictions from two models of Phipps Morgan and Chen (1993) are shown, extrapolated subjectively to 200 mm/y. Penetration to date in Holes 504B and 1256D is shown, with the depth at which gabbros were intersected indicated by the red box. Following core descriptions, a thickness of ~300 m of off-axis lava is shown for Hole 1256D and assumed for Hole 504B. EPR = East Pacific Rise, JdF = Juan de Fuca Ridge, Lau = Valu Fa Ridge in Lau Basin, CRR = Costa Rica Rift, MAR = Mid-Atlantic Ridge.

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Abstract

IODP Expedition 335 "Superfast Spreading Rate Crust 4" returned to ODP Hole 1256D with the intent of deepening this reference penetration of intact ocean crust a significant distance (~350 m) into cumulate gabbros. Three earlier cruises to Hole 1256D have drilled through the sediments, lavas and dikes and 100 m into a complex dike-gabbro transition zone.

Operations on IODP Expedition 335 proved challenging throughout, with almost three weeks spent re-opening and securing unstable sections of the Hole. When coring commenced, the destruction of a hard-formation C9 rotary coring bit at the bottom of the hole required further remedial operations to remove junk and huge volumes of accumulated drill cuttings. Hole-cleaning operations using junk baskets recovered large (up to 3.5 kg) irregular samples that document a hitherto unseen sequence of evolving geological conditions and the intimate coupling between temporally and spatially intercalated intrusive, hydrothermal, contact-metamorphic, partial melting and retrogressive processes.

Hole 1256D has been thoroughly cleared of junk and drill cuttings that have hampered operations during this and previous Expeditions. At the end of Expedition 335, we briefly resumed coring before preserving problematic intervals with cement. It would be prudent for ocean drilling to return to Hole 1256D in the near future to ensure best use is made of the huge efforts to stabilize Hole 1256D and open it to full depth.

Introduction

Drilling a deep hole through intact ocean crust formed at a fast spreading rate has been one of the prime motivations for scientific ocean drilling since its inception. Fast spreading ocean crust is targeted because geological and geophysical observations indicate that for long distances ridge crests behave relatively uniformly. Consequently, the findings from a few deep penetrations should be able to be extrapolated to describe a significant portion of the Earth's surface (~30%). Only through the recovery of a significant section of cumulate gabbro underlying the dikes and erupted lavas will we be able to test competing models of magmatic accretion at fast spreading mid-ocean ridges and evaluate the impact of these processes on the wider Earth system.

IODP Expedition 335 (13th April-3rd June, 2011) was the fourth scientific drilling cruise of the Superfast campaign (Wilson et al., 1999) and returned to ODP Hole 1256D (6°44.163'N, 91°56.061'W) to deepen this ocean crust reference penetration a significant distance into cumulate gabbros (Figure 1a). ODP Hole 1256D is located on 15 Ma-crust in the eastern equatorial Pacific Ocean in oceanic basement that formed during a sustained episode of superfast ocean ridge spreading (>200 mm/yr; Wilson, 1996). Ocean crust formed at a superfast spreading rate was deliberately targeted because there is strong evidence from mid-ocean ridge seismic experiments that gabbros occur at shallower depths in intact ocean crust with higher spreading rates (Figure 1b). Therefore, the often difficult-to-drill upper ocean crust should be relatively thin. Expedition 335 follows on from ODP Leg 206 in 2002 and IODP Expeditions 309/312 in 2005 (Wilson et al., 2003; Teagle et al., 2006) that prepared the first scientific borehole for deep drilling by installing a large reentry cone (Fig. 2), secured with almost 270 m of 16-in casing through the 250 m-thick sedimentary overburden and cemented into the uppermost basement. Hole 1256D was then deepened through a ~810 m-thick sequence of lavas and a thin (~346 m) sheeted dike complex, the lower 60 m of which is strongly contact metamorphosed to granoblastic textures. The first gabbroic rocks were encountered at 1407 meters below seafloor (mbsf) where the hole entered a complex dike-gabbro transition zone that includes two 20 to 50-m thick gabbro lenses intruded into granoblastic dikes. As of the end of Expedition 312 in December 2005, Hole 1256D had a total depth of 1507.1 mbsf and was open to its full depth.

It was hoped that even with a shortened cruise (~6 weeks), coring on IODP Expedition 335 would be able to deepen Hole 1256D ~350 m, completely through the dike-gabbro transition zone and varitextured gabbros and a significant distance into true cumulate gabbros.

Science Objectives of IODP Expedition 335

The specific scientific objectives of IODP Expedition 335 that were to be addressed by deepening Hole 1256D a significant distance into cumulate gabbros were:

- What is the major mechanism of magmatic accretion in crust formed at fast spreading rates? Is the lower crust formed by gabbro glaciers or sheeted sills (e.g. Korenaga and Kelemen 1998) or by some mixed or unknown mechanism?
- How is heat extracted from the lower oceanic crust? Specifically, what is the role of hydrothermal circulation in extracting latent heat from the lower oceanic crust?
- What is the geological significance of the seismic layer 2/3 boundary at Site 1256?
- What is the magnetic contribution of the gabbro layer? Can the magnetic polarity structure of the lower crust be used to constrain cooling rates?

Operations

Expedition 335 re-entered Hole 1256D more than five years after the last expedition to this site (Fig. 2). The expedition encountered and overcame a series of significant engineering challenges, each of which was unique, although difficulties were not unexpected when drilling in a deep, uncased, marine borehole into igneous rocks (Table 1; Expedition 335 Scientists, 2011).

The patient, persistent efforts of the drilling crew successfully cleared a major obstruction at a depth of 920 m that had initially prevented re-entry into the hole to its full depth of 1507 meters. At the bottom of the hole the very hard granular rocks that had proved challenging during the previous Superfast expedition were once more encountered. Although there may only be a few tens of meters of these particularly tenacious granoblastic basalts, their extreme toughness once more proved challenging to sample, resulting in the grinding down of one of the hardest formation coring bits into a smooth stump (Fig. 3).

A progressive, logical course of action was then undertaken to clear the bottom of the hole of metal debris from the failed coring bit and drilling cuttings. This effort required the innovative use of hole-clearing equipment (Fig. 3), including large magnets, and involved about 240 km of drilling pipe deployments (trips) down into the hole and back onto the ship (the total amount of pipe "tripped" was roughly equivalent to the distance from Paris to the English coast, or from New York City to Philadelphia, or Tokyo to Niigata). These efforts returned hundreds of kilograms of rocks and drill cuttings (Fig. 3D), including large blocks (up to 3.5 kg) of the culprit granoblastic basalts that hitherto had only been very poorly recovered through coring (Fig. 4). A limited number of gabbro boulders were also recovered, indicating that we are tantalizingly close to breaking through into the gabbroic layer.

Scientific Results

Hole opening, remediation operations and the comprehensive destruction of a C9 hard formation coring bit resulted in a major loss of time from the coring and wireline activities planned for Expedition 335. Coring on this Expedition deepened Hole 1256D only modestly, from 1507.1 to 1521.6 mbsf (Fig. 5) at low rates of penetration and recovery (0.9 m/hr, 11% respectively).

Hole cleaning operations at the bottom of Hole 1256D, particularly those runs that deployed the reverse-circulation junk basket, brought back a unique collection of large cobbles (Fig. 4), angular rubble and fine cuttings of principally, strongly to completely recrystallized granoblastic basalt with minor gabbroic rocks and evolved plutonic rocks. The granoblastic basalts record high-temperature (granulite facies) metamorphism of previously hydrothermally altered sheeted dikes, with unequivocal evidence for hydrothermal alteration both before and after the formation of granoblastic textures (Teagle et al., 2006; Koepke et al., 2008; Alt et al., 2010, France et al., 2009). The large blocks exhibit intrusive, structural and textural relationships, and overprinting and cross-cutting hydrothermal alteration and metamorphic paragenetic sequences that hitherto have not been observed due to the one dimensional nature of drill cores and the very low rates of recovery of the granoblastic dikes during Expedition 312 (<7% recovery). Some of the rubble and ~30% of the fine cuttings recovered by fishing and cleaning operations clearly came from the lava sequences at the top of the hole on the basis of igneous textures and low temperature alteration minerals (Mg-saponite, amorphous silica). In contrast, the high extent of metamorphic recrystallization exhibited by the granoblastic basalts, and operational factors (e.g. pipe movements), provide strong evidence that the granoblastic basalts, minor gabbros and evolved plutonic rocks were sourced from the lowermost reaches of Hole 1256D (1494.9 to 1521.6 mbsf), most probably from below Gabbro 2 (Fig. 5). Hence, the rocks recovered during Expedition 335 represent a ~15 m interval of the upper crust-lower crust transition, occurring below the ~90 m section, recovered during Expedition 312, of two gabbroic bodies (Gabbro 1 and Gabbro 2) separated by Dike Screen 1 (Fig. 6).

Conclusions

When the textural and contact relationships exhibited by the large rocks recovered from the junk baskets are placed in the geological context of the Hole 1256D stratigraphy, a vision emerges of a complex, dynamic thermal boundary layer zone. This region of the crust between the principally hydrothermal domain of the upper crust and the intrusive magmatic domain of the lower crust is one of evolving geological conditions. There is intimate coupling between temporally and spatially intercalated magmatic, hydrothermal, partial melting, intrusive, metamorphic and retrograde processes.

With only a minor depth advance in Hole 1256D, we are yet to recover samples of cumulate gabbros required to test models of ocean ridge magmatic accretion and the intensity of hydrothermal cooling at depth. Nor have we crossed the Layer 2/3 boundary at Site 1256. The total vertical thickness of granoblastic basalts is over 114 m, and Dike Screen 2 is now about the same thickness (so far) as Dike Screen 1. Highly perched, isolated gabbro intrusions are uncommon in ophiolites. The energy requirements for the granoblastic recrystallization at granulite facies condition of a >114 m-thick zone of sheeted dikes, massively exceeds the thermal capacity of Gabbros 1 and 2 (e.g. Koepke et al., 2008; Coggon et al., 2008) if a simple sub-horizontal arrangement of these layers is assumed. The enormous heat requirements for such extensive granulite facies recrystallization, the evidence for partial melting, together with the tantalizing presence of minor but not uncommon gabbroic rocks and felsic intrusives, dikelets and veins, strongly indicates that the layer of purely plutonic rocks should be at most only a few tens of meters deeper in the Hole.

Although the extensive remedial operations on Expedition 335 precluded significant deepening of Hole 1256D, significant progress was made in improving the borehole. The most problematic out of gauge zone at ~920 to 960 mbsf that caused re-entry problems on Expeditions 312 and 335 has been stabilized with cement. The bottom of the hole has been cleared of rubble and junk, and there appears to be only a short under-gauge zone (<1 m). Importantly, the regular, large sweeps of high viscosity mud (up to 200 bbls sepiolite, every ~2 hr), have finally overcome and expunged the vast amount of fine cuttings recirculating in the hole, some most likely resident since ODP Leg 206. This is shown by the absence of soft fill in the final ~5 re-entries compared to upwards of 50 m of soft fill at the end of Expedition 312. The engineering efforts on Expedition 335 have repaired and prepared Hole 1256D for further deep drilling, following 5 years of neglect. Hole 1256D is 1500 m of hard rock coring closer to cumulate gabbros than any other options in intact ocean crust and once more poised to answer fundamental questions about the formation of new crust at fast spreading mid-ocean ridges. This would be best achieved by a timely return to the site.

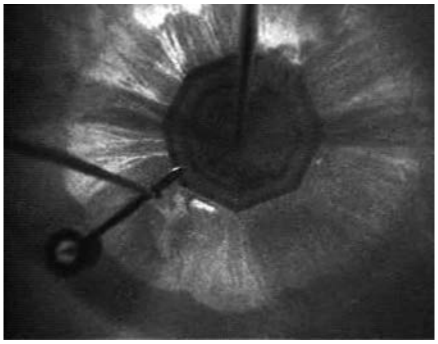

Figure 2: Still image of ODP Hole 1256D reentry cone, from the VIT (Vibration-Isolated Television) Camera, which is deployed on each reentry. This is the 19th reentry in Hole 1256D during Expedition 335. Note the drilling mud and cuttings dispersed around the reentry cone.

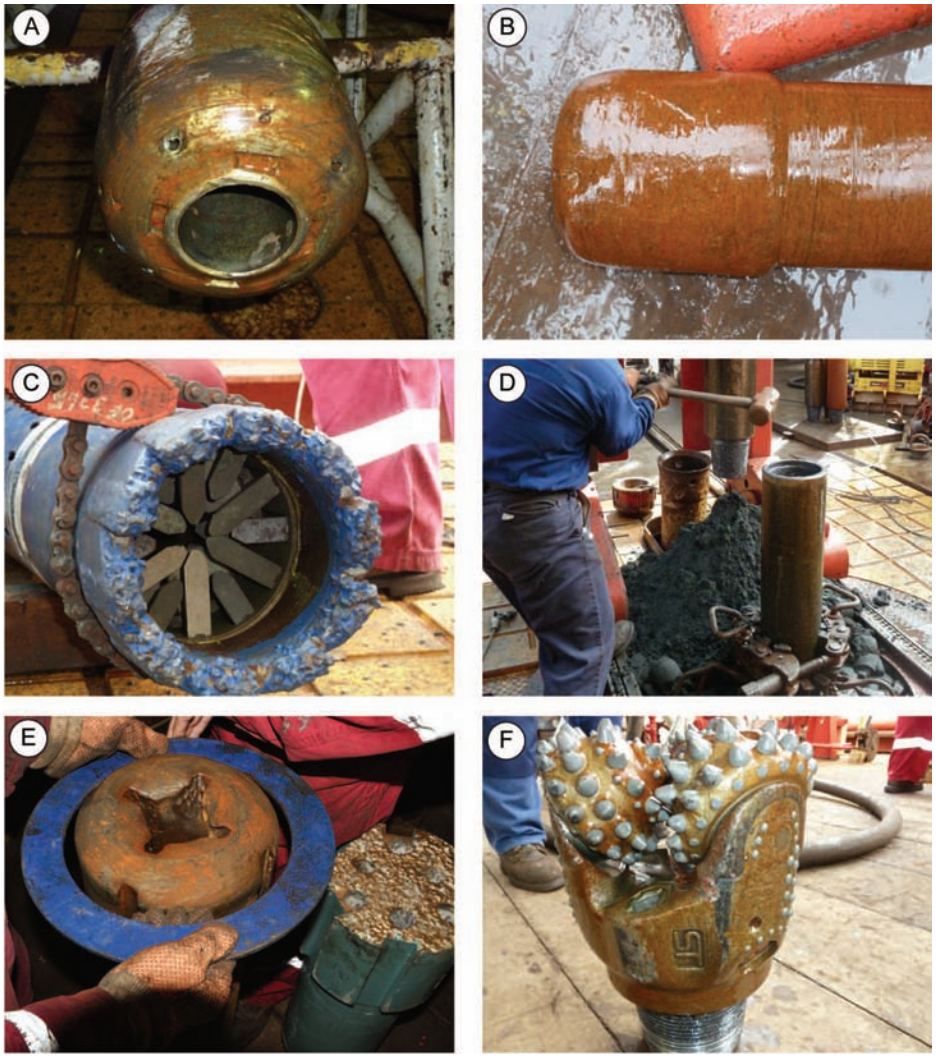

Figure 3: Photographs of some drilling, fishing, and milling tools illustrating the multiple operations achieved during IODP Expedition 335. **A & B**. Remains of the Ulterra C9 RCB coring bit used during Run 9. The bit was probably used for ~10 h after it disintegrated, which resulted in this spectacularly abraded and sculptured bit ("Stumpy"), something never seen before by the drillers. **C**. Bottom of the Bowen Reverse Circulation Junk Basket (RCJB), showing its hard-facing structure and the junk catcher spring fingers inside. This tool recovered a series of large scale cobbles (up to 5 kg) of granoblastic basalt. **D**. A series of RCJB runs returned a Bottom Hole Assembly packed by fine-grained cuttings. This contributed efficiently to cleaning Hole 1256D. **E**. Heavily worn and undergauge 9 inch flat-bottomed milling tool. This tool worked at the bottom of the hole for 12 h; its final state indicates the very abrasive nature of metal debris and/or rocks at the bottom of the hole and an undergauge lowermost portion (tens of centimeters) of the hole. Note for comparison the hard-facing structure of the next milling tool on the right side of the picture. **F**. 9-inch Smith FH3VPS tricone bit used for Run 16. This armored bit was efficient to ream and clean the undergauge bottom of the hole.

Figure 4: Granoblastic dike samples were recovered in abundance by fishing tools during successive hole remediation operations. Sumiyo Miyashita and Yoshiko Adashi, from Niigata University, examine unusually large rock samples from Hole 1256D.

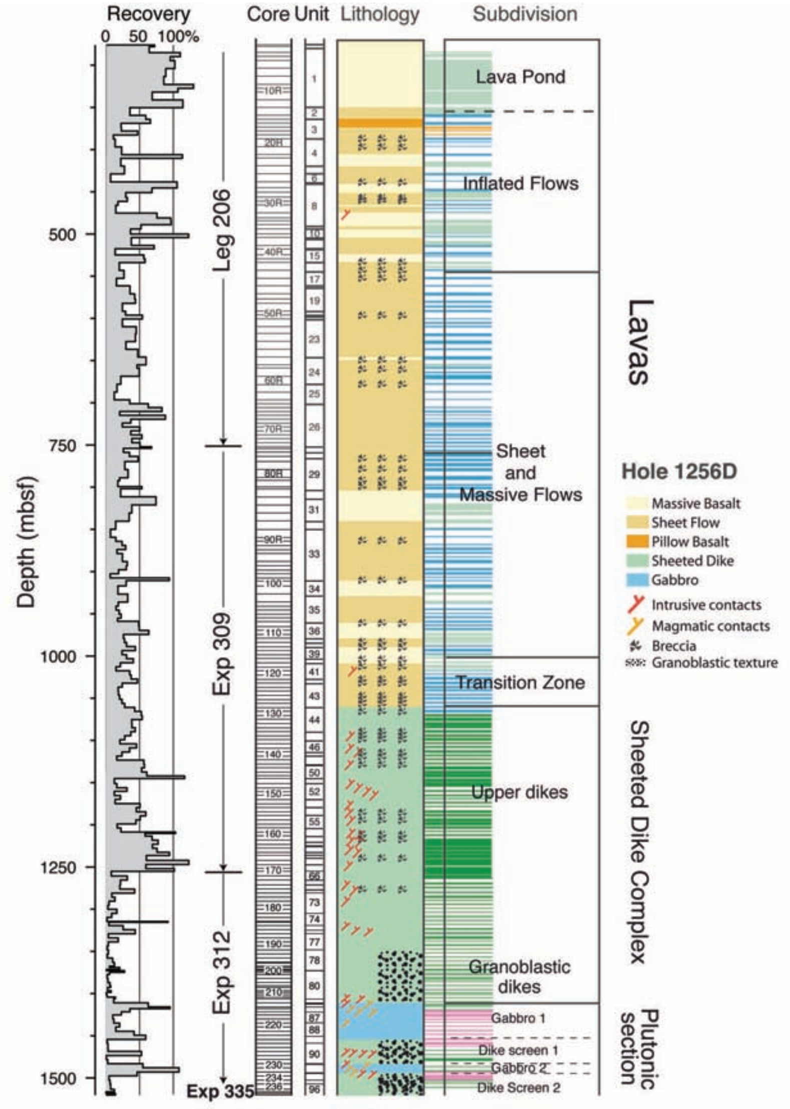

Figure 5: Stratigraphic column for Hole 1256D at the end of Expedition 335, showing the major and minor lithologic divisions of the upper oceanic crust.

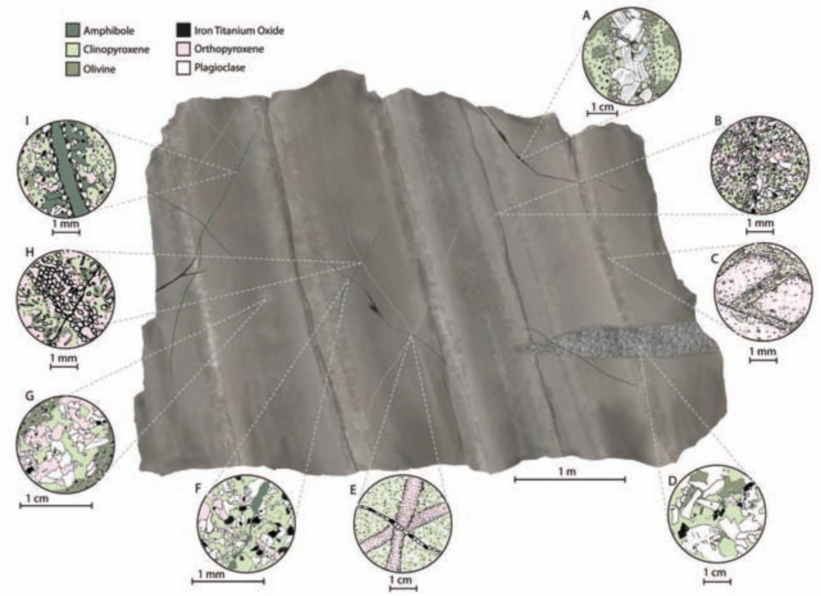

Figure 6: Sketch of a hypothetical outcrop in a future Site 1256 ophiolite of the dike–gabbro transition zone showing the contact relationships observed in the cores and junk basket rocks recovered during Expedition 335. Small sketches are drawn from sample and thin section descriptions done during Expedition 335. **A**. Diorite dikelet, comprised predominantly of primary igneous amphibole and plagioclase, crosscutting granoblastic basalt. **B**. Finegrained dike chilled against coarser grained dike. The entire sample is recrystallized to granoblastic assemblages of plagioclase, orthopyroxene, clinopyroxene, magnetite, and ilmenite. Later fine postcontact-metamorphic hydrothermal amphibole veins (not shown) cut across the contact and both dikes. **C**. Chilled and brecciated dike margin recrystallized to granoblastic assemblages. Angular clasts consist of granoblastic plagioclase with minor orthopyroxene, clinopyroxene, ilmenite, and magnetite and are recrystallized from chilled dike margin breccia protolith. Clast matrix is orthopyroxene rich with minor clinopyroxene, plagioclase, and oxides and is recrystallized from hydrothermal minerals (amphibole and chlorite) that veined and cemented the breccia protolith. **D**. Subophitic texture in gabbro. **E**. Diorite vein crosscutting a conjugate set of metamorphic orthopyroxene veins. **F**. Postcontact-metamorphic hydrothermal hornblende vein cutting granoblastic basalt. **G**. Granoblastic basalt with a diorite patch. **H**. Granoblastic orthopyroxene vein, recrystallized from precursor hydrothermal vein, in granoblastic dike. Orthopyroxene vein is cut by small postcontact-metamorphic hydrothermal amphibole vein. **I**. Postcontact-metamorphic hydrothermal amphibole vein cutting granoblastic basalt, with 1 mm wide amphibole-rich alteration halo where pyroxenes are replaced by amphibole.

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