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1. Leg 206 Synthesis: Initiation of Drilling an Intact Section of Upper Oceanic Crust Formed at a Superfast Spreading Rate at Site 1256 in the Eastern Equatorial Pacific[1]

Damon A.H. Teagle[2] and Douglas S. Wilson[3]

ABSTRACT

Drilling a complete section of oceanic crust has been an unfulfilled ambition since the inception of scientific ocean drilling. Recovery of in situ oceanic crust is imperative to understanding igneous accretion and the complex interplay between magmatic, hydrothermal, and tectonic processes, as well as providing a means for calibrating remote geophysical observations, particularly seismic and magnetic data. Ocean Drilling Program (ODP) Leg 206 was the initial phase of the Superfast Spreading Rate Crust campaign to ODP Site 1256, a multicruise program to exploit the observed relationship between the depth to axial low-velocity zones imaged at active mid-ocean ridges and spreading rate. Because of the known difficulties of drilling young ocean basement, targeting a region where gabbros should occur at their shallowest optimizes the chances of reaching gabbro in intact ocean crust by reducing the distance to be drilled and the time required on site. Following the recent recognition of an episode of superfast spreading (200–220 mm/yr) on the East Pacific Rise ~11–20 m.y. ago, Site 1256 (6.736°N, 91.934°W) on ~15-Ma oceanic lithosphere of the Cocos plate was identified as the optimal site for a new deep drill hole into ocean crust. Even allowing for significant burial by lavas that flowed off axis (~300 m), the upper gabbros,

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[2]National Oceanography Centre, School of Ocean and Earth Science, University of Southampton, European Way, Southampton S014-3ZH, UK. dat@noc.soton.ac.uk
[3]Department of Earth Science and Marine Science Institute, University of California, Santa Barbara, Santa Barbara CA 93106-9630, USA.

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thought to be the frozen axial melt lens, are predicted at ~1275–1550 meters below seafloor (mbsf).

To fully characterize the sedimentary overburden and establish depths for the casing strings, three pilot holes were cored, recovering a nearly complete section of the 250.7 m of sediment overlying basement and penetrating 88.5 m into basement with very good recovery (61.3%). The sediments can be subdivided into two main lithologies: Unit I (0–40.6 mbsf) is clay rich with a few carbonate-rich intervals, whereas Unit II (40.6–250.7 mbsf) is predominantly biogenic carbonate.

Following installation of a reentry cone with a 16-in-diameter casing string that extended 20 m into basement in Hole 1256D, >500 m of young Pacific extrusive lavas was cored with moderate to high rates of recovery. These upper lavas comprise sheet flows with subordinate pillow lavas, hyaloclastites, and rare dikes, capped by an evolved, massive flow >74 m thick and other sheet flows that probably ponded in small faulted depressions several kilometers off axis. The lavas have normal mid-ocean-ridge basalt chemistries, with evolved compositions more common upsection, and heterogeneous incompatible element ratios.

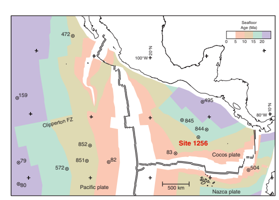
Hole 1256D was exited cleanly, leaving the hole clear of debris, open to its full depth, and primed for the future deepening into the sheeted dikes and gabbros that took place early in the next phase of scientific ocean drilling during Integrated Ocean Drilling Program Expeditions 309 and 312. This *Scientific Results* volume comprises a collection of papers, mostly data reports, of the initial postcruise research undertaken by the ODP Leg 206 science party. This synthesis also briefly describes research published to date in the external scientific literature. With follow-up cruises to deepen Hole 1256D occurring soon after Leg 206, we anticipate that numerous future manuscripts and data that investigate the complete upper crustal section at Site 1256 will soon be available in the wider scientific literature.

INTRODUCTION

Sampling a complete section of oceanic crust has been a primary objective of scientific ocean drilling since its inception. However, this goal has proved difficult to achieve because of the fractured nature of ocean floor basalts and the time-consuming nature of hard rock drilling (see Wilson, Teagle, Acton, et al., 2003; Teagle et al., 2004). Recovery of intact ocean crust is imperative to understanding igneous accretion and the complex interplay between magmatic, hydrothermal, and tectonic processes, as well as providing a means for calibrating remote geophysical observations, especially seismic and magnetic data. This *Scientific Results* volume is a collection of shore-based postcruise studies of cores and data recovered during Ocean Drilling Program (ODP) Leg 206 to Site 1256 in the eastern equatorial Pacific Ocean (Fig. **F1**) (Wilson, Teagle, Acton, et al., 2003). The principal aim of this expedition was to establish for the first time a deep drill hole into ocean crust formed at a fast spreading rate with the eventual goal of drilling completely through the upper ocean crust into gabbros. Only by drilling a complete section of upper crust formed in a simple tectonic setting can the processes operating at normal mid-ocean ridges be understood.

ODP Leg 206 (6 November 2002–4 January 2003) completed the initial phase of a planned multileg project to drill a complete in situ section of the upper ocean crust that will eventually extend through the extrusive layer and sheeted dikes and into gabbros. Operations were

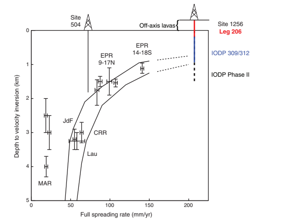
F1. Age map of Site 1256 area, p. 12.



conducted at Site 1256 into 15-Ma oceanic lithosphere of the Cocos plate that was formed during a period of superfast seafloor spreading (~220 mm/yr) on the East Pacific Rise.

The rationale for drilling crust formed at a superfast spreading rate follows the observation that an inverse relationship exists between spreading rate and the depth to axial low-velocity zones imaged by multichannel seismic experiments at mid-ocean ridges (Fig. F2). Although the exact geological nature of these zones remains unknown, they are hypothesized to be axial melt lenses or magma chambers positioned near the dike/gabbro boundary. Therefore, to reach the dike–gabbro transition in normal ocean crust with minimal drilling, it is best to target crust formed at the fastest possible spreading rate.

F2. Depth vs. rate models, p. 13.

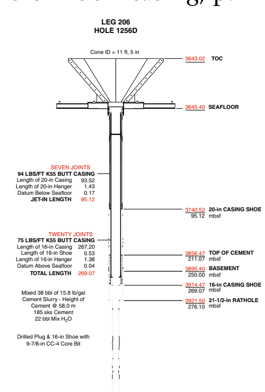


Recent interpretation of magnetic anomalies formed at the southern end of the Pacific/Cocos plate boundary identified crust that was formed at full spreading rates of ~200 to 220 mm/yr from ~20 to 11 Ma (Wilson, 1996) (Fig. F1). This interpretation led to selection of Site 1256 based on its high spreading rate, rapid initial sedimentation rate, heat flow predicted at only two-thirds that in ODP Hole 504B, and logistically favorable location in calm seas close to Central American ports and the oft-transited Panama Canal.

Operations

Site 1256 lies at 6°44′N, 91°56′W in 3635 m of water, ~1150 km east of the present crest of the East Pacific Rise, and four boreholes were drilled at the site during Leg 206. Three test holes were drilled to thoroughly characterize the sedimentary sequences (Holes 1256A, 1256B, and 1256C) and the uppermost basement (Hole 1256C). Deep drilling was initiated in Hole 1256D and achieved 502 m of basement penetration with moderate recovery (~48%) before a full suite of wireline tools was successfully deployed in the hole (Wilson, Teagle, Acton, et al., 2003). Importantly, Hole 1256D is the first hole prepared with the infrastructure desirable for drilling a moderately deep hole into the oceanic basement (1.5–3 km). This hole was done by installing a large reentry cone supported by 95 m of 20-in casing and 270 m of 16-in casing that penetrated completely through the sediment cover and was cemented ~20 m into basement (Fig. F3). This is the first scientific ocean drilling experiment with wide-diameter casing set into basement, and the cone and casing will allow multiple reentries and maintain hole stability, essential for deepening Hole 1256D through the dikes and gabbros. The large-diameter casing allows two additional narrower casing strings (13⅜ in and 10¾ in) to be inserted into Hole 1256D should the need arise to isolate unstable portions of the hole. Armoring the sediment/basement boundary reduces erosion of the borehole walls at this weak point and assists in clearing of drill cuttings from the hole.

F3. Hole 1256D casing, p. 14.



This synthesis is divided into two principal sections covering the "Sedimentary Overburden" and studies of the "Basement Formed at a Superfast Spreading Rate." Our initial cruise results were published in the ODP 206 *Initial Reports* volume (Wilson, Teagle, Acton, et al., 2003) and further publicized in the *JOIDES Journal* (Teagle et al., 2003) and *Eos* (Teagle et al., 2004) as well as many national scientific ocean drilling newsletters. To ensure that the postcruise research resulting from the superfast drilling campaign has the highest profile and impact, a special theme "Formation and Evolution of Oceanic Crust Formed at Fast Spreading Rates" was established with the American Geophysical Union (AGU) electronic journal *Geochemistry-Geophysics-Geosystems* (www.agu.org/contents/sc/ViewCollection.do?collectionCode=CRUST1&journalCode=GC), and the reader is directed to the growing collection of Site 1256-related research published there. Although this theme focuses on studies of the ocean crust drilled at Site 1256, it is not restricted to studies of that region and also contains other relevant geological, tectonic, geophysical, and geochemical studies of the ocean crust formed at fast spreading rates.

Subsequent drilling at Site 1256 during the first phase of the Integrated Drilling Program (IODP) during Expeditions 309 and 312 has confirmed the rationale for drilling in superfast spreading crust. The reader is directed to the exciting early results of those cruises (Expedition 309 Scientists, 2005; Expedition 309 and 312 Scientists, 2006; Wilson et al., 2006; Teagle, Alt, Umino, Miyashita, Banerjee, Wilson, et al., 2006).

SEDIMENTARY OVERBURDEN

A nearly complete sedimentary section was recovered in Holes 1256A, 1256B, and 1256C. The sedimentary overburden is divided into two units: Unit I (0–40.6 meters below seafloor [mbsf]) is clay rich with a few carbonate-rich layers, and Unit II (40.6–250.7 mbsf) is predominantly biogenic carbonate. The interval from 111 to 115 mbsf is rich in biogenic silica that forms a distinct diatom mat deposited at ~10.8 Ma. The calcareous microfossil biostratigraphy is in good agreement with the magnetostratigraphy. Calculated sedimentation rates vary from ~6 to 39 m/m.y.; these rates generally decreased with time as the site moved away from the high-productivity zone near the paleoequator. An abrupt drop in sedimentation rate after the deposition of the diatom mat may be due to a "carbonate crash" that affected the east Pacific and the Caribbean Sea (Farrell et al., 1995). Shipboard analyses indicate negligible active fluid movement in the sediment pile at Site 1256, and interstitial pore water chemistries are controlled by diffusion between seawater and basement fluids, with a near-continuous chert bed at 158 mbsf acting as a low-diffusivity restriction. The negligible fluid movement is consistent with the measured heat flow of 113 mW/m^2, close to the prediction for conductive cooling of oceanic lithosphere.

Shore-based investigations have refined our knowledge of the biostratigraphy, sedimentary history, and chemical composition of the sedimentary overburden at Site 1256. **Jiang and Wise** (this volume) further refine the shipboard biostratigraphy of Site 1256 through detailed investigation of calcareous nannofossils present in the Leg 206 cores. The nannofossil assemblage is, in general, moderately to well preserved and is typical of low latitudes with abundant *Gephyrocapsa, Discoaster,* and *Sphenolithus*. Linear sedimentation rates, calculated using 28 nannofossil datums and age estimates, are high in the middle Miocene (39.1 m/m.y.), decrease from the late Miocene to the Pliocene (ranging 6.1–13.2 m/m.y.), and then increase upsection (11.8 m/m.y.). A basement age of 14.5 Ma was obtained by extrapolating the 39.1-m/m.y. rate in the middle Miocene to the basement at 250.7 mbsf and is consistent with the ~15-Ma age of the oceanic crust estimated from marine magnetic anomalies.

Jiang et al. (this volume) further explore the causes of the late to middle Miocene "carbonate crash," observed in the Site 1256 cores as an abrupt drop in carbonate mass accumulation rate. Paleontological observations coupled with bulk stable isotope data (^{18}O and ^{13}C) suggest a coupling between carbonate mass accumulation and the surface water productivity of calcite-secreting organisms. These authors speculate about possible mechanisms for surface circulation-induced infertility.

Inductively coupled plasma–atomic emission spectroscopy (ICP-AES) has been championed as the primary analytical tool for rock and fluid elemental analysis during the final voyages of the Ocean Drilling Program (from Leg 187). **Ziegler and Murray** (this volume) make one of the first detailed calibrations of the shipboard preparation and ICP-AES techniques through comparison with shore-based flux-fusion major and trace element analyses of samples from the sedimentary overburden. They also compare their standard flux fusion results with a new microwave-assisted acid (HF, HCl, and HNO_3) dissolution technique that utilizes boric acid to neutralize excess HF. Shipboard and both methods of shore-based analysis compare well, confirming that current shipboard methods are adequate for first-order geochemical analysis of sediments. The microwave-assisted acid digestion technique allows Si to be measured without the use of a contaminating flux that contains high concentrations of Li and B. Also, key elements that are often compromised by the formation of insoluble fluorides are preserved in solution.

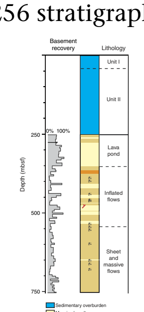
Ziegler et al. (2007) investigate changes in atmospheric circulation in the central and eastern equatorial Pacific Ocean during the Cenozoic by establishing the eolian, volcanogenic, and authigenic components of sediments from Sites 1215 and 1256. Site 1215 is in the central Pacific Ocean (26°02′N, 147°56′W) and provides a sedimentologic record back to 58 Ma. At Site 1256, volcanogenic phases together with refractory barite make up the great majority of the residual component extracted from the biogenic sediments. The volcanogenic component at Site 1256 appears to be more mafic than that at Site 1215 and is interpreted to be input to the site from the volcanic arcs of Central America.

OCEAN CRUST FORMED AT SUPERFAST SPREADING RATE

Pilot Hole 1256C penetrated 88.5 m into the basement with a core recovery of 61.3%. The total depth of penetration in Hole 1256D, located ~30 m due south of Hole 1256C, was 752 mbsf at the end of Leg 206, including 502 m drilled into basement; recovery was 47.8%. A summary of the igneous stratigraphy is presented in Figure **F4**. The igneous basement is dominated by thin (tens of centimeters to ~3 m) basaltic sheet flows that make up ~60% of the cored interval in both holes. Massive flows (>3 m thick) are the second most common rock type in both holes and include a thick ponded flow near the top of each hole. Minor intervals of pillow lavas (~20 m thick) and hyaloclastite (a few meters thick) and a single dike were recovered in Hole 1256D.

Identification of thickness of lavas that crystallized off-axis as opposed to those that erupted and cooled directly at the axis is a critical parameter for predicting the depth to gabbros at Site 1256. The uppermost basement at this site comprises a ~100-m-thick sequence of lava dominated by a single flow >74 m thick in Hole 1256D. From observations of core from Holes 1256C and 1256D, igneous Units 1256C-18 (32 m thick) and 1256D-1 (>74 m thick) are interpreted to be two intersections of a single cooling unit of cryptocrystalline to fine-grained basalt. In Hole 1256C the deformed upper surface of the flow was recovered and consists of ~75 cm of cryptocrystalline to glassy aphyric basalt. The

F4. Site 1256 stratigraphy, p. 15.



upper portion of the flow was not recovered in Hole 1256D because of the installation of casing. The interior of this flow develops downhole into an intergranular to coarse variolitic fine-grained massive basalt. The groundmass abruptly becomes cryptocrystalline ~1.5 m from the base of the flow, and this region is strongly deformed and recrystallized (Wilson, Teagle, Acton, et al., 2003). This massive basalt is interpreted as a thick ponded lava flow and this would require ~100 m of seafloor relief to pool the lava. On modern fast-spreading ridges such topography does not normally develop until 5–10 km from the axis (Macdonald et al., 1996). Lavas from several flows including the ponded flow yield steeply dipping magnetic field inclinations (>70°) as opposed to the more shallowly dipping inclinations of the underlying sheet and massive flows, as is typically expected for lavas that crystallized near the Equator. These inclinations suggest that this uppermost sequence including the ponded lava accumulated rapidly over, at most, a few centuries.

The lavas immediately below the lava pond include sheet and massive flows and minor pillow lavas (Units 1256D-2 through 15; 350.3–533.9 mbsf) grouped together as the "inflated flows." Although rocks exhibiting a number of eruptive styles are included here, the critical criterion for subdivision is the occurrence of subvertical elongate fractures filled with quenched glass and hyaloclastite (e.g., Sections 206-1256D-21R-1 and 40R-1) at the top of individual lava flows. These features indicate flow-lobe inflation that requires eruption onto a subhorizontal surface at less than a few degrees (e.g., Umino et al., 2000, 2002). Thus, we now estimate the total thickness of off-axis lavas at Site 1256 to be 284 m, close to the thickness assumed when initially predicting the depth to gabbros (1275–1550 mbsf; ~1100–1300 meters subbasement [msb]) (Expedition 309 Scientists, 2005; Expedition 309 and 312 Scientists, 2006; Wilson et al., 2006; Teagle, Alt, Umino, Miyashita, Banerjee, Wilson, et al., 2006).

Although very large lava flows have been mapped on the modern ocean floor (e.g., Macdonald et al., 1989), an extremely thick lava flow such as the >75-m-thick ponded lava encountered in Holes 1256C and 1256D has not been sampled before by scientific ocean drilling. These ponded lava samples and near-complete core recovery provide the opportunity to examine textural variations within a thick mid-ocean-ridge ponded lava. **Umino** (this volume) describes the glassy, folded crust recovered from the top of the ponded lava (Unit 1256C-18), the coarse-grained, thick massive lava body, and the unusually recrystallized and deformed base cored in Unit 1256C-18. Tartarotti et al. (2006) and Crispini et al. (2006) provide further detailed study of the ductile and brittle-ductile structures within the lava pond. Much of the flow-related deformation at the top and bottom of the lava pond involves the deformation of hot, ductile coalesced spatter clasts erupted during the early stages of emplacement.

All lavas from Site 1256 plot in the normal mid-ocean-ridge basalt (N-MORB) field on a Zr-Y-Nb ternary diagram. Indicators of magmatic evolution such as Mg# (Mg# = $100 \times Mg^{2+}/[Mg^{2+} + Fe^{2+}]$) (atomic) are bimodally distributed in the crust penetrated during Leg 206, with an evolved population (Mg# = 53 and Cr = 70 ppm) dominated by Hole 1256C lavas and the massive flows from Hole 1256D and the primitive population (Mg# = 61 and Cr = 220 ppm) dominated by thin sheet flows from Hole 1256D. Because massive flows become less common with depth, this bimodal distribution leads to overall correlations between fractionation and depth (Wilson, Teagle, Acton, et al., 2003).

Trace element analyses indicate that the igneous basement at Site 1256 is geochemically consistent with N-MORB. The massive ponded flow sampled in both Holes 1256C and 1256D is distinguished by higher abundances of rare earth elements (REE) and most of the other trace elements analyzed (Wilson, Teagle, Acton, et al., 2003). Drilling at Site 1256 now provides the first complete sequence of upper oceanic crust, and **Cooper** (this volume) presents the first published trace element data from the Leg 206–Expedition 309/312 "sampling pool." This collaboration between scientists from ODP Leg 206 and IODP Expeditions 309 and 312 will generate a comprehensive geochemical database for a representative suite of samples from this site. Although most samples yield compositions of typical East Pacific Rise MORB, **Cooper** (this volume) identified one interval of highly altered basalt (Sections 206-1256D-57R-2 through 57R-3) that has significantly higher concentrations of Cs, Rb, and Ba and lower concentrations of Sr, Pb, Zr, Hf, Sc, and most REE than samples of background alteration or halos. Preliminary Li isotopic analyses have been made on a subset of these samples (Cooper et al., 2004). Further basalt whole-rock trace element and isotopic (Sr, Nd, and Pb) data from Site 1256 are presented by Sadofsky et al. (in press) together with analyses from other drill holes (Sites 1039 and 1040) and dredge sites in the region. These authors also provide cursory isotopic and trace element analyses of sediments from Site 1256.

Establishment of the processes and intensity of hydrothermal alteration of crust formed at fast spreading rates is an important goal of Site 1256 drilling because this pace of accretion accounts for ~50% of present ocean basins. Much of the chemical exchange between seawater and basalt occurs at low temperature on the extensive ridge flanks and the quantification of elemental fluxes is important for understanding global chemical cycles. Before the drilling of Hole 1256D there had been few drill holes successfully cored into fast spreading rate ocean crust, and the only successful moderate depth (474 msb) drilling was into Jurassic ocean crust in ODP Hole 801C (167 Ma) formed when ocean conditions may have been very different than the Tertiary (Plank, Ludden, Escutia, et al., 2000; Alt and Teagle, 2003). **Alt and Laverne** (this volume) provide major and minor element chemical compositions of secondary minerals formed by low-temperature alteration by seawater. This study focuses on the major secondary phases such as phyllosilicates and less abundant feldspars but also includes analyses of carbonates and apatite. Further mineral analyses of both primary magmatic (e.g., titanomagnetite, plagioclase, and clinopyroxene) and secondary alteration minerals in rocks from the ponded lava flow are presented by **Laverne et al.** (this volume). Hydrothermal cooling within the coarse-grained core of the lava pond occurred at much higher temperatures than typical seawater exchange with ocean floor lavas. Late magmatic and deuteric alteration phases analyzed in this study include green secondary clinopyroxene, amphibole, secondary alkali feldspars, and chlorite as well as both brown (biotite and phlogopite) and green phyllosilicates.

Laverne (this volume) and Laverne et al. (2006) recognize for the first time the occurrence of an unusual Ti-, Ca-, and Fe-rich andraditic garnet "hydroschorlomite" associated with celadonite in black or dark green alteration halos in the deeper lavas drilled during Leg 206 (661–749 mbsf). Detailed petrological and mineralogical studies by optical microscope, electron microprobe, scanning and transmission electron microscope, and micro-Raman spectroscopy are used to characterize this hydrogarnet. Textural relationships indicate that hydroschorlomite forms at low temperatures (<100°C) by the replacement of igneous titanomagnetite contemporaneously with the formation of celadonite and saponite within alteration halos. Hydroschorlomite is an indicator of alteration at temperatures transitional from low-temperature alteration to hydrothermal conditions where titanomagnetite would be replaced by titanite.

Busigny et al. (2005) provide the first measurement of nitrogen and nitrogen isotopes of altered oceanic basement to investigate the effects of low-temperature alteration in this increasingly important stable isotope system. Secondary minerals (up to ~500 ppm) and altered rocks (1–10 ppm) are all enriched in nitrogen compared to fresh MORB, but a large range of nitrogen isotopic compositions are displayed ($\delta^{15}N$ = –2.1‰–5.8‰). Petrologic studies suggest that nitrogen in altered basalts occurs as ammonium ion (NH_4^+) hosted in secondary minerals including celadonite, K and Na feldspars, and saponite. Nitrogen isotope data support the interpretation that nitrogen in metasomatizing fluid occurred as N_2 derived from deep seawater, likely mixed with magmatic N_2 contained in basalt vesicles.

Calcium carbonate is a common secondary precipitate that fills veins and cements breccias in the upper basement as a result of low-temperature seawater-basalt interactions on the ocean ridge flanks. Coggon et al. (2004) demonstrated how calcium carbonate veins that precipitated in upper basement accurately predict the chemistry of ridge flank hydrothermal fluids, with increasing temperature, across the eastern flank of the Juan de Fuca Ridge. Continuing with this approach **Coggon et al.** (this volume) present comprehensive elemental (Ca, Mg, Sr, Fe, and Mn) and isotopic (^{13}C, ^{18}O, and $^{87}Sr/^{86}Sr$) analyses for aragonite and calcite from Site 1256.

Visible and near-infrared spectroscopy may in the future provide a means for automatic quantification of hydration of basaltic cores during seawater alteration of the basement. **Kerneklian and Jarrard** (this volume) utilize a calibration developed from measurements of other basement sites of the spectral response of visible and near-infrared spectroscopy (VNIS) against geochemical measurements of structural water percentage. They then applied this calibration to numerous measurements of Leg 206 cores to estimate variations in hydration and smectite abundance throughout the lavas drilled at Site 1256.

Automated measurements of bulk physical properties of hard rock cores made using the shipboard multisensor track are commonly disregarded because of the difficulties of dealing with irregular and discontinuous cores. **Jarrard and Kerneklian** (this volume) present new shore-based measures of bulk density, porosity, and matrix density, and they reprocessed the shipboard multisensor track measurements to minimize the effects of core segmentation and calibration problems.

Accurate knowledge of the volcanostratigraphy of the ocean crust is vital to understand processes of crustal construction and submarine magmatism and to estimate chemical exchange with seawater. However, this is most often not achieved because of very low rates (0%–40%) of core recovery in most basement holes. Core-log integration is also the only method to reorient ODP/IODP cores that become rotated about the vertical during drilling. Because of the low magnetic latitude of Site 1256, reorientation to a geographic framework is essential to determine the true geometry of paleomagnetic vectors and structural features and the origin of marine magnetic anomalies. **Tartarotti et al.** (this volume) reoriented brittle structures in cores from the thick ponded flow (igneous Unit 1256D-1) to the geographic coordinates by correlating structures observed on the core with unoriented images of the exterior of the core obtained by scanning whole-core pieces with the Deutsche Montan Technologie (DMT) digital color core-scanner. These data are then matched with oriented borehole images from continuous wireline measurements such as those obtained using the Formation MicroScanner (FMS)-sonic (Dipole Shear Imager [DSI]) tool string and the Ultrasonic Borehole Imager (UBI) that can be oriented to magnetic north using the general purpose inclinometer tool.

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Leg 206 Scientific Party

Co-Chief Scientists: Douglas Wilson and Damon Teagle
Staff Scientist: Gary Acton
Shipboard Science Party: Jeffrey Alt, Neil Banerjee, Samantha Barr, Rosalind Coggon, Kari Cooper, Laura Crispini, Florence Einaudi, Shijun Jiang, Ulrich Kalberkamp, Marcie Kerneklian, Christine Laverne, Holly Nichols, Rachel Sandwell, Paola Tartarotti, Susumu Umino, and Christa Ziegler

REFERENCES

Alt, J.C., and Teagle, D.A.H., 2003. Hydrothermal alteration of upper oceanic crust formed at a fast-spreading ridge: mineral, chemical, and isotopic evidence from ODP Site 801. *Chem. Geol.,* 201(3–4):191–211. **doi:10.1016/S0009-2541(03)00201-8**

Busigny, V., Laverne, C., and Bonifacie, M., 2005. Nitrogen content and isotopic composition of oceanic crust at a superfast spreading ridge: a profile in altered basalts from ODP Site 1256, Leg 206. *Geochem., Geophys., Geosyst.,* 6(12):Q12O01. **doi:10.1029/2005GC001020**

Cande, S.C., and Kent, D.V., 1995. Revised calibration of the geomagnetic polarity timescale for the Late Cretaceous and Cenozoic. *J. Geophys. Res.,* 100(B4):6093–6096. **doi:10.1029/94JB03098**

Carbotte, S., Mutter, C., Mutter, J., and Ponce-Correa, G., 1997. Influence of magma supply and spreading rate on crustal magma bodies and emplacement of the extrusive layer: insights from the East Pacific Rise at lat 16°N. *Geology,* 26(5):455–458. **doi:10.1130/0091-7613(1998)026<0455:IOMSAS>2.3.CO;2**

Coggon, R.M., Teagle, D.A.H., Cooper, M.J., and Vanko, D.A., 2004. Linking basement carbonate vein compositions to porewater geochemistry across the eastern flank of the Juan de Fuca Ridge, ODP Leg 168. *Earth Planet. Sci. Lett.,* 219(1–2):111–128. **doi:10.1016/S0012-821X(03)00697-6**

Cooper, K.M., Elliott, T.R., and Teagle, D.A.H., 2004. Lithium isotopic composition of altered oceanic crust at ODP Site 1256, Leg 206 [14th Annual V.M. Goldschmidt Conference, Copenhagen, Denmark, 5–11 June 2004].

Crispini, L., Tartarotti, P., and Umino, S., 2006. Microstructural features of a subaqueous lava from basaltic crust off the East Pacific Rise (ODP Site 1256, Cocos plate). *Ofioliti,* 31:117–127.

Expedition 309 Scientists, 2005. Superfast spreading rate crust 2: a complete in situ section of upper oceanic crust formed at a superfast spreading rate. *IODP Prel. Rept.,* 309. **doi:10.2204/iodp.pr.309.2005**

Expedition 309 and 312 Scientists, 2006. Superfast spreading rate crust 3: a complete in situ section of upper oceanic crust formed at a superfast spreading rate. *IODP Prel. Rept.,* 312. **doi:10.2204/iodp.pr.312.2006**

Farrell, J.W., Raffi, I., Janecek, T.C., Murray, D.W., Levitan, M., Dadey, K.A., Emeis, K.-C., Lyle, M., Flores, J.-A., and Hovan, S., 1995. Late Neogene sedimentation patterns in the eastern equatorial Pacific Ocean. *In* Pisias, N.G., Mayer, L.A., Janecek, T.R., Palmer-Julson, A., and van Andel, T.H. (Eds.), *Proc. ODP, Sci. Results,* 138: College Station, TX (Ocean Drilling Program), 717–756. **doi:10.2973/odp.proc.sr.138.143.1995**

Laverne, C., Grauby, O., Alt, J.C., and Bohn, M., 2006. Hydroschorlomite in altered basalts from Hole 1256D, ODP Leg 206: the transition from low-temperature to hydrothermal alteration. *Geochem., Geophys., Geosyst.,* 7(10):Q10003. **doi:10.1029/2005GC001180**

Macdonald, K.C., Fox, P.J., Alexander, R.T., Pockalny, R., and Gente, P., 1996. Volcanic growth faults and the origin of Pacific abyssal hills. *Nature (London, U. K.),* 380(6570):125–129. **doi:10.1038/380125a0**

Macdonald, K.C., Haymon, R., and Shor, A., 1989. A 220 km^2 recently erupted lava field on the East Pacific Rise near lat 8°S. *Geology,* 17(3):212–217. **doi:10.1130/0091-7613(1989)017<0212:AKRELF>2.3.CO;2**

Phipps Morgan, J., and Chen, Y.J., 1993. The genesis of oceanic crust: magma injection, hydrothermal circulation, and crustal flow. *J. Geophys. Res.,* 98:6283–6297.

Plank, T., Ludden, J.N., Escutia, C., et al., 2000. *Proc. ODP, Init. Repts.,* 185: College Station, TX (Ocean Drilling Program). **doi:10.2973/odp.proc.ir.185.2000**

Purdy, G.M., Kong, L.S.L., Christeson, G.L., and Solomon, S.C., 1992. Relationship between spreading rate and the seismic structure of mid-ocean ridges. *Nature (London, U. K.),* 355(6363):815–817. **doi:10.1038/355815a0**

Sadofsky, S., Hoernle, K., Hauff, F., Werner, R., and Garbe-Schönberg, D., in press. Trace element and Sr-Nd-Pb isotope geochemistry of the sedimentary and upper igneous section of the subducting Cocos plate offshore of Central America: data report. *Geochem., Geophys., Geosyst.*

Tartarotti, P., Crispini, L., and the IODP Expeditions 309 and 312 Shipboard Scientific Parties, 2006. ODP-IODP Site 1256 (East Pacific Rise): an in-situ section of upper ocean crust formed at a superfast spreading rate. *Ofioliti,* 31:107–116.

Teagle, D.A.H., Alt, J.C., Umino, S., Miyashita, S., Banerjee, N.R., Wilson, D.S., and Expedition 309/312 Scientists, 2006. *Proc. IODP,* 309/312: College Station, TX (Integrated Ocean Drilling Program Management International, Inc.). **doi:10.2204/iodp.proc.309312.2006**

Teagle, D.A.H., Wilson, D.S., and Acton, G.D., 2004. The "road to the MoHole" four decades on: deep drilling at Site 1256. *Eos, Trans. Am. Geophys. Union,* 85(49):521. **doi:10.1029/2004EO490002**

Teagle, D.A.H., Wilson, D.S., Acton, G.D., and the Leg 206 Shipboard Scientific Party, 2003. ODP Leg 206: upper oceanic crust formed at a superfast spreading rate. *JOIDES J.,* 29:13–17.

Umino, S., Lipman, P.W., and Obata, S., 2000. Subaqueous lava flow lobes, observed on ROV *KAIKO* dives off Hawaii. *Geology,* 28(6):503–506. **doi:10.1130/0091-7613(2000)028<0503:SLFLOO>2.3.CO;2**

Umino, S., Obata, S., Lipman, P.W., Smith, J.R., Shibata, T., Naka, J., and Trusdell, F., 2002. Emplacement and inflation structures of submarine and subaerial pahoehoe lavas from Hawaii. *In* Takahashi, E., Lipman, P.W., Garcia, M.O., Naka, J., and Araamaki, S. (Eds.), *Hawaiian Volcanoes: Deep Underwater Perspectives*. Geophys. Monogr., 128:85–101.

Wilson, D.S., 1996. Fastest known spreading on the Miocene Cocos–Pacific plate boundary. *Geophys. Res. Lett.,* 23(21):3003–3006. **doi:10.1029/96GL02893**

Wilson, D.S., Teagle, D.A.H., Acton, G.D., et al., 2003. *Proc. ODP, Init. Repts.,* 206: College Station, TX (Ocean Drilling Program). **doi:10.2973/odp.proc.ir.206.2003**

Wilson, D.S., Teagle, D.A.H., Alt, J.C., Banerjee, N.R., Umino, S., Miyashita, S., Acton, G.D., Anma, R., Barr, S.R., Belghoul, A., Carlut, J., Christie, D.M., Coggon, R.M., Cooper, K.M., Cordier, C., Crispini, L., Durand, S.R., Einaudi, F., Galli, L., Gao, Y., Geldmacher, J., Gilbert, L.A., Hayman, N.W., Herrero-Bervera, E., Hirano, N., Holter, S., Ingle, S., Jiang, S., Kalberkamp, U. Kerneklian, M., Koepke, J., Laverne, C., Vasquez, H.L.L., Maclennan, J., Morgan, S., Neo, N., Nichols, H.J., Park, S.-H., Reichow, M.K., Sakuyama, T., Sano, T., Sandwell, R., Scheibner, B., Smith-Duque, C.E., Swift, S.A., Tartarotti, P., Tikku, A.A., Tominaga, M., Veloso, E.A., Yamasaki, T., Yamazaki, S., and Ziegler, C., 2006. Drilling to gabbro in intact ocean crust. *Science,* 312(5776):1016–1020. **doi:10.1126/science.1126090**

Ziegler, C.L., Murray, R.W., Hovan, S.A., and Rea, D.K., 2007. Resolving eolian, volcanogenic, and authigenic components in pelagic sediment from the Pacific Ocean. *Earth Planet. Sci. Lett.,* 254(3–4):416–432. **doi:10.1016/j.epsl.2006.11.049**

Figure F1. Age map of the Cocos plate and corresponding regions of the Pacific plate. 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 10- to 20-m.y. isochrons to the south reflects the extremely fast (200–220 mm/yr) full spreading rate. FZ = fracture zone.

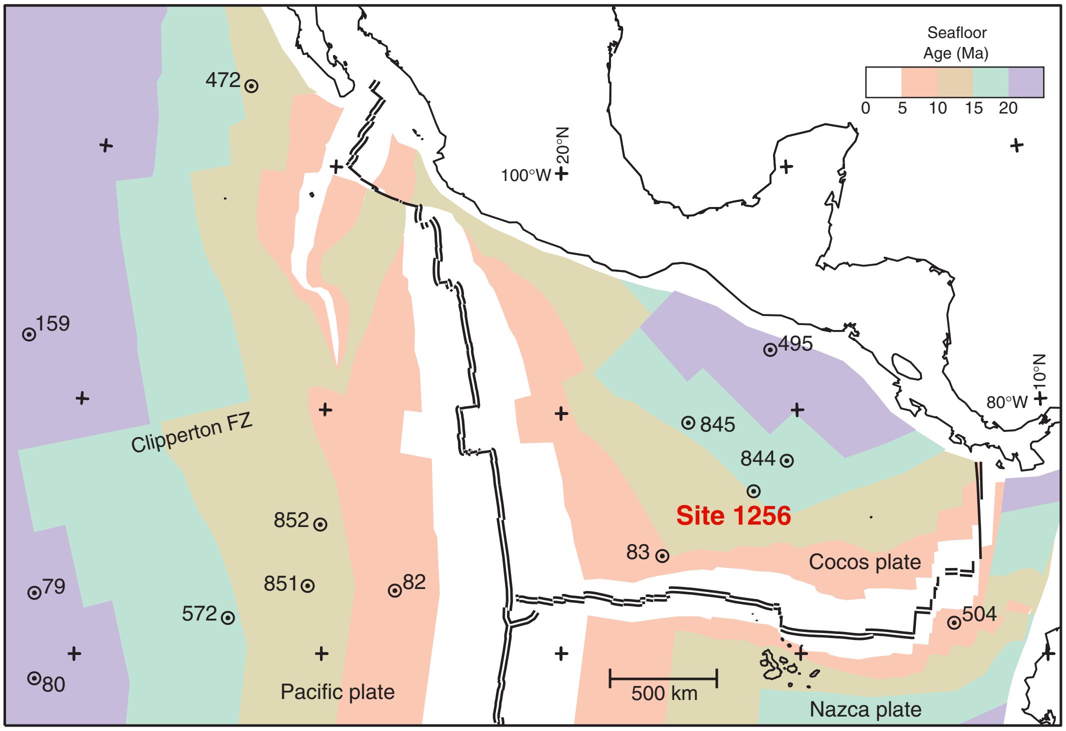

Figure F2. Depth to axial low-velocity zone plotted against spreading rate, modified from Purdy et al. (1992) and Carbotte et al. (1997). Depth vs. rate predictions from two models of Phipps Morgan and Chen (1993) are shown, extrapolated subjectively to 200 mm/yr (dashed lines). Penetration to date in Holes 504B and 1256D is shown by solid vertical lines. MAR = Mid-Atlantic Ridge, EPR = East Pacific Rise, JdF = Juan de Fuca Ridge, Lau = Valu Fa Ridge in Lau Basin, CRR = Costa Rica Rift.

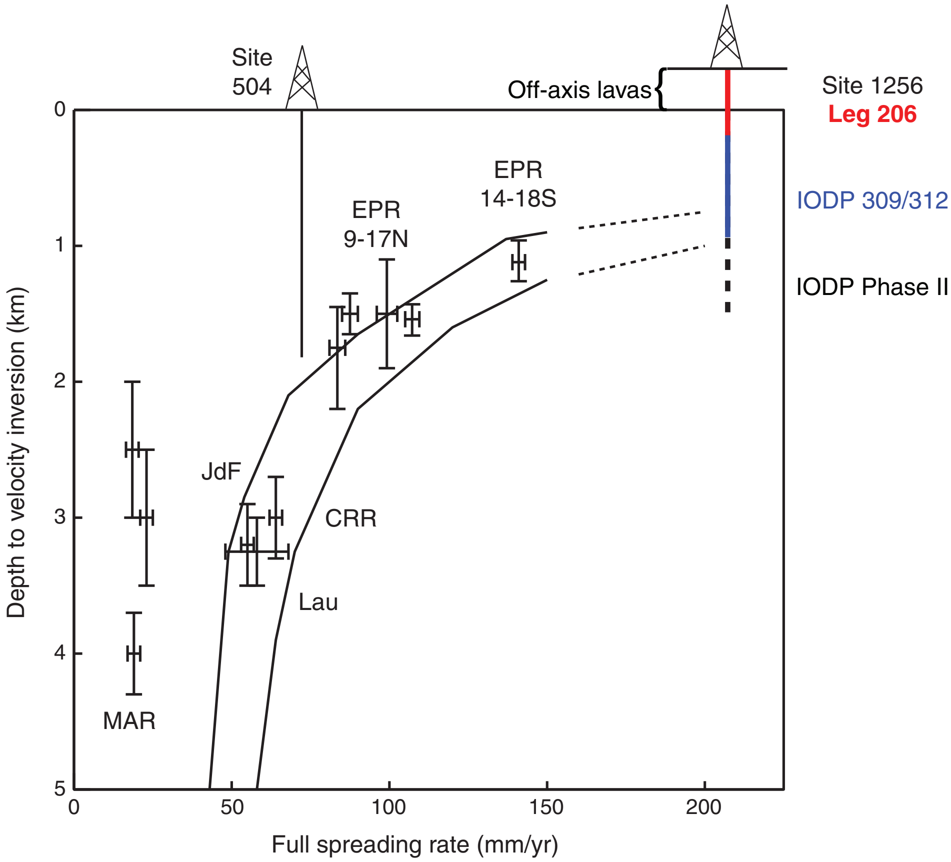

Figure F3. Schematic of the reentry cone and casing installed in Hole 1256D. TOC = top of casing, ID =inner diameter, TD = total depth.

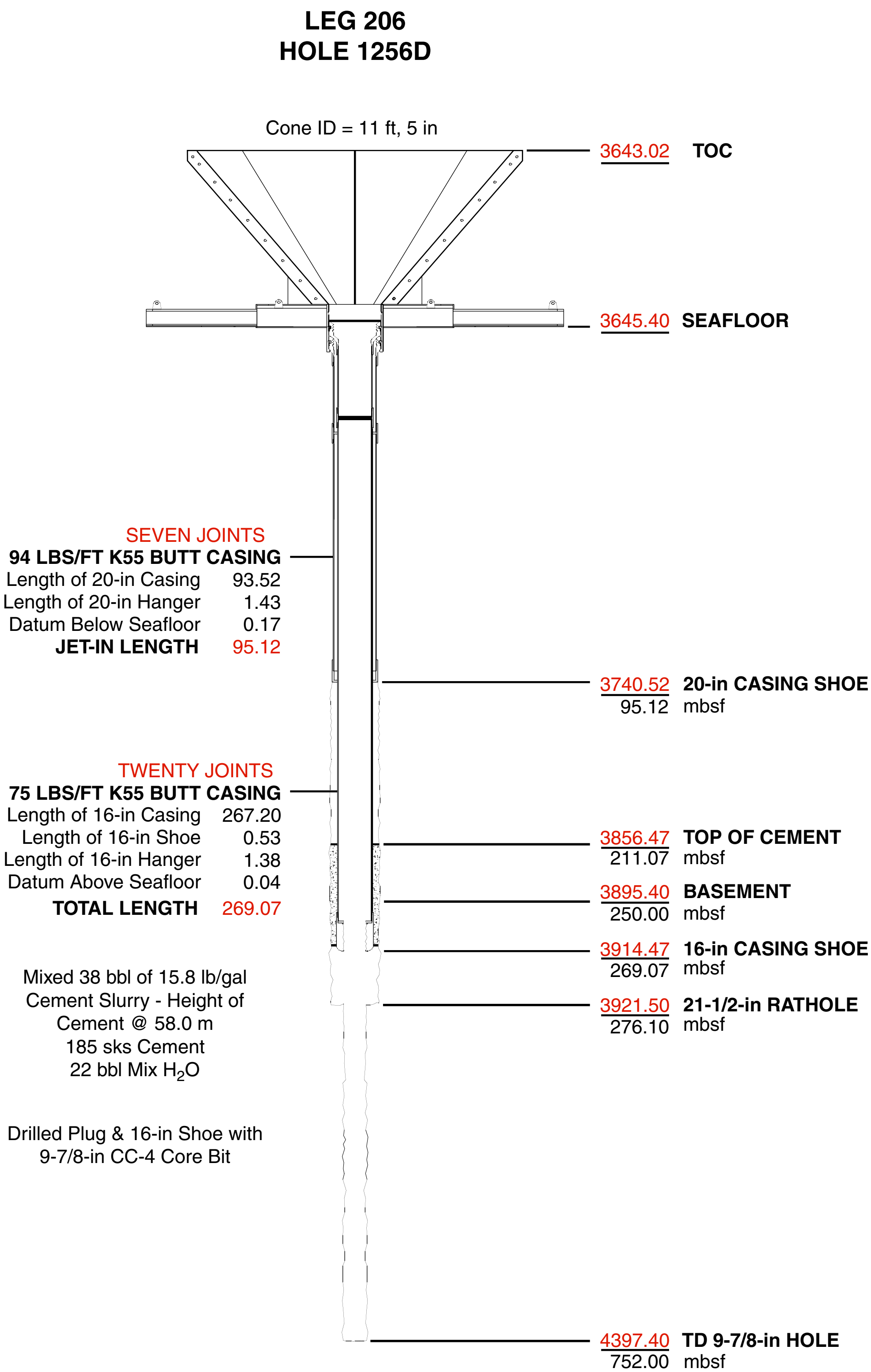

Figure F4. Simplified stratigraphic column of drilling at Site 1256 during ODP Leg 206. The basement stratigraphy is for Hole 1256D.