IODP Expeditions 304 and 305: Oceanic Core Complex Formation, Atlantis Massif

by the IODP Expeditions 304 and 305 Scientists

Scientific ocean drilling started in the early 1960s with the goal of understanding the nature of the crust–mantle boundary (the Mohorovicic discontinuity, or the Moho). This project, known as Mohole, was succeeded by the Deep Sea Drilling Project, the International Phase of Ocean Drilling, the Ocean Drilling Program, and the current Integrated Ocean Drilling Program. The major scientific goal common to all these efforts has been to recover a complete section of normal ocean crust and uppermost mantle, with the ultimate objective of understanding solid Earth cycles. This decades-old goal has not yet been fulfilled, but as geological and geophysical studies and scientific drilling have progressed over the years, we have learned a lot more about the oceanic crust. One striking discovery was that portions of slow-spreading ridges are volcanic-poor areas, classically interpreted as magma-starved regions, made of outcropping lower crust or upper mantle rocks (e.g., Cannat and Casey, 1995; Lagabrielle et al., 1998). Locally, lower crustal sections may be exposed on the seafloor by long-lived detachment faults that potentially provide a means of accessing the crust–mantle boundary. These detachment faults are exposed at the seafloor in shallow, dome-shaped features, with prominent surface corrugations trending parallel to the direction of plate spreading (e.g., Cann et al., 1997; Tucholke et al., 1998). Rocks recovered from or within a few tens of meters of the corrugated surfaces include highly deformed fault gouges and mylonites (Blackman et al., 1998; MacLeod et al., 2002; Escartin et al., 2003; Schroeder and John, 2004). The detachment faults and the corresponding series of offset tectonic blocks are referred to as oceanic core complexes (OCC), by analogy with metamorphic core complexes (e.g., Wernicke, 1981) in extensional continental terranes. The rolling hinge model (Fig. 1) of core complex formation predicts that large rotations would characterize the tectonic blocks within an OCC; as deep lithospheric rocks are exhumed along the fault, the footwall of the detachment fault (i.e., core) rolls over, laying out the geological cross section across the seafloor (Wernicke and Axen, 1988; Buck, 1988; Lavier et al., 1999).

IODP Expeditions 304 and 305 drilled on the Atlantis Massif, an OCC on the western flank of the Mid-Atlantic Ridge at 30°N (Fig. 2). Atlantis Massif formed since 1.5–2 Ma at the intersection of the Mid-Atlantic Ridge and the Atlantis fracture zone. High-density mantle rocks invoked to explain observed gravity anomalies (Blackman et al., 1998, 2004) and high seismic velocities inferred from seismic refraction analysis (Collins and Detrick, 1998) were interpreted to occur less than 1 km below the seafloor. Crust as thin as <1 km (compared to an oceanic average of 6–7 km) would result from tectonic unroofing along a series of detachment faults, and this appeared to be an ideal place to reach the Moho with the currently available ocean drilling technology.

IODP Expeditions 304 and 305 had two main objectives: (1) to document the structural and lithologic properties associated with the formation of OCCs and (2) to verify the observed increase in seismic velocity at depth, determining what role seawater alteration played, and to obtain unaltered mantle peridotite from below the Moho. To accomplish these objectives, we drilled at one site in the footwall at and below the detachment fault, and at one site in the originally overlying upper crustal (basaltic) hanging wall, which is now down-dropped to the east.
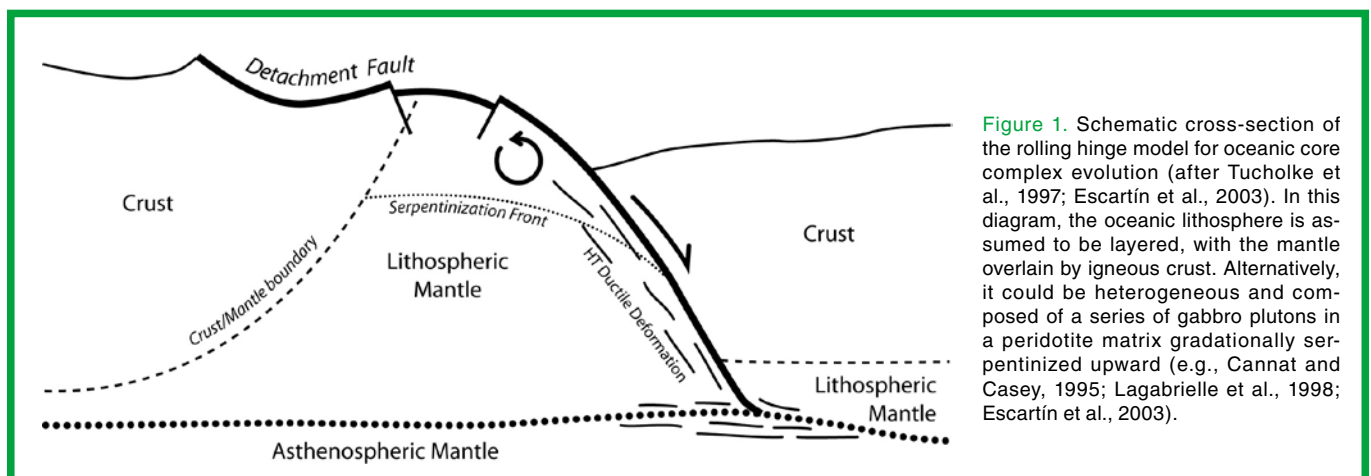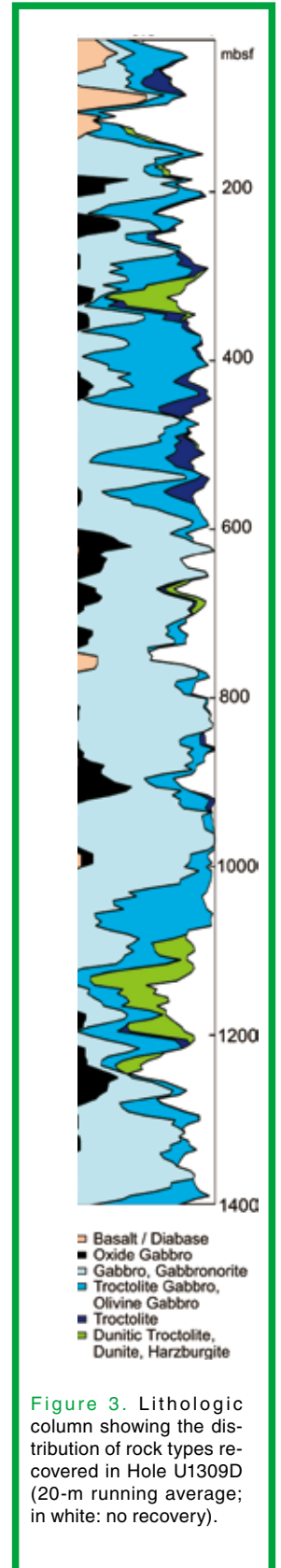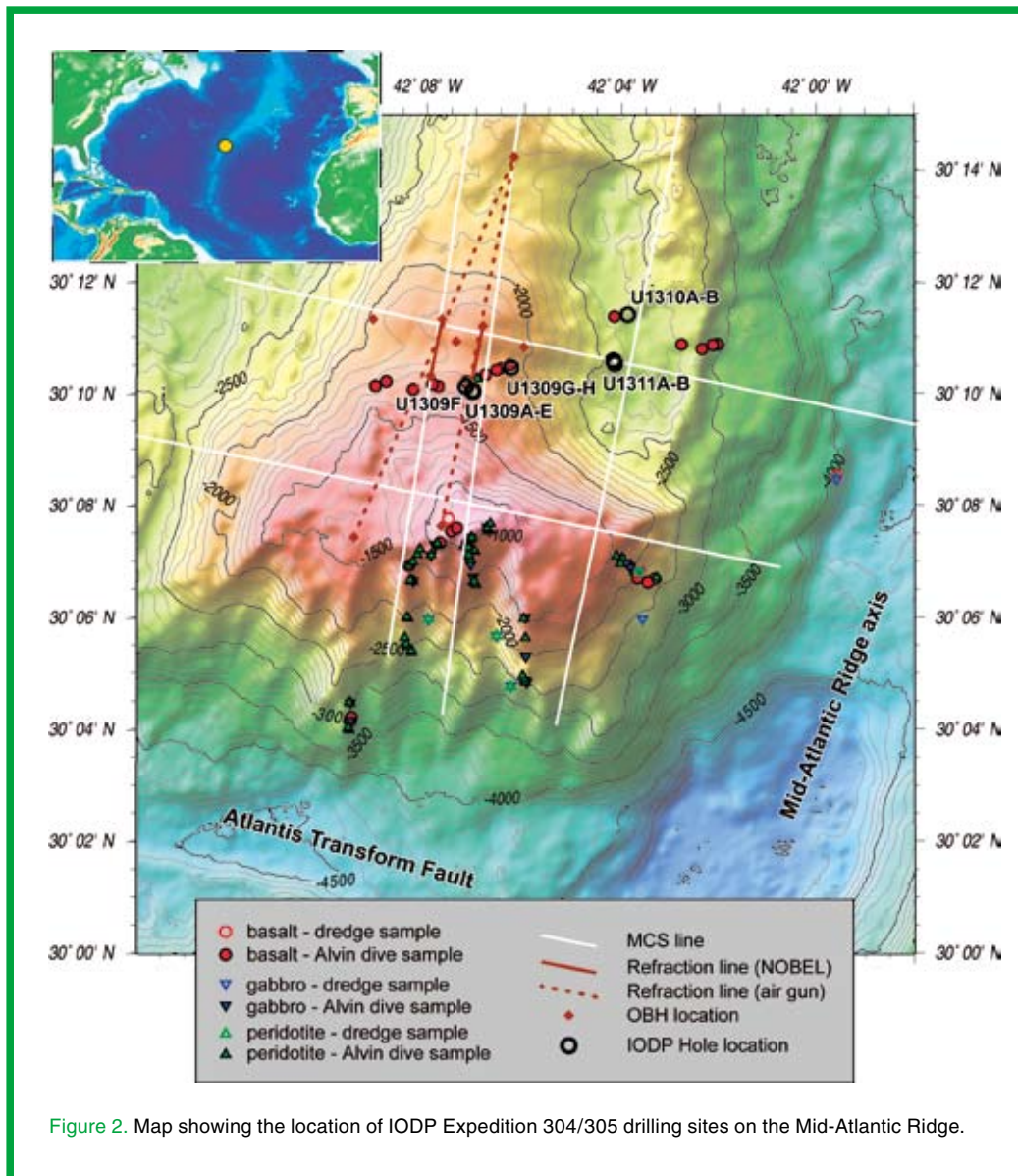

Figure 1. Schematic cross-section of the rolling hinge model for oceanic core complex evolution (after Tucholke et al., 1997; Escartín et al., 2003). In this diagram, the oceanic lithosphere is assumed to be layered, with the mantle overlain by igneous crust. Alternatively, it could be heterogeneous and composed of a series of gabbro plutons in a peridotite matrix gradationally serpentinized upward (e.g., Cannat and Casey, 1995; Lagabrielle et al., 1998; Escartín et al., 2003).

Attempts to drill the hanging wall during Expedition 304 were thwarted by difficulties associated with working in very young, fractured basalt with little sediment covering, whereas drilling at the footwall site was quite successful. A pilot hole at IODP Site U1309 (Fig. 2) on the central dome of Atlantis Massif reached just over 100 m depth. The main effort was at Hole U1309D, initiated during Expedition 304 and drilled to 401.3 mbsf with an average core recovery of 64%. During Expedition 305, the hole was deepened to 1415.5 mbsf with an average core recovery of 74.8%. Downhole geophysical measurements and electrical and acoustic imaging, together with the very high recovery accomplished in Hole U1309D, provided an unprecedented opportunity for core–log integration for a deep borehole in the oceanic lithosphere. Hole U1309D is the third-deepest hole in the oceanic crust, below the sediment cover, and the second-deepest hole in lower crustal and upper mantle rocks. At the end of Expedition 305, the hole was open and in good condition for future work.

The ~1.4-km sequence recovered from Hole U1309D was dominantly crustal rock types (Fig. 3), with basaltic rocks comprising ~3%, interlayered gabbro of highly variable grain size and modal mineralogy about 91%, and ultramafics (olivine-rich troctolite and peridotite) comprising ~5%. The gabbroic rocks have compositions that are among the most primitive sampled along the Mid-Atlantic Ridge, as reflected in Mg numbers ranging from ~67 to 90. The ultramafic rocks have distinctive textures (rounded olivines, interstitial plagioclase or clinopyroxene) and could represent the primitive end-member of the recovered mafic section. The recovery of such rocks is rare at mid-ocean ridges; in Hole U1309D the

Figure 2. Map showing the location of IODP Expedition 304/305 drilling sites on the Mid-Atlantic Ridge.

Figure 3. Lithologic column showing the distribution of rock types recovered in Hole U1309D (20-m running average; in white: no recovery).

thickest ultramafic units occur between ~1090 and 1240 mbsf and most of these have undergone some hydrothermal alteration. Locally, however, some intervals are very fresh with less than 1% or 2% serpentinization, which is unique in ocean drilling records (Fig. 4).

The structural and metamorphic history recorded in Hole U1309D is separated into high- and low-temperature phases, with little deformation occurring under intermediate (amphibolite facies) conditions. Except for the very upper part of core from Hole U1309D, neither the high- nor the low-temperature deformation show preferential geometries expected for spreading-parallel detachment faulting and associated deformation. This indicates that these processes must have occurred below conditions where large-scale ductile deformation was possible and that strain was localized in very narrow zones (1–20 m thick) that may be preferentially located in the upper few tens of meters of the footwall at Site U1309. Shipboard paleomagnetic data indicate in general little deviation (≤20˚) from the expected geocentric axial dipole orientation, especially in the upper 180 m of the hole; however, interpretations regarding the amount of tectonic rotation of the recovered sequence can only be speculative at this stage.

The nature of the recovered lithology, the fault orientations and unexpectedly low levels of the deformation within these rocks, and the apparent lack of anomalous paleomagnetic signature each present a paradox with respect to prior hypotheses. The dominantly mafic lithology challenges the model that OCCs form during periods of amagmatic rifting (e.g., Karson, 1990; Tucholke and Lin, 1994), as well as shows that the footwall of Atlantis Massif is not predominantly ultramafic, at least in the central dome region. The lack of extensive amphibolite facies deformation in the upper part of the core, together with the minor apparent rotation below the Curie temperature, appears difficult to reconcile with a single, deep-rooted, concave, normal fault as pictured in Fig. 1. The detachment fault capping the Atlantis Massif may have captured the gabbroic sequence recovered in Hole U1309D at a relatively shallow depth and transferred it to its present-day position with only minor tectonic rotation.

Clearly, we face a number of exciting challenges as we begin our post-cruise analyses. The existing geophysical data require further analysis, using existing but more complex processing methodologies to assess various 3-D subsurface possibilities suggested by the geologic results.
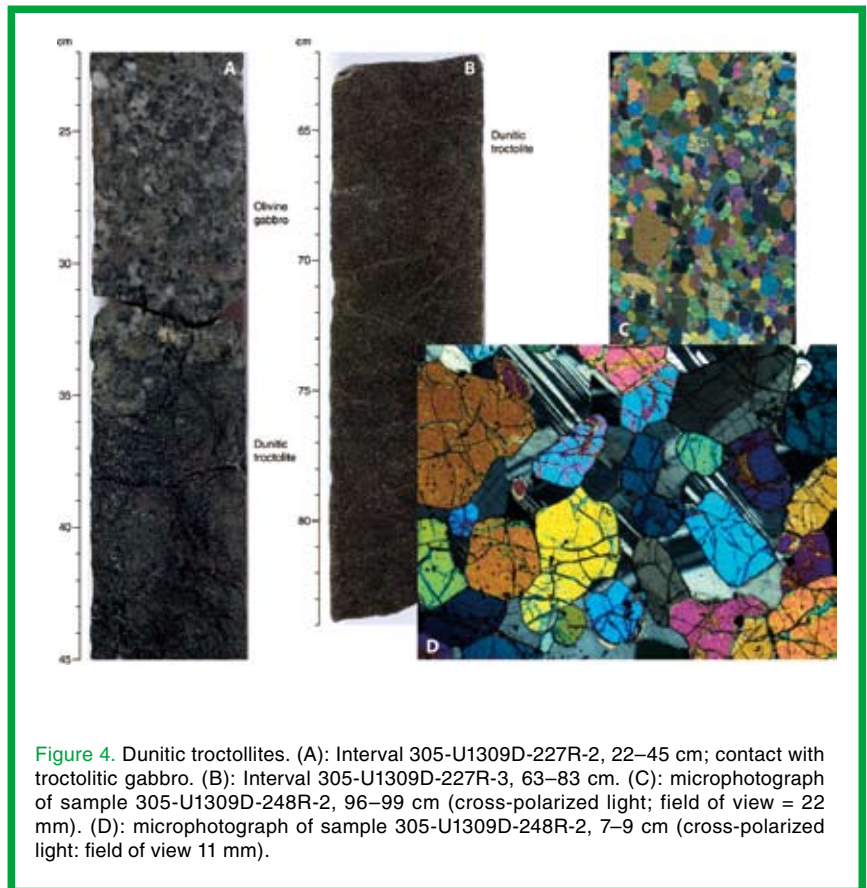

Figure 4. Dunitic troctollites. (A): Interval 305-U1309D-227R-2, 22–45 cm; contact with troctolitic gabbro. (B): Interval 305-U1309D-227R-3, 63–83 cm. (C): microphotograph of sample 305-U1309D-248R-2, 96–99 cm (cross-polarized light; field of view = 22 mm). (D): microphotograph of sample 305-U1309D-248R-2, 7–9 cm (cross-polarized light: field of view 11 mm).

The core and logging data from Hole U1309D bring an unprecedented opportunity to understand lower crustal accretion at slow-spreading ridges. The igneous sequence represents the most primitive section of crustal rocks yet obtained in the oceans, and this is further enhanced by the fact that some sections are essentially unaltered—another first for marine igneous samples. In addition, the alteration history recorded in these rocks will allow constraints to be placed on hydrothermal and structural processes that characterized the evolution of this OCC.

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