Oceanic core complexes and crustal accretion at slow-spreading ridges

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ABSTRACT

Oceanic core complexes expose gabbroic rocks on the seafloor via detachment faulting, often associated with serpentinized peridotite. The thickness of these serpentinite units is unknown. Assuming that the steep slopes that typically surround these core complexes provide a cross section through the structure, it has been inferred that serpentinites compose much of the section to depths of at least several hundred meters. However, deep drilling at oceanic core complexes has recovered gabbroic sequences with virtually no serpentinized peridotite. We propose a revised model for oceanic core complex development based on consideration of the rheological differences between gabbro and serpentinized peridotite: emplacement of a large intrusive gabbro body into a predominantly peridotite host is followed by localization of strain around the margins of the pluton, eventually resulting in an uplifted gabbroic core surrounded by deformed serpentinite. Oceanic core complexes may therefore reflect processes associated with relatively enhanced periods of mafic intrusion within overall magma-poor regions of slow- and ultra-slow-spreading ridges.

Keywords: Integrated Ocean Drilling Program, Ocean Drilling Program, oceanic lithosphere, mid-ocean ridges, Mid-Atlantic Ridge, oceanic core complex, gabbro, serpentinite.

INTRODUCTION

Oceanic core complexes (OCCs) have been recognized along both slow- and ultra-slow-spreading ridges (e.g., Tucholke et al., 1998; Cannat et al., 2006; Smith et al., 2006), and are characterized by domal bathymetric highs interpreted as portions of the lower crust and/or upper mantle denuded via low-angle normal or detachment faulting (e.g., Tucholke and Lin, 1994; Cann et al., 1997). The spreading-parallel extents of the cores of OCCs are typically tens of kilometers. OCCs are interpreted to form episodically at or near the spreading axis, beneath detachment faults that typically slip for periods of ~1–3 m.y. before becoming inactive (e.g., Tucholke et al., 1998). At slow spreading rates (i.e., <~5 cm/yr), the style of axial magmatism (both volcanism and plutonism) varies along strike and over time, and plays a key role in controlling seafloor morphology as well as the compositional architecture of the lithosphere. This has led to the concept that the oceanic crust at some slower spreading ridges is a heterogeneous "plum pudding" of discrete gabbro bodies hosted by peridotite, locally capped by a thin layer of extrusive basalt (Cannat, 1996).

Many models of OCC formation (e.g., Karson, 1990; Tucholke and Lin, 1994; Escartin et al., 2003; Buck et al., 2005) emphasize the role of reduced magma supply in the development and long-term localization of strain along detachment faults. OCCs are therefore often inferred to represent periods of reduced magmatism at a given section of the spreading segment.

Our revised model is motivated by recent deep (>100 m below seafloor, mbsf) drilling results from three OCCs: (1) Atlantis Bank, Southwest Indian Ridge, Ocean Drilling Program (ODP) Holes 735B (Robinson et al., 1989; Dick et al., 2000) and 1105A (Pettigrew et al., 1999); (2) the 15°45′N OCC on the Mid-Atlantic Ridge, ODP Site 1275 (Kelemen et al., 2004); and (3) Atlantis Massif, Mid-Atlantic Ridge, 30°N, Integrated Ocean Drilling Program (IODP) Site U1309 (Blackman et al., 2006). In this paper we emphasize new results from Site U1309, making comparisons to Hole 735B and Hole 1275D in conjunction with geophysical and geological mapping data. Although the mechanisms and structures required in our model are not new, we show that by considering the rheological properties of a heterogeneous "plum pudding" crust, a revised view emerges as to how episodes of OCC formation fit within the overall history of a given section of the mid-ocean ridge system.

ATLANTIS MASSIF, 30°N, Mid-Atlantic Ridge

Atlantis Massif formed within the past 1.5–2 m.y. (Blackman et al., 1998, 2002), and bounds the median valley on the western flank of the Mid-Atlantic Ridge (Fig. 1). The core of the massif, exposed on its upper surface by a corrugated detachment fault, comprises upper mantle rocks and gabbroic intrusions. The basaltic block to the east is interpreted as the hanging wall to the detachment fault system.

Exposures along the south face of the massif are interpreted as providing cross-sectional views into the core complex; collected samples comprise ~30% gabbro (+basalt and/or diabase dikes) and ~70% serpentinized harzburgites (Blackman et al., 2002; Karson et al., 2006).

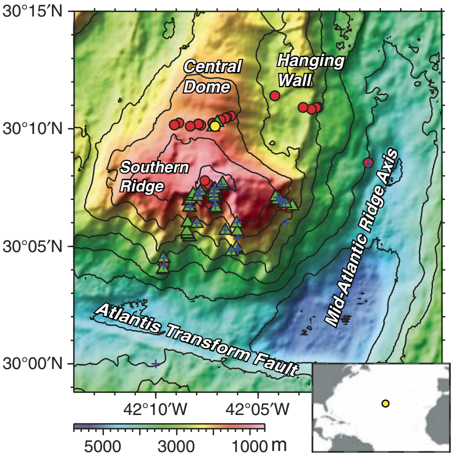

Figure 1. Bathymetric map of Atlantis Massif showing location of Site U1309 (yellow) and seafloor samples. Red—basalt, blue—gabbro, green—serpentinized peridotite.

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Gravity modeling (Blackman et al., 2002) suggests that rocks within the central and southern dome have a density 200–400 kg/m^3 greater than the surrounding rock. Rock samples from the top of the central dome are mostly angular talus and rubble of serpentinized peridotite, metabasalt, and limestone. Highly altered gabbroic veins, now dominantly talc, tremolite, and chlorite, commonly cut these rocks (Schroeder and John, 2004; Boschi et al., 2006).

IODP EXPEDITIONS 304 AND 305 RESULTS

IODP Expeditions 304 and 305 penetrated 1415.5 m of the footwall of the central dome of Atlantis Massif at Site U1309 (average core recovery 75%). Hole U1309D is dominantly gabbroic, and is thus far unique in its highly primitive nature (Fig. 2; Blackman et al., 2006). Holes U1309B and U1309D have interfingered intrusive units that vary in thickness from centimeters to ~100–200 m. Contact relations suggest that gabbro is generally intrusive into more olivine-rich rocks, and is in turn intruded by oxide gabbro and leucocratic dikes. Three thin (<1 m) intervals of ultramafic rocks interpreted as residual mantle peridotite are intercalated with gabbro in the upper 225 m of Site U1309. Diabase intrudes all rock types throughout the section, but forms a greater proportion of the core in the upper 150 mbsf. These tholeiitic basalts overlap glass compositions typical of the Mid-Atlantic Ridge. The relative intensity of alteration and vein development of intrusive contacts suggest that some of the diabase dikes were emplaced late in the history of the footwall.

Overall, the recovered section is moderately altered at conditions ranging from magmatic to zeolite facies, and little deformed (Fig. 2C). While there is a spectrum of metamorphic facies, an overall decrease in total alteration and a change in style of alteration occur with depth. Whereas the upper 380 m of the core shows an alteration profile characteristic of pervasive static infiltration of seawater with decreasing temperature, at greater depths alteration is generally restricted to halos adjacent to veins, fractures, and igneous contacts. Extensive amphibolite facies metamorphism and deformation are lacking and high-strain ductile shear zones are rare. High-strain crystal-plastic deformation is typically restricted to a few, mostly granulite grade, shear zones ranging in width from millimeters to a few meters. In many places, weak crystal-plastic deformation seems to overprint magmatic foliation. The amount of strain recorded by brittle fracture and cataclasis is limited overall, except for fault zones concentrated in the upper 150 m of Hole U1309D and a few discrete intervals downhole. Fragments of schistose talc-bearing fault rock recovered at the seafloor are likely derived from the detachment fault.

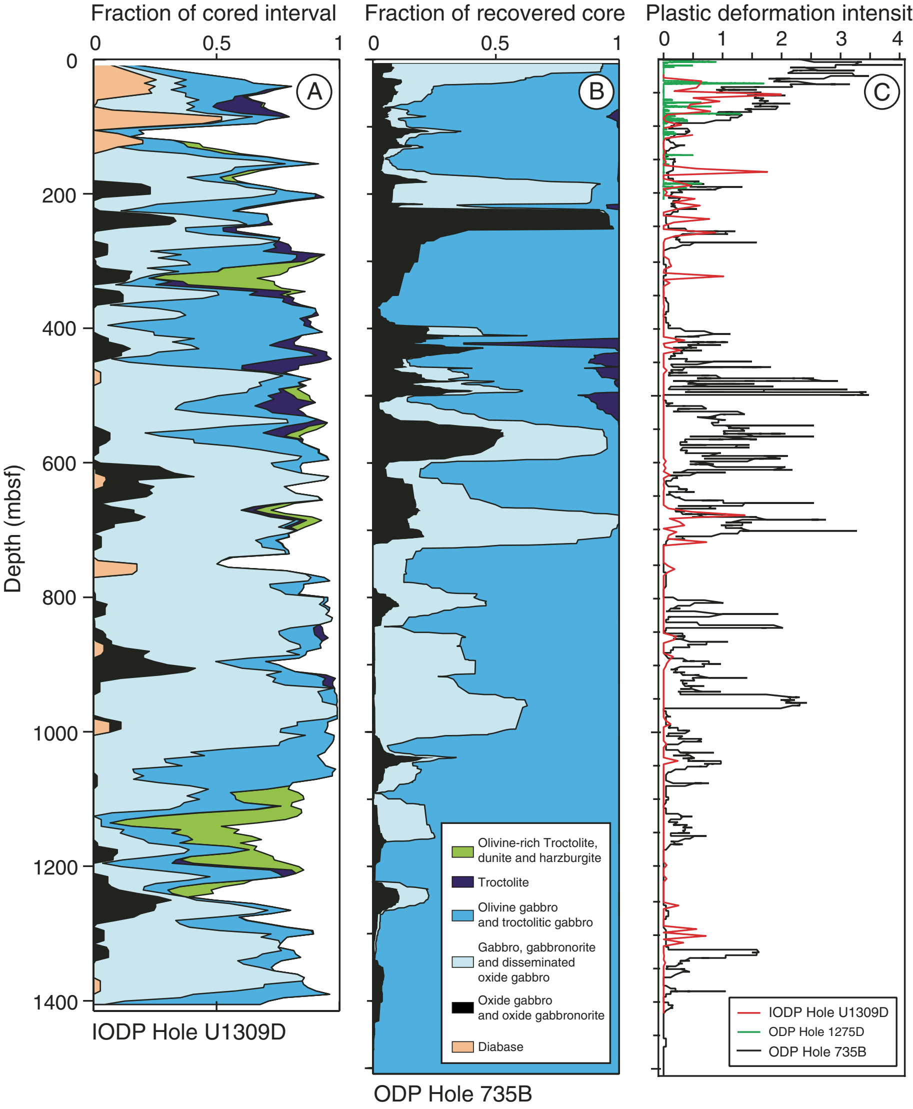

Figure 2. Summary of lithology and deformation in boreholes penetrating oceanic core complex. A: Core U1309D lithology (20 m running average). B: Core 735B lithology (20 m running average) (after Dick et al., 2000). C: Crystal-plastic deformation intensities for all cores. Deformation intensity scale: 0 = undeformed, 1 = weakly foliated, 2 = strongly foliated, 3 = porphyroclastic, 4 = mylonitic. ODP—Ocean Drilling Program; IODP—Integrated Ocean Drilling Program; mbsf—meters below seafloor.

COMPARISON WITH PREVIOUSLY DRILLED OCC

The deepest hole drilled to date in slow-spreading ocean crust is the 1508-m-deep ODP Hole 735B, at Atlantis Bank, adjacent to the Atlantis II transform and ~90 km south of the active Southwest Indian Ridge. Hole 735B recovered a gabbroic series (Fig. 2B), dominated by olivine gabbro, gabbro, and oxide gabbro (Dick et al., 2000). The 158-m-deep ODP Hole 1105A, ~1.3 km NE of Hole 735B, recovered the same rock types. Short seabed rock drill cores from the flat top of Atlantis Bank show it to be dominated by amphibolite facies gabbro mylonite with subhorizontal fabrics, suggesting that it is an OCC denuded by a detachment fault (MacLeod et al., 1999). Talc-tremolite schists, inferred to be derived from serpentinized peridotite, are described at Atlantis Bank, due west of Hole 735B (Dick et al., 2001).

In the Atlantic, an OCC has also been investigated at 15°45′N, ~25 km west of the Mid-Atlantic Ridge axis. ODP Holes 1275B and 1275D were drilled into the OCC to depths of 108.7 and 209 mbsf, respectively (Kelemen et al., 2004). Prior to drilling, this corrugated domal bathymetric high was sampled by submersible (Fujiwara et al., 2003), dredging, and an oriented seabed rock-coring device (MacLeod et al., 2002; Escartin et al., 2003). These studies suggest that a discrete (≥30 km^2 in map) body of gabbro and accompanying diabase dikes intruded peridotite. The roof of the gabbro body is tens to a couple of hundred meters below a detachment fault zone composed of talc-chlorite-tremolite schists (MacLeod et al., 2002; Escartin et al., 2003). ODP Cores 1275B and 1275D recovered troctolitic rocks above gabbroic rocks (Kelemen et al., 2004). The olivine-rich troctolites in the upper few tens of meters of the section are similar in composition and texture to those in the lower part of Hole U1309D, but were tentatively interpreted as impregnated mantle peridotite (Kelemen et al., 2004). They are interpreted on the basis of regional data to be part of the country rock to the gabbro intrusion (MacLeod et al., 2002; Escartin et al., 2003).

The similarity between Atlantis Massif and 15°45′N OCC in particular is striking. In both cases serpentinized peridotites are exposed on the seafloor but nearly absent in deep boreholes. Both have fault rocks (mostly talc-chlorite-tremolite or serpentinite schists) at the seafloor and late intrusion of basaltic dikes. In both cases the gabbro bodies have undergone little high-temperature deformation. Atlantis Bank is similar in many respects, although evidence for low-temperature deformation of serpentinized peridotite is rare. The major difference between the three OCCs is the thickness and intensity of deformation recorded by the gabbroic sections (Fig. 2C). Core from Hole 735B is spectacularly more deformed than the gabbros of Sites U1309 and 1275, with extensive, high-temperature crystal-plastic plastic deformation, including numerous mylonitic shear zones as thick as 20 m (Dick et al., 2000). The upper ~100 m in Core 735B is a mylonite zone, with a downward-decreasing deformation intensity.

REVISED MODEL

Our revised model builds on the concept (e.g., Cannat, 1996) that at least part of the oceanic lithosphere formed at slow-spreading centers comprises peridotite with gabbroic intrusions in varying proportions (the "plum pudding" concept). Because significant weakening of peridotite occurs in response to even small degrees of serpentinization (Escartin et al., 1997, 2001), the peridotite host will rapidly become weaker than the solidified gabbro intrusions as cracking and fluid penetration initiate. This may occur by two complementary mechanisms: local alteration associated with magmatic fluids escaping around the edges of a mafic intrusion within peridotite, and faulting of the lithosphere to allow seawater to penetrate from above. Geological relationships at 15°45′N clearly show how extensive strain can localize on low-temperature structures once seawater has penetrated, and weak hydrous minerals formed (MacLeod et al., 2002).

We posit that "plum pudding" lithosphere at the ridge axis is likely to be rheologically heterogeneous on a plate scale because of the contrast between the stronger gabbro and weaker hydrated mantle peridotite. Ongoing extensional deformation during regional plate separation is therefore likely to be concentrated in the altered peridotites, at the margins of the larger gabbro bodies. With progressive strain weakening, displacement localizes onto fewer, larger-offset shear zones, and a single detachment fault eventually forms. Such a feedback mechanism combined with the lateral rheological heterogeneities would likely promote an asymmetric rather than symmetric style of faulting, and lead to development of the sheath-like serpentinite and/or talc-lubricated detachment around the low-strain core of the gabbro body (Fig. 3).

In light of the "plum pudding" model for the architecture of magma-poor slow-spreading ocean lithosphere (Cannat, 1996), and consequent potential for strain localization around the gabbro bodies, it follows that most or many OCCs should have a gabbroic core. It is clear that magma supply to slow-spreading ridges can be episodic; some episodes may generate intrusion of larger magma bodies (Figs. 3B, 3C). Such episodes could be related to enhanced melt delivery from the underlying mantle, and/or (when OCCs are located at segment ends) enhanced melting at the segment center and along-axis magma transport. If the intrusion occurs at the base of the lithosphere, it would be surrounded by fresh peridotite and would thus be buoyant; alternatively it could be emplaced at shallower levels directly, possibly intruded up shear zones (Allerton and MacLeod, 1998). As magmatic activity wanes, continuous spreading results in stretching of the lithosphere, accommodated by conjugate normal faults (Fig. 3D), enabling uplift of gabbro and mantle blocks from the base of the lithosphere (e.g., Lagabrielle et al., 1998). The lack of extensive ductile deformation within the section recovered at U1309D and at the 15°45′N OCC suggests that crystallization of the intrusion was nearly complete before large strains were achieved. In contrast, at Atlantis Bank it is clear that deformation must have accompanied or closely followed intrusion (Dick et al., 2000). In this so-far unique example, the role of surrounding serpentinized peridotites may be less critical.

Relative slip between the intrusive body when it is at depth and the overlying sequence probably reflects a combination of buoyancy (gabbro less dense than relatively fresh peridotite) and spreading forces (uplift and transfer via alternating axial faults). The gabbro body rises to the depth where it is captured by a fault that becomes the long-lived detachment fault to unroof the core (Fig. 3E). The shallow dip and longevity of the exposed detachment fault reflect the scale of the large competent gabbro body (Fig. 3F). During stages E to F (Fig. 3), diabase dikes may cut through the crystal-

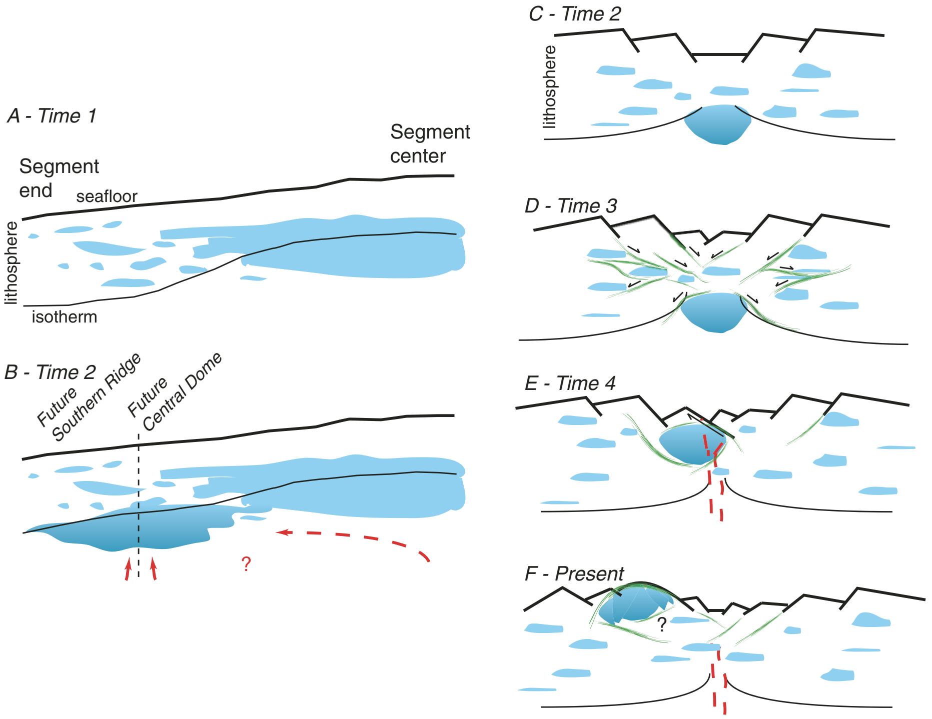

Figure 3. Sketch of revised model for oceanic core complex formation. A, B: Along-axis sections. Vertical dashed line shows location of cross sections. C–F: Spreading-parallel cross sections. For simplicity, only gabbro intrusions are pictured. White part of lithosphere is presumed to be dominantly peridotite at segment end; basalt cover, if present, is concentrated via detachment faulting toward flank opposite to core complexes.

lized gabbro body and faulted serpentinites, as observed at Site U1309, and in short cores from the 15°45′N OCC (MacLeod et al., 2002).

The model implies that serpentinized fault zones envelop the gabbro bodies, explaining the paradox of dominantly gabbroic cores in the vicinity of seafloor serpentinites on top or flanks of OCCs. Further work is required to determine the location of the peridotite-gabbro boundary at Atlantis Massif. Does the active serpentinization signature of venting at the Lost City hydrothermal field just below the peak of Atlantis Massif (Kelley et al., 2001) indicate multi-kilometer thickness of peridotite there? Or, do recent three-dimensional gravity models (Blackman and Collins, 2006) with gabbroic densities throughout the core (both central dome and southern ridge) of the massif better represent the structure? Peridotite is dominant over gabbro on the most intensively studied upper few hundred meters of the southern wall (Boschi et al., 2006; Karson et al., 2006), but the extent to which this is true for the entire southern ridge is unknown. Deep drilling on the southern ridge could provide answers and direct testing of southward extent of the gabbroic pluton sampled down to 1415 mbsf at IODP Site U1309.

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