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Oceanic Core Complex Development in Modern and Ancient Oceanic Lithosphere: Gabbro-Localized versus Peridotite-Localized Detachment Models

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ABSTRACT

q1 Drilling and submersible studies of the Atlantis Bank (Southwest Indian Ridge) and the Atlantis Massif (Mid-Atlantic Ridge) oceanic core complexes reveal “gabbro-localized” and “peridotite-localized” end-member models of strain localization and deformation during core complex development, in which the gabbroic fault rocks exhibit extensive and rare high-temperature ductile-deformation fabrics, respectively. Both models emphasize a footwall cored by gabbroic intrusions, therefore precluding an amagmatic origin of core complex formation. We test these models by using relict oceanic core complexes preserved in the western Mirdita Ophiolite in Albania. The Puka and Krabbi massifs display traits of the peridotite-localized detachment model, whereby amagmatic tectonic extension is not required for the formation of this category of core complexes.

Introduction

q2 Oceanic core complexes (OCCs) are normal-fault systems that are found along intermediate- to ultraslow-spreading mid-ocean ridges (<55 mm/yr) and are thought to be a largely tectonic manifestation of mid-ocean ridge spreading (e.g., Ohara et al. 2001; Cannat et al. 2006; Smith et al. 2006, 2008). These fault systems are distinctive dome-shaped massifs that typically exhibit ~1000 m of relief above the surrounding sea floor (Tucholke et al. 1998), and they form along mid-ocean ridge segments at locations ranging from ridge segment centers to ridge-transform intersections (Cann et al. 1997; Cannat 2006; Smith et al. 2006, 2008). Denudation of footwall rocks beneath moderate-angle, inward-dipping (toward the axis), large-offset detachment faults results in the development of domes through either passive rotation or flexure of the detachment-fault surface to low-angle orientations (e.g., Dick et al. 1981, 1992; Tucholke and Lin 1994; Lavier et al. 1999; Smith et al. 2006; Schroeder et al. 2007). Oceanic core complexes commonly expose lower-crustal and upper-mantle

rocks on the sea floor, providing an unparalleled opportunity to study oceanic lithosphere that would not otherwise be exposed.

Oceanic core complexes are regarded as “tectonic windows” into oceanic lithosphere because they expose lower-crustal and upper-mantle rocks on the sea floor (e.g., Bonatti et al. 1971; Engel and Fisher 1975; Karson 1990, 1998). At spreading rates of <55 mm/yr, magmatism and volcanism are spatially and temporally variable along ridge segments because of the ephemeral nature of the axial magma chamber. This fluctuating magma supply may lead to increased tectonic partitioning of sea-floor spreading and significant thinning and denudation of oceanic crust that promote the formation of core complexes (Sinton and Detrick 1992; Tucholke et al. 1994, 2008; Blackman et al. 1998; Buck et al. 2005). The interplay of tectonic deformation and magmatism at these mid-ocean ridges results in lithospheric architecture that is distinct from the layered, Penrose-type ophiolite sequence (cf. Dilek et al. 1998). Mid-ocean ridges with intermittent magma supply and replenishment are instead characterized by isolated gabbro intrusions within serpentinized peridotite and discontinuous volcanic cover (e.g., Cannat 1993, 1996). Studies of core com-

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plex formation are thus essential for understanding both the architecture of oceanic lithosphere and the mode, rate, and interplay of tectonic and magmatic processes operating at sea-floor spreading centers.

A few OCCs have been explored with both sea-floor sampling and deep drilling via the Ocean Drilling Program (ODP) or the Integrated Ocean Drilling Program (IODP): the Atlantis Bank, Southwest Indian Ridge (SWIR); the Kane inside corner high, 23°30'N, Mid-Atlantic Ridge (MAR); the 15°45'N core complex, MAR; and the Atlantis Massif, MAR (e.g., Karson and Lawrence 1997; Dick et al. 2000; Blackman et al. 2006; Kelemen et al. 2007). Of these core complexes, the Atlantis Bank (SWIR) and Atlantis Massif (MAR) OCCs are the sites of the deepest ODP and IODP drill holes, respectively, and they have been sampled by more submersible dives than any other drilled core complexes (fig. 1). These localities therefore offer the most thorough insight into OCC structural development. In situ

examination of these two core complexes reveals fundamental differences in the mechanisms by which strain is localized along detachment faults. In this article, (1) we summarize published results of submersible and drill core sampling to discuss the internal structure of these two core complexes and to compare and contrast their characteristic fault rocks and deformation fabrics, and (2) we use key exposures of similar detachment-fault structures preserved in ophiolites for a complementary study of detachment faulting and core complex formation. Our results suggest that the Atlantis Bank and the Atlantis Massif may represent two distinct end-member models for OCC development, which we term “gabbro-localized” and “peridotite-localized” detachment models, respectively. We suggest that the well-preserved Mirdita Ophiolite may be an ancient example of the peridotite-localized detachment model. Integrated studies of in situ and relict OCCs allow us to test these two end-member

Figure 1. Bathymetric maps of the Atlantis Bank (A) and the Atlantis Massif (B), showing the locations of Ocean Drilling Program (ODP) Hole 735B and Integrated Ocean Drilling Program (IODP) Hole 1309D (modified from Matsumoto et al. 2002; Schroeder and John 2004; Blackman et al. 2006; Atlantis Bank GMT map created by A. Graham Baines, using data from Matsumoto et al. 2002). Structural features of the detachment-fault systems are interpreted over the bathymetry and shown in green (footwall), brown (hanging wall), and gray (detachment-fault surface).

models, and they provide insight into the magmatic and tectonic processes involved in the denudation of lower-crustal and upper-mantle rocks along sea-floor spreading centers.

Structure of Oceanic Core Complexes and Current Models

Sea-floor sampling reveals that the detachment-fault surfaces of the Atlantis Massif and 15°45'N OCCs along the slow-spreading Mid-Atlantic Ridge are dominated by serpentized peridotites and fault schists (e.g., Blackman et al. 1998; MacLeod et al. 2002; Escartín et al. 2003). The ultramafic rocks recovered from these fault surfaces have been used to invoke a limited role of magmatism during core complex formation, leading to the development of many "amagmatic" models of oceanic detachment faulting (Tucholke and Lin 1994; Tucholke et al. 1998; Escartín et al. 2003). In contrast, the detachment-fault surfaces of the Atlantis Bank (SWIR) and Kane (MAR) core complexes are dominated by gabbroic and troctolitic rocks and fault schists (Karson and Lawrence 1997; MacLeod et al. 1998; Arai et al. 2000; Kinoshita et al. 2001; Matsumoto et al. 2002), leading to models of core complex development that emphasize moderate levels of magmatism during detachment faulting (Dick et al. 1992, 2000; Cannat et al. 1997; Karson 1999; MacLeod et al. 2003; Ildefonse et al. 2007). However, recent deep drilling of two core complexes thought to have developed during reduced magma supply, the Atlantis Massif and the 15°45'N, has revealed long sections (~1400 and ~200 m, respectively) of gabbroic rocks in the footwalls of both massifs (Blackman et al. 2006; Kelemen et al. 2007). The recovery of gabbroic rocks in these drill cores has prompted revision of the amagmatic models of OCC development (Ildefonse et al. 2007), leading to new models that suggest that core complexes form when 30%–50% of the total extension is accommodated by magmatic accretion, requiring significant magma intrusion into the footwalls of OCCs during detachment faulting (Tucholke et al. 2008). In light of these new models, we present two end-member models of core complex development, neither of which require amagmatic extension; instead, they differ in (1) the relative proportions of gabbro and peridotite rocks in the footwall and (2) the nature of fabric development within their respective detachment-fault shear zones.

Atlantis Bank, 32°S, SWIR: "Gabbro-Localized" Detachment Core Complex

The Atlantis Bank core complex, formed between 13 and 10 Ma, is located ~90 km south of the SWIR (fig. 1A), adjacent to the Atlantis II Transform (57°E; Dick et al. 1991b, 2000; Matsumoto et al. 2002; Baines et al. 2003; Hosford et al. 2003; Schwartz et al. 2005). Its detachment-fault system (~300 km² in area) developed initially by dipping toward the axial valley to the north, accommodating at least 15 km of slip parallel to the spreading direction (Dick et al. 2000; Matsumoto et al. 2002). The Atlantis Bank has been extensively sampled with deep drilling efforts (ODP Holes 735B and 1105A), more than 20 manned submersible dives, more than 40 short seabed rock drill cores, and more than 50 dredge hauls, all of which yielded dominantly gabbroic rocks (Dick et al. 1991a; MacLeod et al. 1998; Shipboard Scientific Party 1999b, 1999c; Arai et al. 2000; Dick et al. 2000; Kinoshita et al. 2001; Matsumoto et al. 2002). In situ rock samples collected with submersibles span roughly 3 m.yr. of crustal accretion (Schwartz et al. 2005) and are derived from structural depths between the uppermost 400 m of the footwall and the detachment-fault surface (Arai et al. 2000; Kinoshita et al. 2001; Matsumoto et al. 2002; Miranda 2006; E. A. Miranda and B. E. John, submitted).

Hole 735B penetrated ~1500 m of gabbroic rocks that consist of olivine gabbro, gabbro, and oxide gabbro (fig. 2A), and Hole 1105A penetrated ~150 m of similar gabbroic rocks (Shipboard Scientific Party 1999b; Natland and Dick 2002). Although 77% of the Hole 735B core is largely undeformed, strain is localized in the remaining intervals of the core within crystal-plastic shear zones (fig. 2B) and in brittle fault zones (Cannat et al. 1991; Shipboard Scientific Party 1999c; Dick et al. 2000). Many crystal-plastic shear zones coincide with bands of magmatic foliation development, suggesting that the onset of deformation began in the presence of melt and was followed by progressive subsolidus deformation (Cannat et al. 1991; Dick et al. 1991a, 2000). These shear zones increase in abundance and width toward the 100-m-thick main detachment-fault shear zone at the top of Hole 735B (Dick et al. 1991a, 2000). The main detachment shear zone exhibits granulite-grade mylonites that are successively overprinted by thinner, progressively lower-grade shear zones (Shipboard Scientific Party 1999c). These observations indicate that strain became localized with decreasing temperature, ultimately resulting in the development of a brittle detachment-fault zone, which was intersected in

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Figure 2. Downhole lithostratigraphic (20-m running average) and crystal-plastic fabric intensity variations for the Atlantis Bank and Atlantis Massif oceanic core complexes. *A*, Relative abundances of igneous rocks in Ocean Drilling Program (ODP) Hole 735B at the Atlantis Bank, Southwest Indian Ridge (modified from Dick et al. 2000). *B*, Downhole crystal-plastic deformation intensity in ODP Hole 735B (red) and Integrated Ocean Drilling Program (IODP) Hole 1309D (blue; modified from Shipboard Scientific Party 1999a and Expedition 304/305 Scientists 2006). The fabric intensity is classified as follows (Cannat et al. 1991): (0) undeformed; (1) weakly deformed, no penetrative foliation; (2) penetrative foliation, dynamic recrystallization limited; (3) well-foliated, extensive dynamic recrystallization; (4) mylonitic bands (1 mm), extensive dynamic recrystallization; (5) mylonitic foliation, extensive dynamic recrystallization. *C*, Relative abundances of igneous rocks in IODP Hole 1309D at the Atlantis Massif, Mid-Atlantic Ridge (modified from Expedition 304/305 Scientists 2006).

the top of Hole 735B (Dick et al. 1991a; Stakes et al. 1991). Together, the deformation textures in Hole 735B imply that detachment faulting began contemporaneously with magmatic intrusion and continued down-temperature through the ductile, semibrittle, and brittle regimes, all within gabbroic rocks (Cannat et al. 1991; Dick et al. 1991a, 2000).

Microstructural observations from in situ submersible samples collected from the Atlantis Bank core complex support the interpretations from Hole 735B (Miranda 2006; E. A. Miranda and B. E. John, submitted), and the distribution of submersible samples shows that little lateral heterogeneity exists in footwall rock composition (Arai et al. 2000; Kinoshita et al. 2001; Matsumoto et al. 2002). The submersible samples also demonstrate the presence of amphibole-chlorite schists and rare talc-tremolite schists in a ~20-m-thick zone immediately below the brittle detachment surface (Arai et al. 2000; Kinoshita et al. 2001; Matsumoto et al. 2002). The schists developed as fracture-induced infiltration of hydrous fluids promoted dissolution-precipitation creep growth of amphibole and chlorite at the expense of plagioclase, with progressive down-temperature detachment faulting (Miranda 2006; E. A. Miranda and B. E. John, submitted).

The development of submagmatic, crystal-plastic, semibrittle, and brittle fabrics within gabbroic rocks suggests that down-temperature changes in gabbro rheology resulted from synkinematic fracturing and progressive hydrous-fluid infiltration (e.g., Cannat et al. 1991; Alt and Bach 2001; Miranda 2006; E. A. Miranda and B. E. John, submitted). These processes collectively played a major role in detachment faulting and attendant strain localization at the Atlantis Bank. Detachment faulting appears to have begun contemporaneously with magmatic intrusion, continued well after crystallization of gabbroic magmas, and resulted in a complete down-temperature spectrum of fabric development in lower-crustal rocks. In this case of gabbro-localized detachment faulting, amagmatic sea-floor spreading was not required for core complex development (e.g., Dick et al. 1992, 2000; fig. 3A).

Atlantis Massif, 30°N, MAR: "Peridotite-Localized" Detachment Core Complex

The Atlantis Massif core complex formed at ~2 Ma along an east-dipping detachment fault at the intersection of the Atlantis Transform and the MAR (fig. 1B). The massif consists of a central dome and a southern ridge that have been extensively sampled by IODP drilling and submersibles, respec-

tively. Drilling in IODP Hole U1309D at the crest of the central dome resulted in the recovery of ~1400 m of dominantly primitive gabbroic and troctolitic rocks (fig. 2C; Blackman et al. 2006). The recovery of brecciated ultramafic fault schist and fractured metadiabase from the upper 20 m of the core suggest that the top of the massif is characterized by a high-strain brittle fault surface (Blackman et al. 2006). The core shows that extensive high-strain granulite-grade crystal-plastic shear zones are rare (fig. 2B) and that amphibolite-grade crystal-plastic deformation is lacking. Fracturing and cataclasis are restricted to a few narrow zones in the upper 150 m of the core.

The rock types and deformation fabrics recovered by submersibles contrast with the results from IODP Hole 1309D, suggesting lateral variability of footwall rock compositions and strain localization mechanisms. Submersible samples from the southern ridge of the Atlantis Massif core complex are comprised of (in order of decreasing abundance) serpentinitized peridotite, gabbro, and talc-amphibole-chlorite schists (Schroeder and John 2004; Boschi et al. 2006). Schroeder and John (2004) documented the development of crystal-plastic fabrics in both peridotite and gabbro at temperatures >500°C and the partitioning of semibrittle and brittle deformation into serpentinitized peridotite at lower temperatures. Other studies (Boschi et al. 2006; Karson et al. 2006) instead suggest that metasomatism and the development of mafic and ultramafic fault schists in the upper 100 m of the footwall of the detachment fault promoted strain localization and core complex development at the Atlantis Massif.

Lateral heterogeneity in footwall composition may have been the primary control on detachment faulting and attendant strain localization at the Atlantis Massif (Ildefonse et al. 2007). The combined drilling and submersible sampling suggests that detachment faulting began largely after magmatic intrusion and crystallization and resulted in mid- to low-temperature fabric development in lower-crustal and mantle rocks. The dispersed nature of gabbroic bodies within mantle rocks (Cannat 1996) suggests that enhanced conductive cooling of these nested plutons may have suppressed extensive high-temperature ductile deformation in gabbroic rocks and instead promoted strain partitioning into ultramafic rocks, resulting in a detachment-fault system localized within dominantly ultramafic rocks. Implicit in this peridotite-localized model of core complex development is the role of synkinematic fracturing in the initiation of serpentinitization and the rheological weakening of ultramafic footwall rocks (MacLeod et al. 2002; Ildefonse et

Figure 3. Schematic cross sections through the Atlantis Bank (Southwest Indian Ridge [SWIR]) “gabbro-localized” detachment core complex during active detachment faulting (A) and the Atlantis Massif (Mid-Atlantic Ridge [MAR]) “peridotite-localized” detachment core complex (modified after Escartín et al. 2003; Ildefonse et al. 2007; B). The cross sections show an interpretation of the lithospheric architecture of the core complex footwalls. The relative age and temperature of detachment fault-related fabric development in the footwall rocks are indicated by the width of the shear zone symbol; the thickest line indicates early high-temperature ductile deformation ($>800^{\circ}\text{C}$), whereas the intermediate-width and thin lines indicate later, lower-temperature semibrittle ($800^{\circ}\text{--}500^{\circ}\text{C}$) and brittle ($<500^{\circ}\text{C}$) deformation, respectively. In the gabbro-localized model, early high-temperature deformation and subsequent lower-temperature deformation are localized within gabbroic rocks. In the peridotite-localized model, early high-temperature deformation occurs within both peridotite and gabbro, but subsequent deformation is partitioned into peridotite. The primary differences between the two models include (1) the relative proportions of gabbro and peridotite rocks in the footwall and (2) the intensity of fabric development in the peridotite and gabbro footwall rocks.

al. 2007). The fabric development in both lower-crustal and mantle rocks also demonstrates that amagmatic sea-floor spreading is not required for oceanic detachment-fault development in this peridotite-localized model (fig. 3B).

Detachment Faulting Preserved in Ophiolites

Given the inherent difficulty of in situ sampling of oceanic lithosphere, ophiolites may provide a nat-

ural laboratory for testing these models of OCC development. The term “ophiolite” refers to on-land exposures of oceanic crust and mantle rocks formed in former ocean basins. Many ophiolites commonly exhibit a layered stratigraphy of pillow lava, sheeted dikes, gabbro, and peridotite, and this layered sequence is often referred to as the Penrose model of oceanic lithosphere (Anonymous 1972). Modern submersible and drilling studies of both fast-spreading ($>55\text{ mm/yr}$) and slow-spreading (<55

Figure 4. Simplified geologic map of the Puka and Krabbi massifs, Mirdita Ophiolite, Albania (modified from Nicolas et al. 1999; Meshi et al. 2009; Tremblay et al. 2009). The massifs are located in the northern region of the Western Mirdita Ophiolite. The map shows the locations (*stars*) of the field photos in figures 5 and 6. The northwest-southeast traverse of the southeastern margin of the Krabbi massif is labeled (A–A') and marked with a black line. The tremolite-chlorite amphibole schists (this study), chlorite-amphibole schists (Meshi et al. 2009; Tremblay et al. 2009), olivine-antigorite schists (Nicolas et al. 1999), and unspecified amphibole schists (all studies) are labeled trem-chl, chl-amph, ol-antig, and amph, respectively.

mm/yr) mid-ocean ridges reveals that this layered sequence is more characteristic of fast-spreading mid-ocean ridges and that slow-spreading ridges often exhibit irregular lithospheric architecture that is lacking in stratified structure and often dissected by normal fault systems (e.g., Karson 1998; Dick et al. 2006). Recognizing that oceanic lithosphere derived from slow-spreading ridges may be represented in the global ophiolite suite, some workers began to recognize “dismembered ophiolites,” that is, those that exhibit an incomplete or faulted Penrose sequence, as relict pieces of slow-spread lithosphere (e.g., Norrell and Harper 1988; Lagabrielle and Cannat 1990). It follows that OCCs, though anomalous in development (e.g., Cannat et al. 2006), may be preserved in relatively intact ophiolites that are derived from slow-spread oceanic lithosphere, although this class of ophiolite may be rare.

Mirdita Ophiolite, Albania

The Middle Jurassic Mirdita Ophiolite in northern Albania exposes 3–12-km-thick crustal and upper-

mantle rocks in a narrow corridor between the Apulian and Pelagonian microcontinents in the Balkan Peninsula and is largely unaffected by syn- and post-emplacement Alpine deformation (Nicolas et al. 1999; Dilek et al. 2005, 2008; Meshi et al. 2009). The fossil oceanic lithosphere of the Western Mirdita Ophiolite (WMO) is similar to the architecture of modern slow-spread lithosphere, exposing domed lherzolitic peridotite massifs, laterally discontinuous exposures of mylonitic gabbros, and basaltic volcanic rocks that are limited in areal extent (fig. 4). Some workers have suggested that the Puka and Krabbi peridotite massifs of the WMO formed by amagmatic tectonic extension along west-dipping detachment faults (Nicolas et al. 1999; Tremblay et al. 2009), reminiscent of older models of OCC development (e.g., Tucholke and Lin 1994; Tucholke et al. 1998).

Puka and Krabbi Massifs

In light of new models of OCC development, several features within the Puka and Krabbi massifs are

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inconsistent with amagmatic extension along detachment faults. The massifs expose mylonitic, melt-impregnated lherzolitic peridotites and less abundant gabbroic rocks that exhibit both magmatic and mylonitic fabric development (Nicolas et al. 1999). These observations suggest that melt was present in the core complex footwall, either in distributed channels within peridotite or in small crustal magma chambers, similar to the architecture of some slow-spread oceanic lithosphere (Cannat 1993). Outcrops of footwall rocks in a valley within the western part of the saddle between the two massifs expose the intrusive contact between gabbroic rocks and serpentinites, showing the structurally shallow position of the mantle rocks over the deeper plutonic rocks (fig. 5). Gabbroic intrusions within the peridotites may therefore be more widespread than those exposed at the surface, likely forming the core of massifs similar to modern OCCs.

The distribution of crust and mantle rocks in the Puka and Krabbi massifs is inconsistent with amagmatic extension. Assuming that the paleoridge segment was located to the west of the massifs (Nicolas et al. 1999), amagmatic extension along a west-dipping detachment fault would result in the initial denudation of lower-crustal rocks, followed by that of mantle rocks and their exposure in the eastern and western flanks of the massifs, respectively. According to this model, crustal rocks do not develop high-temperature ($>800^{\circ}\text{C}$) ductile fabrics during detachment faulting, because of the suppression of magmatism and associated heat. However, lower-crustal rocks are observed on the western flanks of the massifs, and high-temperature mylonitic fabrics are developed within both lower-crust and mantle rocks on the western flank of the

Puka Massif and the eastern flank of the Krabbi Massif (Nicolas et al. 1999).

Extensive development of magmatic and mylonitic fabrics in the footwall peridotites suggests that deformation associated with core complex development occurred during and shortly after the intrusion of melt. A northwest-southeast traverse across the southeast portion of the Krabbi Massif (fig. 4) reveals melt-impregnated plagioclase- and amphibole-bearing lherzolites (fig. 6A) that exhibit a thick ($>2000\text{-m}$) zone of magmatic and mylonitic in contact with gabbroic rocks to the south. Magmatic foliations (fig. 6B) are identified by alternating layers of foliated lherzolite and troctolite because of the inhomogeneous distribution of plagioclase melt impregnation through the sample. The peridotite mylonites (fig. 6C) exhibit dynamically recrystallized olivine, pyroxene, and plagioclase, indicative of deformation at granulite-grade temperatures ($800\text{--}1000^{\circ}\text{C}$; Nicolas et al. 1999; Meshi et al. 2009). These granulite-grade fabrics are synonymous with the "low-temperature" fabrics of Nicolas et al. (1999) and Meshi et al. (2009). The granulite-grade mylonitic fabrics overprint the impregnation textures in the lherzolites, suggesting that melt intrusion (in the form of impregnation) was closely followed by high-temperature ductile deformation associated with core complex development.

The gabbroic units of the footwall exhibit rare and restricted occurrences of mylonitic and magmatic fabrics. The traverse across the southeast portion of the Krabbi Massif (fig. 4) reveals granulite- and upper-amphibolite-grade ($\sim 1000\text{--}800^{\circ}\text{C}$) mylonitic fabrics, concentrated in small gabbroic veins ($\sim 10\text{ cm}$ -wide) within mantle rocks (fig. 6D), and isolated occurrences of mylonitic fabrics (fig.

Figure 5. Intrusive contact between gabbro and serpentinitized peridotite. The serpentinite is located structurally above gabbroic plutonic rocks in the saddle between the Krabbi and Puka massifs. Location of photo is shown in figure 4. A color version of this figure is available in the online edition or from the *Journal of Geology* office.

Figure 6. *A*, Impregnated mantle peridotite in the Krabbi Massif. *B*, Magmatic foliation in peridotite of the Krabbi Massif. *C*, Granulite-grade mylonitic fabric in peridotite of the Krabbi Massif. *D*, Mylonitic gabbroic veins within peridotite in the Krabbi Massif. *E*, Upper-amphibolite-grade mylonitic fabric in gabbroic rocks in the Krabbi Massif. *F*, Isotropic gabbro in the Krabbi Massif. *G*, Gabbros in the southwestern part of the Krabbi Massif exhibit folded magmatic foliations. *H*, Tremolite-chlorite amphibole schists interlayered with peridotite mylonites in the northern part of the Puka Massif. Locations of photos are shown in figure 4. A color version of this figure is available in the online edition or from the *Journal of Geology* office.

6E) within the ~300 m of massive gabbro nearest the contact with mantle rocks. These isolated fabrics have moderately to steeply dipping foliation oriented parallel to the contact with mantle rocks. We do not observe intense fracturing or brecciation indicative of a detachment-fault contact between the peridotites and the gabbroic units of the massifs. The remainder of the ~2-km-thick section of lower-crustal rocks along the traverse is composed of isotropic gabbro (fig. 6F). The isotropic gabbro is increasingly fractured toward the southeast, near the detachment-fault contact with volcanic rocks in the saddle between the Krabbi and Puka massifs. In the southwestern portion of the Krabbi Massif, gabbros exhibit rare magmatic fabrics (fig. 6G) nearest the contact with mantle rocks but are dominantly isotropic in texture. The restricted occurrence of magmatic and mylonitic fabrics in the gabbroic rocks near the peridotite contacts suggests that these contacts are intrusive and that deformation accompanied gabbroic intrusion into the peridotites of the footwall.

The detachment-fault zone in the footwalls of the Puka and Krabbi massifs is characterized by a ~100-m-thick shear zone of amphibole schists overlain by highly fractured fault rocks that are poorly preserved. These fault schists are tectonically overlain by intensely altered and fractured volcanic rocks of the hanging wall. We follow previous workers in attributing these amphibole schists to faulting related to core complex development (Nicolas et al. 1999; Tremblay et al. 2009). A 100-m-thick zone of chlorite-rich amphibole schists is identified along the southern margin of the Krabbi Massif (Meshi et al. 2009; Tremblay et al. 2009). We observe sphene-bearing tremolite-chlorite schists interlayered with amphibole- and spinel-bearing peridotite mylonites along the northern margin of the Puka Massif (figs. 4, 6H), and other workers have identified olivine-antigorite schists along the southern margin of the massif (Nicolas et al. 1999). The individual layers of amphibole schists and peridotite mylonites are each on a scale of a few meters thick, and they are interlayered over a total thickness of ~100 m. The tremolite-chlorite schistose foliation dips moderately to the northwest, parallel to the slope of the domed massif, and lineations plunge shallowly to the southwest. Relict porphyroclasts are observed in the tremolite-chlorite schists, suggesting that the schistose fabric overprints a mylonitic fabric. In both massifs, we observe fault schists that are confined to the contacts between volcanic crustal rocks and mantle rocks, where the schistosity is locally oriented parallel to the domed massif fault surfaces, but other

workers have documented amphibole schists within the interior of the Krabbi massif (Nicolas et al. 1999; Meshi et al. 2009).

Discussion

We suggest that the WMO Puka and Krabbi massifs are gabbro-cored OCCs that exhibit elements of the peridotite-localized detachment model and that amagmatic extension is not required for their formation (fig. 7). The exposure of abundant mantle and minor gabbroic rocks along the massif surfaces is reminiscent of lateral compositional heterogeneity of the peridotite-localized model. Melt-impregnated lherzolites (fig. 6A), dikes, and dikelets of gabbro in peridotite (fig. 6D), minor gabbro units exposed in the footwall (fig. 4; fig. 6E, 6F), and field observations of serpentinite structurally above gabbroic rocks (fig. 5) suggest that core complex development did not take place in the absence of melt. These observations also suggest a more abundant proportion of gabbroic rocks than is revealed by the surface outcrops, perhaps forming the core of the massifs, as documented in modern OCCs. However, gabbroic rocks may remain concealed within the interior of the massifs because of insufficient erosion. The absence of sedimentary basins in the topographically low regions surrounding the massifs (fig. 4) suggests limited erosion from the tops of the domes. Even moderate erosion (tens of meters) from the tops of the domes might not fully expose gabbroic rocks in the interior of the massifs. For example, from the results of IODP drilling in Hole 1275D at the modern 15°45'N OCC, there might be as much as ~70 m of ultramafic rocks structurally overlying gabbroic rocks in the core of the massifs (Kelemen et al. 2007).

The amphibole schists also suggest the presence of both peridotite and gabbroic rocks in the footwalls of the massifs. The local exposures of tremolite-chlorite schists along the massif surfaces resemble fault schists that characterize the upper 20–100 m of footwall beneath the detachment-fault surfaces of modern OCCs (Escartín et al. 2003; Schroeder and John 2004; Boschi et al. 2006; Karson et al. 2006; Miranda 2006; E. A. Miranda and B. E. John, submitted). Fluid flow from deep within the footwall and dissolution-precipitation creep processes within the detachment-fault shear zone contribute to the development of fault schists (Schroeder and John 2004; Boschi et al. 2006; McCaig et al. 2007; E. A. Miranda and B. E. John, submitted). In modern OCCs, the presence of talc and relict spinel has been used to interpret an ultramafic protolith for some fault schists (e.g., Escartín et al.

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Figure 7. Schematic cross section through the Puka and Krabbi massifs (A–A' in fig. 4), showing a reinterpretation of the massif architecture and development based on the “peridotite-localized” model of modern oceanic core complex formation (modified from Nicolas et al. 1999).

2003). The tremolite-chlorite schists in the Puka Massif do not contain talc, relict spinel, or serpentine; this is consistent with a mafic protolith. That the schists are interlayered with spinel-bearing peridotite mylonites yet do not contain spinel also suggests that they are not derived from ultramafic mylonites. The large relict porphyroclasts in some tremolite-chlorite schists are consistent with a gabbroic protolith, although other workers suggest volcanic rocks for the protolith because of their proximity to volcanic rocks of the hanging wall (Tremblay et al. 2009). However, the olivine-antigorite schists along the southern flank of the Puka Massif are consistent with an ultramafic protolith. We interpret the compositional variety of schists found in the Puka Massif as indirect evidence of the presence of gabbroic rocks within the core of the massif, and we suggest that fluid flow within gabbroic and ultramafic rocks of the Puka footwall contributed to the development of the fault schists in the detachment-fault shear zone.

Although the gabbroic rocks exposed along the surfaces of the massifs exhibit high-temperature magmatic and mylonitic fabrics, the rarity of these fabrics is consistent with the fabric development associated with footwall rocks in the peridotite-localized detachment model. The peridotites and intrusive gabbro bodies in the footwalls of the massifs both show magmatic and mylonitic fabrics, which we interpret as evidence that detachment faulting

began during melt intrusion and continued after gabbro crystallization. However, the gabbros that intrude the peridotite mylonites show significantly less hypersolidus and subsolidus deformation than do the peridotites, indicating that deformation may have been preferentially accommodated within the mantle rocks. The intrusion of magma was closely followed by hypersolidus and granulite- and upper-amphibolite-grade deformation that is concentrated in the gabbros near contacts with the peridotites, leaving the remainder of the gabbro essentially undeformed. The restricted occurrence of such fabrics may also indicate that conductive cooling of the gabbro plutons in the lithosphere suppressed the ductile deformation of gabbroic rocks below amphibolite-grade temperatures and instead resulted in strain partitioning into peridotite below upper-amphibolite-grade temperatures.

The rock types and fabrics exposed in the Puka and Krabbi massifs provide insight into the rheology of footwall rocks during core complex development. The development of high-temperature ductile fabrics in both lower-crust and mantle rocks implies comparable rheologic strength of both rock types during early stages of detachment faulting. However, the onset of synkinematic fracturing in lherzolites at 800°C (Nicolas et al. 1999) suggests that mantle rocks became rheologically weaker than lower-crust rocks as deformation changed from ductile to semibrittle in nature. The fractures

likely functioned as conduits for fluids that promoted amphibole growth in lherzolites, the onset of serpentinization, and the semibrittle deformation of mafic rocks, ultimately leading to the development of olivine-antigorite fault schists, amphibole schists within lherzolite, and tremolite-chlorite schists. The presence of fault schists within the detachment-fault shear zone suggests that strain localization was promoted by serpentinization and metasomatism of mafic and ultramafic rocks. However, the abundance of ultramafic rocks exposed along the massif surfaces suggests that strain remained localized within mantle rocks with continued detachment faulting, perhaps deflected around more competent gabbroic bodies forming the massif cores.

Conclusions

Oceanic core complexes represent exhumed lower-crustal and upper-mantle rocks in the footwalls of extensional detachment faults and commonly occur along ultraslow- to intermediate-spreading mid-ocean ridges. The igneous makeup of the footwall rocks, the occurrence of synextensional magmatism, and strain localization mechanisms affect the nature of detachment faulting and exhumation processes during core complex formation. Gabbro-localized detachments develop extensive magmatic and high-temperature ductile fabrics in lower-crustal rocks, where footwalls are dominated by lower-crust rocks, whereas peridotite-localized detachments exhibit fabric development largely within mantle rocks, where footwalls contain a smaller proportion of lower-crustal gabbroic rocks. Both models emphasize the presence of lower-crustal rocks in the footwall, precluding amagmatic extension as a mechanism for core complex development.

The subaerial exposure of the Puka and Krabbi massifs of the WMO in Albania makes them ideal analogs for testing models of OCC development, and we suggest that the geology of these massifs is consistent with a peridotite-localized model of core complex development. The occurrence of serpentinized peridotites and gabbroic rocks along the surface of the massifs suggests lateral footwall compositional heterogeneity typical of this model. The presence of magmatic and mylonitic fabrics in gabbroic and peridotite rocks indicates that detachment faulting began during the early stages of melt impregnation of the peridotites and continued during gabbro intrusion and crystallization. The abundance of fabrics in the serpentinized peridotites and the limited occurrence of fabrics in the gabbroic

rocks suggest that strain was dominantly localized within ultramafic rocks, further suggesting that gabbroic rocks may have been more rheologically competent than fractured, serpentinized, and amphibolitized peridotite during progressive strain localization associated with detachment faulting.

Our results from the Puka and Krabbi massifs yield insight into the development of modern peridotite-localized OCCs such as the Atlantis Massif (MAR). At the Atlantis Massif, the gabbroic samples collected from the southern wall via submersible exhibit far more mylonitic fabric development than the gabbroic rocks in the IODP drill core; the proportions of ultramafic rocks recovered from the two locations are 70% and 5%, respectively (Blackman et al. 2006; Karson et al. 2006). By analogy with the Krabbi Massif, the more intensely deformed gabbros at the Atlantis Massif may have been sampled close to contacts with ultramafic rocks, similar to the location of figure 6E in the Krabbi Massif (fig.), whereas the nearly undeformed gabbros from the IODP core may have been sampled from the interior of a large gabbro body, similar to the location of figure 6F. It follows from analogy with the Krabbi Massif that conductive cooling of gabbro bodies within the lithosphere may have had a substantial role in suppressing pervasive ductile deformation of gabbroic rocks at the Atlantis Massif and perhaps at other peridotite-localized core complexes. In light of the Tucholke model of core complex development (Tucholke et al. 2008), we speculate that peridotite-localized core complexes may represent the lower end (30%) of melt input to plate spreading predicted by their model and that gabbro-localized core complexes (i.e., Atlantis Bank, SWIR) may represent the upper end (50%) of melt input.

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QUERIES TO THE AUTHOR

1 A provisional running head has been added ("Oceanic Core Complex Development"). Please confirm or correct it.

2 It has been assumed that the abbreviation OCC (first used near the end of the section "Structure of Oceanic Core Complexes and Current Models") stands for "oceanic core complexes." Following journal style, the abbreviation has been defined at the earliest opportunity and used exclusively thereafter (except to begin sentences). Please confirm or correct this definition of "OCC."

3 Cannat (2006) is not listed in "References Cited." Is Cannat et al. (2006), which is cited elsewhere in the text, intended? If not, please provide a full reference entry.

4 Lavier et al. (1999) is not listed in "References Cited." Is Lavier (1999), which is listed but not cited in the text, intended? If not, please provide a full reference entry for Lavier et al. and indicate where, if at all, the Lavier work is to be cited.

5 The first sentence of this paragraph repeats much of the preceding sentence. To reduce this repetition, the preceding sentence could be deleted and this sentence could be extended as follows: "...Karson 1990, 1998); they therefore provide an unparalleled opportunity to study oceanic lithosphere that would not otherwise be exposed." Would such a change be acceptable?

6 Tucholke et al. (1994) is not listed in "References Cited." Is Tucholke and Lin (1994), which is cited elsewhere in the text, intended? If not, please provide a full reference entry.

7 In the first sentence of the paragraph, "N" has been added after "15°45'." Is this correct?

8 In the figure 1 legend, please spell out "GMT."

9 (a) Has the work cited as "submitted" been accepted for publication? If not, it will be cited in text only as "unpublished manuscript." (b) It has been conjectured that the authors are E. A. Miranda and B. E. John and that all citations of "Miranda

and John, submitted" refer to the same work. Please confirm or correct these conjectures.

10 Should "The main detachment shear zone" be "The main detachment-fault shear zone"?

11 Nicolas et al. (1999) is not listed in "References Cited." Is Nicolas and Boudier (1999), which is listed but not cited in the text, intended for the many times this work is cited? If not, please provide a full reference entry for Nicolas et al. and indicate where, if at all, Nicolas and Boudier is to be cited.

12 The sentence beginning "Gabbroic intrusions" has been revised to make the context of "more widespread than" clearer. Does the revised sentence express your intended meaning accurately?

13 In the sentence beginning "A northwest-southeast traverse," something seems to be missing after "zone of magmatic and mylonitic." Please provide the missing word(s).

14 The abbreviation LT has been deleted because it is not used again in the article.

15 In the second sentence of this paragraph, "A northwest-southeast traverse" has been changed to "The traverse" on the assumption that this is the same traverse mentioned in the preceding paragraph. Is this assumption correct?

16 The sentence beginning "However, gabbroic rocks" has been revised for simplicity. Does the revised sentence express your intended meaning accurately?

17 In the sentence beginning "By analogy with," was the "blank" figure reference in parentheses intended to refer to figure 6E? If so, it will be deleted as unnecessary. If not, please indicate which figure is to be referred to here.

18 In the last sentence of the article, the "i.e." in parentheses suggests that the Atlantis Bank is the only gabbro-localized OCC. Should "i.e." be "e.g." instead?

19 In references from some ODP publications, the number of pages has been given rather than a page range, because in the manuscript, the Alt and Bach (2001) and Natland and Dick (2002) references had what appeared to be overlapping page ranges.

20 The Karson (1990) entry has been revised (editors, full title of proceedings volume, page range). Please confirm or correct the added information.

21 Shipboard Scientific Party 1990*a* and 1999*b* have been transposed to put them in “Leg” order.

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