Hydrothermal circulation and the dike-gabbro transition in the detachment mode of slow seafloor spreading

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ABSTRACT

One of the most ubiquitous boundaries within our planet is between sheeted dikes and gabbros in fast-spreading ocean crust. This boundary marks the brittle-ductile transition at the ridge crest, and is localized by a decametric conductive boundary layer between hydrothermal circulation in the sheeted dike layer and a shallow quasi-steady-state melt lens. In contrast, at slow-spreading ridges, the crustal structure appears chaotic, with no consistent sheeted dike layer and widespread occurrences of gabbro and serpentinized peridotite on the seafloor. Recent work suggests that as much as 50% of the Atlantic Ocean crust formed by a detachment mode of seafloor spreading, including the formation of oceanic core complexes capped by long-lived, convex-upward detachment faults. These detachment faults are often associated with large hydrothermal systems in which the location of any magmatic heat source is uncertain. Here we show that detachment faults can act as thermal boundaries between gabbroic melt in the fault footwall and hydrothermal circulation in the fault zone and hanging wall, thus explaining the link between faulting and black smoker systems. We suggest that interaction between magmatism and hydrothermal circulation means that detachment faults can act as the dike-gabbro transition in the detachment mode of spreading, inevitably leading to exposure of gabbros on the seafloor through continued faulting. This concept provides a means of unifying apparently contrasting processes and crustal structures at different spreading rates.

INTRODUCTION

At fast-spreading ridges, the first-order relationship between hydrothermal circulation and magmatism is clear (Von Damm, 2004). Black smoker systems are small and closely spaced (8–15 km), and are invariably located within the zone of active volcanism (German and Lin, 2004). They extract heat from a shallow (~1.5 km below seafloor, bsf) quasi-steady-state melt lens (Fig. 1A) through a conductive boundary layer (CBL), which has to be very thin (decametric) to match the rate of heat extraction from the magma to the heat output of the black smoker system (Cann et al., 1985; Lowell and Germanovich, 2004). Fossil CBLs have been described at the dike-gabbro transition in the Troodos (Cyprus; Gillis, 2002) and Oman (France et al., 2009) ophiolites, and at Integrated Ocean Drilling Program (IODP) Site 1256 in the Pacific Ocean (Koepke et al., 2008). They are characterized by intrusive contacts between gabbro and hydrated diabase dikes, and by extremely high metamorphic temperatures of 800–1000 °C. It is important to recognize that the CBL localizes the brittle-ductile transition at the ridge crest and hence the depth of the transition from essentially ductile gabbro to the essentially brittle sheeted dike complex, probably one of the most pervasive lithological boundaries in the Earth. Hydrothermal circulation is thus a first-order control on the extremely consistent layered structure of Pacific Ocean crust.

At slow-spreading ridges, the consistent lithological layering inferred at fast-spreading ridges does not exist (Cannat, 1993). Even in magmatically robust segments, melt lenses are thought to be ephemeral and largely confined to segment centers (Singh et al., 2006). As much as 50% of crust in the Atlantic Ocean formed by a detachment mode of seafloor spreading (Escartín et al., 2008; Tucholke et al., 2008; MacLeod et al., 2009; Escartín and Canales, 2011) in which gabbro and serpentinized peridotite are exposed on the seafloor in oceanic core complexes (OCCs). OCCs form the footwalls of convex-upward oceanic detachment faults that carry 50%–100% of the plate separation velocity (Tucholke et al., 2008; Grimes et al., 2008) in the periods when they are active. At first sight, the internal structure of crust spread by the detachment mode is chaotic, but consistent patterns occur in the internal structure of OCCs (Ildefonse et al., 2007; Canales et al., 2008; McCaig et al., 2007, 2010). Several examples in the Atlantic have a gabbroic core mantled by serpentinized peridotite, and are capped by talc-tremolite-chlorite fault rocks showing strong isotopic alteration by fluids at black smoker temperatures. The aim of this paper is to show that hydrothermal circulation plays a key role in controlling these patterns of crustal structure by localizing the dike-gabbro transition within long-lived detachment faults and stabilizing slip on them.

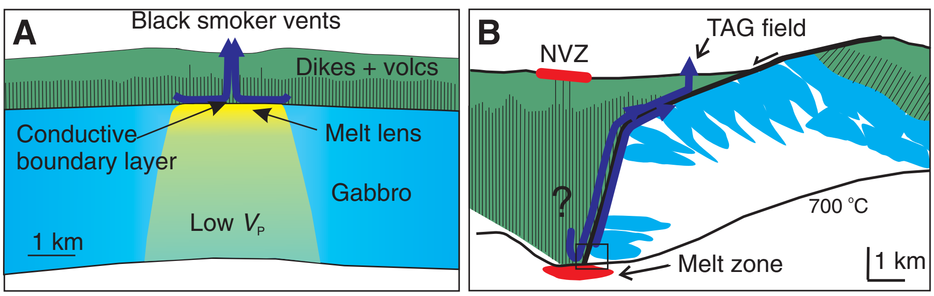

Figure 1. Hydrothermal circulation and dike-gabbro transition in fast- and slow-spreading (detachment mode) ocean crust. A: Typical situation at fast-spreading ridge (volcs—volcanics; *V*p—P wave velocity). High-level quasi-steady-state melt lens localizes both base of hydrothermal system and dike-gabbro transition. Arrows show fluid discharge paths; recharge is probably dominantly along strike. B: Model of hydrothermal discharge and detachment faulting at TAG (Trans-Atlantic Geotraverse) hydrothermal field (deMartin et al., 2007; McCaig et al., 2010). The 700 °C isotherm corresponds to base of microseismicity. Thick dike section in hanging wall is speculative, but is possible consequence of deep melt lens feeding neovolcanic zone (NVZ). Footwall gabbro geometries are also speculative, but based on previous models (Grimes et al., 2008; Escartín and Canales, 2011). Rectangle indicates area of Figure 4.

HYDROTHERMAL SYSTEMS AT SLOW-SPREADING RIDGES

At slow-spreading ridges, active black smoker systems are more widely spaced along axis (50–100 km) and have heat outputs typically an order of magnitude higher than at fast-spreading ridges (German and Lin, 2004). In magmatically robust segments, they typically occur in the neovolcanic zone, and the main difference from fast-spreading ridges is the greater depth of the axial magma chamber (~3.5 km at the Lucky Strike segment of the Mid-Atlantic Ridge, which is the one place in normal Atlantic crust where a melt lens has been imaged) and hence of hydrothermal circulation (Singh et al., 2006). In contrast, in segments spread by the detachment mode, black smoker systems are typically a few kilometers away from the neovolcanic zone and located either on the hanging wall or footwall of detachment faults (McCaig et al., 2010). Figure 1B illustrates the TAG (Trans-Atlantic Geotraverse) model in which fluid discharge is believed to be occurring up an active detachment fault from depths as great as 7 km bsf (deMartin et al., 2007). Although the TAG hydrothermal system is the only active example so far discovered in the hanging wall of a detachment fault, hydrothermal activity appears to have been highly episodic, with long dormant periods separating short (100–200 yr) periods of intense activity over the 140 k.y. lifetime of the field (Lalou et al., 1995); therefore, there may be other TAG-like systems that have not been detected because they are quiescent.

The only realistic heat source for the estimated 1000 MW heat output of the TAG field (Humphris and Cann, 2000) is crystallizing magma separated from hydrothermal fluid by a conductive boundary layer (Cannat et al., 2004; Lowell and Germanovich, 2004). Extracting heat through a migrating cracking front (Wilcock and Delaney, 1996) might explain the current heat output, but not the recurrence of activity over >100 k.y. (Lalou et al., 1995). It is likely that each episode of hydrothermal activity was driven by renewed intrusion of magma somewhere beneath the TAG field. Seismic velocities 1–3 km beneath the TAG black smoker field are anomalously high (Canales et al., 2007), and are consistent with solid gabbro in the footwall of the detachment fault, rather than partially molten rock; any sizeable melt body in the TAG system is below the 3 km bsf depth limits of available seismic tomography.

EVIDENCE FOR A DIKE-GABBRO TRANSITION IN THE ATLANTIS MASSIF

The best available model for geological relationships beneath the TAG field comes from inactive OCCs such as the Atlantis Massif at 30°N, where IODP Hole U1309D penetrated 1400 m of gabbro in the footwall of a detachment fault (Blackman et al., 2006, 2011). The fault rocks forming the roof of the massif are inferred to have been a discharge zone for hydrothermal fluids on the basis of metamorphic temperatures and strong isotopic alteration (McCaig et al., 2010). In the upper part of the hole, hydrothermally altered diabase and basalt intrusions chill both against altered gabbro and against fault breccias composed mainly of earlier metabasaltic intrusions (Fig. 2A). Analysis of the recovered core (data in Blackman et al., 2006) shows that metadiabase intrusions compose 35%–40% of the upper 130 m of IODP Holes U1309B and U1309D, whereas the remainder of Hole U1309D contains <1% diabase. The intrusions share the same paleomagnetic inclination as the host gabbros (Blackman et al. 2006), which have been shown to have undergone significant flexural rotation (Morris et al., 2009). This is compatible with intrusion before rotation of the fault zone to its current shallow attitude.

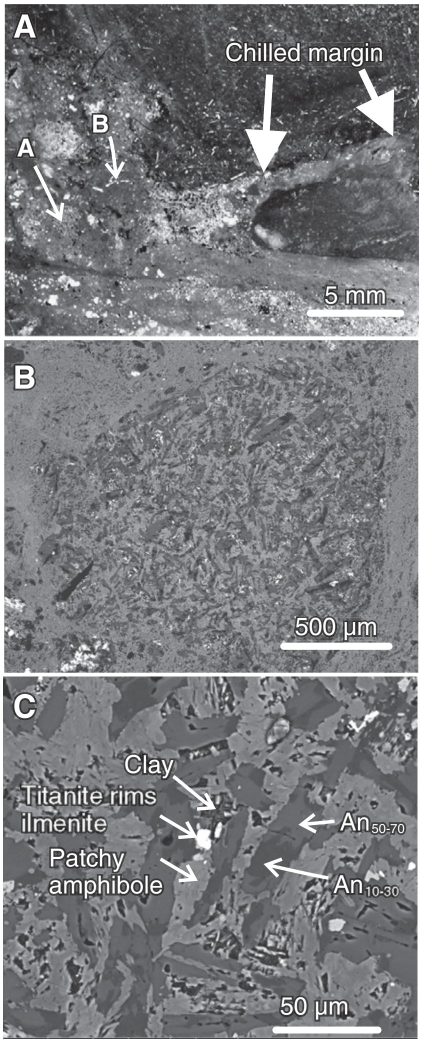

Figure 2. A: Photomicrograph of fault breccia (Integrated Ocean Drilling Program thin section U1309B-3R-1_36-38) ~20 m below seafloor, cut by metadiabase intrusion with chilled margin (arrows); A and B are clasts. B: Backscattered electron microscopy photo of clast A, showing microdiabasic texture of randomly oriented plagioclase laths surrounded by amphibole. Bright spots are Ti-rich phases as shown in C, where titanite rims ilmenite. Note extremely heterogeneous plagioclase, which is mixture of $An_{50–70}$ and $An_{10–30}$, and patchy amphibole with mixtures of Ti-rich and Ti-poor compositions. Amphibole is locally altered to clay minerals. Clast B contains skeletal plagioclase microlites (visible in A) in fine-grained matrix of granoblastic amphibole, relict clinopyroxene, and plagioclase, and is derived from chilled margin of earlier intrusion.

Amphiboles in fault breccia clasts (Fig. 2) show a very wide range in composition, from actinolite to titanian tschermakite with as much as 0.5 Ti and 1.95 Al in the formula unit (see the GSA Data Repository[1]). Geothermometry (Fig. 3) yields a bimodal temperature distribution, including a group giving exceptionally high temperatures of 840–1040 °C for metamorphic amphiboles. Amphiboles in the margin of the later diabase intrusion are mostly in the low-temperature group, but two analyses give temperatures >850 °C. Lack of equilibrium is evident from the spread of values (including unrealistic pressures) and the fact that some amphiboles show combinations of Al_2O_3 and TiO_2 that cannot be plotted in Figure 3. The normal assumption is that this represents failure to saturate the amphiboles in Al and/or Ti, and all temperature values are therefore mimina. Use of the amphibole-plagioclase geothermometer (Blundy and Holland, 1990) is hampered by lack of clear equilibrium pairs (cf. Fig. 2B), but yields somewhat lower but possibly more realistic maximum temperatures of 750–870 °C, depending on assumed plagioclase composition. While the absolute values given by the geothermometry should be treated with caution, there can be no doubt that unusually high temperature amphiboles occur. Amphiboles with high TiO_2 contents in oceanic gabbros are often ascribed to a magmatic origin (Coogan et al., 2001), but in this case, textures demonstrate a metamorphic origin, replacing pyroxene in diabase and in the matrix of a brecciated basaltic chilled margin (Fig. 2).

The rapid upward increase in the proportion of dike rocks immediately below the detachment zone suggests that it was very close to a dike-gabbro transition, even if the geometry of this may have been very different from such transitions at fast-spreading ridges. The high metamorphic temperatures in amphibole show that diabase was intruded into a hot wet environment, probably close to a magmatic heat source. Although we have not found the unequivocal evidence for gabbro intruding into and metamorphosing dike rocks seen at IODP Site 1256 and in the Troodos ophiolite, our section has been strongly overprinted by later deformation and hydrothermal activity, and we interpret the high metamorphic temperatures to have originated within a conductive boundary layer.

[1]GSA Data Repository item 2012100, Table DR1, electron microprobe data plotted in Figure 3, is available online at www.geosociety.org/pubs/ft2012.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

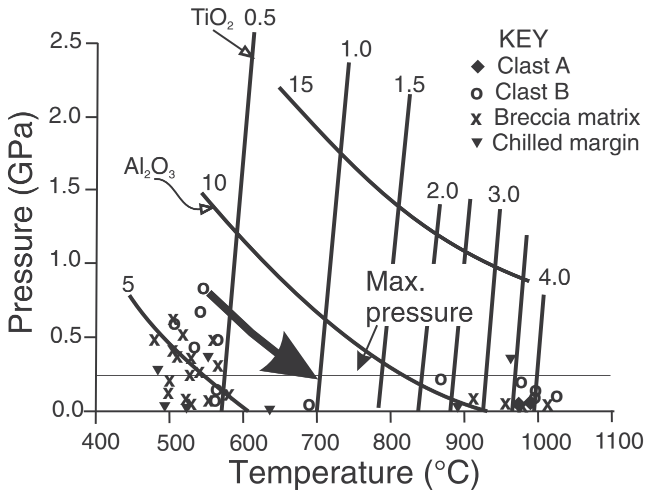

Figure 3. Amphibole data from breccia clasts A and B in Figure 2; breccia matrix and chilled margin of later intrusion were plotted using empirical geothermometer of Ernst and Liu (1998). Horizontal line shows maximum likely pressure of amphibole growth corresponding to depth of ~7 km below seafloor; amphiboles plotting above this line were probably not saturated in Ti, and estimated growth conditions can be shifted to higher temperatures, as shown by arrow. Because lack of equilibrium is most likely to be caused by undersaturation in either Al and or Ti (despite presence of buffering phases; see Fig. 2C), all temperatures should be regarded as minima, assuming that geothermometer is correctly calibrated.

DISCUSSION

Location of the Dike-Gabbro Transition and Exhumation of Gabbro

The key difference between our model (Fig. 4) and the situation at fast-spreading ridges is that because the dike-gabbro transition is located within an active detachment fault zone, it is inevitably exhumed to the seafloor together with the underlying gabbro (Fig. 1B). In this process, the CBL is strongly overprinted by brittle deformation and by the prolonged hydrothermal circulation typical of large Atlantic hydrothermal systems. At any one time, the CBL only affects a small part of the fault zone, and at higher structural levels, discharge of black smoker fluid will buffer the fault zone at ~400 °C, leading to rapid cooling of footwall gabbros toward this temperature (McCaig et al., 2010). Because melt supply at slow-spreading ridges is likely to be highly episodic, the combination of a melt body, a CBL, and active black smoker discharge may only be present for short periods in the overall slip history of the fault, and at other times the black smoker system may be dormant, as suggested for TAG (Lalou et al., 1995). The heterogeneous development of melt bodies in both time and space also means that the dike-gabbro transition is likely to have several different geometries in slow-spreading crust, only one of which is discussed here. Figure 4 also emphasizes the rotation that has probably occurred since the dikes were intruded (Morris et al., 2009), in which case the CBL (and dike-gabbro transition) is largely a lateral boundary. The asymmetry of the thermal structure that results is a very significant feature of the detachment mode of seafloor spreading (McCaig et al., 2010), the consequences of which have yet to be explored.

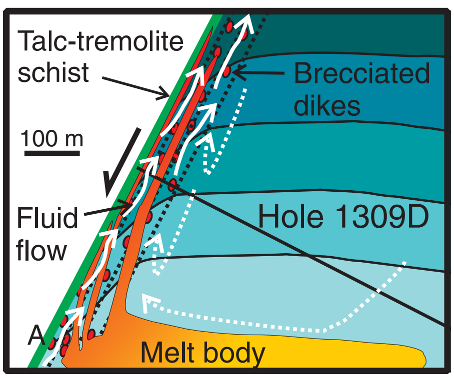

Figure 4. Model of detachment fault as conductive boundary layer (CBL) between gabbroic intrusions in footwall, and active hydrothermal circulation within fault zone. Diagram corresponds approximately to box in Figure 1B. Original orientation of Integrated Ocean Drilling Program Hole 1309D before flexural rotation is shown. Also shown are diabase intrusions emanating from melt body and chilling against earlier gabbro (shades of blue) and fault rocks containing previously broken diabase intrusions. CBL forms at A and is extensively overprinted by deformation, hydrothermal circulation, and intrusion of further diabase during exhumation. Note that gabbro intrusion probably occurs over zone in fault footwall (Grimes et al., 2008), producing more complex pattern than that shown.

Hydrothermal Control on Melt Lens Depth

Morgan and Chen (1993) modeled the correlation between melt lens depth and spreading rate at fast- and intermediate-spreading ridges in terms of a balance between melt supply and hydrothermal heat removal; they suggested that magma collects at the 1200 °C isotherm, but this model fails to predict the depth of magma chambers at slow-spreading ridges (Chen, 2004). In reality, the depth of the melt lens at fast-spreading ridges correlates just as well with the base of the hydrothermal system at 400 °C as it does with the 1200 °C isotherm, and we suggest that magma rises until it reaches a depth where the permeability is sufficiently high to allow intense hydrothermal circulation. Above this depth, heat is removed too rapidly for magma to pond, and any intrusions cool rapidly as diabase dikes or sills. At fast-spreading ridges, this depth is likely to be close to any preexisting dike-gabbro transition because of the permeability associated with fractured dike margins. Hence the melt lens continually reforms at or near the same depth, and a uniformly layered structure results. In the detachment mode of spreading, faulting can create permeability at much greater depths, allowing the approach of gabbroic magma in the footwall of a fault to trigger vigorous fluid circulation within the fault zone. This gives a mechanism for localizing the CBL, and hence the dike-gabbro transition within the fault zone, and thus for trapping episodic gabbroic intrusions in the footwall of the fault. The result is a "gabbro growth fault" (Dick et al., 2008; Schouten et al., 2010), with the volumetric strain associated with gabbro emplacement adding to the preexisting slip rate of the fault. The increased slip rate enhances the permeability due to a higher frequency of fracturing events, and further localizes hydrothermal discharge. In this way, the positive feedbacks between magmatic strain, fault slip, and hydrothermal cooling could stabilize a steep fault and allow it to evolve through slip and flexure into a long-lived convex-upward detachment.

CONCLUSIONS

At fast-spreading ridges, it is clear that axial hydrothermal circulation plays a major role in controlling the location of the dike-gabbro transition, and hence the layered structure of the ocean crust. We suggest that the very different structure of detachment mode crust at slow-spreading ridges can be explained in a similar way, with the addition that because the CBL corresponds to the detachment fault, the gabbro beneath it is exhumed onto the seafloor. The widespread occurrence of gabbro at high levels in detachment mode crust is not simply an accidental consequence of fault movement, but an expression of the same fundamental balance between magmatism and hydrothermal circulation that produces the layered structure at fast-spreading ridges. Thus, the same physical processes can explain very different crustal structures.

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