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Paired melt lenses at the East Pacific Rise and the pattern of melt flow through the gabbroic layer at a fast-spreading ridge

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ABSTRACT

From geophysics, two thin and narrow sill-like melt lenses occur directly beneath the ridge axis on the East Pacific Rise (EPR) near 9°N. One is at the base of sheeted dikes, and the other at the base of the crust in the mantle transition with largely crystalline material in between. Along-axis continuity indicates that the upper one is a steady-state feature along much of the EPR.

What causes melt to pool at two levels in the crust, with little melt in between? Normative densities of gabbro sampled from Hess Deep, eastern Pacific, at solidus temperatures are greater than melt densities calculated from compositions of basalt glass from the EPR. Therefore, abyssal-tholeiite liquids of all compositions are buoyant in a hot gabbroic crystalline matrix with no more than a few percent melt. There is therefore no level in the gabbroic layer at which pure basaltic melt attains neutral buoyancy, and by this means produces sill-like rather than dike-like intrusives. Instead, the upper melt lens appears to collect at a combined compositional and permeability barrier, defined by the coarse-grained base of the dike sequence sampled on the northern rift margin at Hess Deep. About 200 m of massive dike rocks with ophitic to subophitic coarse-grained texture occur just above gabbronorite and oxide–gabbro cumulates which are the crystallized relics of highly differentiated ferrobasaltic and ferroandesitic liquids in the melt lens. At temperatures of crystallization of cumulates at the level of the melt lens (1100–1000 °C), the basal dike rocks of less differentiated basaltic composition just above this were 90–98% crystalline, and they annealed to the point where dike contacts cannot be seen on outcrop surfaces. These slightly molten rocks need to be fractured by rift dilatancy or overpressure from beneath for magmas to ascend beyond the melt lens. Neutral buoyancy occurs in fine-grained dikes above where densities of escaping magma finally match those of the fractured and porous formation and this is the level that can be laterally intruded.

The base of the crust, on the other hand, presents an abrupt reduction in the density contrast between ascending melt and surrounding rock, and a higher concentration of melt pockets and channels. Neutral buoyancy can be attained where primitive gabbros are first encountered if the ascending magmas are picritic, laden with olivine phenocrysts. High olivine concentrations in the narrow bodies of moving magma can be attained by a combination of sinking, relative plagioclase flotation, and flow differentiation. Sill-like intrusions that crystallize to dunite and plagioclase–peridotite cumulates will result. Such rocks are found but their structural orientation is unknown at the base of the intra-rift ridge at Hess Deep; sill-like analogs are found in some ophiolites. Lateral leakage of deep melt lenses into transform faults might account for both primitive picritic tholeiites and strongly plagioclase-phyric basalts found, for example, at Siqueiros Fracture Zone at 8°30′N along the EPR.

1. Introduction

Geophysical evidence indicates that magma pools at two levels beneath fast-spreading ridges. The upper was first imaged at about 1.5 km below the sea floor by seismic reflection techniques nearly three decades ago (e.g., Ludwig et al., 1980; Herron et al., 1980). It is widespread and considered to reside just beneath the base of sheeted dikes (Kent et al., 1993). The lower melt lens is at the base of the crust, just above the mantle. Garmany (1989) proposed its presence based on seismic refraction results, and its existence was confirmed along the same portion of the East Pacific Rise (EPR) using compliance techniques (Crawford et al., 1999). Those authors considered that both lenses are thin (50–100 m), narrow (1–1.5 km), axially centered, and mostly molten. The rocks in between the two lenses are nearly solid, with no more than 2.5–18% melt, at least at the time the geophysical experiments were conducted—the variance depending on model parameters.

Ryan (1993, 1994) proposed that the upper melt lens is a sill-like body because it resides at a neutral-buoyancy horizon, where melt densities match the density of fractured and porous rock in the upper ocean crust, and thus magma tends to intrude laterally as sills rather than vertically as dikes. However, Hooft and Detrick (1993) deduced

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from seismic and drilling evidence that this density crossover is only 100–400 m below the seafloor at most places along spreading ridges, whereas all observed upper melt lenses are deeper than this. They concluded that axial thermal structure, not neutral buoyancy, must be the principal control on the depth to the shallower melt lens (cf., Phipps Morgan and Chen, 1993). Other studies have suggested that melt ponds beneath spreading ridges collect as sill-like bodies beneath permeability barriers created by freezing (Phipps Morgan et al., 1994), crystallization (Kelemen and Aharanov, 1998), or–at slowly-spreading ridges–intervals of recrystallization induced by crystal-plastic deformation (Natland and Dick, 2001).

Geophysical interpretation supports observations from the Oman ophiolite that the lowermost ocean crust consists primarily of primitive cumulates which crystallize from small, sill-like intrusives (e.g., Boudier et al., 1996; Kelemen et al., 1997), and that the entire lower crust at Oman formed in sandwich-like fashion between two bodies of melt, one at the top, and one at the base, of the gabbroic layer (Boudier et al., 1996). A complex history of intrusion and deformation also characterizes the lowermost gabbros and ultramafic rocks of the Table Mountain massif, Bay of Islands Ophiolite (Bédard, 1991, 1993; Bédard and Hébert, 1996). Whether sill-like intrusions occur in the deep ocean crust has not yet been demonstrated using exposures like those found at Hess Deep, a rift basin that exposes plutonic rocks produced at the equatorial EPR, which we consider later in this paper.

The following proceeds from the assumption that both the geophysical information and the observations on ophiolites reflect similar processes and should be considered together in models of how the ocean crust is constructed, especially at fast-spreading ridges (cf., Sinton and Detrick, 1992). Observations on rocks obtained by submersible and drilling are also now sufficient to apply to the question. We ask, how do *two* sill-like melt lenses originate at the EPR?

The presentation is keyed to illustrations summarizing textures of rocks and aspects of their chemical composition. To allow higher resolution in color, all illustrations with photomicrographs are presented in electronic format (Appendix A), but these will be cited as integral to the text. We first develop a composite chemical stratigraphy for fast-spread ocean crust, using samples obtained at Hess Deep (Fig. 1A). Next, we compare textures and compositions of fine-grained dikes, coarse-grained dikes, and high-level gabbro cumulates, to develop the notion of the presence of an igneous cap rock that traps the upper melt lens. Then we consider melt buoyancy relative to densities of gabbro cumulates, in order to demonstrate that only magmas laden with olivine crystals can inject the crust laterally at the base of the crust. Discussion of the origin and functioning of melt lenses concludes the paper.

2. The gabbro–dike transition

2.1. The composite section

A steep and uninterrupted section of the upper ocean crust occurs at an uplifted marginal horst along the northern rift wall of Hess Deep (Fig. 1B). It exposes some 1300 m of extrusive pillows, flows, and sheeted dikes, and about 600 m of gabbro. The section was sampled during *Alvin* dives in 1990 (Karson et al., 1992) and was re-examined as part of a larger near-bottom survey of the northern rift wall in 1999 (Karson et al., 2002).

Much of the lower ocean crust, presenting about 3 km of gabbro with peridotites at its base, is found on the western half of a tilted fault block, termed the intra-rift ridge, adjacent to the deepest portion of Hess Deep itself (Fig. 1C). It was sampled during *Nautile* dives in 1988 and recently using the remotely operated vehicle, *Isis* (MacLeod et al., 2008). Samples from the *Nautile* dives were described by Hékinian et al. (1993) and analyzed by Blum (1991). ODP Hole 894G was drilled near the summit of the intra-rift ridge in 1992 (Gillis et al., 1993). We combine these two sections into one composite section to consider the attributes of melt lenses in constructing the ocean crust at the EPR.

Whereas the upper part of the section exposed at the horst is simple and its structure may readily be compared to standard sections of ocean crust inferred from ophiolites or seismic studies (Fig. 2, A and B), the lower part of the section represented by the Intra-rift ridge may be internally faulted and have portions missing. It is both intruded by, and at mid-slope levels partially carapaced with, basalts derived from the tip of the Cocos–Nazca Spreading Center, which is currently propagating from the east into Hess Deep (Allan et al., 1996). Previously, the mid-slope basalt carapace was interpreted to represent extrusives and dikes of a foundered block of the EPR (Fig. 1C; Francheteau et al., 1990). However, the basalts do not have compositions of nearby *bona fide* lavas of the EPR such as those of the uplifted marginal horst. Instead they resemble basalts of the propagating rift tip (Allan et al., 1996). They are less differentiated, indeed quite primitive, with high $Mg^{\#}$, and include no ferrobasalts. They are porphyritic with olivine, plagioclase, and spinel phenocrysts. Finally, they are more depleted in light rare-earth elements.

The composite section proposed here assumes that these structural complexities do not make much difference, and that the upper and lower parts can simply be sutured, at least conceptually, because of similarities in rock types (mostly strongly differentiated gabbronorites in both cases). Gabbros of the intra-rift ridge are strongly differentiated toward the top, above the mid-slope basalts, and are much more primitive below these basalts, where both troctolites and plagioclase peridotites were obtained in submersible traverses (Hékinian et al., 1993). These latter rocks may represent a sill complex.

In the composite section, we have placed the gabbronorites of Hole 894G just below those of the northern dive locality. This is somewhat arbitrary, but even though the rocks are similar, most gabbronorites from the northern dive locality lack olivine whereas it occurs, albeit in small amounts, in gabbros of Hole 894G. Average $Mg^{\#}$ of clinopyroxene is lower and oxide gabbros are also more abundant at the northern dive locality (Natland and Dick, 1996). We have thus placed this more differentiated section higher in the composite stratigraphy. Nevertheless, the oxide gabbros at the northern dive locality may simply represent a local pocket of more differentiated magma–a lateral variability–rather than an actual shallower level, nearer dikes, in the ocean crust.

2.2. Chemical stratigraphy of the composite section

Aspects of chemical composition are shown versus depth in Fig. 2, C and D. The composite section is strung from the summit depth of the uplifted marginal horst, at 1600 m. The original depth of the seafloor was probably about 2500 m. The dashed line separates samples of this locality (above) from those of the intra-rift ridge (below). Samples analyzed from the marginal horst include extrusive basalt with glass, fine-grained dikes, coarse-grained dikes (shown as GBC, for "gabbros of basaltic composition"), gabbro cumulates (mostly gabbronorites and oxide gabbros), and one tonalitic veinlet. Over 150 samples of all of these rock types have been analyzed using X-Ray Fluorescence (Blum, 1991; Nilsson, 1993; and Table 1). Note that the term "gabbros of basaltic composition" derives from an initial field (at sea) description, and was based mainly on grain size. Some of these rocks are even coarser-grained than gabbro cumulates, despite their having the composition of simple basalts.

The main points are 1) glassy basalts, the dikes, and the "gabbros of basaltic composition" have overlapping compositions; 2) most cumulates from the uplifted horst are gabbronorites with lower Zr and higher $Mg^{\#}$ than basalts and dikes; 3) cumulates are even more primitive downward, reaching troctolitic compositions near the base of the intra-rift ridge; 4) a few cumulates from the northern dive locality are oxide ferrogabbros with higher Zr, and some of them have *lower* $Mg^{\#}$ than basalts or dikes, and also higher TiO_2. These are associated with a few, thin, tonalite/trondhjemite dikelets.