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Diverse magma flow directions during construction of sheeted dike complexes at fast- to superfast-spreading centers

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ABSTRACT

Dike intrusion is a fundamental process during upper oceanic crustal accretion at fast- to superfast-spreading ridges. Based on the distribution of magma along fast-spreading centers inferred from marine geophysical data, models predict systematic steep flow at magmatically robust segment centers and shallow magma flow toward distal segment ends. Anisotropy of magnetic susceptibility (AMS) fabrics from 48 fully-oriented block samples of dikes from upper oceanic crust exposed at Hess Deep Rift and Pito Deep Rift reveal a wide range of magma flow directions that are not consistent with such simple magma supply models. The AMS is interpreted to arise from distribution anisotropy of titanomagnetite crystals based on weak shape-preferred orientation of opaque oxide and plagioclase crystals generally parallel to AMS maximum eigenvectors. Most dike samples show normal AMS fabrics with maximum eigenvector directions ranging from subvertical to subhorizontal. The distributions of inferred magma flow lineations from maximum eigenvectors show no preferred flow pattern, even after structural correction. We use a Kolmogorov–Smirnov test (KS-test) to show that the distribution of bootstrapped flow lineation rakes from Pito Deep are not statistically distinct from Hess Deep, and neither are distinguishable from Oman and Troodos Ophiolite AMS data. Magma flow directions in sheeted dikes from these two seafloor escarpments also do not correlate with available geochemistry in any systematic way as previously predicted. These results indicate distinct compositional sources feed melt that is injected into dikes at fast- to superfast-spreading ridges with no preference for subhorizontal or subvertical magma flow. Collectively, results imply ephemeral melt lenses at different along-axis locations within the continuous axial magma chamber and either direct injection or intermingling of melt from other deeper ridge-centered or off-axis sources.

1. Introduction

Beneath surficial lava units, dike intrusion accommodates nearly all plate separation at fast- to superfast-spreading mid-ocean ridges and represents the primary mechanism of magma transport in upper oceanic crustal accretion (Curewitz and Karson, 1998; Delaney et al., 1998). Repeated incremental emplacement of subparallel dikes occurs within a narrow zone (<50 m wide) below the ridge axis (Kidd, 1977; Hooft et al., 1996), and results in the construction of sheeted dike complexes that are known from ophiolites (Kidd, 1977; Pallister, 1981; Varga, 1991; Nicolas and Boudier, 1992), seafloor escarpments (Auzende et al., 1989; Francheteau et al., 1992; Karson et al., 2002a, 2002b, 2005), and crustal drilling investigations (Alt et al., 1996; Wilson et al., 2006). Magma delivery from subaxial storage chambers to the upper crust and seafloor by dike injection is likely to have significant mechanical effects over most or all of the axial region of fast-spreading ridges, and to play an important role in development and modification of rift morphology, topography, faulting, and hydrothermal systems (Chadwick and Embley, 1998; Curewitz and Karson, 1998; Delaney et al., 1998; Soule et al., 2009). Despite the considerable influence of dikes, the details of spatial and temporal variation in magma flow during construction of the sheeted dike complex are largely unknown. Fundamentally, magma transport and emplacement into sheeted dikes within the uppermost crust relies upon the distribution of available melt stored in the axial region. Since subaxial magmatic processes cannot be directly observed, these processes must be inferred from oceanic and subaerial rift

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geophysical and geochemical data or from textural studies of dikes in exhumed rifted crust.

Dike intrusion at fast-spreading ridges is typically viewed in terms of a spreading center model with along-axis variations in magma supply based on marine geophysical and geochemical investigations of fast-spreading ridges (>90 mm yr^{-1}, full rate). These studies show that ridge segments exhibit systematic along-axis variations in axial depth (Macdonald et al., 1984; Macdonald and Fox, 1988), ridge crest morphology (Scheirer and Macdonald, 1993), basalt geochemistry (Langmuir et al., 1986; Sinton et al., 1991), and hydrothermal activity (Haymon et al., 1991). The correlation of many of these observations is commonly attributed to variations in local supply of magma along spreading segments, with increased supply at broad and shallow portions of the ridge and decreased delivery at narrower and deeper ridge sections, near axial discontinuities (Macdonald et al., 1984; Macdonald and Fox, 1988). Beneath the ridge is a triangular-shaped low-velocity zone thought to represent a region of crystal mush, or relatively low ($<18\%$) melt fraction, above the Moho (Harding et al., 1989; Toomey et al., 1990; Vera et al., 1990; Dunn et al., 2000; Crawford and Webb, 2002). At the apex of the low-velocity zone, direct evidence for the distribution of magma arises from multi-channel seismic surveys that reveal a nearly continuous reflector at $\sim$1 to 2 km depth beneath the fast- to superfast-spreading East Pacific Rise (EPR) axis (Detrick et al., 1987; Harding et al., 1989; Kent et al., 1990; Detrick et al., 1993; Kent et al., 1993a, 1993b). This reflector is interpreted as the top of an axial magma chamber (AMC), and although it appears relatively continuous, variations in S-wave velocity imply varying proportions of melt within the AMC along the EPR axis (Singh et al., 1998). Recent surveys along the EPR resolve present-day discontinuities of the AMC and characterize discrete melt lens segmentation that coincides spatially with distinct lava compositions at the surface (Carbotte et al., 2013). Spatial correlation of these data is considered to indicate that two recent eruptions were fed by vertical magma transport from three discrete melt lenses. A comparable coincidence of compositional boundaries of lavas with an axial discontinuity along the southern EPR axis are also thought to indicate vertical magma transport through dikes to the seafloor (Sinton et al., 2002; Bergmanis et al., 2007). Although mounting correlative evidence appears to support dominant vertical magma flow in dikes at fast-spreading ridges, extensive additional evidence for subhorizontal magma transport also exists from several extensional settings.

Supporting evidence for predominantly subhorizontal magma transport in dikes away from shallow crustal magma chambers into adjacent rift zones also emerges from geophysical, geochemical and geological studies from a variety of extensional regimes. Seismic, geodetic, and field observations in subaerial rift settings are consistent with incremental rifting episodes featuring several lateral dike intrusion events in Afar (Abdallah et al., 1979; Wright et al., 2006; Keir et al., 2009) and Iceland (Björnsson et al., 1977; Sigurdsson and Sparks, 1978; Björnsson et al., 1979; Brandsdottir and Einarsson, 1979). Magnetic fabric and macroscopic field evidence corroborate these studies and reveal the presence of laterally-emplaced dikes within the sheeted dike complex in the Troodos Ophiolite (Staudigel et al., 1992). Subhorizontal injection of a dike is also inferred from laterally-migrating seismic activity away from Axial Volcano, a large, isolated bathymetric high at the intermediate-spreading Juan de Fuca Ridge (Dziak et al., 1995; Dziak and Fox, 1999). Conversely, distinct geochemistries of adjacent sheeted dikes in fast-spread crust exposed at two seafloor escarpments indicate separate parental magma compositions interpreted as evidence for lateral magma emplacement from different along-axis sources (Stewart et al., 2002; Pollock et al., 2009). Additional magnetic fabric data of subset of dikes from superfast-spread crust exposed at Pito Deep Rift suggest predominantly subhorizontal magma flow (Varga et al., 2008). Recent anisotropy of magnetic susceptibility (AMS) results from Integrated Ocean Drilling Program Hole 1256D have been interpreted to reflect shallow flow (Veloso et al., 2013), though few of these dikes have the normal magnetic fabrics typically used to estimate flow directions. Thus, there appears to be some disagreement regarding the mode of magma transport during sheeted dike accretion at fast- to superfast-spreading ridges; is it dominantly vertical or horizontal?

The robust magma supply and relative continuity of the AMC at fast- to superfast-spreading ridges might be expected to result in dominantly vertical magma flow in dikes, however the abundant evidence for lateral intrusion requires a reassessment. According to a magma supply model with discrete AMC partitioning, dike intrusion at areas along the ridge axis with an increased supply of magma may be expected to have more vertical magma flow in dikes, while areas with lower supply may have more subhorizontal magma flow (Fig. 1). Assuming a steady-state system with melt continually replenishing the same long-lived melt lenses at segment centers, the persistence of magmatic segmentation would be expected to directly affect the sheeted dike complex produced at different locations along a spreading segment. Sheeted dike complexes generated near segment centers may form by mainly vertical intrusion whereas those near segment ends may be constructed by increasing proportions of laterally-intruded dikes (Fig. 1). The question is whether magma flow directions in sheeted dike complexes can be used to understand variations in AMC melt distribution and physical properties through time. If observed magma flow directions from ridge-perpendicular cross-sections of adjacent dikes are consistent with a simple magma supply model (Fig. 1), then perhaps we can extract spatial and temporal information regarding discrete AMC melt lenses along the ridge axis over geologic time. Moreover, if magma flow directions resemble one of the cross-sections through the sheeted dike complex, then these data could help constrain the location of crustal generation along the ridge axis (e.g. segment center vs. end).

We present anisotropy of magnetic susceptibility (AMS) data of fully-oriented basalt dike samples collected from two seafloor escarpments, Hess Deep Rift and Pito Deep Rift, to quantify magma flow directions in dikes injected beneath fast- and superfast-spreading centers, respectively. AMS provides a rapid measure of the orientation or distribution of magnetic minerals that typically parallels silicate fabric, and has demonstrated its utility to study magma flow directions in basalt dikes (Knight and Walker, 1988; Rochette et al., 1991; Tauxe et al., 1998; Varga et al., 1998). The AMS data of 16 and 32 fully-oriented basalt dikes measured from Hess Deep and Pito Deep Rifts, respectively, show a wide range of flow lineations within the sheeted dike complex. Although predominantly subhorizontal flow directions from a subset of Pito Deep dike samples were presented in an earlier paper (Varga et al., 2008), the full data set reveals additional complexities and a basis for comparison with Hess Deep samples. We employ a Kolmogorov–Smirnov test (KS-test) to determine if magma flow lineations in dikes from these two seafloor escarpments are statistically distinct, and whether either is distinct from other AMS data from Oman and Troodos Ophiolites. These results contradict generally accepted simple models of dike emplacement, thus indicating a more elaborate generation of sheeted dike complexes involving a range of intrusive directions from chemically-distinct dikes with implications for spatial and temporal variations of melt lenses in the axial region.

2. Tectonic setting of study areas

Only a few large seafloor escarpments along the EPR offer opportunities to study *in situ* cross-sections of oceanic crust