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Lava Geochemistry as a Probe into Crustal Formation at the East Pacific Rise

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Basalt lavas comprise the greatest volume of volcanic rocks on Earth, and most of them erupt along the world's mid-ocean ridges (MORs). These MOR basalts (MORBs) are generally thought to be relatively homogeneous in composition over large segments of the global ridge system (e.g., Klein, 2005). However, detailed sampling of two different regions on the northern East Pacific Rise (EPR) and extensive analysis of the samples show that fine-scale mapping and sampling of the ridge axis can reveal significant variations in lava chemistry on both small spatial and short temporal scales. The two most intensely sampled sites within the EPR Integrated Study Site (ISS) lie on and off axis between 9°17'N and 10°N, and from a wide region centered around 9°N where two segments of the EPR overlap (see Fornari et al., 2012, Figure 3, in this issue). The chemical composition of erupted lavas, similar to the genotype of an organism, can be used by igneous petrologists to trace the evolution of magmas from the mantle to the seafloor. The extensive and detailed geochemical studies at the EPR highlight how a thorough understanding of the variability in lava compositions on small spatial scales (i.e., between lava flows) and large spatial scales (i.e., from segment center to segment end and including discontinuities in the ridge crest) can be used in combination with seafloor photography, lava morphology, and bathymetry to provide insights into the magmatic system that drives volcanism and influences hydrothermal chemistry and biology at a fast-spreading MOR.

Comprehensive rock sampling programs in concert with in situ visual observations conducted along the 9°17'N to 10°N section of the EPR crest during 18 cruises between 1991 and 2007 recovered over 1,600 discrete lava samples using the submersible *Alvin*, the

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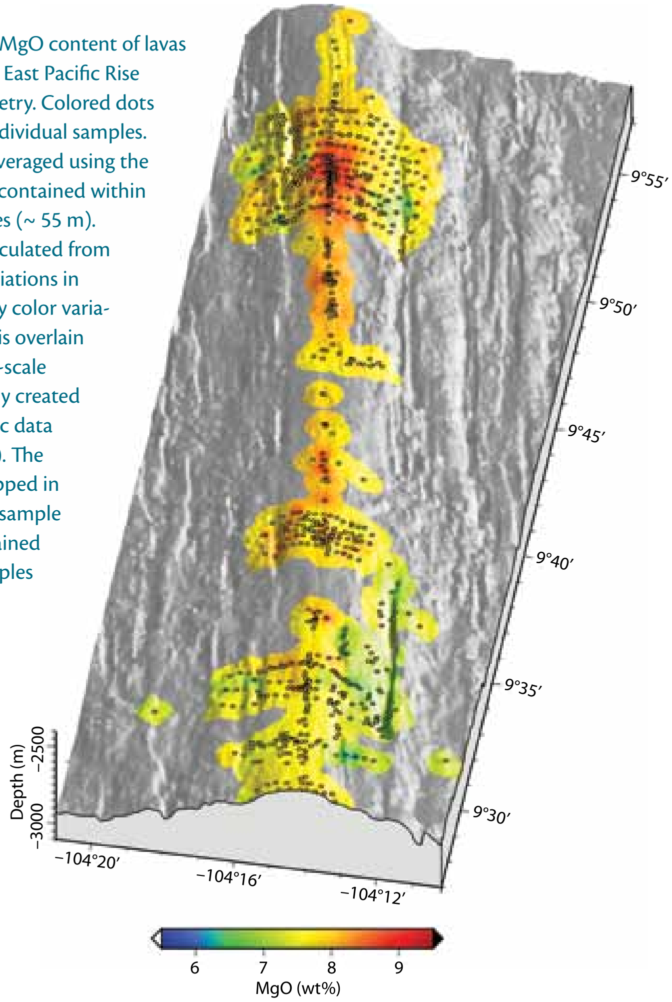

Figure 1. Spatial variation of MgO content of lavas collected from the northern East Pacific Rise overlain on seafloor bathymetry. Colored dots represent the locations of individual samples. MgO concentrations were averaged using the median value of all samples contained within a grid space of 0.0005 degrees (~ 55 m). A contoured surface was calculated from the averaged values with variations in MgO content represented by color variation (see scale). The surface is overlain on a three-dimensional gray-scale image of seafloor topography created from multibeam bathymetric data (http://www.ngdc.noaa.gov). The geochemical surface was clipped in a 1 km radius of the limit of sample locations to avoid unconstrained extrapolation where no samples have been collected.

remotely operated vehicle *Jason 2*, as well as traditional rock cores, dredges, and samples from wax balls on the TowCam digital camera system (Fornari, 2003). Along this ~ 85 km of ridge, the sample density is 14.5 samples per kilometer, making it the most densely and thoroughly sampled segment of the global MOR (Figure 1). Although most of the samples were recovered in and around the axial summit trough (AST), many were recovered from off-axis flows and constructional features across the axial plateau out to ~ 5 km (~ 100,000 years old based on the ~ 5.5 cm^{-1} half spreading rate [Carbotte and Macdonald, 1992; Fornari et al., 1998, 2004; Kurras et al., 2000; White et al., 2002; Schouten et al., 2002; Soule et al., 2005, 2007; Escartín et al., 2007; Fundis et al., 2010]).

Overall, the observed major element chemical variations in MORB from the EPR can largely be explained by shallow-level crystal fractionation in the oceanic crust (e.g., Batiza and Niu, 1986; Perfit, 2001; Perfit and Chadwick, 1998; Smith et al., 2001). However, trace element and radiogenic isotopic variations require variable sources and extents of melting in the sub-ridge mantle (Langmuir et al., 1986; Perfit et al., 1994; Sims et al., 2002, 2003; le Roux et al., 2006; Goss et al., 2010; Waters et al., 2011). Additionally, the distribution of the different basalt types is not symmetric across the crustal plateau. This lack of a consistent pattern is due partly to off-axis eruptions and additionally is a consequence of the asymmetric way in which lava flows away from eruptive fissures at the axis, often determined by meter-high variations between opposing rims of the AST (Soule et al., 2005, 2009). Results of our detailed geochemical investigations show that the most recent magmatic events associated with the present AST (within ~ 500 m of the axis) erupted relatively homogeneous and mafic (> 7.5 wt % MgO) normal mid-ocean ridge basalt (N-MORB), characterized by very low abundances of the most incompatible trace elements such as barium, uranium, and potassium (e.g., K_2O/TiO_2 x 100 < 13). In comparison, the surrounding off-axis, older lavas are typically more chemically evolved with pockets of low MgO (~ 6 wt %) and incompatible-element-enriched MORB (E-MORB; K_2O/TiO_2 x 100 > 13) on the flanks of the crestal plateau and commonly associated with fault scarps and fissures (Figure 1). The range of MORB trace element and isotopic compositions suggests that the basaltic melts were derived from at least two or three distinct mantle sources (Goss et al., 2010; Waters et al., 2011). The only E-MORBs recovered on axis north of the 9°N overlapping spreading center (OSC) are found at the small 9°37'N OSC, suggesting that the various basalt magma "genotypes" that feed the ridge crest are not efficiently mixed under ridge discontinuities where seismically imaged axial magma chambers (AMC) are segmented (Smith et al., 2001; see also Carbotte et al., 2012, in this issue). While it is probable that axial basalts have erupted directly from the AMC (Detrick et al., 1987; Carbotte et al., 2012, in this issue), there must also be compositionally distinct pockets of cool, unmixed melts in the margins of the AMC or from separate segments along strike where the magma lens thins along axis. Although the general observed chemical variations in N-MORB are largely controlled by cooling and crystallization of melts at shallow crustal levels, data from gabbroic xenoliths entrained in some lavas and from the basalts erupted at the EPR near 9°50'N in 2005–2006 also indicate that melt mixing and reaction with pre-existing crystals occurs at depth (Ridley et al., 2006; Goss et al., 2010; see also Rubin et al., 2012, in this issue).

It has previously been shown that lavas erupted along typical ridge segments at fast-spreading centers may produce a range of basaltic lavas over modest (~ 10–100 km) length scales (e.g., Langmuir et al., 1986; Sinton et al., 1991; Batiza and Niu, 1992), but they rarely include highly evolved compositions with MgO concentrations < 5 wt % or SiO_2 > 52 wt %. This relatively limited compositional diversity of MORBs compared to other tectonic settings is commonly attributed to limited crystal fractionation coupled with frequent recharge of axial magma chambers with more primitive, less-evolved magmas (e.g., Klein, 2005; Rubin and Sinton, 2007). However, lavas erupted at ridge-segment discontinuities, such as OSCs, can have highly variable compositions (e.g., Christie and Sinton, 1981; Langmuir et al., 1986; Rubin and Sinton, 2007; Wanless et al., 2010).

In 2007, the Ridge 2000 Program included an R/V *Atlantis* field program at the 9°N OSC that used a near-bottom side-scan sonar, *Jason 2*, and TowCam to determine the range of lava compositions erupted at this major MOR discontinuity, and to correlate those variations with the structural fabric and volcanic features present along the axial zone (White et al., 2009; Wanless et al., 2010). The results from that field and laboratory program constitute one of the most detailed observational, structural, and petrochemical data sets from an OSC (Figure 2). The compositions of lavas recovered (> 275 samples) exhibit remarkable diversity, ranging from basalt to highly evolved andesites and dacites, with 33% of OSC lavas having SiO_2 > 52 wt %, compared to < 5% for ocean-ridge lavas worldwide (Perfit, 2001). Petrologic models indicate that basalts erupting at the 9°N OSC can be explained by greater extents of low-pressure fractional crystallization

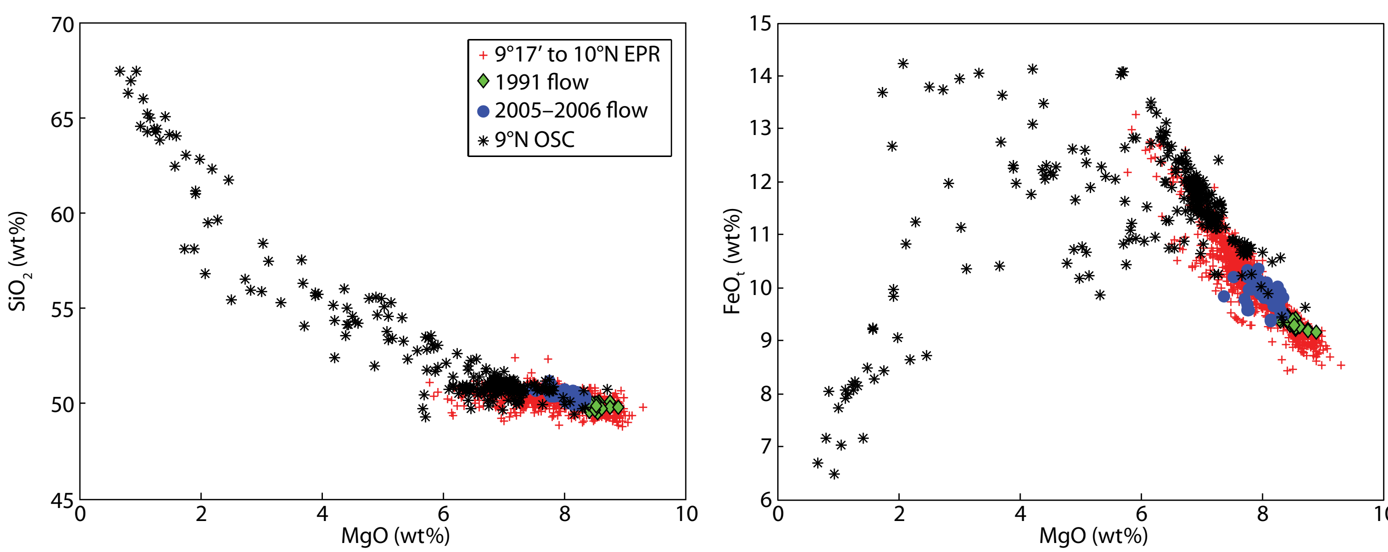

Figure 2. Major element variation diagrams of glasses from 9–10°N on the East Pacific Rise (EPR) showing the range of compositions erupted from the 9°N overlapping spreading center (OSC; black asterisk) compared to ~ 1,600 lavas sampled between 9°17'N and 10°N (red crosses). FeO_t is the total iron content of the glasses measured by electron microprobe, assuming that all the iron is Fe^{2+}. The data are from various publications and are available at PetDB (http://www.petdb.org/) or Marine Geoscience Data Systems (http://www.marine-geo.org/). The general compositional trends in the basalt data (MgO > ~ 6 wt %, SiO_2 < 52 wt %) are primarily due to the effects of low to moderate pressure fractional crystallization. More evolved andesites and dacites also require crustal assimilation coupled with fractional crystallization in the upper oceanic crust as well as mixing between high-SiO_2 melts and FeO-rich basalts (Wanless et al., 2010, 2011). The lavas erupted at 9°50'N in 1991 and 2005–2006 show relatively restricted compositional variations but fall within the larger EPR field. There are, however, distinct differences in the compositions of lavas erupted in 1991 (green diamonds) versus 2005–2006 (blue circles) that reflect magma cooling and mixing during the ~ 15 years between eruptions in the same locality (Goss et al., 2010).

of a primitive N-MORB parent than is typically proposed to occur at segment centers such as the 9°50'N area. In contrast, the formation of andesites and dacites requires a combination of extensive fractional crystallization and assimilation of the altered oceanic crust surrounding the AMC at the propagating segment end, where magmas can undergo extensive cooling and crystallization without repeated magma recharge (Wanless et al., 2010, 2011).

These well-constrained petrologic data sets from the EPR ISS provide a clearer picture of the various MOR magmatic processes that start with melting in the mantle and ultimately end with eruption of basalt on the seafloor. Our findings indicate that compositions of magmas erupted at fast-spreading ridges integrate a variety of processes that modify the compositions of melts as they ascend from the underlying mantle, which is in itself heterogeneous. Melts with different compositions are likely stored within the shallow melt lenses that are located ~ 1.5 km below the seafloor (see Carbotte et al., 2012, in this issue) and act as catchments for magmas that percolate through the oceanic crust. Within these reservoirs, magmas are homogenized and cooled to variable extents, allowing them to differentiate along specific compositional trends. Our fine-scale sampling and mapping studies show that the compositions of most MORB reflect myriad processes dominated by mixing and fractional crystallization of mantle melts that occur over very short timescales (decades). The eruptions that deliver those melts to the seafloor and the resulting lava flows often result in significant variations in chemistry between adjacent lobes of lava on small spatial scales (< 100 m to a few kilometers). Where magmatism is robust and relatively frequent, as in the axial region of the segment around 9°50'N, it appears that lavas are the most primitive and homogeneous. In contrast, the diversity of composition and extents of differentiation increase in off-axis regions and at ridge segment ends, such as the 9°N OSC, where magmatism is more sporadic, melt bodies may be smaller and less continuous, and subridge thermal regimes are cooler.

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