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Primitive melt replenishment and crystal-mush disaggregation in the weeks preceding the 2005–2006 eruption 9°50′N, EPR

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ABSTRACT

The 2005–2006 eruption at ∼9°50′N, East Pacific Rise provides an exceptional opportunity to investigate the magma plumbing system beneath a well-studied ridge system. The eruption was preceded by two years of increasingly intense seismicity and occurred from the same location as a previous and well-characterized eruption in 1991–1992. Here we use the crystal cargo of samples from this eruption to investigate magma reservoir processes in the lead-up to the eruption, as well as their temporal relationship to the seismicity that preceded it. Compositional zoning in some plagioclase crystals indicates primitive melt replenishment occurred roughly six weeks or less before the eruption. This replenishing event is seen only in the crystals from the central region of the eruption (9°50′–9°52′N). This is also the area where the most primitive lava compositions are observed and together these observations support models of replenishment being spatially focused. The short time between the input of a more primitive melt and eruption onto the seafloor suggests replenishment likely contributed to triggering the eruption. Rare resorbed plagioclase crystals, and glomerocrysts of plagioclase and olivine, some of which have rims far from equilibrium with their host melt, suggest that disaggregation of a crystal mush occurred within a few days prior to eruption. Interstitial melt from within this mush zone must have been mixed back into the erupted lava—a form of *in situ* crystallization. Thus, the erupted magmas evolved in a replenished-tapped magma reservoir in which at least a part of the crystallization occurred *in situ*.

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1. Introduction

Magma reservoirs at mid-ocean ridges have long been known to operate as open systems, with replenishment and tapping being required to explain some of the petrological and geochemical aspects of mid-ocean ridge basalts (MORB; e.g., Dungan and Rhodes, 1978; Rhodes et al., 1979). However, we still have a poor understanding of important aspects of the behavior of these magma reservoirs. Firstly, magma differentiation in an open system can lead to the composition of erupted magmas being very different to those predicted by closed system differentiation models; this has important implications for determining parental melt compositions and hence mantle composition and melting process (e.g., O'Hara, 1977). A second, related, question is what are the relationships between tectonic stress, deformation, seismicity, magma intrusion and eruption at mid-ocean ridges? For example, most dikes are roughly 1 m wide suggesting that melt is extracted from a magma reservoir when the combination of lithospheric stress and magma availability are appropriate for dikes of this scale to intrude (Qin and Buck, 2008). However, whether magma reservoir replenishment plays a role in driving eruptions is unclear. Finally, at fast-spreading ridges geophysical studies have imaged a magma reservoir at roughly the depth of the base of the sheeted dikes; this axial magma lens (AML) is 10's of m deep and ∼0.5 to 1 km wide (e.g., Detrick et al., 1987; Kent at al., 1993; Harding et al., 1993). Heat must be extracted through the roof of the AML to drive the axial hydrothermal system, and energy balance calculations indicate that it is impossible to supply sufficient heat unless the AML is replenished on decadal timescales (Liu and Lowell, 2009). However, both the details of the replenishment timescale and whether replenishment is with primitive melt, or more evolved melt from within the crystal mush beneath the AML (Goss et al., 2010), remain unclear.

The 9°50′N area of the East Pacific Rise (EPR), with a full spreading rate of 110 mm yr^{-1}, offers an ideal place to address questions about eruptive processes at fast-spreading ridges. There

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have been two documented eruptive episodes in this area, in 1991–1992 and 2005–2006 (Haymon et al., 1993; Rubin et al., 1994; Tolstoy et al., 2006) allowing the changes in the eruptive products, volumes of lava, and crustal structure to be investigated. Both eruptions occurred between ∼9°46′ and 9°56′N, with the 2005–2006 eruption being 4–5 times larger (Gregg et al., 1996; Soule et al., 2007). The central region of the 2005–2006 eruption at 9°50′–9°52′N corresponds with the largest aerial extent of the eruption off-axis (Soule et al., 2007), the most Mg-rich basalt compositions (Goss et al., 2010), and a region in which the AML is melt-rich (Xu et al., 2010; Xu, 2013). Carbotte et al. (2013) have recently suggested that the eruption in this central region was fed from a "mostly physically isolated" melt lens, separate from the melt lenses that fed the lavas to the north and south. Of note is a well-documented increase in seismic activity leading up to the 2005–2006 eruption; this occurred over ∼2 years with an almost linear increase in the number of seismic events recorded per day on ocean bottom seismometers over this time (Tolstoy et al., 2006).

Here we use the petrology of the crystal cargo of samples from the 2005–2006 eruption to show that primitive melts replenished the AML within the weeks to months prior to eruption. This replenishment led to the mixing of some plagioclase crystals that grew around the time of the 1991–1992 eruption into the melt, as well as the disaggregation of the crystal mush around the AML. Evidence of replenishment is clearest in the central region, suggesting this was the location of primitive melt replenishment, consistent with seismic evidence that there is a shallow (Carbotte et al., 2013) and melt rich (Xu et al., 2010; Xu, 2013) AML in this region.

2. Analytical techniques

Zoning profiles in 48 plagioclase and 8 olivine crystals from 10 samples from the 2005–2006 eruption were analyzed, either from rim-to-core, or rim-to-rim, for both major and trace element compositions. Major elements were analyzed by electron microprobe (EMP) in three laboratories, the University of Barcelona (UB; Cameca SX-50), the Earth Observatory of Singapore (EOS; JEOL JXA-8530F), and the University of British Columbia (UBC; Cameca SX-50). All reported data have been normalized to the UBC data by reanalyzing some zoning profiles measured on other probes to ensure internal consistency; this led to ≤1.5% change in anorthite (An) content ($100 \times Ca/[Ca + Na + K]$), and <7% relative change in MgO wt%, which corresponds to <0.02 wt% MgO absolute difference. We used accelerating voltages of 15–20 kV, beam currents of 15–100 nA, and a ∼2 μm beam diameter. Counting times ranged between 10 and 100 s for both peak and background. Precision, based on EMP counting statistics, is better than 4% relative for MgO in plagioclase (Supplementary Material 1).

Trace element compositions of plagioclase were analyzed by laser-ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) at the University of Victoria using a NewWave 213 nm Nd-YAG UV laser and a Thermo X-series ICP-MS. A 30 second gas blank was measured followed by 50 seconds of sample analysis. The laser power output was 0.7–0.8 mJ, pulsed at 10 Hz, and the beam was rastered along a 30 μm wide and ∼80 μm long line (parallel to the crystal edge) four times for each analysis. Calcium, determined by electron microprobe, was used as the internal standard. Analyses were calibrated against NIST 611, 613, and 615 using the preferred values from Pearce et al. (1997) and Horn et al. (1997). Based on analyses of natural oligoclase (225 ppm Sr) and bytownite (350 ppm Sr), the precision on Sr was better than 6.5% relative (1σ). Within the duration of the analysis of any single crystal the analytical precision was better than 4% relative (1σ). All data are reported in Supplementary Material 2.

3. Background geology and petrology of the sample suite

We studied lavas from the 2005–2006 eruption at ∼9°50′N on the EPR that was mapped by Soule et al. (2007) as being about 18 km long, with lavas distributed furthest off-axis in the central, shallowest, area (the central region; Fig. 1). The 18 samples studied here were collected by Alvin from the northern (8 samples), central (7 samples) and southern (3 samples) regions and thus allow us to investigate variations along the axis. The samples are typical N-MORB (Goss et al., 2010) with <2 vol% crystals that are dominantly plagioclase, with minor olivine and no clinopyroxene.

We use the term phenocryst to describe those crystals >100 μm in their longest dimension, without genetic connotation. Plagioclase phenocrysts in all samples were counted and binned by size and texture. They occur largely as either isolated euhedral crystals, or clusters of euhedral to subhedral crystals; these are collectively referred to as euhedral plagioclase and together make up 92% of all plagioclase crystals. Samples from the central region have fewer small (100–300 μm) euhedral plagioclase relative to samples from the northern and southern regions (Fig. 1). About 65% of euhedral plagioclase occur as clusters that typically contain 2 to 7 crystals, with the other ∼35% occurring as isolated crystals (at least in the plane of the thin section). Similar clusters of plagioclase in EPR MORB were reported by Pan and Batiza (2003).

In addition to the euhedral plagioclase there are also rare rounded and resorbed crystals and glomerocrysts, some of which are far from equilibrium with their host lava (Section 4), that we interpret to represent fragments of a crystal mush zone. Rounded plagioclase phenocrysts make up just 3.5% of the total number of crystals. We observed two glomerocrysts of plagioclase and olivine, one in a sample from the central region, and the other in a sample from the southern region (Fig. 1). The glomerocryst from the central region consists of an olivine (∼2 mm diameter) poikilitically enclosing four plagioclase crystals (∼100 μm). The glomerocryst from the southern region also consists of an olivine (∼2.5 mm diameter) poikilitically enclosing sub- to anhedral plagioclase crystals. Portions of the olivine in both glomerocrysts have rounded margins suggesting dissolution. Only three isolated olivine phenocrysts were observed, all of these are euhedral and are in samples from the central region.

4. Geochemistry

The 2005–2006 lavas are slightly more evolved than those of the 1991–1992 eruption, with MgO contents between 7.3 and 8.4 wt% (Goss et al., 2010), in comparison to 8.5 ± 0.33 wt% (Gregg et al., 1996). In both eruptions the lavas from the central region are the most primitive. Calculated liquidus temperatures of the 2005–2006 lavas are ∼1200 °C (Ghiorso and Sack, 1995; Danyushevsky and Plechov, 2011) and this is used for all temperature-dependent calculations. Here we use the compositions of plagioclase (An, MgO and Sr) and olivine ($Fo = 100 \times Mg/[Mg + Fe]$) to determine the range of melt compositions that the phenocrysts grew from and/or (partially) equilibrated with after growth. We also use the compositions of crystals that are either not in internal equilibrium (zoned), or not in equilibrium with their host-glass, to determine the duration of the disequilibrium conditions by applying diffusion modeling.

The elements studied diffuse at different rates allowing a range of timescales to be investigated. Coupled CaAl–NaSi diffusion in plagioclase is extremely slow (e.g., Grove et al., 1984), meaning that An zoning is virtually unmodified by diffusion. Strontium diffusion in plagioclase is much more rapid than CaAl–NaSi diffusion (Cherniak and Watson, 1994; Giletti and Casserly, 1994), and Sr contents can be modified in a few years on the spatial resolution of our LA-ICP-MS analyses, but many decades are required for

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