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Melt inclusions in olivine and plagioclase phenocrysts from Antarctic–Phoenix Ridge basalts: Implications for origins of N- and E-type MORB parent magmas

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ABSTRACT

The Antarctic–Phoenix Ridge (APR) is a fossil spreading center in the Drake Passage, Antarctic Ocean. Spreading ceased in chron C2A (ca. 3.3 Ma). Although the APR is a normal ridge that is not influenced by a hotspot, enriched (E-type) mid-ocean ridge basalt (MORB) coexists with normal (N-type) MORB in the ridge's axial region. The E-type APR basalt is relatively young (<3.1 Ma) compared to the N-type basalt (>3.5 Ma). The E-type basalt is characterized by elevated K_2O/TiO_2 (=0.4–0.8) and $(La/Sm)_N$ (=2.2–3.4) ratios, relative to the N-type basalt (K_2O/TiO_2=0.1–0.3; $(La/Sm)_N$=0.7–0.8). To better understand the compositional variation in the APR basalts and their mantle source regions through time, silicate melt inclusions in primitive olivine ($Fo_{87–89}$) and plagioclase ($An_{85–89}$) phenocrysts from the N-type APR basalt were studied. Rehomogenized melt inclusions were analyzed by electron microprobe and LA-ICPMS for major and trace elements. The melt inclusions are more primitive than the host basalt, with Mg#s from 67.5 to 74.1. All inclusions exhibit patterns that are depleted in the light rare earth elements. The inclusions have K_2O/TiO_2 from 0.1 to 0.3 and $(La/Sm)_N$ ratios from 0.4 to 0.9; these values overlap with those of the N-type APR basalt. Furthermore, the melt inclusions have elevated $(Lu/Hf)_N$ and $(Sm/Nd)_N$ ratios compared to the E-type basalts. The N-type APR basalts do not contain any melt inclusions that are enriched in incompatible elements. The E-type basalt was generated by a low degree of partial melting of a relatively incompatible-element-enriched mantle source. In contrast, chemistries of melt inclusions and N-type basalts are compatible with high degrees of partial melting of an increasingly depleted mantle source. Assuming a veined or otherwise heterogeneous mantle, the absence of E-type inclusions from the N-type host has implications for cyclic magmatic activity beneath the APR. Multi-stage mantle melting and melt extraction from a composite source with sequential extraction of melt fluids might give rise to the primary melt diversity documented in the APR axis. The mantle source of the N-type melts may have been the residue from an earlier phase of melting that removed the easily melted, enriched components. The N-type APR basalt studied represents melt at the end of single cycle, whereas the E-type basalt may represent the early stage of a new pulse that was dominated by highly enriched components.

1. Introduction

Erupted mid-ocean ridge basalt (MORB) magmas are compositionally diverse at both regional and local scales (Schilling, 1973; Frey et al., 1980; Mahoney et al., 1989; Niu and Batiza, 1991, 1993; Shen and Forsyth, 1995; Dosso et al., 1999; Wendt et al., 1999; Chauvel and Blichert-Toft, 2001; Presnall et al., 2002). Such magmas have been classified into three principal geochemical groups: normal or depleted geochemistry (N-type mid-ocean ridge basalts, or N-MORB), enriched or plume-related geochemistry (E- or P-MORB), and geochemistry that is between the normal and enriched end-members (T-MORB). The origin of E-MORB has generally been attributed to interaction of a ridge with a nearby mantle plume (e.g., Schilling, 1973; Sun et al., 1975; Schilling et al., 1983; Le Roex et al., 1992; Dosso et al., 1993; Taylor et al., 1997; Hekinian et al., 1999). Enriched MORB has also been reported from normal ridge settings (Niu et al., 1999; Donnelly et al., 2004; Choi et al., 2008; Haase et al., 2011). However, the extent of compositional variability in erupted basalts appears to be less than the geochemical diversity that is generated during the processes of mantle melting (Sobolev and Shimizu, 1993; Gurenko and Chaussidon, 1995; Kamenetsky et al., 2000; Slater et al., 2001; Sours-Page et al., 2002; Nielsen et al., 2005; Font et al., 2007; Laubier et al., 2007). Late-stage pre-eruptive processes within the magmatic plumbing system, such as fractional crystallization, magma mixing, and assimilation, may diminish and obscure the original variability of the MORB magmas (e.g., Sobolev, 1996; Kamenetsky et al., 1998; Danyushevsky et al., 2003; Kamenetsky and Gurenko, 2007; Rubin et al., 2009).

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Melt inclusions that are enclosed in minerals that formed early in the process of magma development record early steps in the evolution of magma before aggregation of magma masses at shallower levels (Sobolev, 1996; Shimizu, 1998; Schiano, 2003; Kent, 2008). Studies of melt inclusions may provide important insights into the nature of mantle sources, melting, and melt transportation processes of primitive magma. At the moment of trapping, melt inclusions are in thermodynamic equilibrium with crystallizing host minerals. During cooling of the system, however, the original compositions of inclusions may be modified by post-entrapment processes, such as diffusive re-equilibration, crystallization of more of the host mineral onto internal walls of the inclusions, and crystallization of other daughter phases within the inclusions (Roedder, 1984; Qin et al., 1992; Danyushevsky et al., 2000; Gaetani and Watson, 2000; Cottrell et al., 2002; Gaetani and Watson, 2002; Hauri, 2002; Yaxley et al., 2004; Chen et al., 2011). It is generally necessary to reverse the composition of the melt inclusion to that at the moment of entrapment via homogenization experiments or numerical reconstruction (e.g., Danyushevsky et al., 2002; Schiano, 2003).

The Antarctic–Phoenix Ridge (APR) is a normal spreading ridge far from any known hotspot, but E-MORB coexists with N-MORB in its axial region (Choe et al., 2007; Choi et al., 2008; Haase et al., 2011). Although the presence of the two different magma compositions has been attributed to a mantle source that is compositionally heterogeneous on a small scale together with variation in the degree of melting of parent mantle (Choi et al., 2008), the scale and origin of the source heterogeneities have not been discussed in detail.

In this study, olivine- and plagioclase-hosted melt inclusions that formed early in melt-generation were analyzed to better understand the melting processes that take place in the upper mantle beneath mid-ocean ridges. Homogenization experiments using a heating stage were undertaken to reverse post-entrapment crystallization occurring inside the inclusions and thus to determine the compositions of early melts. We identified the primary mantle source characteristics of coexisting N-MORB and E-MORB lavas in the APR, invoking possibly a cyclic magmatic activity beneath the spreading ridge.

2. Geological setting and sampling

The APR is a fossil spreading center in the Drake Passage, Antarctic Ocean. It consists of three inactive segments (P1, P2, and P3; Fig. 1A). Its spreading slowed abruptly to 16–24 mm/yr at the time of magnetic chron C4 (ca. 7.8 Ma), and ceased during chron C2A (ca. 3.3 Ma; Larter and Barker, 1991; Livermore et al., 2000), which may be induced by extinction of the nearby West Scotia Ridge (WSR, Fig. 1A) and a ridge–trench collision to the southwest of the Hero Fracture Zone (HFZ, Fig. 1A; Larter and Barker, 1991; Barker and Austin, 1998; Livermore et al., 2000). For comparison, the spreading rate of the ultraslow Gakkel Ridge varies between 3 and 6 mm/yr (Cochran et al., 2003).

In the axial region of the APR, E-type basalt coexists with N-type basalt. The E-type basalt is relatively young (<3.1 Ma) compared to the N-type basalt (>3.5 Ma; Choe et al., 2005; Haase et al., 2011). Extinction of the APR may have caused the transition from N-type to E-type volcanism (Choi et al., 2008; Haase et al., 2011). Based on trace element and Sr–Nd–Pb isotope geochemistry, previous studies (Choe et al., 2007; Choi et al., 2008; Haase et al., 2011) argued that the E-type basalt was produced by a lower degree of partial melting of a comparatively enriched mantle source than that responsible for the N-type basalt.

The melt-inclusion-bearing basalts studied were dredged from segment P3 of the APR. The E-type basalt samples (SPR1–4; Fig. 1B) were collected from an axial seamount 2500 m from the axial valley floor in this segment. The axial seamount is flanked by two great ridges to its southwest. The N-type basalt samples (PR3; Fig. 1B) were collected from an area southeastern of these two ridges. The E-type basalt has rare microphenocrysts (~0.3 mm) of olivine and plagioclase in a groundmass of olivine, plagioclase, and devitrified glass. The N-type basalt consists of olivine (~1.0 mm) and plagioclase (1.0–2.5 mm) phenocrysts in a groundmass of the same mineral assemblage, with devitrified glass. The inclusion study was limited to the N-type basalt, because olivine and plagioclase phenocrysts are both small and rare in the E-type basalt.

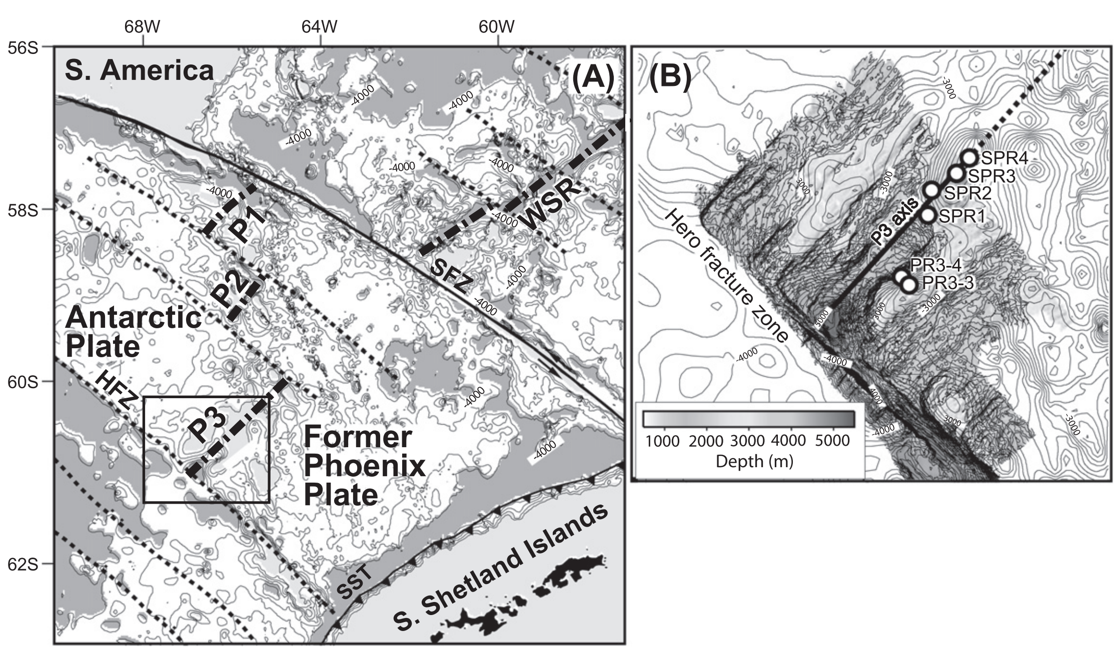

Fig. 1. (A) Regional tectonic setting of the study area. Ridge segments P1, P2, and P3 are after Livermore et al. (2000). (B) Bathymetric profile of segment P3 and sample locations. Contours are depths in meters below sea level. Abbreviations: APR = Antarctic–Phoenix ridge, HFZ = Hero Fracture Zone, SFZ = Shackleton Fracture Zone, WSR = West Scotia Ridge.