



Melting the lithosphere: Metasomes as a source for mantle-derived magmas



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ABSTRACT

Peridotite constitutes most of the Earth's upper mantle, and it is therefore unsurprising that most mantle-derived magmas exhibit evidence of past equilibrium with an olivine-dominated source. Although there is mounting evidence for the role of pyroxenite in magma generation within upwelling mantle plumes, a less documented non-peridotite source of melts are metasomatic veins (metasomes) within the lithospheric mantle. Here we present major and trace element analyses of 66 lavas erupted from a small Miocene shield volcano located within the Ethiopian flood basalt province. Erupted lavas are intercalated with lahars and pyroclastic horizons that are overlain by a later stage of activity manifested in small cinder cones and flows. The lavas form two distinctive petrographic and geochemical groups: (A) an olivine-phyric, low Ti group (1.7–2.7 wt.% TiO₂; 4.0–13.6 wt.% MgO), which geochemically resembles most of the basalts in the region. These low Ti lavas are the only geochemical units identified in the later cinder cones and associated lava flows; (B) a clinopyroxene-phyric high Ti group (3.1–6.5 wt.% TiO₂; 2.8–9.2 wt.% MgO), which resembles the Oligocene HT-2 flood basalts. This unit is found intercalated with low Ti lavas within the Miocene shield. In comparison to the low Ti group, the high Ti lavas exhibit a profound depletion in Ni, Cr, Al, and Si, and significant enrichment in Ca, Fe, V, and the most incompatible trace elements. A characteristic negative K anomaly in primitive-mantle normalized diagrams, and Na₂O > K₂O, suggests a source rich in amphibole, devoid of olivine, and perhaps containing some carbonate and magnetite. While melt generation during rift development in Ethiopia is strongly correlated with the thermo-chemical anomalies associated with the African Superplume, thermobaric destabilization and melting of mantle metasomes may also contribute to lithospheric thinning. In regions impacted by mantle plumes, such melts may be critical to weakening of the continental lithosphere and the development of rifts.

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1. Introduction

The process of mantle melting is foundational to studies of igneous rock, yet the composition of the melt source within the mantle can be difficult to discern from erupted lava compositions. Evidence from seismic, experimental petrology studies, and detailed examination of mantle xenoliths and ophiolites has resulted in a broad consensus where peridotite constitutes the bulk

of the Earth's upper mantle. On the basis of this paradigm, it has been assumed that mantle-derived magmas will exhibit evidence of past equilibrium with a peridotite source, and detailed models outlining the melting modes and intensive parameters of melt generation from peridotite have been constructed. However, inconsistencies have been recognized when such models are applied to broad datasets due to the subtle differences imposed upon primary melt compositions by mass contribution from mantle lithologies other than peridotite.

The acknowledgment that pyroxenite may play a critical role in magma production within upwelling mantle plumes, either through direct melting (Sobolev et al., 2007) or hybridization

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with surrounding peridotite (Herzberg, 2011), has challenged the conventional assumptions of peridotite-dominated mantle melting mechanisms and has resulted in an increased focus on distinguishing the potential source lithologies of mantle melts. Pyroxenite that is located within upwelling mantle plumes or as rafts within the asthenosphere may dominate the mass contribution to magma production from non-peridotitic source lithologies; however, a less well-documented source of non-peridotite derived magmas lies within the lithospheric mantle. Mantle metasomes are regions of the lithospheric mantle that have been modally or geochemically (cryptically) enriched as a result of chromatographic interaction between upper mantle-derived melts/fluids percolating through pre-existing peridotitic lithospheric mantle. As a result of this interaction, peridotite may become enriched in metasomatic phases such as amphibole or phlogopite, or veins/domains dominated by these metasomatic phases. Initial models developed to account for melting of these enriched metasomatic domains considered modal melting equations which incorporated the surrounding peridotitic matrix (e.g., Späth et al., 2001), however experimental evidence suggests that thermobaric perturbation of mantle metasomes will generate melt that is dominated by the metasomatic phases, with little if any contribution from the surrounding peridotite (Pilet et al., 2008). Mantle metasomes therefore represent another non-peridotite source lithology for melt generation.

Studies of primary magmas derived from mantle metasomes have some particular challenges in comparison to the more abundant peridotite- and pyroxenite-derived magmas. Firstly, magmas derived from mantle metasomes are more geographically restricted and are typically better represented in regions with thicker lithospheric mantle – such as on the continents. Secondly, melt transport processes may lead to equilibration between metasome-derived melts and the peridotite which constitutes the bulk of the lithospheric mantle (Pilet et al., 2008). Finally, dilution of melts derived from these relatively small-volume domains by asthenospheric-derived lavas may prevent their effective identification in the first instance. Despite such challenges, constraining the fingerprint of magmas derived from mantle metasomes is necessary in order to effectively unravel their potentially important role in lavas formed from the homogenization of contributions from multiple source domains. While small in volume, melts derived from mantle metasomes can exhibit potentially extreme isotopic heterogeneity and have significant concentrations of many incompatible trace elements (Rosenthal et al., 2009), therefore potentially playing an outsized role in the isotopic budget of mixed source lavas (Rogers et al., 1998). Furthermore, the presence of melt within the lithosphere can have an impact on lithospheric stability by focusing strain and facilitating rifting of the lithosphere with significantly less stress (Buck, 2006). Given the low melting point of lithospheric metasomes (Niida and Green, 1999), relatively minor thermobaric perturbation of the lithosphere may facilitate melt generation (Rogers et al., 1998), with a consequential impact on rift development.

Here we present a study of the geochemical characteristics of a large suite of lavas which we interpret to be derived from the asthenosphere and an amphibole-dominated mantle metasome located in the lithospheric mantle. Through petrographic, major element and trace element analysis we show distinctive differences between metasome-derived lavas and contemporaneous asthenosphere-derived lavas in the region. The metasome-derived lavas exhibit little evidence of equilibration with peridotite and therefore represent an unusually pure endmember of a metasomatically-derived magma. We leverage our whole-rock data with high-precision olivine analysis to show that the unusual compositions of these lavas are imparted onto their olivine phenocrysts. We suggest that the thermal perturbation imparted by the Afar plume upon the East African lithosphere destabi-

lized easily-fusible metasomatic veins which had resided at mid-lithospheric depths since the Pan-African subduction event. We conclude that thermobaric perturbation of the continental lithospheric mantle might facilitate rift development through strain focusing associated with the presence of magma within the lithospheric mantle.

2. Samples

The samples of the Gerba Guracha series were collected from flows emanating from a distinct edifice near the towns of Fiche and Gerba Guracha to the northwest of Addis Ababa on the western Ethiopian plateau (Fig. 1). In hand specimen, Gerba Guracha series rocks appear fresh, an observation confirmed by petrographic examination revealing broadly unaltered crystals and matrix. One of the most notable petrographic characteristics of the Gerba Guracha lavas are the large (cm-scale) zoned clinopyroxene crystals. Zoning in these crystals may manifest as both sector and fine-scale (possibly oscillatory) zoning (Fig. S1). Crystals are typically set in dark, almost glassy matrix. Glomeroporphyritic textures of mm-scale clinopyroxene and olivine are also observed. There are abundant opaque minerals present which can range up to 1 mm-scale. Zeolite- or carbonate-filled vesicles are evident in hand specimen but were largely avoided during sample collection and billet preparation. Some samples where these vesicles were unavoidable produced values with exceedingly elevated concentrations of Sr (e.g. sample 3222ves). A less common variety of strongly olivine-phyric flows were identified on the floor of the volcanic edifice and appear to post-date the rest of the volcanic activity on the basis of morphology.

3. Methods

Whole rock geochemical results were derived from hand samples by preparing ~30 g billets, which were polished to remove saw marks. These billets were then crushed in a steel jaw crusher before being powdered in a BICO flat plate pulverizer that has been fitted with ceramic plates. The resulting powders were fused with lithium tetraborate at a ratio of 1:3 following procedures detailed elsewhere (Rooney et al., 2015). The resulting disks were analyzed for major elements by a Bruker S4 Pioneer XRF at Michigan State University. The glass disks were then analyzed for trace element contents by laser ablation inductively coupled plasma mass spectrometry using a Photon Machine Excimer G2 coupled with a Thermo iCAP-Q at Michigan State University following procedures detailed elsewhere (Rooney et al., 2015). Analytical results and values for standards are provided in Tables S2 and S3.

Samples with visible olivine were selected for high precision electron microprobe analysis of minor elements in olivine (Tables S4, S5), which was undertaken at Rutgers University using the methods described by Sobolev et al. (2007).

Samples of fresh matrix were hand-picked from a single sample and sent for Ar–Ar dating to the Geochronology Laboratory at the University of Michigan under the supervision of Dr. Chris Hall. Analytical details of procedures followed are outlined elsewhere (Rooney et al., 2012a). Ar release spectra for the duplicate analysis are presented in Fig. S3.

4. Results

4.1. Major and trace elements

To a first order, lava series at Gerba Guracha can be divided on the basis of their geochemical characteristics into a high- and low-Ti group (Table S2). The low-Ti group may be further divided into a silica-undersaturated basanitic group and a sub-alkaline basalt

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