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Deep mixing of mantle melts beneath continental flood basalt provinces: Constraints from olivine-hosted melt inclusions in primitive magmas

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Abstract

We present major and trace element compositions of 154 re-homogenised olivine-hosted melt inclusions found in primitive rocks (picrites and ferropicrites) from the Mesozoic Paraná–Etendeka and Karoo Continental Flood Basalt (CFB) provinces. The major element compositions of the melt inclusions, especially their Fe/Mg ratios, are variable and erratic, and attributed to the re-homogenisation process during sample preparation. In contrast, the trace element compositions of both the picrite and ferropicrite olivine-hosted melt inclusions are remarkably uniform and closely reflect those of the host whole-rocks, except in a small subset affected by hydrothermal alteration. The Paraná–Etendeka picrites and ferropicrites are petrogenetically related to the more evolved and voluminous flood basalts, and so we propose that compositional homogeneity at the melt inclusion scale implies that the CFB parental mantle melts were well mixed prior to extensive crystallisation.

The incompatible trace element homogeneity of olivine-hosted melt inclusions in Paraná–Etendeka and Karoo primitive magmatic rocks has also been identified in other CFB provinces and contrasts with findings from studies of basalts from mid-ocean ridges (e.g. Iceland and FAMOUS on the Mid Atlantic Ridge), where heterogeneity of incompatible trace elements in olivine-hosted melt inclusions is more pronounced. We suggest that the low variability in incompatible trace element contents of olivine-hosted melt inclusions in near-primitive CFB rocks, and also ocean island basalts associated with moderately thick lithosphere (e.g. Hawaii, Galápagos, Samoa), may reflect mixing along their longer transport pathways during ascent and/or a temperature contrast between the liquidus and the liquid when it arrives in the crust. These thermal paths promote mixing of mantle melts prior to their entrapment by growing olivine crystals in crustal magma chambers. Olivine-hosted melt inclusions of ferropicrites from the Paraná–Etendeka and Karoo CFB have the least variable compositions of all global melt inclusion suites, which may be a function of their unusually deep origin and low viscosity.

Keywords: Continental flood basalt; Melt inclusion; Mixing; Paraná-Etendeka; Karoo

1. INTRODUCTION

1.1. The melt inclusion record of compositional heterogeneity in magmas

Fractional melting of adiabatically upwelling mantle produces instantaneous melts with highly variable compositions. This compositional variability contrasts strongly with

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the relatively homogeneous chemistry often displayed by suites of lava flows and sometimes extensive volcanic successions (e.g. Cox, 1980; Erlank et al., 1984; Arndt et al., 1993; Wooden et al., 1993; Reidel and Tolan, 2013). A link to processes operating deeper within igneous plumbing systems is provided by olivine-hosted melt inclusions. Melt inclusions represent tiny droplets of liquid trapped by growing crystals and are important because their isolation from the surrounding melt preserves the liquid composition at the time of entrapment. Olivine-hosted melt inclusions from primitive magmatic rocks are of particular interest because they contain important information about how diverse mantle melts combine, homogenise and crystallise within a single magmatic plumbing system.

In oceanic settings, olivine-hosted melt inclusions from primitive magmas frequently display a large variability in incompatible trace element concentrations and ratios. This was first noted in melt inclusions from mid-ocean ridge basalts (MORB) by Sobolev and Shimizu (1993), who attributed the variability to fractional melting in the mantle. Similar observations and interpretations have subsequently been made for ocean island basalts (OIBs) and on Iceland (e.g. Gurenko and Chaussidon, 1995; Sobolev, 1996; Shimizu, 1998; Slater et al., 2001; Norman et al., 2002; Sours-Page et al., 2002; Maclennan et al., 2003; Maclennan, 2008a). Variability has also been identified in the Pb and Sr radiogenic isotopic ratios of olivine-hosted melt inclusions; such variations cannot be attributed to melting processes and indicate high amplitude, short length scale isotopic heterogeneity in the mantle source regions of basalts erupted from individual volcanoes (Saal et al., 1998; Jackson and Hart, 2006; Maclennan, 2008b; Sobolev et al., 2011; Sakyi et al., 2012). As a consequence of studies such as these, incompatible trace element variability in both lavas and melt inclusions has often been interpreted as a product of both mantle melting process and compositional heterogeneity in the source (e.g. Norman et al., 2002; Stracke et al., 2003b; Sobolev et al., 2000, 2011; Rudge et al., 2013). Compositional heterogeneity in mantle melts is quickly destroyed by convective mixing, e.g. in lower crustal sills, but when this process is concurrent with crystallisation it may be captured by the melt inclusion record (Maclennan, 2008a). Although well-established in Iceland (Maclennan et al., 2003; Maclennan, 2008a; Neave et al., 2013), the controls over the timing of convective mixing relative to crystallisation of mantle melts are not well understood at other locations.

In this study, we present analyses of 154 olivine-hosted melt inclusions from primitive olivine-rich rocks from the Paraná–Etendeka and Karoo Continental Flood Basalt (CFB) provinces. These high-MgO rocks are scarce in CFB provinces because extensive crystal fractionation in deep and complex crustal plumbing systems typically produces more evolved magmas with rather monotonous major element compositions (Fig. 1; from the GEOROC database, Sarbas and Nohl, 2008). Nevertheless, if primitive magmas are able to ascend rapidly and bypass large crustal magma chambers, they have the potential to preserve evidence of geochemical variability of the initial mantle melts involved in CFB genesis. The original thick lithosphere beneath CFB provinces limits adiabatic decompression melting in the convecting mantle and further increases the possibility of detecting a geochemical signal of lithological heterogeneity in early-formed magmas, such as those generated by deep melting of pyroxenite and/or peridotite. Moreover, olivine-hosted melt inclusions found in primitive magmatic rocks have the added advantage of preserving initial melts in a relatively closed system and hence provide a window through subsequent crystal fractionation, assimilation and hydrothermal alteration processes that may compromise whole rock data.

Analyses of olivine-hosted melt inclusions have been published from several CFB provinces including: Paraná–Etendeka, North Atlantic, Yemen, Emeishan and Siberian Traps (Kent et al., 2002; Yaxley et al., 2004; Nielsen et al., 2006; Sobolev et al., 2009; Keiding et al., 2011; Kamenetsky et al., 2012; Peate et al., 2012; Starkey et al., 2012). In comparison to other tectonic settings, however, the number of published analyses for primitive magmas in CFB provinces is relatively small. Our new major and trace element data for olivine-hosted melt inclusions in the Paraná–Etendeka and Karoo CFB provinces builds on these previous studies and is focused on two types of high-MgO magmatic rocks: picrite and ferropicrite. These distinct magma compositions are thought to reflect melting of peridotite and pyroxenite, respectively, within elevated temperature mantle upwelling beneath lithosphere of varying thickness (Gibson et al., 2000; Thompson et al., 2001; Gibson, 2002; Tuff et al., 2005; Heinonen and Luttinen, 2008; Heinonen et al., 2013). We compare our new incompatible trace element analyses for olivine-hosted melt inclusions with those from other CFB provinces, and the much larger global database of OIB and MORB, in order to examine the role of the lithosphere and tectonic setting on melt inclusion chemical variability and the relative timing of mantle melt mixing and crystallisation.

1.2. Primitive mantle melts in CFB provinces

Continental flood basalts constitute a major portion of subaerial Large Igneous Provinces (LIPs). The individual CFB successions consist of enormous volumes of magma ($>10^5$ km^3, Bryan and Ernst, 2008) with the bulk of lava piles being erupted over very short timescales ($<\sim$1–5 Myr, Courtillot and Renne, 2003). The rapid production of vast volumes of melt in CFB provinces has generally been linked to adiabatic decompression melting of mantle plume heads impacting beneath rifting lithosphere (Richards et al., 1989; White and McKenzie, 1989). Small volumes of near-primitive, non-cumulate Mg-rich rocks are found in CFB provinces as shallow dykes and sills or thin lava flows. Some of these rocks, known as ferropicrites, have higher FeO_T (>13 wt.%) and lower Al_2O_3 contents (typically <10 wt.%) than true picrites (Gibson et al., 2000; Riley et al., 2005; Heinonen and Luttinen, 2008). Although ferropicrites in general contain olivines with a lower forsterite content (Fo $\leqslant$ 86) than those in picrites (Fo $\leqslant$ 93; Fig. 2), they have similar Ni concentrations