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The evolution and ascent paths of mantle xenolith-bearing magma: Observations and insights from Cenozoic basalts in Southeast China

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ABSTRACT

Studies have shown that mantle xenolith-bearing magmas must ascend rapidly to carry mantle xenoliths to the surface. It has thus been inferred inadvertently that such rapid ascending melt must have undergone little crystallization or evolution. However, this inference is apparently inconsistent with the widespread observation that xenolith-bearing alkali basalts are variably evolved with $Mg^{\#} \leq 72$. In this paper, we discuss this important, yet overlooked, petrological problem and offer new perspectives with evidence.

We analyzed the Cenozoic mantle xenolith-bearing alkali basalts from several locations in Southeast China that have experienced varying degrees of fractional crystallization ($Mg^{\#} = \sim 48–67$). The variably evolved composition of host alkali basalts is not in contradiction with rapid ascent, but rather reflects inevitability of crystallization during ascent. Thermometry calculations for clinopyroxene (Cpx) megacrysts give equilibrium temperatures of 1238–1390 °C, which is consistent with the effect of conductive cooling and melt crystallization during ascent because $T_{Melt} > T_{Lithosphere}$. The equilibrium pressure (18–27 kbar) of these Cpx megacrysts suggests that the crystallization takes place under lithospheric mantle conditions. The host melt must have experienced limited low-pressure residence in the shallower levels of lithospheric mantle and crust. This is in fact consistent with the rapid ascent of the host melt to bring mantle xenoliths to the surface.

1. Introduction

Our present-day knowledge on the thermal structure of subcontinental lithospheric mantle (SCLM) largely comes from petrological, geochemical, experimental and thermodynamic studies of mantle xenoliths brought to the surface by kimberlite eruptions, and most abundantly by eruptions of alkali basalts (e.g., Herzberg, 1993; Mather et al., 2011; Menzies, 1983; Nickel and Brey, 1984; O'Hara, 1967; O'Hara and Schairer, 1963; Rudnick et al., 1998; Sleep, 2005; Wood and Banno, 1973). The worldwide observation that apart from kimberlite, it is alkali basalt (vs. tholeiite) that carries mantle xenoliths to the surface, points to a genetic link between mantle xenoliths and alkali basaltic magmatism. Because mantle xenoliths are lithospheric mantle materials whereas basaltic melts are derived from the asthenosphere at greater depths, it follows that alkali basaltic melts that are enriched in volatiles and alkalis have the capacity to collect and transport lithospheric mantle materials during ascent.

Indeed, reduced solubility of volatiles in the melts with decreasing pressure will result in volatile exsolution during alkali melt ascent, causing the bulk magma volume expansion and viscosity increase with destructive power to break magma conduits in the lithospheric mantle (Gonnermann and Manga, 2013; Lensky et al., 2006; Spera, 1984; Woods and Cardoso, 1997). These broken fragments of lithospheric material are the familiar "mantle xenoliths" carried in alkali basalts during eruption. However, mantle xenoliths are physically denser than, and compositionally not in equilibrium with the host melt, which requires the host melts ascend rapidly, with the aid of increased viscosity due to volatile exsolution and bubble formation, to transport mantle xenoliths to the surface. The ascending rates of mantle xenolith-bearing alkali magmas have been estimated to be 6 ± 3 m/s and 0.2–2 m/s by Demouchy et al. (2006) and O'Reilly and Griffin (2010), respectively, which is consistent with the anticipation of the rapid ascent of xenolith-bearing melt.

The "primary" basaltic melt after being extracted from the asthenospheric source region will undergo varying extent of crystallization during ascent, mostly as a consequence of magma cooling (Niu, 1997, 2005;

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Niu and O'Hara, 2008; O'Hara and Herzberg, 2002). One may anticipate that the rapid ascending xenolith-bearing melt would undergo little crystallization (Higgins and Allen, 1985; McBride et al., 2001; O'Reilly and Griffin, 1984; Sigmarsson et al., 1998; Wass, 1980). However, this inference is inconsistent with the widespread observation that the xenolith-bearing alkali basalts are variably evolved with $Mg^{\#} \leq 72$, which is the minimum value required for the melt to be in equilibrium with mantle olivine in both asthenospheric source region and lithospheric mantle magma conduit. Irving and Price (1981) interpreted some evolved lherzolite-bearing phonolitic lavas from Nigeria, Australia, East Germany and New Zealand as originating from fractional crystallization of basanitic magmas in the upper mantle, which is reasonable and likely. However, this apparent problem still remains rarely addressed until recently when pyroxenites were popularly invoked as source for ocean island basalts (OIB) and alkali basalts (Sobolev et al., 2005, 2007; Yang and Zhou, 2013) with the conclusion that the more evolved host magmas must have derived from pyroxenites, which has many more problems than certainties (see Niu, 2016; Niu et al., 2011, 2012; Niu and O'Hara, 2003, 2007).

We consider that the variably evolved nature of host melts does not negate the rapid ascent of mantle xenolith-bearing melt but emphasizes the importance of melt crystallization during ascent. In this paper, we use bulk-rock major and trace elements and clinopyroxene thermobarometry of several sample suites from Southeast (SE) China as a case study to address the above fundamental yet overlooked petrological problems of global significance. We conclude that the varying extent of crystallization during rapid ascent is inevitable for mantle xenolith-bearing basaltic melts, which in SE China largely take place in magma chambers in lithospheric mantle.

2. Geological background and analytical procedures

2.1. Geological background

Cenozoic basaltic volcanism is widespread in eastern China (Fig. 1a). These basalts have been identified as typical continental-intraplate basalts derived from the asthenosphere, with trace element signatures similar to ocean island basalts (OIB) (Meng et al., 2015; Tu et al., 1991; Wang et al., 2011; Zou et al., 2000). A significant low-degree melt metasomatism within the asthenospheric mantle has been invoked to explain the incompatible element enrichment in these basalts (Guo et al., 2016; Niu, 2005, 2014; Sun et al., 2017).

In SE China, the Cenozoic basaltic volcanism is spatially associated with three extensional fault systems parallel to the coastline (Fig. 1b; Chung et al., 1994; Ho et al., 2003; Huang et al., 2013; Sun et al., 2017). Basalts containing abundant mantle xenoliths were collected from several localities (i.e., Xiadai, Xiahuqiao, Dayangke and Jiucaidi) (see Fig. 1b and Appendix A for sample locations). The mantle xenoliths are 4–10 cm in size (Fig. 2a & b) and are dominated by spinel lherzolite and harzburgite with minor dunite. Clinopyroxene (Cpx) megacrysts with varying size of ~1–6 cm are common in these samples except for those from Xiahuqiao (Fig. 2c & d). They are optically homogeneous with 0.5–1.0 mm gray or brown reaction rims (Fig. 2e & f). In addition to xenoliths, these basalts contain abundant euhedral to subhedral olivine (Ol) and relatively less Cpx phenocrysts in a fine-grained and microlite-bearing groundmass (Fig. 2g & h). The Ar–Ar dating gives eruption ages of 20.2 ± 0.1 Ma for basalts from Jiucaidi, 23.3 ± 0.3 Ma from Xiadai, 9.4 ± 0.1 Ma from Xiahuqiao, 2.2 ± 0.1 Ma from Dangyangke (Ho et al., 2003; Huang et al., 2013).

2.2. Analytical procedures

As we endeavored to study melt compositions by choosing glasses if any, or quenched matrix materials, we crushed fresh samples to chips of ≤5 mm to exclude phenocrysts, xenocrysts and weathered surfaces before repeatedly washing the chips in Milli-Q water, drying them and then ground them into powders with an agate mill. Despite the effort, our analyses still contain contributions from olivine micro-phenocrysts (Fig. 2g & h), rather than melt compositions we endeavored to obtain. In our case, we made corrections for this problem using the method described in Sun et al. (2017) and also a new method to verify the validity of the correction results (see Appendix B).

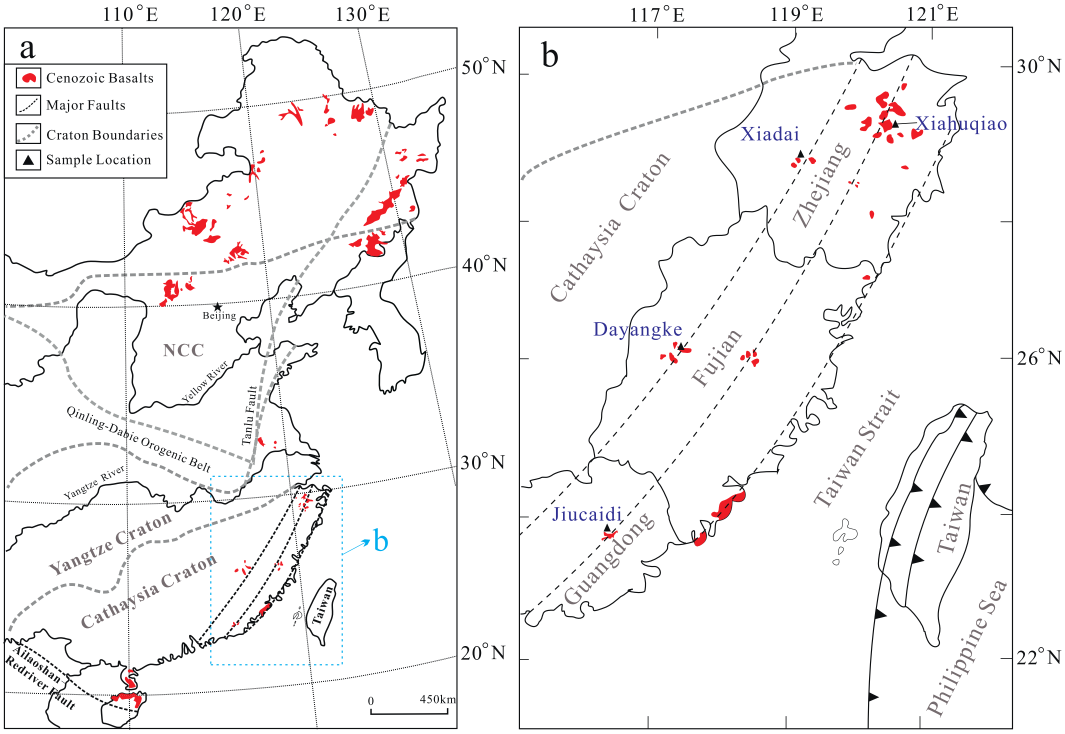

Fig. 1. (a) Distribution of the Cenozoic volcanism in eastern China. (b) Locations of our samples from Southeast (SE) China. Modified from Sun et al. (2017).