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Could sedimentary carbonates be recycled into the lower mantle? Constraints from Mg isotopic composition of Emeishan basalts

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ABSTRACT

Whether or not sedimentary carbonates can be recycled into the lower mantle through subduction remains unclear. To further elucidate this issue, we investigate the Mg isotopic composition of Permian basalts from the Emeishan large igneous province (ELIP). Emeishan basalts can be divided into two major groups: the low-Ti and high-Ti basalts, which exhibit distinct major, trace element, and Sr–Nd–Pb isotopic compositions. However, they both possess mantle-like Mg isotopic compositions with δ^{26}Mg values of −0.33 to −0.19‰ and −0.35 to −0.19‰, respectively. Both the low-Ti and high-Ti basalts have experienced compositional evolution, e.g., fractional crystallization or crustal contamination, because their Mg$^{\#}$ (39.8–61.1) values are significantly lower than that of primary melt (~72.0). However, their δ^{26}Mg values do not vary with Mg$^{\#}$, indicating that the Mg isotopic compositions of the basalts were inherited from their mantle source. The low-Ti basalts are enriched in light rare earth elements with low ε_{Nd}(t) values (mostly ranging from −10.5 to −8.8) and low Ce/Pb, high Ba/Th ratios, suggesting that they were derived from the lithospheric mantle that was metasomatized by slab-derived fluids. Their mantle-like Mg isotopic composition suggests that the metasomatism of slab-derived fluids did not affect their Mg isotopic composition. This is consistent with most of the reported Arc basalts with mantle-like Mg isotopic compositions. On the other hand, the high-Ti basalts display an OIB-like trace element pattern and positive ε_{Nd}(t) values (+0.2 ~ +2.1), which were possibly derived from a mantle plume that originated from the lower mantle. Their mantle-like Mg isotopic composition indicates that sedimentary carbonates recycled into the lower mantle beneath the ELIP were limited (<2%).

1. Introduction

Although carbon cycling theory requires that substantial quantities of sedimentary carbonates are recycled into the mantle by slab subduction (Dasgupta, 2013; Javoy et al., 1982), their precise fate in the mantle remains unknown. For instance, it is possible that they are stored in the mantle wedge (Kelemen and Manning, 2015), continental lithospheric mantle (Hu et al., 2016; Huang et al., 2011a; Ke et al., 2016; Wang et al., 2016a; Xiao et al., 2013; Yang et al., 2009), convective upper mantle (Huang et al., 2015; Li et al., 2017; Tian et al., 2016; Yang et al., 2012), lower mantle (Huang et al., 2011b) or even returned to the Earth's atmosphere by volcanism at island arcs, continents, or oceanic islands. The residence time of recycled carbonates in the mantle could be 5 to 10 Ma in the mantle wedge beneath island arcs (Kelemen and Manning, 2015), 60 to several hundred Ma in the upper mantle (Li et al., 2017) or 1–2 Ga in the lower mantle (Dasgupta and Hirschmann, 2010; Sleep and Zahnle, 2001) depending on where the carbonates are stored. Therefore, it is critical to determine how deep the sedimentary carbonates can be recycled into mantle by plate subduction.

Magnesium isotopes are demonstrated as effective tracers for the recycling of sedimentary carbonates in the mantle source (e.g., Huang et al., 2015; Li et al., 2017; Tian et al., 2016; Yang et al., 2012). This is due to the distinctive Mg isotopic compositions between sedimentary carbonates (δ^{26}Mg = −5.60 to −0.66‰; Beinlich et al., 2014; Saenger and Wang, 2014) and mantle peridotites (δ^{26}Mg = −0.25 ± 0.07‰; Teng et al., 2010). Other processes (e.g. crustal contamination, magma evolution, lithosphere-asthenosphere interaction) can hardly shift Mg isotopic composition of basalts. For example, the crust has low MgO content with an average of ~2.48 wt.% (Rudnick and Gao, 2003) and mantle-like average Mg isotopic composition (δ^{26}Mg = 0.24 ± 0.07‰; Yang et al., 2016). Thus, crustal contamination cannot modify the Mg isotopic compositions of basalts. In addition, Mg isotope fractionation during magmatic evolution (Teng et al., 2007, 2010) and prograde metamorphism dehydration in the subducted slab (Wang et al., 2014) are limited. Moreover, the lithosphere–asthenosphere interaction cannot modify the Mg isotopic composition of upwelling basaltic melts (Tian et al., 2016).

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Recent Mg isotopic studies of continental basalts in eastern China revealed that sedimentary carbonates can be recycled into the mantle transition zone (MTZ, 410–660 km) (Huang et al., 2015; Li et al., 2017; Tian et al., 2016; Yang et al., 2012). However, whether or not sedimentary carbonates could be carried into the lower mantle via subduction is a topic of debate. Combined Ca–Sr isotopes of Hawaiian basalts suggest that approximately 4% ancient marine carbonates were added into the source of the Hawaiian plume (Huang et al., 2011b). However, experimental studies have pointed out that lower mantle carbonates recycling may be limited (Hammouda and Keshav, 2015; Kelemen and Manning, 2015; Thomson et al., 2016). Even though low δ^{26}Mg features were observed in the plume-related Hainan basalts and HIMU-like New Zealand basalts, they are considered to result from recycled carbonated eclogites rather than sedimentary carbonates based on correlations between Mg isotopes and major/trace element ratios (Li et al., 2017; Wang et al., 2016b).

In order to determine whether subduction into the lower mantle can carry sedimentary carbonates, more plume-related basalts derived from the lower mantle should be investigated by Mg isotopes. The Permian basalts from the Emeishan large igneous province (ELIP), southwestern China, are widely accepted to be mantle plume in origin (e.g., Chung and Jahn, 1995; Xiao et al., 2004; Xu et al., 2001, 2004). The Emeishan basalts can be divided into the low-Ti and high-Ti basalts based on their distinctive geochemical characteristics (e.g., Xu et al., 2001; Xiao et al., 2004). Although the petrogenesis of the low-Ti basalts remains controversial (e.g., Song et al., 2008; Wang et al., 2007; Xiao et al., 2004; Xu et al., 2001, 2004, 2007), the high-Ti basalts are considered to originate from a mantle plume (e.g., Chung et al., 1998; Huang et al., 2014; Song et al., 2001, 2008; Xiao et al., 2003, 2004; Xu et al., 2001, 2004; Zhang and Wang, 2002). Due to the high potential mantle temperature (>1550 °C) as inferred by REE inversion in the basalts (Xu et al., 2001) and picrites (Zhang et al., 2006), the mantle plume could be derived from the lower mantle (Song et al., 2001). The data presented in this study show that both types of basalts from the ELIP have mantle-like Mg isotopic compositions, with δ^{26}Mg values of −0.33 to −0.19‰ and −0.35 to −0.19‰, respectively. This suggests that recycled carbonate is limited to less than 2% in the lower mantle source of the Emeishan plume.

2. Geological background and sample descriptions

The Emeishan large igneous province (ELIP) is located in the western margin of the Yangtze craton, southwest China (Chung and Jahn, 1995; Xu et al., 2001) (Fig. 1a), covering an area of ~250,000 km^2. The thickness of the volcanic lavas varies from ~5 km in the west to ~100 m in the east (Chung and Jahn, 1995; Xu et al., 2001). The ELIP can be divided into a central part and an outer zone, based on the thickness of the volcanic lavas, their chemical compositions, occurring rock types, etc. (Song et al., 2005). The exposed volcanic rocks include picrites, basalts, basaltic andesites, rhyolite-trachyte, intrusions, and basaltic pyroclastics (Xu et al., 2001).

The Emeishan basalts unconformably overlie late Permian limestone formations and are overlain by Triassic sedimentary rocks (Chung and Jahn, 1995). They erupted at approximately 260 Ma

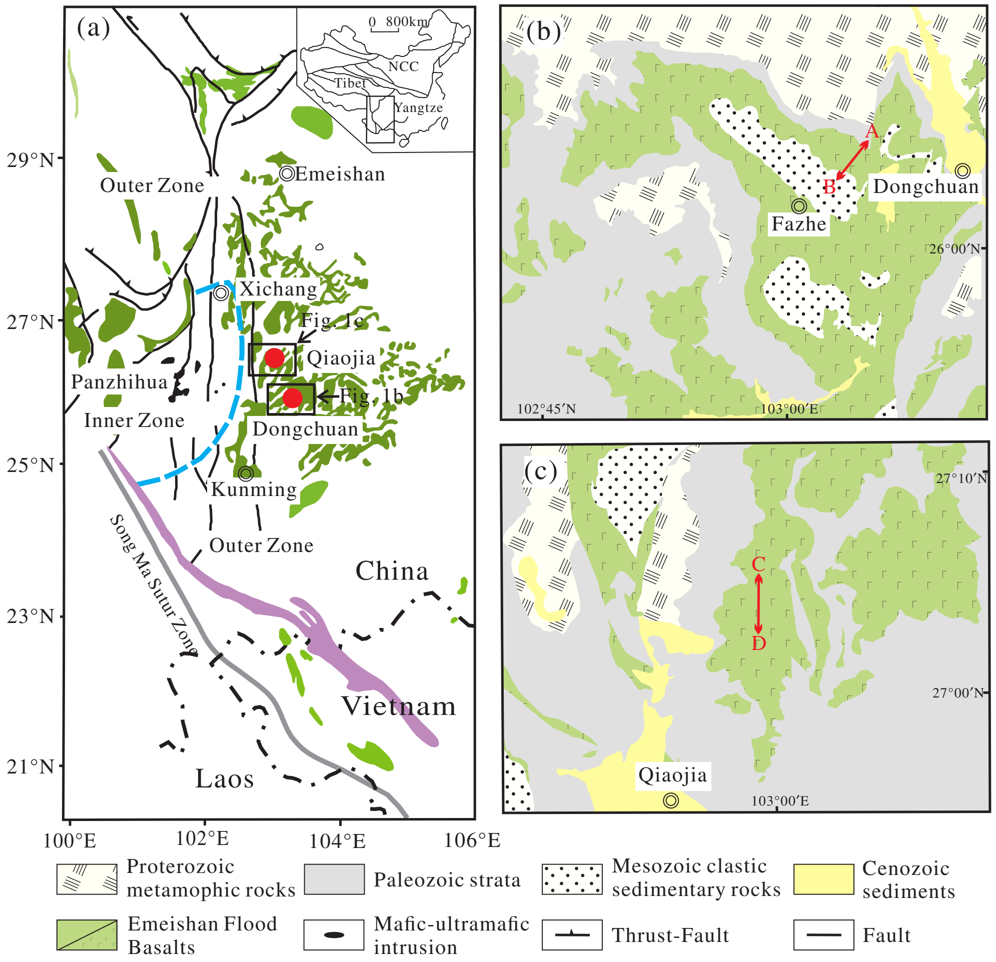

Fig. 1. (a) Geological map of the Emeishan large igneous province, showing the distribution of the continental flood basalts (modified from Song et al., 2008). (b) Simplified map of the Dongchuan area. (c) Simplified map of the Qiaojia area. Lines A–B and C–D represent the profiles where samples were collected from Dongchuan and Qiaojia, respectively.