Geochemical evidence for carbonated metasomatite as the mantle source of Cenozoic alkali basalts in western Qinling, China

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Introduction

Mantle peridotite was considered as the source lithology of alkali basalts. However, experimental petrology indicates that partial melting of peridotite produces different basaltic melts from natural alkali basalts in some major elements. For example, the experimental products show significantly lower CaO and higher Al_2O_3 contents than natural alkali basalts (e.g., Hirschmann et al., 2003; Dasgupta et al., 2007). Instead of the normal peridotite, three major metasomatic lithologies such as carbonated peridotite, pyroxenite and hornblendite have been suggested as the mantle source of alkali basalts (e.g., Hirschmann et al., 2003; Dasgupta et al., 2007; Pilet et al., 2008). Nevertheless, experimentally produced basaltic melts from these metasomatic lithologies also fail to match all the features of natural alkali basalts. The mantle lithology for alkali basalts still remains enigmatic. In addition, the origin of these metasomatic lithologies for alkali basalts also remains controversial.
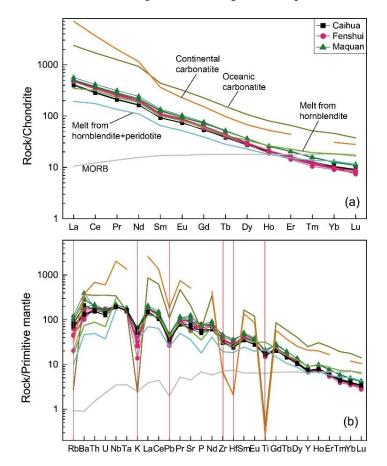
During the subduction of oceanic crust, the recycling of carbonate-bearing sediment at convergent plate margins has played an important role in carbonatitic metasomatism and possible global carbon cycling. In particular, carbonated peridotite has received increasing attention due to its petrogenetic link to alkali basalts. Alkali basalts above ancient subduction zones provide us with an excellent opportunity to investigate the recycling of the subducted crustal materials, and the petrogenesis of alkali basalts. In this study, a combined study of whole-rock major-trace elements and Sr-Nd-Hf isotopes was carried out for Cenozoic alkali basalts in western Qinling orogen of China, which are associated with carbonatite. The results provide insights not only into the slab-mantle interaction in the ancient subduction zone, but also into the mantle lithology for the alkali basalts.

Geochemical results

Alkali basalts from Qinling orogen are all silica-undersaturated alkali basalts. They have low contents of SiO_2 (36.9-40.8 wt.%) and Al_2O_3 (7.3-10.2 wt.%) but high CaO (13.5-14.5 wt.%), with high CaO/Al_2O_3 ratios of 1.42 to 2.19. In the chondrite-normalized REE diagram (Fig. 1a), all the basalts show enrichment in LREE with $(La/Yb)_N$ ratios of 37.9 to 53.0, and without profound Eu anomalies. In the primitive mantle-normalized spidergram (Fig. 1b), they exhibit enrichment in Ba, Nb and Ta but depletion in Rb, K, Pb, Zr and Hf, resembling mafic melts derived from partial melting of hornblendite and hornblendite + peridotite to some extent (Pilet, et al., 2008). The significant depletion in Rb, K, Pb, Zr, Hf and Ti is similar to the trace element patterns of oceanic and continental carbonatites derived from partial melting of carbonated mantle sources. The alkali basalts show low whole-rock $(^{87}Sr/^{86}Sr)_i$ ratios of 0.7041 to 0.7060, and positive $\varepsilon_{Nd}(t)$ values of 3.4 to 4.2 and $\varepsilon_{Hf}(t)$ values of 5.8 to 7.2.
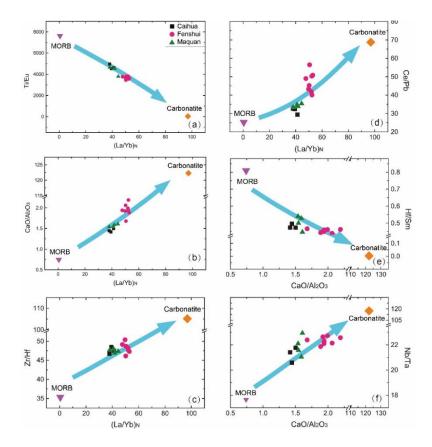
Discussion

For the study of basalt petrogenesis, field and petrographic observations must be combined with major-trace element and stable-radiogenic isotope compositions to make an integrated interpretation. The studied alkali basalts are associated with carbonatite lava in the field. Carbonate globules and irregular patches are also observed under a microscope. These features suggest the role of a carbonated mantle source in generating the West Qinling alkali basalts. For major elements, the alkali basalts exhibit low SiO_2, but high MgO and CaO with high CaO/Al_2O_3 ratios, requiring their derivation from partial melting of fertile ultramafic rocks. For trace elements, the alkali basalts are enriched in incompatible elements such as LREE, Ba and Sr, but depleted in Rb, K, Zr, Hf, and Ti. Such trace element features are significantly different from normal MORB, but similar to carbonatite to some extent (Figs. 1a and 1b).

Thus, these features probably indicate the involvement of carbonate-bearing crustal material in their source region. For radiogenic isotope compositions, they generally exhibit low $(^{87}Sr/^{86}Sr)_i$ ratios, and positive $\varepsilon_{Nd}(t)$ and $\varepsilon_{Hf}(t)$ values, suggesting contribution from juvenile crustal components. Taken together, all these geochemical features indicate that the alkali basalts would be originated from a kind of ultramafic lithologies, which is fertile in lithochemistry, enriched in carbonate composition and melt-mobile incompatible trace elements, but depleted in radiogenic isotopes.

Figure 1: Chondrite-normalized REE patterns (a) and primitive mantle-normalized trace element distribution patterns (b) for alkali basalts from West Qinling. Also compared are the average oceanic and continental carbonatites compositions (Hoernle et al., 2002; Bizimis et al., 2003); melts from hornblendite and hornblendite + peridotite (Pilet et al., 2008).

Because carbonatitic metasomatism would increase the $(La/Yb)_N$ ratios of mantle sources and leads to strong depletion in high field strength elements (Coltorti et al., 1999). $(La/Yb)_N$ together with Ti/Eu ratios can be taken as useful indicators of carbonatitic metasomatism. As shown in Fig. 2a, the West Qinling alkali basalts show significantly higher $(La/Yb)_N$ ratios and lower Ti/Eu ratios than normal MORB, suggesting the carbonatitic metasomatism of their source region. The carbonatitic metasomatism also increases the CaO contents and CaO/Al_2O_3 ratios of mantle peridotite, and thus those of its derived basaltic magma. The high CaO/Al_2O_3 ratios, and the positive correlation between CaO/Al_2O_3 and $(La/Yb)_N$ ratios (Fig. 2b), also suggest significant contribution of carbonatitic component to their origin.

The carbonate melts are also characterized by high Zr/Hf, Nb/Ta and Ce/Pb ratios, but low Hf/Sm ratios. As illustrated in Figs. 2c-2f, the West Qinling alkali basalts show significantly higher Zr/Hf, Ce/Pb and Nb/Ta ratios but lower Hf/Sm ratios than normal MORB, and plot toward the average oceanic and continental carbonatites (Hoernle et al., 2002; Bizimis et al., 2003). There are also correlations between $(La/Yb)_N$ versus Zr/Hf and Ce/Pb ratios, and CaO/Al_2O_3 versus Hf/Sm and Nb/Ta ratios. These features suggest that the alkali basalts record the carbonatitic metasomatism.

Figure 2: Plots of (La/Yb)N versus Ti/Eu (a), CaO/Al2O3 (b), Zr/Hf (c) and Ce/Pb ratios (d) ratios, as well as CaO/Al2O3 versus Hf/Sm (e) and Nb/Ta ratios (f) for alkali basalts from West Qinling, showing carbonatitic metasomatism.

In summary, the West Qinling alkali basalts were originated from carbonated mantle source. A comparison of major-trace elements in the basalts with some representative mantle melts confirms that their mantle lithologies are composed of the carbonated peridotite and hornblendite. Such ultramafic metasomatites would be generated by reaction of the depleted mantle peridotite with anatectic melts, locally rich or poor in carbonate, that originated from the Palaeotethyan oceanic crust in a subduction channel. As carbonation significantly depresses the solidus of mantle lithology, these ultramafic metasomatites are more susceptible to partial melting for the production of alkali basalts.

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