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Crustal recycling processes in generating the early Cretaceous Fangcheng basalts, North China Craton: New constraints from mineral chemistry, oxygen isotopes of olivine and whole-rock geochemistry

Jiangtao Guo [a,c], Feng Guo [b,*], Christina Yan Wang [a], Chaowen Li [b]

[a] Key Laboratory of Mineralogy and Metallogeny, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou 510640, China
[b] State Key Laboratory of Isotopic Geochemistry, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou 510640, China
[c] University of Chinese Academy of Sciences, Beijing 100049, China

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ABSTRACT

The early Cretaceous Fangcheng basalts were erupted in the peak stage of lithospheric thinning of the North China Craton (NCC). They have olivine phenocrysts with forsterite (Fo) contents ranging from 74 to 92, clinopyroxene with high Mg# from 76 to 89, and contain pyroxenite xenoliths. Both the basalts and pyroxenite xenoliths have coexisting high-Ca and low-Al clinopyroxene and high-Mg and low-Ca olivine, indicating that the parental magmas of the basalts have high water contents comparable with arc basalts. They also show similar mineral chemistry and olivine O isotopic compositions ($\delta^{18}O = 5.5$–7.2‰), trace element patterns with large ion lithophile elements (LILEs) and light rare earth elements (LREEs) enrichments and high field strength elements (HFSEs) depletions, as well as enriched Sr–Nd–Hf isotopic features. Therefore, the pyroxenite xenoliths are cognate with the basalts. High $\delta^{18}O$ values (average ~ 6.5‰) of fresh olivine crystals from the basalts and xenoliths indicate the involvement of ^{18}O-rich crustal materials in the mantle source. Incorporation of ^{18}O-rich crustal materials to the mantle source is consistent with the highly evolved Sr–Nd–Hf isotopic signatures of the basalts and the pyroxenite xenoliths. Modeling results based on the Sr–Nd–O isotopic compositions of the basalts indicate that both upper and lower crustal materials of the Yangtze Block may have been incorporated into the mantle source. Therefore, the ^{18}O-rich crustal materials were likely derived from the subducted Yangtze Block in Triassic time. However, neither the NCC subcontinental lithospheric mantle nor the deeply subducted Yangtze crustal materials can provide sufficient water to produce hydrous basaltic magmas, instead exotic fluids may have been derived from the subducted paleo-Pacific slab. Dehydration of the subducted paleo-Pacific slab may have released enough fluids to trigger extensive hydrous melting of the enriched mantle source beneath the Fangcheng and its surrounding regions.

1. Introduction

The North China Craton (NCC) has been taken as a classic example of cratonic reactivation and destruction in recent years (e.g., Fan and Menzies, 1992; Menzies et al., 1993, 2007). Comparative studies between mantle xenoliths hosted in the early Ordovician diamondiferous kimberlites and the widespread Cenozoic alkaline basalts in the eastern NCC indicate a loss of >100 km lithosphere mantle (e.g., Fan et al., 2000; Gao et al., 2002; Xu, 2001). Emplacement of voluminous mafic to felsic lavas and intrusions (Fan et al., 2007; Guo et al., 2001, 2003; Wu et al., 2005; Zhang and Sun, 2002) and lamprophyric dikes (e.g., Guo et al., 2004) in NCC occurred in the early Cretaceous, coeval with the peak stage of lithospheric thinning (e.g., Menzies et al., 2007).

The mechanism of lithosphere thinning is, however, still enigmatic. Several hypotheses have been proposed in the past decade, such as lithospheric delamination (Gao et al., 2008), thermo-chemical erosion (Xu, 2001), metasomatism by melts derived from recycled crustal materials (Zhang, 2005), and mechanical erosion by low angle subduction of Pacific slab (Xu et al., 2012; Zhang et al., 2009). Niu (2005) suggested that the lithosphere thinning was due to a process of hydration that 'transformed' the basal portion of the lithosphere by decreasing its viscosity, and that the water was derived from the subducted palaeo-Pacific slab. In these models, the modification and thinning of the lithospheric mantle beneath NCC was attributed to the involvement of recycled crustal materials in the mantle source, such as melts of delaminated lower crust or subducted continental crust, or fluids from the subducted oceanic crust. However, the nature of the recycled crustal materials, e.g., the subducted Yangtze crust or delaminated NCC lower crust; and the melting mechanism, either hydrous melting or anhydrous melting are still unclear. Therefore, the contribution of the recycled crustal materials in the formation of the Mesozoic mafic rocks and constraint on the melting conditions should be evaluated to reexamine the above hypotheses.

The early Cretaceous Fangcheng basalts that erupted during the peak stage of lithospheric thinning have remarkably high MgO and contain

* Corresponding author.
E-mail address: guofengt@263.net (F. Guo).

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both olivine and clinopyroxene phenocrysts with complex compositional zonation and pyroxenite xenoliths (Xu et al., 2013; Zhang, 2005; Zhang et al., 2002). The xenoliths include dunite, olivine websterite and clinopyroxenite, which are considered to be mantle residues formed due to interaction of mantle peridotite with recycled crustal melts (e.g., Zhang, 2005). Olivine with high forsterite (Fo = ~92) content from the Fangcheng basalts has been interpreted as xenocrysts from the refractory lithosphere mantle beneath NCC despite the absence of 'true' mantle xenoliths such as spinel- and/or garnet-facies peridotites in the basalts (Zhang, 2005). On the other hand, mafic-ultramafic rocks that are mainly composed of olivine and clinopyroxene are reported to have formed from hydrous magmas at crust-level chambers, similar to arc-related ophiolitic suites in Oman and Egypt (e.g., Gahlan et al., 2012; Koepke et al., 2009; Koga et al., 2001) and Alaska-type ultramafic-mafic complexes in Alaska and New Zealand (e.g., Li et al., 2012; Spandler et al., 2003). Olivine phenocrysts with very high Fo (up to 94) were also reported in the arc basalts in Solomon Islands (Kamenetsky et al., 2006; Rohrbach et al., 2005). Recent experimental studies on hydrous basaltic magmas also support the fractional crystallization origin of such high-MgO mineral assemblage (Feig et al., 2006; Gaetani et al., 1993; Koepke et al., 2009). Therefore an alternative interpretation is that the high-Fo olivine phenocrysts from the Fangcheng basalts may have crystallized from a hydrous primary magma.

The upper crust is mainly composed of sediments and weathered, and/or hydrothermally altered rocks and commonly has $\delta^{18}O$ values much higher than the bulk mantle ($\delta^{18}O = \sim 5.5 \pm 0.2‰$, Mattey et al., 1994). O isotope fractionation mainly occurs in near-surface processes and O isotope is a sensitive indicator for the presence of the upper crust materials in mantle-derived magmas, either by subduction process or contamination during magma differentiation (Eiler et al., 2001; Taylor and Sheppard, 1986). Whole-rock O isotopic analysis failed to distinguish between these two processes (e.g., Bindeman et al., 2008; Eiler et al., 2011). However, early crystallized minerals such as olivine may preserve the O isotopic compositions of the primary magma, and can thus be used to evaluate the involvement of recycled crustal components in mantle source.

Olivine phenocrysts from the Fangcheng basalts are very complex. They are usually cracked and have compositional zonation and so are not suitable for a routine approach to analyze O isotopes of bulk grains. In this study, O isotope compositions of olivine crystals from the basalts and pyroxenite xenoliths were analyzed by in situ O isotope analysis using a secondary ion microprobe spectrometer (SIMS, Cameca IMS-1280). Together with mineral chemistry and whole-rock major and trace elements and Sr–Nd–Hf isotopic compositions of the basalts and pyroxenite xenoliths, we discuss the interaction of the mantle source with crustal components in the formation of the Fangcheng basalts. Our results also indicate that the lithospheric mantle beneath NCC may be markedly hydrous at the time of intensive thinning.

2. Geological setting

The North China Craton is the oldest craton in China with an Archaean (~2.8 Ga) lithospheric mantle (Gao et al., 2002; Zhang et al., 2008). It is composed of western and eastern blocks separated by the Trans-North China Orogen (Fig. 1) (Zhao et al., 2001). The NCC is bordered by Paleozoic and Mesozoic orogens, suture zones and faults. The northern boundary is the Permo-Triassic Solonker suture, which marks the closure of the paleo-Asian Ocean and the termination of the Central Asian Orogenic Belt after collision of the NCC and Mongolia Block by the end of Permian (Xiao et al., 2003). The southern margin is the Qinling–Dabie–Sulu collisional orogen, along which the NCC and South China (or Yangtze) Block collided in the early Triassic. The Sulu orogen has been displaced by the Tan-Lu fault zone in Mesozoic time (Fig. 1; Li, 1994).

Extensive magmatic activities occurred in early Cretaceous along the Tan-Lu fault zone. ~125 Ma Fangcheng basalts (Zhang et al., 2002) occur in the small fault-bounded Pingyi Basin, 70 km west of the Tan-Lu fault zone. The basalts make up the lower-middle part of the lower Cretaceous Qingshan Formation. The adjacent Feixian picritic basalts (Gao et al., 2008) are considered to represent the less evolved counterpart for the Fangcheng basalts. The Feixian picritic basalts were erupted at 119.0 ± 2.3 Ma, temporarily similar to the Fangcheng basalts (Gao et al., 2008).

3. Petrography

The Fangcheng basalts are porphyritic with predominant olivine and clinopyroxene phenocrysts. The matrix is composed of clinopyroxene, plagioclase microcrystallines and Fe–Ti oxides. Olivine phenocrysts are different in shapes and most of them are equant or elongated, rounded and ellipsoidal globules with a few euhedral to subhedral crystals (Fig. 2a). Olivine phenocrysts range in grain sizes from 0.2 to 2 mm (Fig. 2b–d). Some olivine crystals are more or less skeletal by patches of matrix (Fig. 2e). Clinopyroxene phenocrysts are generally subhedral to anhedral, and commonly rounded in shape with smooth or ragged outlines. They have grain size ranging from 0.4 to 8 mm, and most grains are of ~1 mm in size (Fig. 2a, f and g). Clinopyroxene in the matrix is generally short columnar or ellipsoidal in shape and is commonly ~0.05 mm in size.

Pyroxenite xenoliths are usually <10 cm in size and are cumulates composed of clinopyroxene, olivine and orthopyroxene and minor Cr-spinel with a granular texture (Fig. 2h, i and k). Olivine is subhedral and ranges from 2 to 4 mm in size. Clinopyroxene is usually subhedral to euhedral and ranges in size from 2 to 8 mm. A few small orthopyroxene grains are enclosed in clinopyroxene (Fig. 2i and k). Fine carbonate veins are commonly seen in the xenolith (Fig. 2k).

4. Analytical techniques

4.1. Mineral compositions

Back-scattered electron (BSE) images and chemical compositions of minerals were performed on a JEO LIXA-8100 Electron Microprobe at the Guangzhou Institute of Geochemistry (GIG), Chinese Academy of Sciences (GIG, CAS). Normal operating conditions were 15 kV accelerating voltage, 10 nA beam current, and 1 ~ 2 μm beam diameter. Extended counting time was used following the method described in Sobolev et al. (2007) for olivine. Based on repeated analyses of the natural and synthetic standards, relative analytical uncertainty is <2% for the major elements and <5% for minor elements. ZAF correction procedure was used for data reduction. Back-scatter photos of minerals were also taken on this system. The representative analyses of olivine and clinopyroxene are attached in Appendix 1 and 2, respectively.

4.2. In situ oxygen isotope

In situ olivine oxygen isotope analysis was carried on the Cameca IMS-1280 in the Institute of Geology and Geophysics, CAS. San Carlos olivine standard grains were mounted adjacent to the thick-polished sections in epoxy. The Cs^+ primary beam was accelerated at 10 kV with an intensity of ca. 2 nA. The spot size was about 20 μm in diameter (10 μm beam diameter + 10 μm raster). An electron gun was used to compensate for sample charging during analysis. Secondary ions were extracted with a −10 kV potential. Oxygen isotopes were measured in multi-collector mode with two off-axis Faraday cups with each analysis consisting of 20 cycles × 4 counting time. External reproducibility of olivine standards was typically better than 0.4% (2σ) for $\delta^{18}O$. Detailed description of the analytical procedure was reported in Li et al. (2010). Matrix effects are negligible within the errors of measurement for olivine with variable Fo on Cameca IMS 1270/1280 in recently work (Bindeman et al., 2008; Eiler et al., 2011; Gurenko et al., 2011). The grains selected for SIMS were imaged in back-scattered electrons to ensure that the surface is free of secondary alteration products. The spots analyzed by SIMS