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Zircon Hf–O isotope evidence for crust–mantle interaction during continental deep subduction

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ABSTRACT

In-situ SIMS zircon U–Pb dating and O isotope analysis as well as LA-(MC)-ICPMS zircon U–Pb dating and Lu–Hf isotope analysis were carried out for postcollisional mafic–ultramafic rocks in the Dabie orogen, China. The zircon U–Pb dating gave consistent ages of 126 ± 1 to 131 ± 1 Ma for magma crystallization. Survival of residual zircon cores is identified by CL imaging and U–Pb dating, yielding ages of 697 ± 10 and 770 ± 11 Ma that agree with protolith U–Pb ages of UHP metaigneous rocks in the Dabie orogen. The zircon Hf–O isotope compositions show systematic variations that can be categorized into three groups. Group I has the lowest $\delta^{18}O$ values of 2.0 to 2.9‰ but the highest $\varepsilon_{Hf}(t)$ values of −3.5 to −1.0 with the youngest Hf model ages of 1.2 to 1.4 Ga. Group II displays intermediate $\delta^{18}O$ values of 4.0 to 5.1‰ and $\varepsilon_{Hf}(t)$ values of −22.5 to −13.2 with Hf model ages of 2.0 to 2.6 Ga. Group III exhibits the highest $\delta^{18}O$ values of 5.2 to 7.3‰ but the lowest $\varepsilon_{Hf}(t)$ values of −29.1 to −18.6 with the oldest Hf model ages of 2.4 to 3.0 Ga. The three groups of Hf–O isotope compositions correspond to a three-layer Hf–O isotope structure in the subducted continental crust, suggesting their involvement in the mantle source. Along with existing data for whole-rock Sr–Nd isotopes and trace elements, it appears that the mantle source for the postcollisional mafic–ultramafic rocks is characterized by fertile lithochemistry, the arc-like signature of trace elements, the heterogeneous enrichment of radiogenic isotopes, the differential incorporation of supracrustal materials, and the variable concentrations of water. Clearly, such a source is neither the asthenospheric mantle nor the refractory subcontinental lithospheric mantle (SCLM). It is a kind of the orogenic SCLM that would be generated by reaction of the overlying SCLM-wedge peridotite with hydrous silicate melts derived from different layers of the subducted continental crust. Therefore, the postcollisional mafic–ultramafic rocks provide a petrological record of crust–mantle interaction during the continental deep subduction.

1. Introduction

Subduction-zone magmatism is considered as an important mechanism for exchanging mass and energy between the mantle and the crust (e.g., Coltice, 2000; Simon and Lécuyer, 2005). While the mantle becomes depleted in chemistry by extraction of mafic melts to form the crust, crustal materials can be recycled into the mantle in oceanic subduction zones to cause mantle heterogeneity in not only major and trace elements but also stable and radiogenic isotopes (e.g., Hofmann, 1997; Willbold and Stracke, 2010; Zhang et al., 2009; Zindler and Hart, 1986). Thus, the crust–mantle interaction is caused by elemental and isotopic transfers in plate convergent zones, with chemical reactions at the interface between the subducting slab and the overlying mantle wedge. Since much attention has been paid to recycling of the subducted oceanic crust, it is intriguing whether recycling of the subducted continental crust takes place in continental subduction zones. The latter issue also has great bearing on chemical geodynamics in convergent plate margins, with potential implications for chemical differentiation of the continental crust.

Continental deep subduction is commonly characterized by the generation of ultrahigh-pressure (UHP) metamorphic rocks at mantle depths (Chopin, 2003; Liou et al., 2009), with possible interaction between the subducting continental crust and the overlying mantle wedge. However, no arc-type syn-subduction magmatism has been identified so far in continental collision zones, which is explained by the significant lack of aqueous fluids during the continental crustal subduction (Liou et al., 1997; Zheng et al., 2003). Instead, postcollisional magmatic rocks are common in typical continent collisional zones (e.g., Chung et al., 2005; Eyal et al., 2010; Jahn et al., 1999; Zhao and Zheng, 2009). They are, in lithochemistry, mainly potassic and in particular high-K calc-alkaline with subordinate amount of shoshonitic rocks (Bonin, 2004; Liégeois, 1998). Insights into the origin of these rocks (especially mafic–ultramafic rocks) are crucial to understanding of the crust–mantle interaction in continental subduction zones.

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Voluminous postcollisional magmatic rocks crop out in the Dabie–Sulu orogenic belt of China that formed by the Triassic subduction of the South China Block beneath the North China Block (e.g., Jahn et al., 1999; Zhao et al., 2007a; Zhao and Zheng, 2009). They are composed of massive granitoids and sporadic mafic–ultramafic rocks. Previous studies have demonstrated that these magmatic rocks were mainly formed in the Early Cretaceous (113–143 Ma; Zhao and Zheng, 2009). It has been well established from geochronological and geochemical studies that the postcollisional granitoids were formed by partial melting of the subducted continental crust of the South China Block (e.g., Huang et al., 2006; Zhang et al., 2010; Zhao et al., 2007a). In addition, the previous studies showed that the postcollisional mafic–ultramafic rocks are characterized not only by the arc-like features of trace element compositions such as enrichment in large ion lithophile elements (LILE) and light rare earth elements (LREE) but depletion of high field strength elements (HFSE), but also by the ancient crust-like feature of radiogenic isotope compositions such as high initial Sr isotope ratios and negative $\varepsilon_{Nd}(t)$ values. These element and isotope features were interpreted to indicate incorporation of the subducted continental crust into the mantle source (e.g., Fan et al., 2004; Huang et al., 2007; Jahn et al., 1999; Wang et al., 2005; Zhao et al., 2005). However, it is unclear what kind of the mantle was metasomatized by the crust during the continental deep subduction and how the subducted continental crust was recycled into the mantle. If such recycling did occur, there remain some fundamental questions to answer: which part of the subducted crust was involved in the crust–mantle interaction? When and by which mechanism do the subducted crustal rocks affect the mantle-wedge peridotite? Does the compositional difference in the postcollisional mafic–ultramafic rocks reflect the differential effects of different subducted crustal materials on the mantle source?

In order to answer the above questions, we performed a combined in-situ study by means of both SIMS and LA-(MC)-ICPMS techniques on zircons from postcollisional mafic–ultramafic rocks in the Dabie orogen. The SIMS analyses were made firstly for zircon O isotopes and then for U–Pb isotopes. Afterwards, the same grains of zircon were analyzed by LA-(MC)-ICPMS for a simultaneous determination of U–Pb and Lu–Hf isotopes. The results provide new insights not only into the nature of mantle source in collisional orogens, but also into mechanism of the crust–mantle interaction during the continental deep subduction.

2. Geological setting and samples

The Dabie–Sulu orogenic belt is located in east-central China and it was formed by the Triassic subduction of the South China Block beneath the North China Block (e.g., Li et al., 1999; Zheng, 2008). The Dabie orogen is considered as its western part, truncated by the Tan-Lu fault that offsets the Dabie orogen from the Sulu orogen in Shangdong Peninsula about 500 km (lower right insert in Fig. 1). The UHP metamorphism is indicated by occurrences of coesite and micro-diamond inclusions in metamorphic minerals (Okay et al., 1989; Wang et al., 1989; Xu et al., 1992). According to metamorphic P–T conditions on the outcrop scale, the Dabie orogen can be divided into five parts (Zheng et al., 2005a): (1) Beihuaiyang low-T/low-P greenschist-facies zone, (2) North Dabie high-T/UHP granulite-facies zone, (3) Central Dabie mid-T/UHP eclogite-facies zone, (4) South Dabie low-T/UHP eclogite-facies zone, and (5) Susong low-T/HP blueschist-facies zone. All of these metamorphic units are intruded by postcollisional magmatic rocks in the ages of Early Cretaceous (Zhao and Zheng, 2009).

The North Dabie zone is mainly composed of granitic orthogneisses in trondhjemite–tonalite–granodiorite (TTG) compositions, with subordinate eclogites, granulites, amphibolites, and migmatites (Liu and Li, 2008; Zhao et al., 2008; Zheng et al., 2005a). They were intruded by voluminous granitoids and minor mafic–ultramafic rocks in the ages of Early Cretaceous (Bryant et al., 2004; Chen et al., 2002; Huang et al., 2007; Jahn et al., 1999; Ma et al., 1998; Wang et al., 2007; Xu et al., 2007; Zhang et al., 2002; Zhao et al., 2004, 2005, 2007a). The mafic–ultramafic rocks are mainly composed of pyroxenite, hornblendite and gabbro, and they are characterized by variably high MgO contents of 6.5 to 29.0 wt.% and Ni contents of 87 to 509 ppm as well as Mg# values of 59 to 87 (Huang et al., 2007; Jahn et al., 1999; Zhao et al., 2005). In particular, they show enrichment of LREE and LILE but depletion of HFSE as well as high initial Sr isotope ratios and negative $\varepsilon_{Nd}(t)$ values (Fig. 2), typical of the geochemical signatures of continental crust.

The samples used in this study were collected from Daoshichong (09DSC04 and 09DB97) and Zhujiapu plutons (09ZJP01 and 09DB100), two major postcollisional mafic–ultramafic intrusions in North Dabie (Fig. 1). The Daoshichong pluton consists of hornblendite and plagioclase-rich hornblendite, and the Zhujiapu pluton is composed of olivine pyroxenite, pyroxenite, hornblendite, gabbro, plagioclase-rich hornblendite and biotite diorite. These mafic–ultramafic rocks are generally undeformed and unmetamorphosed, and some of them display cumulate textures.

Samples 09DSC04 and 09DB97 from Daoshicong are petrographically named as hornblendite and plagioclase-rich hornblendite according to modal abundances of rock-forming minerals. Hornblendite 09DSC04 consists of hornblende (>98%), biotite, minor ilmenite, magnetite, apatite and zircon. Hornblende grains are commonly medium-sized (2–5 mm) with subhedral or anhedral morphology. They show similar morphology and texture of inter-irregular cumulation, suggesting their nearly simultaneous crystallization from the host magma. Compared to hornblendite 09DSC04, plagioclase-rich hornblendite 09DB97 contains less hornblende (~60%) but more plagioclase (30%) and biotite (5%).

Pyroxenite 09ZJP01 from Zhujiapu is composed of clinopyroxene (60%), orthopyroxene (35%), hornblende (2%) and minor accessory minerals including magnetite, ilmenite and zircon. Clinopyroxene is locally enclosed by hornblende. Plagioclase-rich hornblendite 09DB100 consists of hornblende (55%) and plagioclase (45%), with minor clinopyroxene, magnetite, ilmenite, apatite and zircon. Clinopyroxene and hornblende partially convert to chlorite, with enclosure of clinopyroxene within hornblende.

3. Analytical methods

Zircon was separated by the standard density and magnetic separation techniques, and then selected by hand picking under a binocular microscope. Representative zircon grains were mounted in epoxy resin, and then polished to expose grain center. As a guide to selection of in-situ analysis spot, transmitted and reflected light micrographs as well as cathodoluminescence (CL) were taken to reveal their external morphology and internal structure. The CL images were obtained using HITACHI S3000-N scanning electron microscope at Beijing SHRIMP Center.

3.1. SIMS O isotope analysis and U–Pb dating

Zircon O isotopes were analyzed using Cameca IMS 1280 at State Key Laboratory of Lithospheric Evolution in Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing. Analytical procedures are the same as those described in detail by Li et al. (2010a). The Cs^{+} primary ion beam was accelerated at 10 kV, with an intensity of ca. 2 nA (Gaussian mode with a primary beam aperture of 200 μm to reduce aberrations) and rastered over a 10 μm area. The analysis spot was about 20 μm in diameter. Oxygen isotopes were measured in multi-collector mode using two off-axis Faraday cups. The NMR (Nuclear Magnetic Resonance) probe was used for magnetic field control with stability better than 2.5 ppm over 16 h on mass 17. One analysis takes ~4 min consisting of pre-sputtering (~120 s),