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Geochemical constraints on petrogenesis of marble-hosted eclogites from the Sulu orogen in China

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ABSTRACT

Marble-hosted eclogite is volumetrically minor in collisional orogens, but its geochemistry has great bearing on the origin of deeply subducted crustal rocks and the fluid mobility of subduction zones. This paper presents a combined study of whole-rock major-trace elements and Sr—Nd isotopes, mineral O isotopes, carbonate C and O isotopes, and zircon U—Pb ages and Lu—Hf isotopes for marble-hosted ultrahigh-pressure metamorphic eclogites from Rongcheng and Sanqingge in the Sulu orogen. The results provide insights into the protolith nature of eclogites and the fluid mobility of subduction zones. Zircon U—Pb dating yields consistent middle Triassic ages for the two occurrences of eclogites, indicating new growth of metamorphic zircon during continental collision. The Sanqingge eclogite shows LREE-enriched patterns and negative $\varepsilon_{Nd}(t)$ of -16.6 to -14.3 for whole-rock and negative $\varepsilon_{Hf}(t)$ of -27.1 to -15.2 for metamorphic zircon. A few relict zircon domains show middle Neoproterozoic U—Pb ages and negative $\varepsilon_{Hf}(t)$ of -35.2 to -15.5. Thus, the Sanqingge eclogite was metamorphosed from a mafic rock that was derived from partial melting of an anciently enriched mantle source. In contrast, the Rongcheng eclogite exhibits flat or even LREE-depleted patterns with negative $\varepsilon_{Nd}(t)$ values of -12.2 to -1.0 for whole-rock but positive $\varepsilon_{Hf}(t)$ values of 5.4 to 10.4 for zircon. The occurrence of interstitial and highly cuspate plagioclase along grain boundaries indicates the presence of partial melting in the eclogite. Thus, its positive zircon $\varepsilon_{Hf}(t)$ values are ascribed to the eclogite protolith of juvenile origin, whereas the LREE depletion is due to extraction of LREE-rich anatectic melt from the eclogite during the Triassic continental collision. As such, the Rongcheng eclogite was metamorphosed from a mafic rock that was derived from partial melting of a less enriched mantle source. All the eclogites from both areas show variably high $\delta^{18}O$ values of 9.4‰ to 19.5‰. Oxygen isotope fractionations between mineral pairs mostly yield eclogite-facies temperature of 600 to 800 °C, suggesting that the high $\delta^{18}O$ signature was inherited from their protoliths before the Triassic subduction. In combination with the field relation between the eclogite and marble, it is inferred that the eclogite protolith is probably basaltic tuff and its high $\delta^{18}O$ value would be acquired together with the marble protolith during their deposition from the surface water. Therefore, there would be the limited isotopic exchange between marble and eclogite during continental collision.

1. Introduction

Ultrahigh-pressure (UHP) metamorphic eclogites in collision orogens were generated by subduction of mafic lithologies to subarc depths of >100 km (Ernst and Liou, 1999; Chopin, 2003; Schertl and O'Brien, 2013). Thus a wealth of physiochemical information can be decoded by investigating the composition of such rocks. According to the relationships between eclogite and its host rocks, three types of eclogite have been recognized (Jahn, 1998; Zheng et al., 2003): (1) G-type, as enclave in orthogneiss and paragneiss of felsic composition; (2) M-type, as enclave in or interlayer with marble or metaclastic sediment; (3) P-type, as enclave and interlayer with ultramafic rock such as peridotite and pyroxenite. Although the M-type eclogite is volumetrically minor, it has great bearing on the recycling of surface water and carbon into the mantle during subduction-zone metamorphism (e.g., Zheng et al., 2003; Wang et al., 2014a).

Eclogites of continental affinity typically show LREE-enriched distribution patterns (Jahn, 1998; Rumble et al., 2003). However, some eclogites from the Dabie-Sulu orogenic belt show prominent LREE depletion (Zhao et al., 2007; Wang et al., 2014b). This compositional feature is important for unraveling their metamorphic history and protolith nature. Petrological and geochemical studies have indicated that some Dabie-Sulu eclogites experienced partial melting during exhumation (e.g., Zhao et al., 2007; Zeng et al., 2009; Zheng et al., 2011; Gao et al., 2012). The extraction of melt from eclogite can lead to the

LREE-depleted residue (Zhao et al., 2007; Wang et al., 2014b). On the other hand, different REE patterns of eclogites may be inherited from their protoliths. If the protoliths were juvenile oceanic crust that was derived from decompressional melting of asthenospheric mantle, it should be characterized by LREE-depleted patterns like those for normal mid-ocean ridge basalts (N-MORB) (Hofmann, 1988). Such eclogite protoliths are considered to have an oceanic affinity and rarely occur in collisional orogens (Zheng, 2012).

Eclogite from the Dabie-Sulu orogenic belt is well known for the extreme ^{18}O depletion (Yui et al., 1995; Zheng et al., 1996, 1998a, 2003; Rumble and Yui, 1998). However, M-type eclogite in this belt shows high $\delta^{18}O$ values (Rumble et al., 2000; Zheng et al., 2003; Wu et al., 2006a; Wang et al., 2014a), much higher than normal mantle $\delta^{18}O$ values of 5.3–5.7‰ (Eiler, 2001). Thus, it remains to be resolved whether this signature was directly inherited from the protolith or produced by subduction-zone processes. In addition, such eclogite exhibits significantly lower $\delta^{26}Mg$ values than the mantle (Wang et al., 2014a), being interpreted as the result of Mg isotope exchange between eclogite and carbonate during subduction. However, carbonate minerals can be incorporated into the eclogite or produced by other processes, depending on the protolith feature of eclogite and the relationship between the eclogite and host marble. This requires a possible discrimination between these different processes.

Zircon is a versatile mineral and its U—Pb radiometric system has been widely used to date high grade metamorphism (e.g., Wu et al., 2006a; Liu et al., 2007). In addition, the Hf—O isotope compositions of zircon are excellent geochemical tracers for protolith nature and metamorphic effect (Zheng et al., 2004, 2005, 2006; Wu et al., 2006a). Eclogite-facies metamorphism can result in significantly reduced $^{176}Lu/^{177}Hf$ but elevated $^{176}Hf/^{177}Hf$ ratios for metamorphic zircon compared to the relict magmatic zircon (Zheng et al., 2005). Furthermore, the O isotope composition of metamorphic and metamorphosed zircons can be redistributed if the rocks have interacted with external fluids prior to the UHP metamorphism (Chen et al., 2011). Thus, caution must be taken when linking zircon Hf isotope composition to the protolith nature of UHP metamorphic rocks (Zheng et al., 2005).

In order to unravel the protolith nature and metamorphic history of M-type eclogite, we have carried out a combined study of whole-rock major-trace elements and Sr—Nd isotopes, silicate mineral O isotopes, carbonate C and O isotopes, and zircon U—Pb ages and Lu—Hf isotopes for the eclogite in the Sulu orogen. The eclogite shows different REE patterns and Sm—Nd isotope compositions, but consistently high $\delta^{18}O$ values. Zircon in the eclogite also exhibits distinct Hf isotope compositions. Therefore, the present study provides geochemical constraints not only on the origin of high $\delta^{18}O$ M-type eclogite in the Sulu orogen, but also on the partial melting of eclogite during continental collision. In addition, it has bearing on carbon recycling at subduction zones.

2. Geological setting and samples

The Dabie-Sulu orogenic belt in east-central China was built by the Triassic subduction of the South China Block beneath the North China Block (Li et al., 1993; Cong, 1996; Zheng et al., 2013). The NNE trending Tan-Lu fault separates this belt into two segments, the E-W trending Dabie orogen in the west and the NE-trending Sulu orogen in the east (Fig. 1). The Sulu orogen is subdivided into HP and UHP metamorphic zones (Fig. 1). Both zones are unconformably covered by Jurassic clastic sediments and Cretaceous volcaniclastic rocks, and intruded by Mesozoic granites (Xu et al., 2006). The HP metamorphic zone is located in the south and mainly composed of schist, paragneiss, granitic gneiss, and marble. The UHP metamorphic zone in the north is primarily composed of orthogneiss and paragneiss, with minor amounts of eclogite, garnet peridotite, quartzite and marble. The eclogite is mostly enclosed in granitic gneiss, but some occurs together with marble and garnet peridotite. Coesite was identified in eclogite and its country rocks, indicating in situ UHP metamorphism at mantle depths (e.g., Liu and Liou, 2011).

The UHP metamorphic rocks in the Sulu orogen were produced by subduction of continental crust to subarc depths of >100 km at 3.0–4.5 GPa and 730–850 °C, and the UHP metamorphism occurred at 240–225 Ma with a duration of ~15 Myr in the coesite stability field (Zheng et al., 2009; Liu and Liou, 2011). Most of the UHP rocks have igneous protoliths of middle Neoproterozoic age with various degrees of ^{18}O depletion (Zheng et al., 2004; Tang et al., 2008a, 2008b; Chen et al., 2011, 2014b; Fu et al., 2013). Petrological studies indicate that the UHP eclogite-facies zone around Rongcheng in the northeastern Sulu orogen was significantly overprinted by granulite-facies metamorphism during early exhumation (Wang and Liou, 1993; Zhang et al., 1995; Banno et al., 2000; Nakamura and Hirajima, 2000).

Three types of eclogites in the Sulu orogen are associated with different host rocks (Jahn, 1998; Zheng et al., 2003). Most eclogites belong to G-type and occur as small enclaves within granitic gneiss, and others occur as small boudins within marble (M-type eclogite) or in association with peridotite/pyroxenite (P-type eclogite). These eclogites experienced at least three metamorphic stages during the Triassic continental collision: (1) UHP eclogite-facies metamorphism, (2) HP eclogite-facies recrystallization, and (3) either granulite-facies or amphibolite-facies overprinting (Wang and Liou, 1993; Zhang et al., 1995; Kato et al., 1997; Liu et al., 2007; Zhu and Zhu, 2007; Liu and Liou, 2011). The P-T-t paths for eclogite-marble associations in the UHP zones have been well constructed (Liu et al., 2006, 2007; Zhu and Zhu, 2007).

This study deals with M-type eclogites in the Sulu orogen, which occur at Sanqingge in Ganyu County of Jiangsu province and at Tengjia and Shanjia in Rongcheng city of Shandong province (Fig. 1). Eclogite occurs as pods or lenticular layers (Fig. 2a,b) or as concordant layers within marble (Fig. 2c,d). The contact boundaries between eclogite and marble are usually sharp and eclogite layers are parallel to the marble bands (Fig. 2c,d), representing original depositional bedding. Many Rongcheng eclogites are fresh. They display typical eclogite-facies assemblage of garnet and omphacite (Fig. 3a,b), with minor amounts of quartz, phengite, rutile, calcite, dolomite, magnetite, apatite and zircon. Coesite inclusions occur within zircon and garnet from the eclogite (Liu et al., 2007; Zhu and Zhu, 2007; Zhu et al., 2009), demonstrating that such eclogite experienced UHP metamorphism. For the purpose of comparison, P-type eclogite was also sampled from an outcrop in Rongcheng.

Minor coronas of titanite around rutile are observed in fresh eclogites, suggesting slight amphibolite-facies retrogression. Three eclogite samples (03SD33, 05SD19 and 06SD116) were moderately overprinted by amphibolite-facies retrogression. In these samples, omphacite is partially replaced by amphibole or symplectite of amphibole + plagioclase. However, some samples (e.g., 09SL18 and SQG01 to SQG09) from Sanqingge experienced strong amphibolite-facies retrogression, leaving some relicts of rutile and garnet. Most other minerals were replaced by amphibole, plagioclase, titanite and biotite. For eclogite from both areas, calcite and dolomite occur as minor minerals in the matrix or are enclosed by other silicate minerals. In Rongcheng eclogites, abundant plagioclase grains occur as interstitial phases in triple junctions or along grain boundaries of garnet and amphibole (Fig. 3c–i). Many grains show highly cuspate shape, and some penetrate into garnet grain boundaries without significant reaction (Fig. 3c–i). However, this feature was not found for Sanqingge eclogite.

Mineral abbreviations in the text, figures and tables follow Whitney and Evans (2010). For trace elements, it follows the conventions for large ion lithophile elements (LILE), light rare earth elements (LREE), heavy rare earth elements (HREE), and high field strength elements (HFSE).

3. Analytical methods

Mineral separation was made using a combination of magnetic, heavy liquid and hand-picking techniques to ensure purity. Zircon