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Continental origin of eclogites in the North Qinling terrane and its tectonic implications

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ABSTRACT

Eclogites in an orogen, serving as a credible marker for deep subduction of oceanic or continental crust, are a key to decipher the process and fate of plate subduction. The nature of eclogite precursors bears important information on orogenic mechanism and pre-subducted geological history. Despite their importance, the nature of ultra-high pressure (UHP) eclogites in the North Qinling (NQ) terrane is still poorly constrained, which leads to conflicting tectonic scenarios for the evolution of the Qinling orogenic belt. In this paper, we provide a combined study of zircon U–Pb ages, major and trace element data, and Sr–Nd–Pb–Hf isotope compositions for eclogites from the NQ terrane. U–Pb age determinations on magmatic zircon cores of two eclogite samples yield similar ages of ca. 800 Ma, indicating that the protoliths of the NQ UHP eclogites formed in the Neoproterozoic. The NQ eclogites have tholeiitic compositions and are characterized by high TiO_2 (1.40–2.40%), and low P_2O_5 (0.09–0.22%), Na_2O (1.10–2.49%) and K_2O (0.17–1.04%) contents. They are moderate fractionation in REEs (La_N/Yb_N = 2.31–4.20) and show negligible Nb, Ta, Ti, and Eu anomalies (Eu/Eu* = 0.82–1.10). The eclogites have high positive whole-rock $\varepsilon_{Nd}(t)$ (2.81–5.53) and zircon $\varepsilon_{Hf}(t)$ (10.5–11.9) values, indicating their derivation from a relatively depleted mantle source. On geochemical discriminant diagrams based on immobile element ratios, the NQ eclogites fall in the field of continental basalts. Moreover, both the geochronological and geochemical features of the eclogite protoliths are quite different from those of the Erlanpging basaltic rocks, but comparable to those of the coeval continental basalts in South Qinling (SQ) orogen and the northern margin of the South China Block (SCB). As the mid-Neoproterozoic basaltic rocks in the SQ orogen and the northern margin of the SCB were well documented to form in a continental rift setting in response to the global-scale breakup of the Rodinia supercontinent, it is inferred that the NQ eclogite precursors might also form in a continental rift setting at ca. 800 Ma, which resulted in the splitting of the NQ terrane from the SCB. As the protoliths of the NQ eclogites have a continental property, we suggest that the ca. 490 Ma UHP metamorphism of the NQ unit might result from its northward subduction beneath the Erlangping arc and thus manifested an arc-continent collision process.

1. Introduction

Eclogite is a special metamorphic rock type that forms under high to ultrahigh pressure (HP–UHP) conditions (Godard, 2001). Due to its unusually high density, eclogite is viewed as the main driving force for transfer of crustal materials into mantle (Rudnick, 1995; Seber et al., 1996), which is a critical part of the cycle of mantle convection and further contributes to the mantle heterogeneity (Hart, 1988; Hofmann, 1997). At the Earth's surface, eclogites commonly occur as xenoliths entrained by magma within a craton (e.g. Aulbach et al., 2011), or as isolated fragments embedded in HP–UHP or non HP–UHP rocks in an orogen (e.g. Wu et al., 2008a; Zheng, 2008; Herwartz et al., 2011). The eclogitic xenoliths that are transformed from deep-seated basic rocks within a craton dictate thickened lower continental crust at depths, which play an important role in delamination and vertical compositional differentiation of continental crust (Rudnick, 1995). Whereas the eclogites that are produced by HP–UHP metamorphism of supracrustal rocks in an orogen serve as a credible marker for deep subduction of oceanic or continental crust (Zheng et al., 2003; Agard et al., 2009; Wu et al., 2009a; Zheng, 2012). Further differentiating of these two types of subduction bears on the fundamental question whether the protoliths of eclogites are of continental origin, indicative of a collisional orogeny (Jahn, 1998; Zheng, 2012), or whether they

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just represent subducted oceanic crust, implying an accretionary orogeny (Bebout, 2007; Zhang et al., 2008; Agard et al., 2009; Wu et al., 2009a). In addition, ascertaining the tectonic setting and origin of eclogites in an orogen is also crucial for uncovering the geological record prior to subduction (e.g. Utsunomiya et al., 2011). Accordingly, comprehensive knowledge of eclogite precursors is vital not only for deciphering the orogenic mechanism and process of plate subduction, but also for delineating multistage evolution of a fossil orogen.

The Qinling-Tongbai-Dabie orogenic belt is formed by a multi-stage amalgamation process among the South China Block (SCB), the North China Block (NCB), and their intervening microcontinent and/or island arc (Ratschbacher et al., 2003, 2006; Yang et al., 2003; Zheng et al., 2003; Li et al., 2007; Wu et al., 2008a, 2009a; Dong et al., 2011a; Liu et al., 2011a; Wang et al., 2011a; Wu and Zheng, 2013). During this amalgamation process, at least three stages of HP–UHP metamorphism occurred: the Triassic, Carboniferous, and early Paleozoic (Yang et al., 2003; Zheng et al., 2003; Wu et al., 2006, 2009a; Wang et al., 2011a). The Triassic UHP eclogites in the Dabie-Sulu orogen were formed by the final continental collision between the SCB and the NCB. They commonly have Neoproterozoic protolith ages, which were attributed to rift magmatism along the northern margin of the SCB during the breakup of the Rodinia supercontinent (Zheng et al., 2004, 2006). Most of the Carboniferous eclogites in the Hong'an terrane have late Silurian protolith ages, MORB-like trace element patterns, and high positive $\varepsilon_{Hf}(t)$ and $\varepsilon_{Nd}(t)$ values (Fu et al., 2002; Wu et al., 2009a), which were suggested to represent the subducted Paleotethys oceanic crust (Wu et al., 2009a). In contrast, there are two conflicting tectonic scenarios for the formation of the early Paleozoic eclogites in the North Qinling (NQ) terrane. Dong et al. (2011a) suggested that the eclogites were formed by the southward subduction of the Erlangping backarc basin beneath the Qinling island arc. This model was based on the observation that the eclogites had EMORB- or OIB-like patterns of trace element distribution (Hu et al., 1997; Zhang et al., 2003; Chen and Liu, 2011) and thus their protolihs might represent subducted oceanic crust of the Erlangping backarc basin (Dong et al., 2011b). On the other hand, Ratschbacher et al. (2003) and Wang et al. (2011a) attributed the eclogite formation to the northward subduction of the NQ unit and an arc-continent collision process was further proposed by Wang et al. (2011a). Obviously, the eclogites of the NQ unit were viewed as a continental origin in this model. To resolve the controversies, it is necessary to carry out comprehensive studies on the nature of the early Paleozoic UHP eclogite precursors in the NQ terrane. Such kinds of studies are, however, still scarce. In this paper, we employ zircon U–Pb geochronology, major and trace element geochemistry, and Sr–Nd–Pb–Hf isotope compositions to unravel the origin and tectonic setting of the eclogites from the NQ terrane. The results show that the eclogite precursors may form in a continental rift setting at ca. 800 Ma when the NQ terrane split from the SCB. The protoliths of these eclogites are of continental origin and thus argue for an arc-continent collision resulting from the deep subduction of the NQ unit beneath the Erlangping intra-oceanic arc.

2. Geological setting and samples

The Qinling-Tongbai-Dabie orogenic belt is an important geological boundary that separates the NCB from the SCB (Fig. 1) (Zheng et al., 2003; Ernst et al., 2007; Li et al., 2010a, 2011a; Dong et al., 2011a; Wu and Zheng, 2013). It is famous to geologists in the world for the occurrence of the hugest HP–UHP metamorphic terranes (Yang et al., 2003; Ratschbacher et al., 2003, 2006; Ernst et al., 2007; Zheng, 2008; Wu et al., 2009a). The eastern Qinling segment, which contains the most completed units of this tectonic belt, is divided into the South and North Qinling orogens by the Shangdan Fault (SDF) (Fig. 1a) (Meng and Zhang, 1999; Dong et al., 2011a,b). The South Qinling (SQ) orogen consists mainly of Neoproterozoic Wudangshan and Yaolinghe volcanic–sedimentary sequences and about 12 km-thick Upper Sinian to Triassic sedimentary rocks, with sporadic Archean basements (Mattauer et al., 1985; Meng and Zhang, 1999, 2000; Ratschbacher et al., 2003; Zhang et al., 2004a). In the northern part of the Wudang core complex, Triassic HP blueschist rocks have been reported (Mattauer et al., 1985; Ratschbacher et al., 2003), which may correspond to the Triassic HP–UHP rocks in the Tongbai-Dabie-Sulu orogenic belt (Liu et al., 2008a; Wu et al., 2008a; Zheng, 2008 and references therein). In contrast, the NQ orogen is composed of three fault-bounded, penetrative deformed units, from north to south, which include: (1) the Kuanping unit; (2) the Erlangping unit; and (3) the NQ unit (Fig. 1a) (Kröner et al., 1993; Ratschbacher et al., 2003, 2006; Hacker et al., 2004; Dong et al., 2011a; Wang et al., 2011a,b).

The Kuanping unit is the northernmost unit of the Qinling orogen, which is separated from the southern edge of the NCB by the Luonan-Luanchuan Fault (LLF) and from the Erlangping unit by the sinistral Qiaoduan Fault (Fig. 1a) (Meng and Zhang, 2000; Dong et al., 2011a; Liu et al., 2011a). The Kuanping unit comprises mica schists, quartzites, marbles and amphibolites, whose protoliths were wackes, carbonate rocks, and tholeiitic basalts. The metamorphic grades of this unit range from greenschist-facies to upper amphibolite-facies (Mattauer et al., 1985; Ratschbacher et al., 2003; Liu et al., 2011a; Wu and Zheng, 2013). A metabasic rock with NMORB-like geochemical characteristics gave a zircon U–Pb age of 943 ± 6 Ma (Diwu et al., 2010). Whereas the metabasic rocks that show EMORB-like patterns of trace element distribution and high $\varepsilon_{Nd}(t)$ values yielded a late Neoproterozoic age of 611 ± 13 Ma (Yan et al., 2008). These suggest that an oceanic basin might last for a long time in the Kuanping unit. Detrital magmatic zircons from metasedimentary rocks of this unit yielded the youngest age group of ca. 600 Ma, constraining the maximum age of those sedimentary rocks (Diwu et al., 2010; Zhu et al., 2011). Ordovician fossils were discovered in the clasolites that underwent little metamorphism and deformation (Wang et al., 2009a), indicating an early Paleozoic sedimentary age for some parts of this unit. A hornblende Ar–Ar age of 434 ± 2 Ma from a foliated amphibolite, two zircon U–Pb ages of 442 ± 6 and 415 ± 5 Ma from a garnet amphibolite and a zircon U–Pb age of 439 ± 24 Ma from a deformed pegmatite indicated that the metamorphism of this unit occurred in the Silurian time (Zhai et al., 1998; Liu et al., 2011a). Based on the studies above, distinct tectonic regimes for the Kuanping unit were proposed, which included: (1) a part of the southern passive margin of the NCB (Xue et al., 1996a; Zhai et al., 1998); (2) an accretionary wedge during the Late Proterozoic (Ratschbacher et al., 2003, 2006); or (3) an early Paleozoic backarc basin (Lu et al., 2003, 2009). As it has an dominant Neoproterozoic age peak on detrital zircon age spectra, the Kuanping unit was recently suggested to have a tectonic affinity of the SCB prior to its final integration with the NCB (Wu and Zheng, 2013).

The Erlangping unit is sandwiched between the Kuanping unit in the north and the NQ unit in the south. It is mainly composed of minor ultramafic rocks, mafic to intermediate volcanic rocks, hypabyssal dykes, fine-grained clastic rocks and interlayered turbidites and cherts with Cambrian–Ordovician fossils. Thick-layer marbles (the Zimugou Formation in the Chinese literature) distribute in the southern side of the Erlangping unit, which were thrusted on the NQ unit (Zhong et al., 2007). The Erlanping unit underwent upper greenschist to amphibolite facies metamorphism (Ratschbacher et al., 2003; Dong et al., 2011a; Wu and Zheng, 2013) with peak metamorphic conditions of 550–600 °C and 6.3–7.7 kbar (Liu et al., 2011a). The volcanic rocks have trace element features similar to island arc or E-MORB rocks, implying that they were