Lithos 244 (2016) 122–139

Contents lists available at ScienceDirect

Lithos

journal homepage: www.elsevier.com/locate/lithos

The tectonic transition from oceanic subduction to continental subduction: Zirconological constraints from two types of eclogites in the North Qaidam orogen, northern Tibet

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ARTICLE INFO

Article history:
Received 18 July 2015
Accepted 11 December 2015
Available online 19 December 2015

Keywords:
North Qaidam
Zircon
Eclogite
Oceanic subduction
Continental subduction

ABSTRACT

In the plate tectonics theory, continental subduction is pulled by subduction of dense oceanic crust. In practice, however, it is not easy to demonstrate that preceding oceanic crust exposes as oceanic-type eclogite together with continental-type eclogite in collisional orogens. The North Qaidam orogen in northern Tibet is an ultrahigh-pressure (UHP) metamorphic belt that contains the two types of eclogites, providing us with an excellent opportunity to study the tectonic transition from oceanic subduction to continental subduction. In order to constrain the protolith nature and metamorphic evolution of eclogites, we performed a combined study of zircon U–Pb ages, trace elements, mineral inclusions and O–Hf isotopes for various eclogites from the orogen. We discriminate the two types of eclogites by their differences in zircon U–Pb ages and O–Hf isotopes. CL-dark zircon domains exhibit high Th/U ratios, steep HREE patterns and significantly negative Eu anomalies, indicating that they are protolith zircons of magmatic origin with different extents of metamorphic recrystallization. Relict magmatic zircon domains in Type I eclogites yield Neoproterozoic protolith ages of >830 Ma and Hf model ages of 850–1100 Ma, whereas those in Type II eclogites yield Cambrian protolith U–Pb ages of >489 Ma and Hf model ages of 500–650 Ma. Most of the CL-bright zircon domains show low Th/U ratios, flat HREE patterns and no negative Eu anomalies, and contain mineral inclusions of garnet, omphacite and rutile, indicating their growth under eclogite-facies metamorphic conditions. These metamorphic domains have consistent eclogite-facies metamorphic ages of 433–440 Ma throughout the North Qaidam orogen, regardless of the eclogite types and locations. The metamorphic zircon domains in Type I eclogites mostly exhibit $\delta^{18}O$ values higher than normal mantle values, whereas Type II eclogites mostly have $\delta^{18}O$ values lower than the normal mantle values. The difference in the $\delta^{18}O$ values indicates that their protoliths underwent different temperatures of hydrothermal alteration at different tectonic settings. Combining zircon U–Pb ages and O–Hf isotope compositions with local tectonics, it is inferred that Type I eclogites were metamorphosed from Neoproterozoic continental mafic rocks, whereas Type II eclogites were metamorphosed from oceanic mafic rocks that were subducted prior to the continental subduction. The consistent eclogite-facies metamorphic ages for the two types of eclogites indicate that the exhumed oceanic-type eclogite was detached from the subducted oceanic crust and then entrained by the exhuming continental crust. Therefore, the coexistence of oceanic- and continental-type eclogites in the North Qaidam orogen demonstrates the tectonic transition from oceanic subduction to continental collision in the early Paleozoic.

1. Introduction

Since the findings of coesite and diamond in supracrustal rocks of metamorphic origin (Chopin, 1984; Smith, 1984; Sobolev and Shatsky, 1990; Xu et al., 1992), it is well established that low-density continental crust is subductable to mantle depths, transformed into ultrahigh-pressure (UHP) metamorphic rocks, and then exhumed to the surface (Chopin, 2003; Gilotti, 2013; Zheng, 2012). As the continental crust is too low in density to sink into the mantle, it is generally held that preceding subduction of dense oceanic slab drives subduction of the attached continental slab to mantle depths subsequent to the closure of oceanic basins (Davies and von Blanckenburg, 1995; O'Brien, 2001). After breakoff between the oceanic and continental slabs, the buoyancy force of continental crust leads to its exhumation along the subduction channel to shallow levels (Davies and von Blanckenburg, 1995; Ernst et al., 1997; Guillot et al., 2009; Zheng et al., 2013a). Thus continental collision zones containing high-pressure (HP) to UHP metamorphic

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http://dx.doi.org/10.1016/j.lithos.2015.12.003
0024-4937/

rocks would have experienced the tectonic evolution from oceanic subduction to continental subduction (e.g., O'Brien, 2001; Song et al., 2006, 2014; Zheng et al., 2015).

In some HP–UHP metamorphic zones, the subducted oceanic crust was also exhumed together with the subducted continental crust to the surface. This is illustrated in the western Alps orogen of western Europe (Compagnoni and Rolfo, 2003) and the Hong'an orogen of east-central China (Wu and Zheng, 2013; Wu et al., 2009; Zhou et al., 2015). The concomitant outcrops of HP–UHP metamorphic rocks with protoliths of both oceanic and continental origins allow the bulk processes of crustal subduction and collisonal orogenesis to be restored (Beltrando et al., 2010; Wu and Zheng, 2013; Wu et al., 2009; Zhou et al., 2015). Knowledge about the consumption of oceanic crust and the subduction of continental crust as well as their transition depends on the correct recognition and distinction between oceanic and continental units in the same HP–UHP metamorphic zones. Eclogite is a common lithology in HP–UHP zones and it may be metamorphosed from mafic rocks of continental and oceanic origins, respectively, corresponding to continental-type and oceanic-type eclogites. Information about previously subducted protolith and HP–UHP metamorphism can be well preserved in eclogites compared to other lithologies. Therefore, the protolith nature and age of eclogites are pivotal not only in deciphering the spatial-temporal distributions of oceanic and continental units but also in revealing the tectonic transition from oceanic subduction to continental subduction (Rubatto et al., 1998; Wu and Zheng, 2013; Wu et al., 2009; Zhou et al., 2015).

Zircon is a robust mineral that has been widely used for U–Pb dating and geochemical tracing (Chen et al., 2010; Hanchar and Hoskin, 2003; Harley and Kelly, 2007; Hawkesworth and Kemp, 2006; Scherer et al., 2007). In deeply subducted crustal rocks, the mineral inclusions, trace element composition and O–Hf isotopes of relict and metamorphic zircon domains have been used to constrain the protolith and metamorphic ages, protolith nature and metamorphic conditions (Chen et al., 2011; Liu and Liou, 2011; Rubatto and Hermann, 2003, 2007; Zheng et al., 2005, 2006). In HP–UHP metamorphic zones with concomitant outcrops of oceanic- and continental-type eclogites, the mafic protoliths of oceanic- and continental-type eclogites may be extracted from depleted or enriched mantle sources at different ages. While the mafic protolith of oceanic origin would be present for a short timescale before subduction, the mafic protolith of continental origin would be present for a long timescale before subduction (Zheng, 2012). Thus relict magmatic zircon domains can be used to determine protolith U–Pb ages and geochemical compositions. The difference in the residence time and subduction history of mafic protoliths also leads to the differences in the U–Pb ages and O–Hf isotopes of metamorphic zircon in eclogites. Therefore, both the relict magmatic and metamorphic zircon in eclogites are not only crucial in revealing the protolith nature of various eclogites, but also vital in constraining the timescale of orogenic evolution.

The North Qaidam orogen, located in the northeastern edge of Tibetan Plateau, is an early Paleozoic collisional orogen with the characteristic occurrence of continental-type eclogites (Song et al., 2006, 2014; Zhang et al., 2008, 2013a). The occurrence of oceanic-type eclogites was also suggested, but it has been debated whether the fossil oceanic unit did exist (Yu et al., 2013; Zhang et al., 2010). This is primarily related to the distribution and age of possible oceanic-type eclogites in this orogen (Mattinson et al., 2006; Song et al., 2006, 2014; Zhang et al., 2008, 2013a). If it is true, this orogen is an excellent candidate to study the distinction between oceanic- and continental-type eclogites and the tectonic transition from oceanic subduction to continental subduction. This paper presents an integrated study of zircon U–Pb ages, trace elements, mineral inclusions and O–Hf isotopes for eclogites from the North Qaidam orogen. The results provide insights into the protolith nature and metamorphic evolution of eclogites. Furthermore, the geochronological evolution of oceanic- and continental-type eclogites is also constrained with respect to the tectonic transition from oceanic subduction to continental subduction in the early Paleozoic.

2. Geological setting and samples

The North Qaidam orogen extends in a NW–SE direction between the Qaidam Block to the south and the Qilian Block to the north for about 400 km, and is located in the northeastern margin of Tibetan Plateau (Fig. 1). It is truncated by the Wenquan Fault in the southeast and the giant Altyn Tagh Fault in the northwest. It is a typical Alpine-type UHP metamorphic zone due to the early Paleozoic subduction of the Qaidam Block beneath the Qilian Block (e.g., Liou et al., 2009; Song et al., 2014). There are four subunits exposing UHP metamorphic rocks from southeast to northwest (Fig. 1): the Dulan eclogite-gneiss terrane, the Xitieshan eclogite-gneiss terrane, the Lüliangshan peridotite-gneiss terrane and the Yuka eclogite-gneiss terrane. Metamorphic lithologies are dominated by granitic and pelitic gneisses, with eclogites occurring as interlayers and lenses in the gneisses in the Dulan, Xitieshan and Yuka terranes. Coesite inclusions have been found in zircon and garnet from metapelites and eclogites (Liu et al., 2012a; Song et al., 2003; Yang et al., 2002; Yu et al., 2013; Zhang et al., 2009a, 2009b, 2010). Diamond inclusions in zircon and garnet exsolution structures have also been observed in peridotite from the Lüliangshan terrane (Song et al., 2004, 2005a, 2005b). These observations indicate the subduction of continental crust to a mantle depth greater than 200 km for UHP metamorphism. The UHP metamorphic rocks are in fault contact with volcanic and sedimentary rocks of the Tanjianshan group. The basaltic rocks of the Tanjianshan group, with eruption ages of 468–534 Ma, are considered to be island arc volcanics or obducted ophiolitic rocks (Shi et al., 2006; Zhu et al., 2015). The UHP metamorphic rocks are also widely intruded by granitic intrusions with variable ages ranging from Ordovician to Permian (e.g., Song et al., 2014).

Earlier studies claimed that all the eclogites from the North Qaidam orogen are derived from subducted oceanic crust, based on their partial similarity in trace element patterns and positive $\varepsilon_{Nd}(t)$ values to mid-ocean ridge basalts (Song et al., 2006; Yang et al., 2006). However, later studies have demonstrated that the majority of eclogites have geochemical features similar to continental rift or flood basalts with >800 Ma protolith ages and 420–460 Ma eclogite-facies metamorphic ages (Song et al., 2014, and references therein). Thus these eclogites are suggested to derive from metamorphism of continental basalts. However, two cross sections from the Yematan and Shaliuhe area in the Dulan terrane with the outcrops of ultramafics and eclogites, sharing some geochemical characteristics with oceanic lithosphere, are suggested to be metamorphosed ophiolite-like sequence (Song et al., 2014; Zhang et al., 2008, 2009a, 2013a). Zircon U–Pb dating for a kyanite eclogite from the Shaliuhe section yields Cambrian protolith ages, in contrast to the Neoproterozoic protolith ages for continental-type eclogites elsewhere (Song et al., 2003, 2006; Zhang et al., 2008, 2009a, 2013a). However, the interpretation of eclogite geochemistry is versatile and the few discordant Cambrian U–Pb ages with large errors may result from metamorphic resetting. Therefore, it is still debated whether the oceanic-type eclogites do exist (Yu et al., 2013; Zhang et al., 2010). Furthermore, if the oceanic-type eclogites are indeed present, their distribution, metamorphic evolution and protolith nature are still not well constrained. On the other hand, the interpretation for the large range of eclogite-facies metamorphic ages is debated. The protracted metamorphic ages are explained to result from either multiple metamorphic episodes during the transition from oceanic subduction to continental collision (Song et al., 2014), or prolonged metamorphism in the large UHP terrane (Mattinson et al., 2006). The correct interpretation of metamorphic ages for the different types of eclogites is critical to the tectonic transition from oceanic subduction to continental collision.

This study deals with eclogites and their retrograde counterparts, which were collected from all three subunits that expose eclogites in