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Multiple episodes of anatexis in a collisional orogen: Zircon evidence from migmatite in the Dabie orogen

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ABSTRACT

A combined study of mineral inclusions, U–Pb ages and trace elements was carried out on zircon from migmatites in the Dabie orogen. The results provide insights into multistage anatexis of ultrahigh-pressure metamorphic rocks in the continental collision orogen. Zircon grains in thin sections and mounts record four episodes of magmatic, metamorphic and anatectic events: (1) middle Neoprotrozoic U–Pb ages for domains that contain Qz ± Ap ± Pl inclusions and exhibit high Th/U ratios (>0.1), steep HREE patterns with marked negative Eu anomalies, dating protolith emplacement; (2) late Triassic U–Pb ages of 212 ± 5 to 219 ± 4 Ma for domains that contain Cpx ± Grt inclusions and show low Th/U ratios (<0.1), flat HREE patterns without negative Eu anomalies, dating quartz eclogite-facies metamorphism during the early exhumation of deeply subducted continental crust; (3) U–Pb ages of 192 ± 4 to 200 ± 4 Ma for domains that contain multiphase solid inclusions of Qz + Pl + Hem + Cal, Qz + Kfs + Ep, Qz + Bt + Ap and Qz + Pl + Bt, and exhibit low Th/U ratios (<0.1), steeper HREE patterns with negative Eu anomalies and high Nb and Ta contents, dating the first episode of anatexis in association with granulite-facies overprinting during the late exhumation; and (4) early Cretaceous U–Pb ages of 124 ± 1 to 140 ± 4 Ma for domains that contain Qz inclusion and show variable Th/U ratios, typical magmatic REE patterns, dating the second episode of anatexis which occurred during the Cretaceous in the postcollisional stage. The zircon domains in the two episodes of anatexis exhibit a large range of U–Pb ages, suggesting protracted durations of anatexis in both exhumational and postcollisional stages. There are considerable differences in the compositions of zircons between the two episodes of anatexis, suggesting differential behaviors of their anatexis. The first episode of anatexis is caused by dehydration melting in association with decompressional exhumation, resulting in coprecipitation of zircon and REE-rich minerals such as allanite/epidote and monazite from the anatectic melt. The second episode of anatexis is caused by both dehydration and hydration melting due to breakdown of monazite and hydrous minerals such as allanite/epidote and amphibole with local focus of aqueous solutions. This leads to variable Th/U ratios but relatively consistent magmatic zircon-like trace element compositions, with the widespread occurrence of poikilitic amphibole in the leucosome. In either case, the anatectic zircons record the partial melting of ultrahigh-pressure metamorphic rocks at different times and P–T conditions.

1. Introduction

Partial melting has been increasingly recognized in ultrahigh-pressure (UHP) metamorphic rocks of continental collision orogens (e.g., Zheng et al., 2011 and references therein). In some high-T/UHP terranes, anatexis is likely to occur close to the peak UHP stage (e.g., Labrousse et al., 2011). In some low-T/UHP and mid-T/UHP terranes, on the other hand, anatexis may occur during exhumation of deeply subducted continental crust (e.g., Auzanneau, et al., 2006; Chen et al., 2013a, 2013b; Hermann, 2002; Hermann and Green, 2001; Lang and Gilotti, 2007; Li et al., 2014; Ragozin et al., 2009; Xia et al., 2008; Zhao et al., 2007). Recognition and dating of crustal anatexis at the uppermost mantle and lower crustal depths are therefore crucial not only for deciphering the exhumational mechanism of UHP metamorphic rocks but also for understanding the relationships between partial melting, granitic magmatism and orogenic processes (e.g., Keay et al., 2001; Wallis et al., 2005; Whitney et al., 2009; Zheng et al., 2011). However, it is hardly straightforward to demonstrate explicitly that the incipient melting indeed took place in UHP metamorphic rocks because many UHP rocks suffered extensive retrograde reaction

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and reequilibration during exhumation. This is particularly so for those UHP rocks that experienced amphibolite-facies overprinting. Nevertheless, such refractory minerals as zircon may provide robust records of anatexis.

Zircon is a refractory mineral and has very low rates of Pb diffusion (Cherniak, 2010), thus its U–Pb age can readily reflect its growth from anatectic melts rather than simple cooling along a metamorphic P–T path (e.g., Baldwin et al., 2007; Liu et al., 2012; Wu et al., 2007). The extremely stable property of zircon and its high closure temperature of Pb diffusion leave its isotopic system completely or partly undisturbed by subsequent metamorphism and migmatization. In situ U–Pb dating of zircon domains can thus provide important age information on the complicated evolution history of its metamorphic/migmatic host (e.g., Keay et al., 2001; Li et al., 2014; Liu et al., 2012; Rubatto et al., 2009; Wu et al., 2007). Furthermore, based on mineral inclusions and trace elements in zircon, it is feasible to distinguish metamorphic zircon from magmatic and anatectic zircons, and further link the different origins of zircon domains to specific geological processes (e.g., Chen et al., 2010, 2011, 2013a; Li et al., 2013, 2014; Liu and Liou, 2011; Rubatto, 2002; Rubatto and Hermann, 2003; Xia et al., 2009, 2010, 2013; Zheng, 2009).

Zircon studies have been extensively performed on UHP metamorphic rocks from the Dabie–Sulu orogenic belt, one of the largest UHP metamorphic terranes on Earth (e.g., Liou et al, 2009; Zheng, 2012). In terms of the differences in metamorphic P–T conditions, the Dabie UHP slices are subdivided into low-T/UHP, mid-T/UHP and high-T/UHP zones, respectively (Liu and Li, 2008; Zheng, 2008). While amphibolite-facies retrogression is prominent in the mid-T/UHP zone, granulite-facies overprinting is remarkable in the high-T/UHP zone. According to the experimental data available for the stability of white micas such as muscovite and phengite (Auzanneau et al., 2006; Hermann, 2002; Zheng et al., 2011) and the P–T paths of the three UHP zones (Liu and Li, 2008; Zheng, 2008), partial melting is expected to take place during their exhumation to lower crust levels. This is confirmed by microscale studies of petrography, mineralogy and geochemistry on UHP eclogite and granitic gneiss in the mid-T/UHP zone of Central Dabie (Gao et al., 2012; Liu et al., 2013) and the low-T/UHP zone of South Dabie (Xia et al., 2008). However, it is still unclear whether the high-T/UHP zone of North Dabie also underwent partial melting during the exhumation. Partial melting is very prominent in the eastern part of the Sulu orogen, where UHP rocks underwent late Triassic migmatization (Chen et al., 2013a, 2013b; Liu et al., 2010a, 2012; Zeng et al., 2011; Zong et al., 2010a) and granitic magmatism (e.g., Yang et al., 2005; Zhao et al., 2012). In view of the middle Triassic U–Pb ages for UHP metamorphism in the coesite stability field (Liu and Liou, 2011; Zheng et al., 2009), it is evident that the partial melting of UHP rocks primarily took place during the exhumation of deeply subducted continental crust. Nevertheless, early Cretaceous migmatization and magmatism are remarkable in the North Dabie high-T/UHP zone (e.g., Wang et al., 2013; Wu et al., 2007; Zhang et al., 1996; Zhao and Zheng, 2009). Thus, it is critical to distinguish the postcollisional anatexis from the synexhumation anatexis in the UHP metamorphic rocks.

This paper presents an integrated study of zircon mineragraphy, U–Pb geochronology and trace element geochemistry for migmatites from the Dabie orogen. The results indicate that the migmatites have a Neoproterozoic protolith age and a late Triassic metamorphic age, implying their involvement in the Triassic continental collision. In addition, there are two groups of U–Pb ages in the late Triassic to early Jurassic and the early Cretaceous, respectively, for anatectic zircons from the migmatites. This indicates multistage anatexis of the UHP metamorphic rocks in the exhumational and postcollisional stages, respectively. Because of the significant difference in the time of crustal anatexis, the present study provides insights into the difference in anatectic P–T conditions between the exhumational and postcollisional stages and thus into the tectonic evolution of the continental collision orogen. It also sheds light on the geochemical distinction between magmatic, migmatic and anatectic zircons.

2. Geological setting

The Dabie–Sulu orogenic belt in east-central China was built by the Triassic continental collision between the South China Block and the North China Block (e.g., Li et al., 1993; Xu et al., 2006; Zheng et al., 2003). Identifications of coesite and microdiamond in eclogites (e.g., Wang et al., 1989; Xu et al., 1992) and granitic gneiss from this belt (e.g., Liu and Liou, 2011) demonstrate that crustal materials were subducted to mantle depths of at least 120 km for UHP metamorphism. The Tanlu Fault separates the Dabie–Sulu orogenic belt into eastern and western segments, which are named the Sulu and Dabie orogens, respectively (Fig. 1). The Dabie orogen is composed of five fault-bounded metamorphic units that are named the main tectonic zones from north to south (Zheng et al., 2005): (1) the Beihuaiyang low-T/low-P greenschist-facies zone, (2) the North Dabie high-T/UHP granulite-facies zone, (3) the Central Dabie mid-T/UHP eclogite-facies zone, (4) the South Dabie low-T/UHP eclogite-facies zone, and (5) the Susong low-T/high-P blueschist-facies zone. The majority of these metamorphic rocks have igneous protoliths, which have been dated to have zircon U–Pb ages of 740–780 Ma (e.g., Zheng et al., 2009). Postcollisional magmatic rocks are dominated with felsic rocks with sporadic mafic rocks, which occur in all the five metamorphic units (e.g., Zhao and Zheng, 2009).

The North Dabie high-T/UHP zone is primarily composed of granitic orthogneiss, with minor eclogite, peridotite, pyroxenite, marble and granulite. These metamorphic rocks were intruded by voluminous granitoids and minor mafic-ultramafic bodies of early Cretaceous age (e.g., Bryant et al., 2004; Zhao and Zheng, 2009). Geochronological studies indicate that protoliths of the eclogite, granulite and regional orthogneiss are mostly Neoproterozoic igneous rocks with minor Paleoproterozoic rocks (e.g., Hacker et al., 1998; Jian et al., 2012; Wu et al., 2008; Xie et al., 2010). The eclogite and granitic gneiss contain not only mineral exsolutions in metamorphic garnet and clinopyroxene but also diamond and coesite inclusions in metamorphic zircon (Liu et al., 2007a, 2007b, 2011a, 2011b; Tsai and Liou, 2000; Xu et al., 2003, 2005), indicating the UHP metamorphism of these rocks. Triassic zircon U–Pb and mineral Sm-Nd ages were obtained for the eclogite and granitic gneiss (e.g., Li et al., 1993; Liu et al., 2007a, 2011b; Xie et al., 2004, 2006, 2010; Zhao et al., 2008), indicating that the North Dabie zone was involved in the Triassic continental subduction (Zheng et al., 2005).

Subsequent to the UHP eclogite-facies metamorphism, eclogite and gneiss in the North Dabie zone were first subject to granulite-facies overprinting, and then to amphibolite-facies retrogression (e.g., Liu et al., 2007a, 2011a, 2011b; Tsai and Liou, 2000), with local overprinting of migmatization (e.g., Zhang et al., 1996; Zhao et al., 2008). This differs from metamorphic rocks in the Central and South Dabie UHP zones, where the granulite-facies overprinting has not been recognized so far. Accordingly, four metamorphic stages are recognized in the North Dabie zone (Liu et al., 2007a, 2011a, 2011b; Tong et al., 2011): (1) an UHP eclogite-facies stage, with $P = 2.5–4.0$ GPa and $T = 800–980$ °C, witnessed by the occurrence of diamond; (2) a retrograde HP eclogite-facies stage, with $P = 2.0$ GPa and $T = 800–990$ °C, (3) a retrograde granulite-facies stage, with $P = 0.9–1.4$ GPa and $T = 690$-960 °C; (4) a retrograde amphibolite-facies stage, with $P = 0.5–0.7$ GPa and $T = 500–700$ °C. On the other hand, early Cretaceous thermal overprinting and magmatism are widespread in the North Dabie zone (e.g., Bryant et al., 2004; Hacker et al., 1998; Zhao and Zheng, 2009). The postcollisional magmatic rocks intruded into the UHP rocks are composed of voluminous granitoids and minor mafic-ultramafic rocks, with intrusive ages of 117–143 Ma (e.g., Dai et al., 2011; Zhao and Zheng, 2009). The migmatization of early Cretaceous is prominent in the North Dabie zone, with significant occurrences on the outcrop scale (Wang et al., 2002; Wu et al., 2007).

Migmatites are common in the regional orthogneiss of the North Dabie high-T/UHP zone, mainly occurring in the Yuexi dome and the