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Synexhumation anatexis of ultrahigh-pressure metamorphic rocks: Petrological evidence from granitic gneiss in the Sulu orogen

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ABSTRACT

Petrological evidence is provided for partial melting of ultrahigh-pressure (UHP) metamorphic granitic gneiss in the Sulu orogen. Petrographic observations show the occurrence of elongated, highly cuspate feldspars in grain boundaries, interstitial cuspate feldspars in triple junctions, felsic veinlets mainly consisting of K-feldspar + quartz, and feldspar crystal faces against quartz. These features indicate that the feldspar and quartz would have grown from anatectic melts in the granitic gneiss. Zircon domains grown from these melts were identified based on CL images, mineral inclusions and REE patterns. Some large zircon grains (>100 μm) contain small relict domains of magmatic origin, suggesting nearly complete dissolution of the protolith zircon during the anatexis. All newly grown zircon domains are categorized into two groups based on the presence or absence of coesite inclusions. One group of domains contain no coesite inclusion and exhibit high U contents but low Th/U ratios (<0.1), steep REE patterns with strong negative Eu anomalies, and U–Pb ages of 217 ± 2 to 224 ± 2 Ma. The other group of domains contain coesite inclusions and exhibit low U contents and very low Th/U ratios (<0.01), steep REE patterns with strong negative Eu anomalies, and U–Pb ages of 221 ± 5 to 226 ± 3 Ma. The two groups of zircon domains are thus interpreted as growing from the anatectic melts at different pressures because they exhibit marked negative Eu anomalies that are absent for metamorphic zircons grown from aqueous fluids. The zircon U–Pb ages of 217 ± 2 to 226 ± 3 Ma are close to, but slightly younger than, known ages for major UHP metamorphism in the Sulu orogen. Therefore, the UHP gneiss experienced incipient melting during the initial exhumation subsequent to the peak UHP metamorphism and extensive anatexis later at lower pressures. Muscovite relicts coexist with cuspate feldspars, suggesting that the anatectic melts originate from dehydration melting due to decompression breakdown of phengitic muscovite in the UHP granitic gneiss. As the degree of partial melting increases with temperature, significant fractions of the anatectic melts would be produced in the regional gneiss provided that the UHP rocks experienced “hot” exhumation. Such melts can be gathered together, being eventually emplaced as synexhumation granitic intrusions.

1. Introduction

There is rare evidence for partial melting of subducting continental crust during prograde high-pressure (HP) to ultrahigh-pressure (UHP) metamorphism in continental collision zones (Ernst, 2006; Zheng et al., 2003). In contrast, partial melting of exhuming UHP metamorphic rocks has been identified in a number of UHP terranes (Zheng et al., 2011). These include the Dabie–Sulu of China (Chen et al., 2003; Gao et al., 2012a; Wallis et al., 2005; Xia et al., 2008; Zeng et al., 2009; Zhao et al., 2007, 2012), the Kokchetav of Kazakhstan (Dobretsov and Shatsky, 2004; Hermann et al., 2001; Ragozin et al., 2009), and the Western Gneiss Region of Norway (Labrousse et al., 2004, 2011) and its extension in Greenland (Lang and Gilotti, 2007). Such ultrametamorphic anatexis during exhumation is significant because it has great bearing on the tectonothermal evolution of continental collision zones and the exhumation mechanism of deeply subducted crustal slices (Hermann et al., 2001; Hollister, 1993; Jamieson et al., 2011; Wallis et al., 2005) as well as crust–mantle interaction and recycling of crustal materials into the mantle in continental subduction channels (Dai et al., 2011, 2012; Yang et al., 2012a,b; Zhao et al., 2012; Zheng, 2012; Zheng et al., 2011).

It is a fundamental question in continental geodynamics to know how the buoyant continental crust is subducted to mantle depths and then exhumed to crustal levels. Many studies highlight the importance of ultrametamorphic anatexis in exhumation of the deeply subducted continental crust, because the partial melting of UHP rocks at mantle depths would greatly reduce their lithological strength and thus facilitate their exhumation (Hermann et al., 2001; Labrousse et al., 2011; Wallis et al., 2005). To establish the link between anatexis and exhumation in continental collision zones, it is critical to know the exact timing, P–T conditions and spatial

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distribution of partial melting in UHP metamorphic terranes (Labrousse et al., 2011; Wallis et al., 2005; Zheng et al., 2011). Wallis et al. (2005) investigated deformed K-feldspar-rich granitic dikes in the northeastern part of the Sulu orogen, China. Based on elevated initial $^{87}Sr/^{86}Sr$ ratios for the dikes and variable U-Pb ages from 201 ± 2 to 237 ± 2 Ma for newly grown zircon rims, the authors inferred that such zircons record the timespan from the initiation of anatexis around the peak of UHP metamorphism to melt crystallization well after the peak metamorphism. Such a large timespan covers not only the period of peak UHP metamorphism in the stability field of coesite but also the period of exhumation under HP eclogite- and amphibolite-facies conditions (Liu and Liou, 2011; Zheng et al., 2009), which is hardly linked to the tectonothermal regime during continental collision. Labrousse et al. (2011) tried to link the different compositions of leucosomes from the Western Gneiss Region of Norway to the melting conditions such as P–T values and water contents. However, their determination of the timing and pressure for the leucosome formation was only relied on the crosscutting relationship in the field without direct chronometric dating and petrological P–T estimation. Thus, the time and P–T conditions of partial melting are critical parameters in establishing the link between the anatexis of subducted rocks and their exhumation process. It can be potentially resolved by the combined U–Pb dating and mineral inclusion analysis of zircon grains from anatexites.

As a widely used accessory mineral in radiometric dating of HP and UHP metamorphic rocks (including migmatites), zircon has rather sophisticated responses to the action of metamorphic fluid/melt (e.g., Chen et al., 2010, 2012; Harley et al., 2007; Xia et al., 2009, 2010; Zheng, 2009). During partial melting of crustal rocks, Zr preferentially partitions into melts by dissolution of Zr-rich minerals (including protolith zircon). The solubility of zircon in felsic melts is primarily dependent on temperature and melt composition (e.g., Hanchar and Watson, 2003; Hermann and Rubatto, 2009). For a large range of pelitic compositions, protolith zircon can commonly survive the anatexis below 850 °C (Hermann and Rubatto, 2009). This is consistent with observations from migmatites and granitic dikes (e.g., Acosta-Vigil et al., 2010; Rubatto et al., 2009; Wallis et al., 2005). The element and isotope systems in zircon can be partly or even completely reset during ultrametamorphic anatexis (e.g., Xia et al., 2009, 2010). Nevertheless, it is still feasible to link different zircon domains to specific geological processes, especially for HP/UHP metamorphic rocks that have experienced multiple stages of dehydration, reaction and anatexis (e.g., Chen et al., 2010, 2011, 2012; Hermann et al., 2001). Therefore, it is peculiar to elucidate the zircon responses during the HP to UHP metamorphism and anatexis in continental collision zones.

The Dabie–Sulu orogenic belt contains one of the largest UHP metamorphic terranes on Earth (Carswell and Compagnoni, 2003; Liou et al., 2009; Zheng, 2008). The UHP metamorphism in the coesite stability field occurred in the middle Triassic, primarily clustering at 240–225 Ma (Liu and Liou, 2011; Zheng et al., 2009). Synexhumation magmatism at 225–200 Ma, occurring as felsic intrusions, was found only in the northeastern edge of the Sulu orogen, and has been demonstrated to result from partial melting of the UHP granitic gneiss during exhumation (Chen et al., 2003; Liu et al., 2010a; Wallis et al., 2005; Zhao et al., 2012). On the other hand, low degree partial melting occurs more widely in Dabie–Sulu UHP metamorphic rocks. This is indicated by felsic veinlets and multiphase solid (MS) inclusions that are interpreted to be former melt inclusions in metamorphic minerals (Gao et al., 2012a; Xia et al., 2008; Zeng et al., 2009; Zhao et al., 2007; Zheng et al., 2011). Although the partial melting has been postulated to take place during exhumation, the exact timing for anatexis and subsequent crystallization of the microscale products remains uncertain.

Determining the spatial occurrence and temporal sequence of ultrametamorphic anatexis across the bulk orogen is a key to understanding of chemical geodynamics in continental collision zones (e.g., Labrousse et al., 2011; Zheng et al., 2011). However, it is difficult in the field to distinguish whether some foliated leucogneisses underwent anatexis at various pressures or alternatively that they are simply a deformed and metamorphosed product of granitoid protoliths that experienced subsolidus chemical differentiation (e.g., Zhang et al., 2009a). In this case, microstructural analysis is vital for identification of former occurrence of anatectic melts (e.g., Holness et al., 2011; Sawyer, 1999). This paper presents a combined study of petrology, geochronology and geochemistry to decipher the anatexis of UHP granitic gneisses in the Sulu orogen and to explore rather sophisticated zircon responses to the ultrametamorphic anatexis. The timing of anatexis is directly dated relative to the UHP metamorphic event. The mineral inclusions in the zircon grown from anatectic melts enable us to constrain the P–T conditions for the anatexis. The results highlight the important role of anatexis during the exhumation of UHP slices in the continental collision orogen.

2. Geological settings and samples

The Dabie–Sulu orogenic belt was formed by the Triassic subduction of the South China Block beneath the North China Block (Cong, 1996; Ernst et al., 2007; Li et al., 1993; Zheng et al., 2003). The Dabie and Sulu orogens are the western and eastern parts of this orogenic belt, respectively, with a possible offset along the Tan–Lu fault (Fig. 1). The Sulu orogen is bounded by the Jiashan–Xiangshui fault to the south and the Yantai–Wulian fault to the north, and segmented into a number of slices by several NE–SW-trending faults subparallel to the Tan–Lu fault (Xu et al., 2006). Based on petrological and geochemical data, this orogen can be divided into HP and UHP metamorphic zones, both of which are unconformably overlain by the Jurassic clastic strata and the Cretaceous volcaniclastic cover, and intruded by Mesozoic granites (Liu et al., 2004; Xu et al., 2006; Zhang et al., 1995a, 2010). The HP zone in the south mainly consists of schist, paragneiss, orthogneiss, marble and rare blueschist. The UHP zone in the north mainly consists of amphibolite-facies orthogneiss and paragneiss, with minor amounts of garnet peridotite, eclogite, quartzite and marble. The eclogite mainly occurs as blocks or lenses in granitic gneisses, and some are enclosed by marble and garnet peridotite. The ultramafic bodies, meter- to kilometer in size, occur sporadically as layers or blocks throughout the UHP zone. Coesite was identified as inclusions in rock-forming minerals in eclogites (e.g., Liou and Zhang, 1996; Zhang et al., 1995a, 2005) and zircon in the country rocks (e.g., Liu and Liou, 2011; Liu et al., 2004, 2006b, 2008a, 2010a). These observations indicate that the eclogites and their country rocks experienced in-situ UHP metamorphism.

Geothermobarometric studies indicated that the UHP rocks in the Sulu orogen underwent peak metamorphism at 3.0–4.5 GPa and 700–850 °C (e.g., Liu and Liou, 2011; Zhang et al., 2005, 2009b; Zheng, 2008). Majority of the UHP rocks have igneous protolith that formed probably in a continental rift zone in the middle Neoproterozoic (Zheng et al., 2009). Negative $\delta^{18}O$ values up to −10‰ were reported for eclogite, quartz schist and granitic gneiss at Qinglongshan in the Donghai area (Chen et al., 2011; Rumble and Yui, 1998; Yui et al., 1995; Zheng et al., 1996, 1998) and up to −9‰ for granitic gneiss at Zaobuzhen in the Weihai area (Tang et al., 2008). These observations indicate that protolith of the metaigneous rocks interacted with negative $\delta^{18}O$ surface water at high temperatures (Rumble and Yui, 1998; Yui et al., 1995; Zheng et al., 1996, 1998). The U–Pb dating for negative and low $\delta^{18}O$ zircons indicates that the negative $\delta^{18}O$ signature was acquired in the middle Neoproterozoic (Chen et al., 2011; Rumble et al., 2002; Tang et al., 2008; Zheng et al., 2004).

A number of typical outcrops in the Sulu orogen have been intensively studied by petrology, geochronology and geochemistry. The UHP eclogite at Rongcheng and Weihai in the northeastern Sulu orogen experienced granulite-facies overprinting (Banno et al., 2000; Nakamura and Hirajima, 2000; Wang et al., 1993; Zhang et al., 1995b), indicating a rise of temperature during exhumation.