CHEN Yixiang and ZHENG Yongfei, 2013. Petrological Evidence for Dehydration Melting of UHP Metamorphic Rocks during Continental Collision in the Sulu Orogen. *Acta Geologica Sinica* (English Edition), 87(supp.): 448-450.

Petrological Evidence for Dehydration Melting of UHP Metamorphic Rocks during Continental Collision in the Sulu Orogen

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1 Introduction

Anatexis of high-pressure (HP) and ultrahigh-pressure (UHP) metamorphic rocks has great bearing on tectonothermal evolution of continental collision zones and crust-mantle interaction as well as crust recycling in orogenic belts (e.g., Hermann et al., 2001; Labrousse et al., 2011). Because even small fractions of melts can significantly reduce the rock strength (e.g., Rosenberg and Handy, 2005), the anatexis of UHP rocks at mantle depths can promote exhumation of deeply subducted continental slices along subduction channel toward shallow levels (e.g., Wallis et al., 2005; Labrousse et al., 2011; Zheng, 2012). Therefore, it is intriguing to elucidate the temporal-spatial relationships, P-T conditions and mechanisms of anatexis that occurred in various UHP metamorphic rocks.

As the deeply subducted continental crust is generally old, cold and dry compared to the oceanic crust, fluid-induced arc magmatism during subduction does not develop above continental subduction zones (Zheng, 2012). Instead, synexhumation anatexis of UHP slices has been identified in many continental subduction zones, including Dabie-Sulu orogenic belt in east-central China (Zheng et al., 2011). While it is easy to identify large-scale anatexis of UHP metamorphic rocks by field occurrence of syn-exhumation and postcollisional graniticigneous rocks, it is hard to recognize small-scale anatexis at the scales of hand specimen and thin section. In such cases, microstructural analysis is a powerful tool to help identify the possible occurrence of crustal anatexis (e.g., Holness and Sawyer, 2008; Holness et al., 2011). The Dabie-Sulu orogenic belt contains one of the largest and best exposed UHP metamorphic terranes on Earth (e.g., Zheng et al., 2003, 2009). This study focuses on petrological evidence for anatexis of UHP quartzite, granitic gneiss and eclogite in the southwestern part of the Sulu orogen.

2 Petrological evidence for anatexis

Microstructural observations provide petrological evidence for anatexis of the Sulu UHP granitic gneiss and quartzite (Chen et al., 2013a, b). The key observations include: (1) elongated and highly cuspate feldspar grains in grain boundaries, and interstitial cuspate feldspar grains at quartz-quartz-quartz/feldspar triple junctions; (2) the development of K-feldspar crystal faces; (3) the occurrence of felsic veinlets composed of quartz + K-feldspar ± plagioclase ± muscovite along grain boundaries; (4) the "string of beads" texture along the edge of quartz or feldspars. Furthermore, the cuspate feldspars in grain boundaries and triple junctions generally exhibit very low dihedral angles between quartz-quartz-feldspar, and some of them constitute interconnected networks along quartz-quartz grain boundaries. This is also consistent with their pseudomorph of former melt, because the melt-solid dihedral angles are generally $<40^o$, far less than solid-solid dihedral angles of 120^o in textural equilibrium (e.g., Holness and Sawyer, 2008).

In eclogite, three types of multiphase solid (MS) inclusions occur in both garnet and omphacite, which are composed of plagioclase + quartz, plagioclase + quartz + K-feldspar, and barite + plagioclase + K-feldspar ± zoisite/epidote, respectively. The host minerals mostly exhibit radial fractures surrounding the MS inclusions. The first and second types of MS inclusions exhibit high SiO_2 (75-90 wt%) and Na_2O (2.9-7.3 wt%), very low $FeO+MgO+TiO_2$ and variable K_2O (0-2.4 wt%), and they generally have very low trace element concentrations except such large ion lithophile elements as Sr, Ba and Pb. The major and trace element compositions of such MS inclusions indicate they cannot result from the breakdown of jadeite, coesite and K-cymrite, but instead probably derive from a former hydrous melt (e.g., Zeng et al., 2009; Gao et al., 2012, 2013).

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3 Zirconological evidence for anatexis

Mineral responses to crustal anatexis in continental collision zones are usually complex. Minerals can be more efficiently dissolved into anatectic melts than into aqueous fluids, and exhibit resorption or overgrowth texture during melt crystallization (e.g., Hermann et al., 2001; Chen et al., 2013a, b). Thus, they typically display significant compositional zoning in major and trace elements. To resolve the specific conditions for formation of each zoned domain relevant to the anatectic event can provide further constraints on the mechanism and process for partial melting of UHP rocks. As zircon can be efficiently dissolved in anatectic melts and grow from the melts, it can be potentially used to date the anatexis that occurred at various spatial scales, provided that solid evidence can be obtained for zircon growth from the specific anatectic event (e.g., Hermann et al., 2001). Furthermore, zircon Hf-O isotopes can provide geochemical constraints on the processes and mechanisms of crustal anatexis. If the anatectic melts formed by reactants that have different O-Hf isotope compositions, then zircon grown from such melts would be expected to exhibit contrasts in O-Hf isotopes.

Anatectic zircon domains were distinguished in the Sulu UHP gneiss and quartzite from the residual magmatic zircon and metamorphic zircon growth at subsolidus condition (Chen et al., 2013a, b). In the granitic gneiss, such domains exhibit steep REE patterns, distinctly higher U contents and remarkable negative Eu anomalies. In the quartzite, they contain MS inclusions consisting of quartz ± K-feldspar ± plagioclase ± muscovite, and most of them exhibit granophyric intergrowth of two or more phases. Such MS inclusions are generally of granitic composition, probably representative a former hydrous melt. The domains containing such MS inclusions also exhibit steep REE patterns and significant negative Eu anomalies. They yield concordant U-Pb ages of 224 ± 3 to 217 ± 3 Ma with a cluster at 220±2 Ma, younger than predominant ages of 225-235 Ma for UHP metamorphism in the Dabie-Sulu orogenic belt (Zheng, 2012). This corresponds to anatexis during early exhumation of the deeply subducted continent crust. Few domains of the anatectic zircon in the both granitic gneiss and quartzite contain coesite inclusions, exhibiting slightly older U-Pb ages clustered at 224±2 Ma. Some of the UHP anatectic zircon U-Pb ages are indistinguishable from those containing the low-P minerals, suggesting rapid exhumation of the UHP rocks from mantle depth to the lower crust level. As such, the anatexis would have lasted about 10-15 Myr, with its initiation still in the UHP regime during the early exhumation. Therefore, the extensive anatexis postdates the peak UHP eclogite-facies metamorphism.

4 Possible mechanism for anatexis

Considering the P-T path of the UHP granitic gneiss and quartzite and the petrological observation that muscovite relicts occurring with K-feldspar and quartz both in the matrix and in the MS inclusions of anatectic zircons, we proposed that dehydration melting of phengite/muscovite is responsible for the anatexis (Chen et al., 2013a, b). This is consistent with previous experimental results on partial melting in relevant systems (e.g., Vielzeuf and Holloway, 1988; Hermann, 2002). This anatectic reaction results in euhedral garnet of high-Mn composition in the melt pocket of the granitic gneiss. In the quartzite, there are two groups of garnet. One group is Al-rich, with low LREE and Nb contents, and steep REE patterns, which may have grown during the eclogite-facies metamorphism when rutile was stable. The other group exhibits much lower Al and higher Fe contents, with markedly elevated contents of Nb and LREE, and various HREE contents. Metamorphic zircon hosted by the garnet gave concordant U-Pb ages of ca. 214 Ma. This group of garnet is thus interpreted as a peritectic product of the anatectic reaction involving felsic minerals and possibly amphibole and titanite. The possible anatectic reaction for the extensive melting in the relatively low pressure can be: Ms + Qz + Pl + Grt-I ± Amp ± Ttn → melt + Grt-II + Kfs.

In the zoisite-bearing eclogite, the three types of MS inclusions of markedly different bulk compositions suggest derivation from different anatectic reactions. The MS inclusion composed of quartz and plagioclase would be primarily derived from dehydration melting of zoisite with significant involvement of omphacite to form Na-rich melts, whereas the MS inclusion composed of quartz, plagioclase and K-feldspar can be derived from dehydration melting of both zoisite and phengite in the eclogite to form melts with variable K contents. The MS inclusion composed of barite + plagioclase + K-feldspar is a result of interaction between the melt-related aqueous fluid of high oxygen fugacity and the host mineral. This interpretation is generally consistent with the P-T path and the experimental partial melting reactions due to phengite and zoisite breakdown (e.g., Skjerlie and Patino Douce, 2002; Liu et al., 2009; Gao et al., 2012, 2013).

In summary, the breakdown of UHP hydrous minerals in exhuming continental crust triggers dehydration-driven partial melting of the UHP granitic gneiss, quartzite and eclogite in the southwestern Sulu orogen. While the incipient anatexis would probably occur during the early exhumation but still in the UHP regime, the extensive anatexis takes place during the significant exhumation toward the lower crust level. Continental subduction channel processes can explain how variable extents of structural deformation, dehydration metamorphism and partial melting occurred in the detached crustal slices (Zheng, 2012). The extensive anatexis is commonly associated with high-T granulite-facies overprinting during exhumation, which may be promoted by lateral emplacement of the asthenospheric mantle into the continental subduction channel subsequent to breakoff of the subducted continental lithosphere.

Acknowledgments

This study was supported by funds from Natural Science Foundation of China (41221062) and Chinese Ministry of Science and Technology (2009CB825004).

Key words: continental subduction, UHP metamorphism, crustal anatexis, element mobility, anatectic zircon

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