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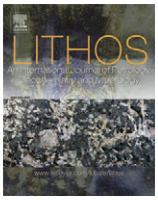

Zirconological tracing of transition between aqueous fluid and hydrous melt in the crust: Constraints from pegmatite vein and host gneiss in the Sulu orogen

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ABSTRACT

Zircon can grow from aqueous fluid and hydrous melt in crustal rocks when they undergo metamorphic dehydration and partial melting under high-pressure (HP) to ultrahigh-pressure (UHP) conditions. A distinction between fluid and melt has important bearing on the development of crustal anatexis in collisional orogens. A genetic transition between fluid and melt is recorded by zircons from pegmatite vein and host UHP gneiss in the Sulu orogen. This transition is elucidated by an integrated study of SIMS U–Pb and O isotope analyses with LA-ICPMS U–Pb isotope and trace element analyses in the zircons. Pegmatite veins yield zircon U–Pb ages of 147–153 Ma for new growths, and 700–800 Ma for relict cores. A one meter-width pegmatite vein exhibits two episodes of zircon growth at 153 ± 3 Ma for inner domain and at 147 ± 2 Ma for outer domain. The two types of domains have a series of differences in CL image, inclusion type, REE content and pattern, trace element contents and ratios, and Ti-in-zircon temperature. The inner domain grew from the hydrous melt at 730–840 °C, whereas the outer domain grew from the aqueous fluid at 520–650 °C. Nevertheless, they have similarly low $\delta^{18}O$ values of 1.0–2.3‰, suggesting their growth from O isotope homogeneous media despite the transition from melt to fluid. The host gneiss of this pegmatite vein exhibits three generations of zircon growth, with 180–205 Ma at 700–770 °C during amphibolite-facies metamorphism, 157 ± 3 Ma at 610–670 °C for fluid-assisted growth, and 147 ± 2 Ma at 780–860 °C for melt-assisted growth. The last two types of growth record the development of crustal anatexis from hydration melting to dehydration melting. The other decimeter-width pegmatite vein exhibits only one episode of zircon growth from melt at 149 ± 2 Ma and 660–860 °C. Its host gneiss exhibits a residual melt texture but no significant growth of zircon, indicating low degree of dehydration melting. Therefore, the zircon domains in the host gneisses record their growth during a transition from aqueous fluid to hydrous melt along a temperature-increasing path, whereas the zircon domains in the pegmatite veins record their growth during a transition from hydrous melt to aqueous fluid along a temperature-decreasing path. Despite the difference in the direction of fluid/melt evolution, the all zircon domains in these gneisses and pegmatite veins record the same event of crustal anatexis in the UHP gneisses. The present study also provides insights into a genetic definition of anatectic melt and thus anatectic zircon.

1. Introduction

Aqueous fluid and hydrous melt are two principal species of geological fluid under high-pressure (HP) to ultrahigh-pressure (UHP) conditions (e.g., Hermann et al., 2006; Zheng et al., 2011). They are distinguished from each other by differences in physicochemical property and geochemical composition. They occur in high-grade metamorphic terranes as metamorphic fluid and melt as well as magmatic fluid and melt, respectively (e.g., Zheng, 2012). The metamorphic fluid and melt are produced by dehydration and anatexis, respectively, during high-grade metamorphism under amphibolite-, eclogite- and granulite-facies conditions. The metamorphic melt is also referred to as anatectic melt that has not escaped from parental metamorphosed rocks such as migmatite and granulite. In contrast, the magmatic melt has escaped from its source rocks through significant ascent and accumulation of anatectic melt. The magmatic fluid has evolved and separated from the magmatic melt because the solubility of water in hydrous melt decreases with decreasing pressure–temperature (P-T) during magma emplacement. Although the genetic classification between the metamorphic and magmatic fluids/melts is straightforward, it is challenging to distinguish them by means of mineralogical records. Because the difference in the extent of incompatible element saturation is a critical parameter, minerals crystallized from the fluids/melts are important targets to investigate.

Aqueous fluid plays a critical role in anatexis of the continental crust under HP to UHP conditions (e.g., Zheng et al., 2011). Within the crust, anatexis may be caused by an ingress of aqueous fluid into crustal rocks via fluid-induced (hydration) melting (e.g., Berger

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et al., 2008; Prince et al., 2001; Rubatto et al., 2009), or by breakdown of hydrous minerals as dehydration-driven melting (e.g., Brown, 2010; Skjerlie and Patiño Douce, 2002; Zheng et al., 2011). The former takes place at the wet solidus with the saturation of water, whereas the latter occurs at elevated temperatures above the wet solidus with the undersaturation of water. In either case, silicate melts are produced with variable amounts of water, depending on the contents of water in the parental rocks and the P-T conditions and timescale of partial melting. This has important bearing on the solution of incompatible elements in hydrous melts because water behaves like the most incompatible element during partial melting and fractional crystallization. There is also genetic relationship between source and sink for water and incompatible elements in crustal rocks (Zheng, 2009, 2012).

It has been noted petrologically that the amount of hydrous melts derived from partial melting of granitic rocks sometimes far exceeds what can be produced through the breakdown of hydrous minerals in the rocks (e.g., Berger et al., 2008; Burri et al., 2005; Slagstad et al., 2005). Petrogenetic modeling also demonstrated that only a small percentage of melt can be generated from the breakdown of micas at temperatures in excess of 800 °C in a granitic rock (Schulmann et al., 2008). This suggests involvement of additional water from somewhere, either external or internal origins. The internal fluid can be generated by the exsolution of structural hydroxyl and molecular water in nominally anhydrous minerals (Zheng, 2009). Furthermore, partial melting of granitic rocks may initially take place at the wet solidus primarily due to local accumulation of aqueous fluids (Sawyer, 2010; Zheng et al., 2011). In this regard, there exists the evolution from metamorphic aqueous fluid to anatectic hydrous melt in the lithological system with increasing temperature. The segregation, ascent and accumulation of anatectic melt, on the other hand, can eventually evolve to magmatic melt, in which magma results after crystallization of significant amounts of rock-forming minerals. During magma evolution, aqueous fluid would approach saturation in magmatic melt and eventually exsolved as magmatic fluid. Thus, there exists the evolution from hydrous melt to aqueous fluid in the magmatic system. In this context, metamorphic fluid, anatectic melt, magmatic melt and magmatic fluid may be generated by continuous processes with changing P-T conditions.

Granitic pegmatite is an example that crystallizes from hydrous melt to aqueous fluid (Simmons and Webber, 2008; Thomas et al., 2000). Some pegmatite veins were formed from partial melting of granitic rocks (London, 2005) and also reported in UHP metagranite in the Sulu orogen of China (e.g., Liu et al., 2010a; Wallis et al., 2005). These pegmatite veins, together with their parental rocks, are excellent samples to study the generation and evolution of aqueous fluid and hydrous melt during regional metamorphism and crustal anatexis. However, it is difficult in petrology to trace the transition between aqueous fluid and hydrous melt because the evidence of hydration melting was mostly erased by subsequent dehydration melting at elevated temperatures (Rubatto et al., 2009).

Zircon, a common accessory mineral in high-grade metamorphic rocks, can readily crystallize from aqueous fluid (e.g., Chen et al., 2011a, 2012; Rubatto and Hermann, 2003; Wu et al., 2009; Zheng et al., 2007) and hydrous melt (e.g., Liu et al., 2010a; Rubatto, 2002; Rubatto et al., 2009; Vavra et al., 1996; Xia et al., 2009; Zong et al., 2010). Due to its robustness, refractory property and extremely low diffusion rates for many elements, zircon can commonly retain its growth age, trace element and isotope signatures even if exposed to suprasolidus temperatures (Cherniak and Watson, 2003; Scherer et al., 2007; Zheng et al., 2004). Thus, zircon U–Pb dating is widely used to determine the time of its growth from aqueous fluid and hydrous melt. Furthermore, the trace element composition of zircon is used to distinguish magmatic origin from metamorphic and hydrothermal origins (e.g., Chen et al., 2010, 2012; Hinton and Upton, 1991; Hoskin, 2005; Rubatto, 2002; Whitehouse and Platt, 2003; Wu et al., 2009; Xia et al., 2009, 2010; Zheng, 2009). However, such distinction by the REE composition alone has encountered difficulties in distinguishing hydrothermal zircon from magmatic and metamorphic zircons (e.g., Fu et al., 2009; Hoskin and Schaltegger, 2003; Pettke et al., 2005). So does in distinguishing anatectic zircon from magmatic and metamorphic zircons.

Substantially, the magmatic melt can be viewed as a highly evolved product of the anatectic melt. While it may be originally produced by high-degree partial melting rather than low-degree anatexis in the source, it has also experienced protracted segregation, homogenization and fractional crystallization. As a consequence, the magmatic melt is commonly assumed to have achieved thermodynamic equilibrium in petrology and geochemistry. While the most evolved anatectic melt cannot be distinguished from the magmatic melt, the least evolved anatectic melt cannot be distinguished from the metamorphic fluid. However, a reasonable distinction between the two origins of hydrous melt is very important in petrogenetic and geochemical studies. Zirconology, the integrated study of zircon mineragraphy (internal structure and external morphology), U–Pb geochronology, mineral inclusions, trace elements, Ti content thermometer, and Lu-Hf and O isotope compositions, can potentially distinguish anatectic melt from magmatic melt and metamorphic fluid. In this paper, we present a zirconological study of granitic pegmatite veins and host rock UHP granitic gneisses in the Sulu orogen. The results not only provide geochemical distinction between zircon growths from aqueous fluid and hydrous melt, but also place constraints on the processes of crustal anatexis with regard to the transition between aqueous fluid and hydrous melt.

2. Geological setting and samples

The Dabie–Sulu orogenic belt in east-central China was formed by subduction of the South China Block beneath the North China Block in the Triassic (e.g., Cong, 1996; Zhang et al., 2009; Zheng et al., 2005). The Sulu orogen is considered as its eastern part, with an offset of about 500 km to the northeast along the Tan–Lu fault. This orogen is bounded by the Jiashan–Xiangshui fault in the south and the Wulian–Qingdao–Yantai fault in the north (Fig. 1). It consists of a fault-bounded HP metamorphic zone in the southwest and UHP metamorphic zone in the northeast (Xu et al., 2006), overlain by Jurassic clastic strata and Cretaceous volcanoclastic cover, and intruded by Mesozoic granites (Zhang et al., 1995, 2010; Zhao and Zheng, 2009). The UHP zone primarily consists of UHP gneisses overprinted by amphibolite-facies assemblages, with minor amounts of eclogite, garnet peridotite and marble. Eclogite occurs as layers and blocks within gneisses and marbles. Mineralogical evidence for UHP metamorphism has been recognized in eclogites, schists, ultramafic rocks and gneisses (e.g., Liou and Zhang, 1996; Liu et al., 2010a; Ye et al., 2000; Zhang et al., 1995).

This study focuses on two pairs of pegmatite vein and host gneiss from the Taohang area in the middle part of the Sulu UHP zone, about 5 km south of the Wulian–Qingdao fault. Outcrops in this area mainly consist of granitic orthogneiss, and eclogite sporadically occurs as lenticular bodies or discontinuous layers in the gneiss (Fig. 2). The gneiss was intruded by granodiorite and granitic porphyry dykes, and contains leucocratic veins with sizes from centimeters to meters. Some of the leucocratic veins occur as pegmatite veins. Coesite inclusions were found in zoisite from the eclogite (Yao et al., 2000) and in zircon from the granitic gneiss (Ye et al., 2000), demonstrating that both mafic and felsic metamorphic rocks experienced UHP eclogite-facies metamorphism. Petrological studies indicate that the UHP eclogite experienced HP granulite-facies overprinting (Yao et al., 2000) and the UHP granitic gneiss experienced amphibolite-facies retrogression (Ye et al., 2000) during exhumation.

A few geochronological studies were performed on this UHP slice. The results suggest that the UHP metamorphism occurred at 228–218 Ma (Liu and Liou, 2011), HP eclogite-facies recrystallization at about 214 Ma (Gong et al., 2007), and amphibolite-facies retrogression at about 203–201 Ma (Liu et al., 2009). The bulk O isotope analysis of