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Polyphase growth of accessory minerals during continental collision: Geochemical evidence from ultrahigh-pressure metamorphic gneisses in the Sulu orogen

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An integrated study of petrology, geochronology and geochemistry was performed for ultrahigh-pressure metamorphic gneisses in the Sulu orogen. The results are used to elucidate the polyphase growth of such metamorphic minerals as zircon, titanite and garnet in response to pressure–temperature changes and fluid/melt action during continental collision. This provides insights into the property of metamorphic fluid/melt and their effects on trace element mobility. A combined result from REE patterns, mineral inclusions and Ti-in-zircon temperatures indicates three stages of zircon growth. Prograde growth occurred at ~237 Ma primarily at eclogite-facies, retrograde growth at ~222 Ma mostly at eclogite-facies, and the last growth at ~205 Ma at granulite-facies. The three stages of zircon growth are deciphered by distinct REE patterns and trace element compositions, reflecting the differences in the property of metamorphic fluid/melt. The episodic growth of metamorphic zircon is primarily dictated by the episodic concentration of Zr and Si in metamorphic fluid/melt. Relict domains of magmatic titanite are distinguished from metamorphosed and metamorphic domains by their distinctive REE patterns and trace element compositions. The metamorphic titanite exhibit variably elevated Nb contents and Nb/Ta ratios, suggesting Nb/Ta fractionation due to breakdown of amphibole and/or biotite during metamorphism. Polyphase growth of garnet is suggested by an integrated analysis of mineral inclusions, and major and trace elements in large garnet grains. Trace element abundances vary in different zones of garnet, which is ascribed to changes in the paragenesis and composition of matrix minerals involved in garnet-forming reactions at different P–T conditions. Therefore, the metamorphic growth of zircon, titanite and garnet would have occurred not only during prograde subduction but also during retrograde exhumation in the continental collision zones. Both metamorphic dehydration and partial melting would have taken place episodically during the collisional orogeny. The breakdown of hydrous minerals at high- to ultrahigh-pressure conditions is a key to fluid liberation and element supply for the growth of these accessory minerals.

1. Introduction

Accessory minerals in subduction-zone metamorphic rocks can experience complex compositional changes in response to P–T variations and fluid action. As many of those minerals like zircon, titanite and rutile have high U contents, they are sound objects for U–Pb dating (Zheng, 2012). In addition, they are important carriers of rare earth elements (REE), high field strength elements (HFSE) and other incompatible trace elements. Therefore, the geochemical behavior of such accessory minerals during subduction-zone metamorphism has a great bearing on mass transfer at a plate's interface and thus trace element mobility in subduction channels (Bebout, 2007; Hermann, 2002a; Hermann and Rubatto, 2009; Zheng et al., 2011a).

Zircon commonly exhibit relict cores of magmatic origin and variable volumes of metamorphic growth in high-pressure (HP) and ultrahigh-pressure (UHP) metamorphic rocks (Zheng, 2009). The relict cores experienced different mechanisms of metamorphic recrystallization by solid-state transformation, replacement alteration and dissolution reprecipitation in response to accessibility of metamorphic fluid/melt at different extents. These metamorphic and metamorphosed zircons have been elucidated by integrated microbeam in situ analyses of trace elements, U–Th–Pb isotopes, and O–Hf isotopes (Chen et al., 2010, 2011, 2012; Sheng et al., 2012, 2013; Xia et al., 2009, 2010). In particular, the episodic growth of metamorphic zircon is evident in some UHP metamorphic rocks (Gao et al., 2011; Hermann et al., 2001; Liu et al., 2006; Y.-B. Wu et al., 2006; Zheng et al., 2005a, 2007, 2011b). This suggests that different types of mineralogical reactions were involved for the release of Zr and Si with

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local transport and episodic concentration in metamorphic fluid (Zheng, 2012; Zheng et al., 2011a). Although the behavior of zircon may be complicated during orogenic processes (Harley et al., 2007; Rubatto and Hermann, 2007), it is important to link its specific domains to P–T conditions and growing agents. This issue can be addressed by investigations of mineral inclusions, zircon/garnet trace element partition and Ti-in-zircon thermometry (e.g., Ferry and Watson, 2007; Gao et al., 2011; Hermann et al., 2001; Liu and Liou, 2011; Rubatto, 2002; Zheng et al., 2011b).

Titanite is a common mineral in Ca-, Al-rich silicate rocks (Frost et al., 2000). Similar to zircon, relict domains of magmatic titanite can survive during HP and UHP metamorphism (Aleinikoff et al., 2002; Corfu, 1996; Gao et al., 2012; Pidgeon et al., 1996; Storey et al., 2007). Polyphase growth of metamorphic titanite is also evident in amphibolite-facies gneisses and eclogite-facies calc-silicate rocks (Essex and Gromet, 2000; Gao et al., 2011; Rubatto and Hermann, 2001). Furthermore, titanite can be partly altered by, or grow from, hydrothermal and metamorphic fluids, resulting in distinct trace element compositions from the primary magmatic domains (Buick et al., 2007; Gao et al., 2012; Li et al., 2010). Due to high contents of REE and HFSE, titanite has received considerable attention in petrogenetic studies (e.g., Amelin, 2009; John et al., 2011; Storkey et al., 2005). Especially, titanite can strongly fractionate Nb from Ta because of $D_{Nb/Ta} < 1$ (Olin and Wolff, 2012; Prowatke and Klemme, 2005; Tiepolo et al., 2002), so its breakdown or occurrence as a residual phase can heavily affect the Nb/Ta ratios of rocks. On the other hand, the Nb/Ta ratio of titanite itself can be affected by its formation reaction such as the breakdown of amphibole, biotite or ilmenite, and by the fluid/melt agents that alter titanite or from which the titanite grows. In this regard, it is intriguing to elucidate the processes and conditions that enable the mineral-scale mobility of trace elements, especially HFSE, in subduction channels.

Table 1
Summary of mineral paragenesis in gneisses at Baihushan.

Sample	Major mineral	Minor mineral	Accessory mineral
00BH21	Qz, Pl, Kfs, Bt, Amp	Ttn, Ep, Aln, Grt	Zrn, Ap
00BH05	Qz, Pl, Kfs	Ttn, Mag	Ms, Grt, Zrn
00BH11	Qz, Pl, Kfs	Ttn, Ep, Bt, Mag	Ms, Grt, Zrn, Ap
00BH17a	Qz, Pl, Kfs	Amp, Ttn, Bt, Ms, Ep, Mag	Grt, Zrn, Ap
00BH20a	Qz, Pl, Kfs	Ttn, Ep, Mag	Ms, Grt, Zrn, Ap

Note: The modal contents of major, minor and accessory mineral are >5%, 1–5% and <1%, respectively.

Garnet is a common rock-forming mineral in eclogite, but typically an accessory phase in granitic gneiss. It may grow in different stages during subduction-zone metamorphism, which exhibits significant differences in the types of mineral inclusions and the compositional zoning of major and trace elements (e.g., Kobayashi et al., 2011; Konrad-Schmolke et al., 2006, 2008; Xia et al., 2012; Zhou et al., 2011). In some cases, the zoning of major elements can be decoupled from that of trace elements because of differences in diffusion rates and growth zonations. For example, some metamorphic garnet may exhibit relatively homogeneous major element compositions but significant zoning in trace elements. Relict garnet domains of magmatic origin commonly occur in granitic gneiss but are typically absent in eclogite.

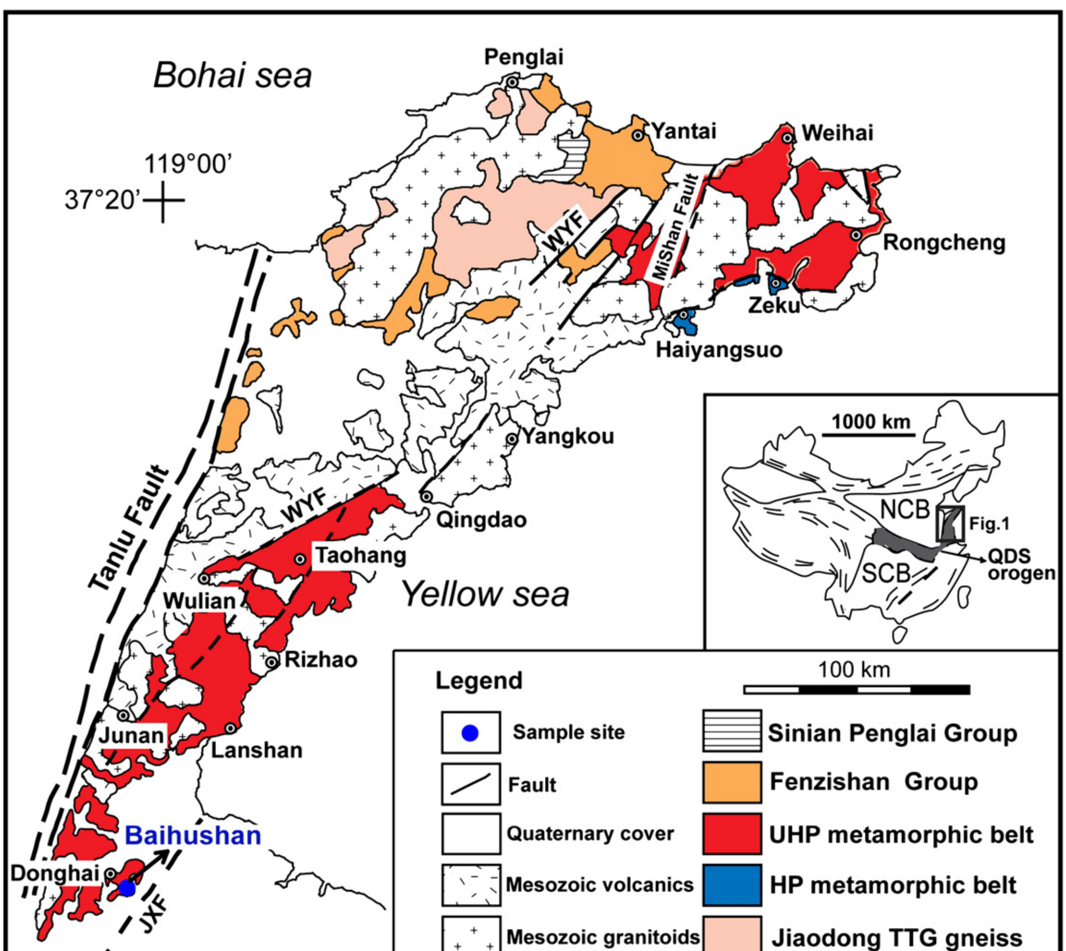

Fig. 1. Geological sketch map of the Sulu orogen (modified after F.L. Liu et al., 2010). The major lithotectonic units and sample locations are shown. Abbreviations: WYF, Wulian–Yantai fault; JXF, Jiashan–Xiangshui fault; QDS, Qinling–Dabie–Sulu.