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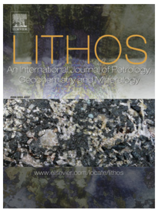

Multiphase solid inclusions in zoisite-bearing eclogite: evidence for partial melting of ultrahigh-pressure metamorphic rocks during continental collision

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ABSTRACT

Multiphase solid (MS) inclusions in both garnet and omphacite were investigated for zoisite-bearing eclogite from the ultrahigh-pressure (UHP) metamorphic zone in the Sulu orogen. The results provide petrological evidence for local anatexis during exhumation of deeply subducted continental crust. There are three types of MS inclusions: (1) plagioclase + quartz, (2) plagioclase + quartz + K-feldspar, and (3) barite + plagioclase + K-feldspar ± zoisite/epidote. The host minerals mostly exhibit radial fractures surrounding the MS inclusions. The first and second types of MS inclusions were analyzed for their bulk compositions, yielding high SiO_2 and Na_2O but very low FeO + MgO + TiO_2 with variable K_2O for the second type. Trace element analyses of representative MS inclusions yield generally very low concentrations except such large ion lithophile elements as Sr, Ba and Rb. These features suggest different origins for the three types of MS inclusions. The first type of MS inclusions would be primarily derived from dehydration melting of paragonite, whereas the second type of MS inclusions would be derived from dehydration melting of both paragonite and phengite. The third type of MS inclusion may result from the interaction between metamorphic fluid and host mineral in view of the occurrence of barite as a filling phase in the fractures of host minerals. Zoisite breakdown is also indicated by its highly cuspate shape in coexistence with quartz, providing components for growth of garnet during the exhumation. Therefore the anatexis of zoisite-bearing UHP eclogite is primarily driven by the breakdown of hydrous minerals such as phengite and paragonite. The major and trace element compositions of MS inclusions in the eclogites mainly depend on the species of hydrous minerals involved in the mineralogical reactions of dehydration melting in subduction channel.

1. Introduction

Partial melting of eclogite at depth by delamination or subduction has great bearing on the crust-mantle interaction and the formation of intraplate basalt magmatism (e.g., Anderson, 2007; Gao et al., 2004; Zheng, 2012). Therefore, many experiments have been directed to investigate the major and trace element compositions of felsic melts derived from partial melting of eclogite at various P-T conditions (e.g., Klemme et al., 2002; Kogiso and Hirschmann, 2006; Laurie and Stevens, 2012; Rapp et al., 2003; Skjerlie and Patino Douce, 2002). However, there is scarce direct evidence for the partial melting in natural ultrahigh-pressure (UHP) eclogites and metapelites. Zoisite pegmatites of tonalitic to trondhjemitic composition from the Münchberg Massif in Germany were ascribed to high-pressure (HP) melting of eclogite (Franz and Smelik, 1995; Liebscher et al., 2007). Multiphase solid (MS) inclusions in garnet from UHP metapelite from Greenland Caledonites were interpreted as reactants and products of the following dehydration melting reaction: phengite + quartz = kyanite + K-feldspar + rutile + melt (Lang and Gilotti, 2007). In particular, the occurrences of MS inclusions composed mainly of quartz and feldspars provide us with an excellent opportunity to decipher the partial melting of natural eclogites in continental subduction zones (e.g., Gao et al., 2012, 2013; Zeng et al., 2009).

The MS inclusion, by definition, is a kind of mineral inclusions that is composed of two or more solid mineral phases, with or without a vapor/fluid phase. Since the pioneer work of Philippot and Selverstone (1991) that reported MS inclusions composed of aqueous brines and various kinds of solid phases in eclogite veins from the Monviso ophiolitic complex in Western Alps, many kinds of MS inclusions have been reported in HP to UHP metamorphic rocks worldwide. Many MS inclusions contain brines and daughter phases like halite, sylvite, carbonate, sulfate and some silicates, which were usually interpreted as forming by interaction between metamorphic rocks and aqueous fluids at various metamorphic stages (Philippot and Selverstone, 1991; Philippot et al., 1995). However, a new kind of MS inclusions was recently found in UHP metamorphic rocks, indicating that the metamorphic fluid at peak P-T

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conditions can contain extraordinarily high silicate solutes and thus cannot be interpreted as the common aqueous fluid (Ferrando et al., 2005; Frezzotti et al., 2007; Hermann et al., 2006; Hwang et al., 2001; Malaspina et al., 2006, 2009; Stockhert et al., 2001; Zhang et al., 2008). Instead, some of these MS inclusions are interpreted to crystallize from the hydrous melt of different compositions (e.g., Hermann et al., 2006; Hwang et al., 2001; Zheng et al., 2011). In fact, experimental studies have indicated that primary hydrous mineral inclusions enclosed by major rock-forming minerals can experience partial melting under UHP conditions (Perchuk et al., 2005, 2008, 2009).

Another kind of MS inclusions is primarily composed of quartz, K-feldspar and/or plagioclase, which has been reported in many UHP terranes such as Dabie-Sulu in east-central China (Enami and Zang, 1990; Enami et al., 1993; Gao et al., 2012, 2013; Yang et al., 1998; Zeng et al., 2009, 2012), Erzgebirge in Germany (Massonne, 2001; Massonne and Nasdala, 2003), Kokchetav in Kazakhstan (Mikhno and Korsakov, 2013; Mikhno et al., 2013) and Northern Qaidam in western China (Song et al., 2003; Zhang et al., 2009a). The petrogenetic interpretation of such MS inclusions is highly debatable. While someone interpreted them as exsolution of the $KAlSi_2O_6$ component from the former K-bearing omphacite (Yang et al., 1998), others attributed them to the former existence of K-cymrite and coesite (Massonne, 2001; Mikhno et al., 2013; Song et al., 2003; Zhang et al., 2009a). The third school advocates that such MS inclusions were formed by crystallization of the former partial melts (Gao et al., 2012, 2013; Liu et al., 2013; Zeng et al., 2009). This interpretation, if correct, has important geodynamic implications for the exhumation of deeply subducted continental crust. Therefore, it is intriguing to know the petrological occurrence and formation mechanism of such MS inclusions in UHP metamorphic rocks.

The major and trace element compositions of MS inclusions can provide important clues to their origin (e.g., Gao et al., 2012, 2013; Korsakov and Hermann, 2006; Korsakov et al., 2006; Zeng et al., 2009). Because of compositional heterogeneity and variable volumes, however, it is practically difficult to obtain the precise compositions of bulk MS inclusions in metamorphic minerals (Bartoli et al., 2013a,b; Cesare et al., 2009; Gao et al., 2013; Halter et al., 2002; Pettke et al., 2004). Previous studies were primarily focused on melt inclusions in volcanic or plutonic minerals, providing geochemical constraints on magma sources or igneous processes (Halter et al., 2002; Kent, 2008; Laubier et al., 2012; Pettke et al., 2004). The melt inclusions are generally small with the typical size up to several tens of micrometers. Furthermore, they are mostly composed of a homogeneous glass, and thus can be measured by conventional methods such as electron microprobe (EMP), laser ablation (LA)-inductively coupled plasma mass spectrometer (ICPMS), and secondary ion microprobe (SIMS) for major and trace elements (e.g., Halter et al., 2002; Pettke et al., 2004). However, if the glass coexists with a daughter phase, or the melt inclusion is completely crystallized, its bulk composition is very difficult to precisely measure. In this case, if directly measured by LA-ICPMS, either a mass ratio between the ablated inclusion and the host mineral must be estimated (Gao et al., 2013), or the composition of one element in the inclusion must be independently obtained (Halter et al., 2002; Pettke et al., 2004). Laboratory re-homogenization was sometimes performed at high pressures and temperatures prior to the bulk analysis (e.g., Bartoli et al., 2013a,b). However, this procedure requires carefully manipulating of the remelting P-T conditions in order to avoid the reaction between melt and host mineral during rehomogenization experiments. Therefore, an appropriate analytical protocol is a key to the precise analysis of major and trace elements in MS inclusions enclosed by HP to UHP metamorphic minerals.

The Dabie-Sulu orogenic belt contains one of the largest UHP metamorphic terranes on Earth (e.g., Liou et al., 2009; Zheng, 2008). Previous studies have found petrological and geochemical evidence for synexhumation anatexis of UHP quartzite, granitic gneiss and eclogite in the UHP metamorphic zone (Chen et al., 2013a,b; Gao et al., 2012, 2013; Liu et al., 2010, 2013; Xia et al., 2008; Zeng et al., 2009, 2011; Zhao et al., 2007). However, an open question is the spatial distribution of anatexis in the bulk orogenic belt and the mechanism of partial melting in the UHP metamorphic rocks of different compositions. This paper presents a combined study of petrology and geochemistry to highlight the partial melting of zoisite-bearing UHP eclogite in the Sulu orogen. Three types of MS inclusions were found in both garnet and omphacite from the eclogite. Especially, the MS inclusions composed of plagioclase + quartz and barite + plagioclase + K-feldspar ± zoisite/epidote, to our knowledge, are firstly reported in UHP eclogites. Combined with previously found MS inclusions in the Dabie-Sulu orogenic belt, we discuss possible mechanisms and implications for the partial melting of UHP eclogites during continental collision.

2. Geological setting and samples

The Dabie-Sulu orogenic belt was formed by the northward subduction of the South China Block beneath the North China Block in the Triassic (Ernst et al., 2007; Zheng et al., 2003). The Sulu orogen belongs to the eastern part of this belt, which was offset of ~500 km to the northeast by the Tan-Lu fault relative to the Dabie orogen (Fig. 1). The Sulu orogen is bounded by the Jiashan-Xiangshui fault to the south and the Wulian-Yantai fault to the north, and segmented into a number of slices by several faults (Xu et al., 2006). According to petrological and geochemical studies, this orogen is 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 (Zhang et al., 1995; Zheng et al., 2005). The HP metamorphic zone in the south is mainly composed of schist, paragneiss, orthogneiss, marble and rare blueschist. The UHP metamorphic zone in the north is mainly composed of orthogneiss and paragneiss, with minor amounts of eclogite, garnet peridotite, quartzite and marble. The eclogite occurs mainly as blocks or lenses in the granitic orthogneiss, and some as enclosures within the marble and garnet peridotite. Coesite was identified in the eclogite and its country rocks, indicating in-situ UHP metamorphism for these rocks (Liou and Zhang, 1996; Liu and Liou, 2011; Zhang et al., 1995, 2005).

The UHP metamorphic rocks in the Sulu orogen underwent peak recrystallization at pressures of 3.0–4.5 GPa and 700–750 °C during subduction but reworking at elevated temperatures of 800–850 °C during exhumation (Zhang et al., 2005, 2009b; Zheng, 2008). The event of UHP metamorphism in the coesite stability field occurred at 225–240 Ma with a duration of 15 ± 2 Myr (Liu and Liou, 2011; Zheng et al., 2009). The majority of UHP rocks have igneous protolith that formed probably in a continental rift zone of middle Neoproterozoic (Zheng et al., 2009). Mineral $\delta^{18}O$ values as low as −10‰ were reported for UHP rocks at Qinglongshan in the Donghai area (Rumble and Yui, 1998; Yui et al., 1995; Zheng et al., 1996, 1998) and as low as −9‰ for granitic gneiss at Zaobuzhen in the Weihai area (Tang et al., 2008). The occurrence of negative $\delta^{18}O$ rocks indicate that the protolith of metaigneous rocks was interacted with the ^{18}O-depleted meteoric water at high temperatures (Zheng et al., 2003, 2009). The U-Pb dating of negative and low $\delta^{18}O$ zircon grains and domains indicates that the negative $\delta^{18}O$ signature was originally acquired in the middle Neoproterozoic, whereas the negative $\delta^{18}O$ fluid of metamorphic origin was generated by metamorphic dehydration during the Triassic continental subduction-zone metamorphism (Rumble et al., 2002; Tang et al., 2008; Y.-X. Chen et al., 2011; Zheng et al., 2004).

Qinglongshan in the southwestern part of the Sulu orogen (Fig. 1) is well known in the UHP community due to the occurrence of negative $\delta^{18}O$ eclogite-facies minerals (Yui et al., 1995; Zheng et al., 1996) and excess argon in phengite (Li et al., 1994). The outcrop lithology at this locality has been intensively studied (e.g., Zhang et al., 1995, 2005). Generally, there are five rock types in this area, including paragneiss, orthogneiss, eclogite, quartzite and schist; all of them contain coesite (Liu and Liou, 2011; Zhang et al., 1995, 2005). The MS inclusions that contain significant amounts of alkali-alumino-silicate minerals were