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Formation of metamorphic and metamorphosed garnets in the low-T/UHP metagranite during continental collision in the Dabie orogen

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ABSTRACT

A combined study of major and trace elements in garnet was carried out for low-T/UHP metagranite in the Dabie orogen. The results show different fashions of element zoning in the garnet, suggesting occurrence of both metamorphic and metamorphosed garnets. Three generations of garnet growth are distinguished on the basis of the assumption that Ca contents, Mn contents and Fe/Mg ratios of garnet in metagranites are a function of pressure and temperature. The first generation of garnet (Grt-I) occurs in the core of a skeletal garnet, showing homogeneously low X_{Grs} values and Fe/Mg ratios but high X_{Sps} values. This implies that the core garnet grew at the highest temperature but the lowest pressure, representing a metamorphosed residue of magmatic garnet in protolith granite. The second generation of garnet (Grt-II) occurs in the mantles and cores of many garnet grains, exhibiting increased X_{Grs} values but decreased Fe/Mg ratios. This is ascribed to a continuous increase in temperature and pressure till the peak pressure, corresponding to metamorphic growth (or overgrowth) during the prograde subduction. The third generation of garnet (Grt-III) occurs in the rims of all garnet grains, displaying decreased X_{Grs} values and Fe/Mg ratios in response to a pressure decrease but a temperature increase till the peak temperature. These rims overgrew subsequent to the peak pressure with continuous heating during the initial exhumation. Grt-I shows steep MREE-HREE patterns and profoundly negative Eu anoalies, consistent with growth from granitic melt. This kind of metamorphosed garnet from protolith granite has still preserved very high contents of many trace elements (such as REE, Rb, Ba, Sr, Pb, Th, U, Nb and Ta) despite the low-T/UHP metamorphism. Grt-II and Grt-III in one sample exhibit steep MREE-HREE patterns, with a continuous decrease in REE contents. This suggests their growth from the almost same matrix of mineral assemblages (plagioclase + K-feldspar + muscovite) during metamorphism. However, Grt-II in the other sample displays flat to steep MREE-HREE patterns, with an increase of REE contents from core to mantle. This implies that the matrix of mineral assemblages for Grt-II changes from common rock-forming minerals (e.g., feldspar, muscovite and biotite) to REE-rich minerals (e.g., epidote, allanite, zircon, amphibole, apatite and titanite). Grt-III in the two samples all displays significantly lowered REE contents compared to those of Grt-I and Grt-II. This may be due to a decrease in pressure and an increase in temperature during the initial exhumation. Therefore, the two-stage growth of metamorphic garnet is evident in the low-T/UHP metagranite during the continental subduction-zone metamorphism. In addition, the highest pressure occurs in the cores or mantles whereas the highest temperature occurs in the rims. This suggests that the peak pressure (P_{max}) did not occur contemporarily at the peak temperature (T_{max}), corresponding to the "hot" exhumation.

1. Introduction

Garnet is one of the common rock-forming minerals in many metamorphic rocks, with various compositions and multistage growth over a wide range of P-T conditions. It can be well preserved during subduction-zone metamorphism for its high refractoriness and low solubility in aqueous fluids. Many petrological studies have demonstrated that garnet is an ideal mineral for the reconstruction of pressure-temperature-time (P-T-t) paths in high-pressure (HP) and ultrahigh-pressure (UHP) metamorphic rocks. For example, the geothermometer of Fe-Mg exchange between garnet and the other minerals (such as clinopyroxene, phengite, biotite, olivine and ilmenite) has been widely applied to different types of metamorphic rocks (e.g., Essene, 1989; O'Brien, 1997; Carswell et al., 1997, 2000; Parkinson, 2000). The garnet-aluminosilicate-plagioclase (GASP) geobarometer is also applied to some metamorphic rocks (e.g., Berman, 1988; Ghent, 1976). The strong preference of garnet partition for HREE over LREE and MREE makes it highly suitable for the chronometric

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dating of Sm-Nd (e.g., Burton and O'Nions, 1991; Li et al., 2000, 2004) and Lu-Hf (e.g., Blichert-Toft and Frei, 2001; Cheng et al., 2011; Duchêne et al., 1997).

Metamorphic garnet generally shows concentric growth zoning in major elements, which is interpreted as a snapshot of its P-T-t path during metamorphism. This is based on the assumption that the chemical profile recorded in garnet reflects equilibrium compositions at different times during garnet growth (Spear, 1993; Spear et al., 1984). The concentric zoning in metamorphic garnet is characterized as a continuous bell-shaped zoning profile, with a progressive decrease of spessartine component from core to rim (e.g., Deer et al., 1982; Spear, 1993). This type of zoning pattern is commonly ascribed to garnet growth along a prograde path during subduction-zone metamorphism (O'Brien, 1997). However, most metamorphic garnet displays discontinuous compositional zoning. This may be controlled by a number of factors, including: (1) change in metamorphic P-T conditions (e.g., Garcia-Casco et al., 2002), (2) modification of the effective bulk-rock composition, (3) transformation of the mineral assemblage (e.g., Jamtveit and Anderson, 1992), and (4) fluid infiltration (e.g., Clechenko and Valley, 2003; Crowe et al., 2001; Stowell et al., 1996; Yardley et al., 1991). Kohn et al. (1997) observed at least four (possibly five) generations of garnet growth in metamorphic rocks from the Fall Mountain nappe in Southwestern New Hampsphire, which were mainly caused by the transformation of mineral assemblages during muscovite and biotite dehydration-melting reactions.

Garnet is an uncommon accessory mineral in igneous rocks, but occurs in some peraluminous granitoids (e.g., du Bray, 1988; Kebede et al., 2001) and S-type granites (e.g., Jung et al., 2001; Villaros et al., 2009). Some researchers suggest that Mn-rich magmas are most conducive to garnet nucleation (Green, 1977; Miller and Stoddard, 1981; Miller et al., 1981; Clemens and Wall, 1981), while others think that the presence of excess aluminum in magmas may be a prerequisite for garnet growth (Dahlquist et al., 2007; du Bray, 1988). Moreover, the compositional zoning of magmatic garnet is distinct from that of metamorphic garnet with high spessartine contents and typical spessartine-decreasing profiles from core to rim (e.g., du Bray, 1988; Leake, 1967). The crystallization of magmatic rocks takes place as temperature decreases, so that magmatic garnet generally display reversal zoning with almandine-rich cores and spessartine-rich rims (Dahlquist et al., 2007; du Bray, 1988; Leake, 1967; Villaros et al., 2009). Nevertheless, some zoned garnet grains in metamorphic rocks do not monotonously vary in major elements. This may be caused by significant modification via intragrain diffusion during metamorphism at high temperatures of over 650 °C (e.g., Carlson and Schwarze, 1997; Chernoff and Carlson, 1997; Florence and Spear, 1991; Spear, 1991, 1993; Yardley, 1977), or by metamorphic overprint on the magmatic garnet (e.g., Habler et al., 2007; Scallion and Jamieson, 2011). As a consequence, distinction between metamorphosed garnet (residue of magmatic garnet) and metamorphic garnets (growth during metamorphism) is critical when dealing with the complex element zoning of garnet in metaigneous rocks because they may contain different origins of garnet.

While the uncertainty has been associated with the P-T-t reconstruct by the major element zoning in garnet, attention has being transferred to trace element zoning in garnet. Because of their large ion radii, trace elements in garnet may be less susceptible to diffusion modification at high temperatures. This has been illustrated by many studies of garnet in different types of metamorphic rocks (e.g., Cherniak, 1998; Chernoff and Carlson, 1997, 1999; Hickmott and Shimizu, 1990; Hickmott and Spear, 1992; Hickmott et al., 1987, 1992; Otamendi et al., 2002; Pyle and Spear, 1999; Spear and Kohn, 1996; Zhou et al., 2011). In addition, trace elements are much more sensitive to changes in accessory mineral assemblages and fluid compositions (e.g., Konrad-Schmolke et al., 2008; Yang and Rivers, 2002; Zheng et al., 2011a; Zong et al., 2007). Therefore, trace element zoning in garnet is a potentially useful monitor of metamorphic processes for garnet growth, which may be not retrievable from major element compositions.

This study focuses on garnet from UHP metamorphic rocks in the Dabie orogen that formed by continental subduction to mantle depths (e.g., Liou et al., 2009; Zheng, 2008). Major element zoning in garnet was previously reported from low-T/UHP eclogite and gneiss in this region (Carswell et al., 2000; Castelli et al., 1998; Li et al., 2004; Zhai et al., 1995). Carswell et al. (2000) observed that the Ca contents (X_{Ca} values) of garnet from granitic orthogneiss are positively correlated with its Fe/Mg ratios, suggesting that the garnet with the peak pressure (maximum X_{Ca}) did not grow at the peak temperature (minimum Fe/Mg ratio). Li et al. (2004) noticed that the rim of zoned garnet from the eclogite has chemical composition similar to non-zoned garnet in kyanite-quartz vein, implying that the garnet would grow under peak UHP metamorphic conditions, with the time prior to or during the lawsonite breakdown into the pseudomorphic Ky-Zos-Qtz assemblage. A combined study of petrology and geochemistry indicates the local appearance of partial melting in the granitic orthogneiss (Xia et al., 2008), implying the possible occurrence of “hot” exhumation in the low-T/UHP metamorphic zone. In this regard, it is intriguing whether there is any petrological evidence for the “hot” exhumation of low-T/UHP rocks. This paper presents in-situ analyses of major and trace elements in garnet from the low-T/UHP granitic orthogneiss (metagranite) in the Dabie orogen. Mineral inclusions in the garnet were also carefully examined under a microscope and further determined by the electron microprobe. Taken together, the results provide insights into the formation of metamorphic and metamorphosed garnets in the low-T/UHP metagranite. In particular, the multi-stage growth of metamorphic garnet lends support to the hypothesis of “hot” exhumation during the continental collision.

2. Geological setting and samples

The Dabie-Sulu orogenic belt is located in east-central China (Fig. 1), which was built up by the Triassic continental collision between the North China Block and the South China Block (e.g., Cong, 1996; Li et al., 1999; Liou et al., 1996; Wang et al., 1995; Zheng et al., 2003, 2009). UHP metamorphism has been recognized by occurrences of coesite and microdiamond in eclogite, gneiss, and marble in the orogenic belt (e.g., Okay et al., 1993; Schertl and Okay, 1994; Wang et al., 1989; Xu et al., 1992, 2003). The orogenic belt is separated into eastern and western segments by the Tanlu Fault, which are named as the Sulu and Dabie orogens, respectively (Fig. 1). The Dabie orogen extends across Anhui, Henan and Hubei provinces in the west. It consists of a series of fault-bounded metamorphic units that can be subdivided into five lithotectonic zones from north to south (Zheng et al., 2005): (1) the Beihuaiyang low-T/low-P greenschist-facies zone, (2) the North Dabie high-T/UHP granulite-facies zone, (3) the Central Dabie mid-T/UHP eclogite-facies zone, (4) the South Dabie low-T/UHP eclogite-facies zone, and (5) the Susong low-T/high-P blueschist-facies zone.

The present study deals with metagranite in the South Dabie low-T/UHP eclogite-facies zone (Fig. 1). Early studies of eclogite in this zone indicated the absence of coesite but the presence of sodic amphibole. Metamorphic conditions were estimated to be 650–700 °C and 1.8 GPa by one group (Castelli et al., 1998; Zhai et al., 1995), but 570–650 °C and 1.8–2.5 GPa by the other (Carswell et al., 1997; Franz et al., 2001; Okay, 1993; Wang et al., 1992). The low-T eclogite, also named as the “cold” eclogite, was commonly called because of the apparent low temperatures relative to the Central Dabie mid-T eclogites (Carswell et al., 1997; Okay, 1993). However, the occurrences of coesite inclusions in zircon from the granitic orthogneiss (Liu et al., 2001) and coesite pseudomorphs in garnet from the eclogite (Li et al., 2004) demonstrate that the gneiss and eclogite also underwent the UHP metamorphism. By means of the mineral-