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A granulite record of multistage metamorphism and REE behavior in the Dabie orogen: Constraints from zircon and rock-forming minerals

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ABSTRACT

A combined study of mineral inclusions, U–Pb ages and trace elements was carried for zircon and coexisting minerals from granulite in the North Dabie Terrane (NDT) of the Dabie–Sulu ultrahigh-pressure metamorphic (UHP) zone, east-central China. The results provide insights into the exhumation history of NDT and into rare earth element (REE) behavior during retrogression. Besides inherited cores and one magmatic rim, zircons separated from the granulite record three episodes of metamorphism under different P–T conditions: (1) 223.8 ± 2.3 Ma for domains that contain Grt + Cpx ± Rt ± F − Ap ± Aln inclusions without plagioclase and show flat HREE patterns without negative Eu anomalies, representing peak eclogite-facies event; (2) 213.3 ± 2.1 Ma for domains that contain Pl ± Cpx ± Grt ± Qtz ± Ap inclusions and show rather flat HREE patterns with negative Eu anomalies, corresponding to granulite-facies retrogression; (3) 199.9 ± 3.3 Ma for domains that contain Amp ± Pl ± Qtz ± Ap inclusions and show high REE contents with steep HREE patterns and remarkable negative Eu anomalies, representing amphibolite-facies overprinting. Therefore, the UHP eclogite in NDT experienced decompression heating during the initial exhumation, with local hydration in the late stage of the Triassic continental collision.

Garnet in the granulite is composed of a corroded core with embayed outline and spongy texture and an overgrowth rim. There is equilibrium distribution of HREE between garnet rim and granulite-facies zircon domain, confirming the geological interpretation of 213.3 ± 2.1 Ma for the granulite-facies metamorphism. There is the prograde HREE depletion in porphyroblastic garnet from core to rim and the continuous decrease of HREE from the eclogitic to granulitic zircons, suggesting that the metamorphic transformation from eclogite-facies to granulite-facies took place in a closed system. On the other hand, the amphibolitic zircons show steep HREE patterns and significantly elevated REE contents, suggesting that the amphibolite-facies metamorphism took place in an open system with introduction of external fluids containing more REE to the granulite-facies rocks. Residual clinopyroxene partially replaced by amphibole has remarkably elevated REE contents relative to euhedral primary clinopyroxene. There is equilibrium distribution of REE between the residual clinopyroxene and the amphibole, marking fluid action during the amphibolite-facies overprinting.

1. Introduction

The exhumation of ultrahigh-pressure (UHP) metamorphic rocks during continental collision is commonly accompanied by multistage retrogression. Precisely and accurately dating of the retrograde metamorphism is crucial for understanding the exhumation history and metamorphic process of target rocks. Zircon, because of its highly refractory nature, high closure temperature and slow diffusion rate of Pb, can potentially preserve multiple stages of metamorphic records, and thus it is an ideal mineral for U–Pb dating of poly-metamorphic rocks (Katayama et al., 2001; Lee et al., 1997; Moller et al., 2002; Wu and Zheng, 2004). Recent advances in analytical capabilities permit in-situ investigation of complex zircon grains at high spatial resolution. In-situ analyses of trace elements and mineral inclusions in zircons also help determine metamorphic P-T conditions under which the zircons formed (e.g., Bingen et al., 2004; Chen et al., 2010; Hermann et al., 2001; Liati, 2005; Liu et al., 2008; Mcclelland et al., 2006, 2009; Rubatto, 2002; Schaltegger et al., 1999; Xia et al., 2009, 2010). However, zircons are sometimes “blind” or unresponsive to high-grade metamorphism. A careful examination using other methods such as investigation of rare earth element (REE) partition between zircon and coexisting minerals is thus required (e.g., Harley and Kelly, 2007). Such examination on mineral/mineral REE distribution is also useful to decipher the REE behavior and mineral chemistry during metamorphism (Nehring et al., 2009).

Zircon studies have contributed much to our understanding of continental subduction-zone metamorphism in the Dabie–Sulu orogenic belt (e.g., Chen et al., 2010; Liu and Liou, 2011; Xia et al., 2009; Zheng et

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al., 2004). Fluid effects on metamorphic growth and recrystallization of zircons are evident in UHP metamorphic rocks (e.g., Gao et al., 2011; Zheng, 2009). The Dabie orogen is composed of three major UHP metamorphic units, namely the north Dabie Terrane (NDT), the central Dabie Terrane (CDT), and the south Dabie Terrane (SDT). Three UHP units have different crustal attributes, e.g., the CDT and NDT represent the subducted upper and lower crust, respectively (Li et al., 2003; Liu et al., 2007a; Zhao et al., 2008), consistent with a multi-slice exhumation model for the UHPM rocks in the Dabie–Sulu orogen (Li et al., 2005, 2009a; Liu and Li, 2008; Liu et al., 2007b; Xu et al., 2006). The UHP rocks from CDT experienced only amphibolite-facies retrogression during exhumation. A detailed geochronological study on Shuanghe UHP rocks has defined a T–t path with two fast cooling stages, suggesting a multistage exhumation (Li et al., 2000). In contrast, the UHP rocks from NDT experienced two stages of retrograde metamorphism (granulite-facies and amphibolite-facies) during exhumation, but geochronological constraints on the exhumation of NDT are rare and debated. Only a few Sm–Nd and U–Pb isotopic ages ranging from 191 to 244 Ma have been reported for eclogites and gneisses from NDT (Li et al., 1993; Liu et al., 2005, 2007a,b, 2011a; Xie et al., 2010; Zhao et al., 2008). Although the peak eclogite-facies metamorphic time of NDT has been constrained to be 224–226 Ma (Liu et al., 2011a), one important question remains that whether other Triassic ages represent the granulite-facies or amphibolite-facies retrogression. This has bearing on the Sm–Nd closure temperature of garnet and omphacite during continental collision, and on preservation of mineral inclusions and trace elements in metamorphic zircons.

Granulite served as a precursor for UHP eclogite-facies metamorphism in Western Gneiss Region of Norway (Austraheim, 1987; Jamtveit et al., 1990), but it overprinted the UHP eclogite in the Dabie orogen (Zhang et al., 1996; Zheng et al., 2001). Despite its rare occurrence, granulite may provide an important record of metamorphic evolution during continental collision in the Dabie orogen. Zircon is one of the most important accessory minerals in metamorphic rocks because it can be used to determine both metamorphic age and facies if microbeam U–Pb dating is combined with analyses of mineral inclusions and trace elements (e.g., Liu and Liou, 2011; Liu et al., 2006). Garnet is one of the most important rock-forming minerals since it can be also used to constrain metamorphic facies if major element analysis is combined with analyses of mineral inclusions and trace elements (e.g., Xia et al., 2011; Zhou et al., 2011). In this paper, we present an integrated study of in-situ U–Pb dating, mineral inclusions and REE analyses on metamorphic zircons and coexisting minerals such as garnet, clinopyroxene, and amphibole in granulite from NDT. The results provide insights into the exhumation history of NDT and the issue about REE behavior during retrograde metamorphism.

2. Geological setting and samples

2.1. Geological background

The Dabie–Sulu orogenic belt formed by continental collision between the South China Block (SCB) and North China Block (NCB) in Triassic (e.g., Li et al., 1993, 1994, 2000; Zheng et al., 2004). It is one of the largest UHP metamorphic zones in the world (Liou et al., 2009; Zheng, 2008). The general geology of the Dabie–Sulu orogenic belt has been described in numerous previous studies (e.g., Hacker et al., 1998; Li et al., 2001; Xu et al., 1992, 1994; Zheng et al., 2003). The Dabie orogen consists of a series of fault-bounded metamorphic units (Fig. 1). They are, from north to south, (1) the Beihuaiyang low-T/LP greenschist-facies terrane (BT); (2) the North Dabie high-T/UHP granulite-facies Terrane (NDT); (3) the Central Dabie mid-T/UHP eclogite-facies Terrane (CDT); (4) the South Dabie low-T/UHP eclogite-facies Terrane (SDT); and (5) the Susong low-T/HP blueschist-facies terrane (ST).

NDT is bounded by the Wuhe–Shuihou Fault to the south and the Xiaotian–Mozitan Fault to the north. It predominantly consists of migmatitic gneisses with minor garnet-bearing amphibolites, eclogites, and granulite lenses, as well as post-collisional granitoids and mafic–ultramafic intrusions. Compared to CDT and SDT, NDT was subjected to more intensive early Cretaceous magmatism and migmatization (e.g., He et al., 2011; Liu et al., 2010b; Wang et al., 2007; Zhao et al., 2007, 2008), which may obscure the earlier metamorphic records. For this reason, whether bulk NDT was involved in the Triassic subduction to experience the UHP metamorphism or not has been the debated issue (e.g., Tong et al., 2011; Zhang et al., 2009). In the last decade, an increasing number of retrograded UHP eclogite relics and HP granulites have been reported from NDT (Faure et al., 2003; Lin et al., 2007; Liu et al., 2001, 2005, 2007a,b; 2011a,b; Malaspina et al., 2006; Tsai and Liou, 2000; Xu et al., 2000, 2003; Zhang et al., 2000). Triassic metamorphic ages and UHP metamorphic evidence (e.g., diamond inclusions from both eclogites and surrounding orthogneisses) suggest that NDT was involved in the Triassic deep subduction of SCB (Liu et al., 2001, 2005, 2007a, 2011a,b; Malaspina et al., 2006; Tsai and Liou, 2000; Xu et al., 2000, 2003, 2005).

Eclogite and gneiss in NDT are overprinted by granulite-facies metamorphism, followed by amphibolite-facies metamorphism during exhumation. Accordingly, NDT experienced three stages of metamorphism (Liu et al., 2001, 2007a; Tsai, 1998; Tsai and Liou, 2000; Xu et al., 2000): (1) eclogite-facies metamorphism at $P = \sim 5$ GPa and $T = 800–870$ °C; (2) granulite-facies retrogression at $P = 1.1–1.4$ GPa and $T = 800–910$ °C; and (3) amphibolite-facies overprinting at $P = 0.5–0.6$ GPa and $T = 500–600$ °C. The granulite-facies overprinting on the UHP eclogite-facies rocks is exclusive in NDT. But it is absent in CDT and SDT, suggesting that NDT has a different exhumation history from CDT and SDT.

2.2. Previous dating results

2.2.1. Eclogite-facies metamorphic event

Only a few Sm–Nd and U–Pb isotopic ages related to the eclogite-facies metamorphism have been reported for NDT. Li et al. (1993) firstly reported a garnet + diopside (sample R-4) and three garnets (sample G-1) Sm–Nd isochron ages of 244 ± 11 Ma and 224 ± 20 Ma for garnet–pyroxenites in NDT, respectively. In contrast, Liu et al. (2007b) utilized zircon SHRIMP U–Pb dating to obtain an age of 218 ± 3 Ma for metamorphic domains from tonalitic gneiss, and interpreted it as representing the UHP metamorphic time of NDT. Recently, Liu et al. (2011a) presented zircon U–Pb age, trace element and mineral inclusion analyses for three eclogites, and argued that the UHP metamorphic time of NDT is best estimated at 226 ± 3 Ma because of the occurrence of coesite inclusion in metamorphic zircon, whereas an age of 214 ± 3 Ma may record a later event of HP eclogite-facies recrystallization time during exhumation.

2.2.2. Granulite-facies and amphibolite-facies metamorphic events

The granulite-facies and amphibolite-facies retrograde metamorphic ages of NDT have not been directly determined yet. Some granulites in NDT, such as felsic granulite at Huangtuling and mafic granulite at Huilanshan, record their granulite-facies metamorphic times of Paleoproterozoic and Cretaceous, respectively (e.g., Chen et al., 1996, 1998; Hou et al., 2005; Wu et al., 2008). They are not related to the Triassic exhumation of NDT. For UHP rocks from NDT, researchers have given various retrograde metamorphic ages. Liu et al. (2005) reported a Sm–Nd isochron age of 212 ± 4 Ma defined by two garnet + two omphacite from eclogite and inferred it as a cooling age corresponding to the granulite-facies metamorphism, but later re-interpreted it as the HP eclogite-facies metamorphic time (Liu et al., 2011a). Liu et al. (2011a) also speculated that the granulite-facies and amphibolite-facies metamorphic ages of NDT might be ~200 Ma and 176–188 Ma, respectively. Xie et al. (2010) conducted