Journal of Asian Earth Sciences 145 (2017) 177–191

Contents lists available at ScienceDirect

Journal of Asian Earth Sciences

journal homepage: www.elsevier.com/locate/jseaes

Review

Partial melting of ultrahigh-pressure metamorphic rocks during continental collision: Evidence, time, mechanism, and effect

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ARTICLE INFO

Keywords:
Continental collision
Ultrahigh-pressure metamorphism
Crustal anatexis
Peritectic reaction
Anatectic melt

ABSTRACT

Partial melting of ultrahigh-pressure (UHP) metamorphic rocks during continental collision has been increasingly found in nature. More and more studies have devoted to the evidence, time, mechanism and effect of crustal anataxis at mantle to lower crust depths. This is particularly so for UHP rocks from the Dabie-Sulu orogenic belt, whereas similar studies on these issues are relatively minor for other UHP terranes. The petrological evidence, especially microstructural observations and multiphase solid inclusion analyses, have been accumulated for the partial melting of UHP metamorphic rocks in collisional orogens. The results indicate that this is a kind of low-degree crustal anataxis at convergent plate margins due to decompressional dehydration of the UHP rocks themselves. Thus it has great bearing on intracrustal differentiation and crust-mantle interaction in continental subduction channels. Zircon may grow through peritectic reactions due to the breakdown of hydrous minerals. By dating of the peritectic zircons that contain coesite or diamond inclusions, the time of crustal anatexis under UHP conditions can be directly determined. In general, the partial melting of UHP rocks mainly took place at the stage of their early exhumation, partly still in the UHP regime and partly in the subsequent high-pressure (HP) regime. The crustal anatexis still at mantle depths is common in many UHP terranes, possibly facilitating exhumation of deeply subducted continental slices toward shallower levels. Petrological and geochemical studies indicate that phengite dehydration-driven melting during exhumation is the common mechanism for the anatexis of UHP rocks, though the other hydrous minerals were also involved in this process. The resulted HP to UHP melts may occur at different spatial scales and show significant fractionation in melt-mobile incompatible trace elements such as LILE and LREE. These melts are enriched in LILE to large extent and LREE and Th to small extent, depending on anatectic conditions. The extraction of such melts can greatly deplete the melt-mobile elements in residues of UHP metapelites and eclogites. The partial melting of an isotopically heterogeneous source can yield isotopic variations between melt and residue. This is primarily controlled by the type of anatectic reactions and the solubility of accessory minerals. Although much progress has been made in the partial melting of UHP metamorphic rocks during continental collision, there are still many key issues that remain to be resolved. These include discriminating peritectic minerals from metamorphic and magmatic minerals, tracing the behavior of accessory minerals during anatexis, determining the geochemical composition of melts formed at UHP conditions, and placing precise constraints on the timescale for melt-forming and melt-transport processes. The clarification of these issues may greatly advance our understanding of the intracrustal differentiation, crust-mantle interaction and crustal recycling at convergent plate margins and thus provides insights into the chemical geodynamics of subduction zones.

1. Introduction

The finding of coesite and diamond in metamorphic rocks of supracrustal origin has revolutionized the traditional wisdom of plate tectonics, indicating that continental crust can be subducted to mantle depths of > 80 km and then exhumed to Earth's surface (Smith, 1984; Chopin, 1984; Sobolev and Shatsky, 1990; Xu et al., 1992). Since then, continental deep subduction and ultrahigh-pressure (UHP) metamorphism have been one of the research frontiers in Earth sciences (e.g., Chopin, 2003; Liou et al., 2009; Zheng, 2012; Hermann and Rubatto, 2014). Continental crust experiences a series of physicochemical changes during its subduction into and exhumation from the mantle, including metamorphism, deformation and anatexis. All of these changes are dictated by the protolith nature of crustal rocks, the

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http://dx.doi.org/10.1016/j.jseaes.2017.03.020
Received 8 December 2016; Received in revised form 14 March 2017; Accepted 21 March 2017

thermal structure of subduction zones and the fluid regime during metamorphism and anatexis (e.g., Zheng, 2009, 2012; Zheng and Chen, 2016).

It is generally assumed that oceanic crust is relatively hot, young with high water contents, whereas the continental crust is relatively cold, old with low water contents (Rumble et al., 2003; Zheng et al., 2003). However, more and more studies indicate that either oceanic or continental crust undergoes metamorphic dehydration at forearc depths of < 60–80 km, making the surface water into hydrous minerals and nominally anhydrous minerals with crustal subduction to subarc depths of 80–160 km (Zheng et al., 2016). Furthermore, subduction zones, either oceanic or continental, are cold during crustal subduction to lithospheric depths if the subducting slab is still coupled with the mantle wedge (Zheng and Chen, 2016). However, partial melting has been indeed found in UHP metamorphic rocks that were produced by crustal subduction to the subarc depths (Zheng et al., 2011). This provides us with an excellent opportunity to decipher the thermal structure of subduction zones and its evolution with changes in their geometric structure, with important implications for the geochemical transfer at the slab-mantle interface in subduction channels (Zheng et al., 2013).

So far there is rare evidence for partial melting of subducting continental crust during prograde HP to UHP metamorphism in collisional orogens (Zheng et al., 2011). Nevertheless, partial melting of UHP metamorphic rocks during exhumation or even still at UHP conditions has been increasingly recognized in many UHP terranes. These terranes include the Dabie-Sulu of China (Wallis et al., 2005; Zhao et al., 2007a; Xia et al., 2008; Zeng et al., 2009; Liu et al., 2010, 2012; Gao et al., 2012; Wang et al., 2014), the Kokchetav of Kazakhstan (Hermann et al., 2001; Dobretsov and Shatsky, 2004; Ragozin et al., 2009; Stepanov et al., 2014, 2016), the Western Gneiss Region of Norway (Labrousse et al., 2011; Gordon et al., 2013) and its extension in Greenland (Lang and Gilotti, 2007), and the D'Entrecasteaux Islands in Papua New Guinea (Gordon et al., 2012). The anatexis of UHP rocks at mantle depths has great bearing on the intracrustal differentiation, tectonothermal evolution, and crust-mantle interaction at convergent plate margins (Wallis et al., 2005; Jamieson et al., 2011; Labrousse et al., 2011, 2015; Zheng et al., 2011, 2015, 2016).

To fully reveal the anatectic significance of UHP metamorphic rocks in collisional orogens, it is substantial to uncover the spatial occurrence of anatectic rocks, the temporal sequence and anatectic P-T conditions and mechanism, and its geochemical and geodynamic effects (e.g., Labrousse et al., 2011, 2015; Zheng et al., 2011; Zheng and Hermann, 2014). Although the large-scale anatexis on the outcrop scale is easily recognized by a combined field and petrological study, it is often difficult to identify the small-scale anatexis at the hand specimen or even the thin-section scale. In this case, the microstructural analysis becomes important to figure out the presence of former melting (e.g., Holness and Sawyer, 2008; Chen et al., 2013a, 2013b). It is also difficult to determine precisely the timing, P-T conditions and mechanism for the anatexis of UHP rocks, which requires a combined, comprehensive study of petrology, geochronology and geochemistry (Chen et al., 2013a, 2013b; Stepanov et al., 2016). This is important to establish a link between the anatexis of UHP slices and the collisional geodynamics of a deeply subducted continental slab (Labrousse et al., 2011, 2015).

This paper presents a review on evidence, time, P-T conditions, mechanism, and geochemical and geodynamic effects for the anatexis of UHP rocks during continental collision. Although observations are mainly from recent studies of partial melting in the Dabie-Sulu orogenic belt of China, results from the other UHP terranes are also taken into account when making arguments. The present study defines metamorphic minerals as growth via metamorphic reactions, peritectic minerals as growth via peritectic reactions, anatectic minerals as crystallization from anatectic melts, and magmatic minerals as crystallization from magmatic melts (Zheng and Hermann, 2014; Zheng et al., 2016). Whereas the anatectic melts are low degree melts without significant mineral fractional crystallization and they are not separated from the parental rocks, the magmatic melts have separated from the parental rocks with significant mineral fractional crystallization during their ascent and transport (Li et al., 2013; Zheng and Hermann, 2014). While various minerals can crystallize from the magmatic melts during their cooling, cooling of the anatectic melts only leads to crystallization of felsic minerals such as feldspar and quartz whereas accessory and mafic minerals are generally the direct product of peritectic reactions. In addition, aqueous solutions are produced by metamorphic dehydration below the wet solidus, whereas hydrous melts are produced by dehydration-driven partial melting above the wet solidus. While magmatic minerals generally crystallize in equilibrium with magmatic melts, peritectic minerals would also grow in equilibrium with anatectic melts. So do metamorphic minerals with metamorphic fluids. However, the composition of both anatectic melts and metamorphic fluids may change during their ascent toward shallower levels, making them in disequilibrium with original peritectic and metamorphic minerals. This is particularly so for the accessory minerals of metamorphic and peritectic origins. Mineral abbreviations are after Whitney and Evans (2010).

2. Geological setting of the Dabie-Sulu orogenic belt

The Dabie-Sulu orogenic belt is located in east-central China (Fig. 1). It was built by the Triassic subduction of the South China Block beneath the North China Block (Li et al., 1993; Cong, 1996; Zheng et al., 2003). The NNE trending Tan-Lu fault separates this belt into two segments, i.e., the E-W trending Dabie orogen in the west and the NE-trending Sulu orogen in the east (Fig. 1). The deep subduction of continental crust to mantle depths of > 80 km is demonstrated by findings of coesite (Okay et al., 1989; Wang et al., 1989; Ye et al., 2000) and microdiamond (Xu et al., 1992) in metamorphic rocks from this orogenic belt. In general, the UHP metamorphic rocks were produced by subduction of continental crust to subarc depths of 80–160 km at 3.0–4.5 GPa and 730–850 °C, and the UHP metamorphism occurred at 240–225 Ma with a duration of ~15 Myr in the coesite stability field (Zheng et al., 2009; Liu and Liou, 2011). Most of the UHP rocks have igneous protoliths of middle Neoproterozoic age with various degrees of ^{18}O depletion, which was attributed to high-temperature continental glacial water hydrothermal alteration during protolith emplacement (Zheng et al., 2003, 2004; Chen et al., 2011a, 2014b; Fu et al., 2013; He et al., 2016).

The Dabie orogen is composed of several fault-bounded metamorphic units (Fig. 1). Based on the lithotectonic characteristics, it can be subdivided into five major 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 with migmatization; (3) the Central Dabie mid-T/UHP eclogite-facies zone; (4) the South Dabie low-T/UHP eclogite-facies zone; (5) the Susong low-T/HP blueschist-facies zone. The peak metamorphic pressure and temperature generally increase from south to north, but the Beihuaiyang zone is the accretionary wedge formed during the early stage of continental subduction (Zheng et al., 2005; Liu et al., 2011). The detailed studies of field occurrence, petrology, geochronology and geochemistry have been carried out for these regional metamorphic rocks in each of the above zones (e.g., Cong, 1996; Zheng et al., 2003; Liu et al., 2007, 2011; Zheng, 2008, 2012; Liu and Liou, 2011). In particular, syn-exhumation partial melting has been found in UHP eclogite and calc-gneiss (Xia et al., 2008, 2016; Gao et al., 2012, 2013; Liu et al., 2013, 2014a,b). The evidence for the partial melting includes the multiphase solid (MS) inclusions in eclogite-facies minerals and the microstructural observations of melt pseudomorph along grain boundaries. Such partial melting is associated with the "hot" exhumation, i.e., a temperature increase during the early decompression, of the UHP rocks, which have been found in all the three UHP zones of the Dabie orogen (Xia et al., 2008, 2010; Gao et al., 2012, 2013, 2014; Liu et al., 2013, 2014a,b,