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Research paper

Partial melting of ultrahigh-pressure metamorphic rocks at convergent continental margins: Evidences, melt compositions and physical effects

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A B S T R A C T

Ultrahigh-pressure (UHP) metamorphic rocks are distinctive products of crustal deep subduction, and are mainly exposed in continental subduction-collision terranes. UHP slices of continental crust are usually involved in multistage exhumation and partial melting, which has obvious influence on the rheological features of the rocks, and thus significantly affect the dynamic behavior of subducted slices. Moreover, partial melting of UHP rocks have significant influence on element mobility and related isotope behavior within continental subduction zones, which is in turn crucial to chemical differentiation of the continental crust and to crust-mantle interaction.

Partial melting can occur before, during or after the peak metamorphism of UHP rocks. Post-peak decompression melting has been better constrained by remelting experiments; however, because of multiple stages of decompression, retrogression and deformation, evidence of former melts in UHP rocks is often erased. Field evidence is among the most reliable criteria to infer partial melting. Glass and nanogranitoid inclusions are generally considered conclusive petrographic evidence. The residual assemblages after melt extraction are also significant to indicate partial melting in some cases. Besides field and petrographic evidence, bulk-rock and zircon trace-element geochemical features are also effective tools for recognizing partial melting of UHP rocks. Phase equilibrium modeling is an important petrological tool that is becoming more and more popular in P-T estimation of the evolution of metamorphic rocks; by taking into account the activity model of silicate melt, it can predict when partial melting occurred if the P-T path of a given rock is provided.

UHP silicate melt is commonly leucogranitic and peraluminous in composition with high SiO_2, low MgO, FeO, MnO, TiO_2 and CaO, and variable K_2O and Na_2O contents. Mineralogy of nanogranites found in UHP rocks mainly consists of plagioclase + K-feldspar + quartz, plagioclase being commonly albite-rich. Trace element pattern of the melt is characterized by significant enrichment of large ion lithophile elements (LILE), depletion of heavy rare earth elements (HREE) and high field strength elements (HFSE), indicating garnet and rutile stability in the residual assemblage. In eclogites, significant Mg-isotope fractionation occurs between garnet and phengite; therefore, Mg isotopes may become an effective indicator for partial melting of eclogites.

1. Introduction

Over the last three decades, continental deep subduction and ultrahigh-pressure (UHP) metamorphism have been increasingly studied by Earth scientists (Chopin, 1984, 2003; Smith, 1984; Okay et al., 1989; Sobolev and Shatsky, 1990; Xu et al., 1992; Ernst and Liou, 2008; Liu and Li, 2008; Kylander-Clark et al., 2012; Gilotti,

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2013). Unlike oceanic subduction zones, continental subduction zones are generally not associated to voluminous volcanic activity. Nevertheless, in some UHP orogens, various degrees of partial melting have been recognized, from the micro- to the macro-scale, in the form of melt inclusions, felsic veins, migmatites or even syn-exhumation granites (Wallis et al., 2005; Baziotis et al., 2008; Kotková and Harley, 2010; Liu et al., 2012, 2014; Massonne and Fockenberg, 2012; Chen et al., 2013, 2014).

Partial melting is one of the most important geological processes that may occur during heating and/or decompression in continental collision belts (e.g. Deniel et al., 1987; Downes et al., 1990; Williamson et al., 1992; Inger and Harris, 1993; Guillot and Le Fort, 1995; Vanderhaeghe and Teyssier, 2001; Visonà and Lombardo, 2002; Solgadi et al., 2007; Groppo et al., 2012; Vanderhaeghe, 2012). Partial melting would strongly affect the thermal and rheological behavior of subducted crust (e.g. Whitney et al., 2003; Rosenberg and Handy, 2005), thus playing a crucial role in varying the exhumation rate of UHP slabs (e.g. Hermann et al., 2001; Labrousse et al., 2002, 2011; Chopin, 2003). Unmelted UHP rocks commonly inherit their bulk compositions from their protoliths (e.g. Zhang et al., 2009); on the opposite, partial melting can significantly modify the abundance of large ion lithophile elements (LILE), high field strength elements (HFSE) and light rare earth elements (LREE) (e.g. Shatsky et al., 1999; Stepanov et al., 2014; Yu et al., 2015) of the restite, if melt extraction occurred. Moreover, partial melting of UHP rocks can lead to Nd isotopic resetting or disequilibrium (e.g. Ayres and Harris, 1997; Kogiso et al., 1997; Chavagnac et al., 2001; Zeng et al., 2005a,b, 2012; Taylor et al., 2015), as well as to the fractionation of Mg-Fe isotopes (e.g. Telus et al., 2012; Su et al., 2015). Therefore, partial melting is not only crucial for the dynamics of continental subduction and exhumation, but is also critical for element transfer and crust-mantle interaction within continental subduction zones.

Recognizing former melts is the first step in the investigation of partial melting. Large scale field evidence like migmatites and leucosomes is important in partial melting research; these features are products of a series of processes including melt generation, segregation, migration, accumulation, contamination and fractionation. In order to reveal the compositions of primary melts, microscale analysis is thus essential. A variety of microstructural criteria to infer the former presence of melts were summarized in Vernon (2011), but most of them do not allow the compositions of the original melts to be retrieved. Peritectic garnet is one of the best tools in these regards, because it can trap primary melts (usually occurring as polyphase inclusions) and protect them from later processes as a rigid container. Moreover, the peritectic garnets and related minerals grown by the melt-producing reactions guarantee equilibrium between the melt inclusions and the host minerals, thus allowing precise estimation of the composition of the primary melt (Korsakov and Hermann, 2006; Ferrero et al., 2012, 2015).

Beside microstructural criteria, zircon trace-elements have also been used to identify partial melting in some case studies (e.g., Rubatto et al., 2009; Imayama et al., 2012).

Phase equilibrium modeling is also an important tool in metamorphic research and can be used to constrain the solidus curves of specific bulk rock compositions. Given the P-T path, this method can tell us when and under what P-T conditions the rock experienced partial melting, together with detailed information of the melt-producing and consuming reactions (e.g., Elvevold et al., 2014; Yin et al., 2014; Lang and Gilotti, 2015).

In this paper, field occurrence, petrographic microtextures, zircon geochemical evidence and phase equilibrium modeling of partial melting are presented, and each one of these techniques have been applied to one or more case studies on UHP rocks. Specifically, various methods have been integrated to identify and characterize partial melting in selected lithologies, and to obtain the compositions, P-T conditions, ages and producing reactions of the melt. Mineral abbreviations through the text and figures are after Whitney and Evans (2010).

2. Evidence of HP-UHP partial melting

2.1. Field occurrence

Field investigation is the first step to deal with in most geological and geochemical studies. Field observations are among the most reliable methods to demonstrate partial melting of UHP rocks. Migmatites are partially melted rocks that can be directly recognized in the field; they consist of leucocratic portions and, commonly, melanocratic portions, reflecting segregation of partial melt from its residue. The lower density and viscosity of melt compared to the residue enable the melt to be segregated from the solid. Pressure gradient developed during deformation is generally accepted to be the driving force of melt migration (Robin, 1979; Sawyer, 1994), and that is why leucosomes are usually closely associated with deformation structures. The distributions and structures of leucosome often show the progression of partial melting, including melt segregation, melt migration, melt accumulation and melt ascent (e.g. Brown et al., 2011).

The Sulu orogen is an excellent natural laboratory exhibiting numerous field evidence of partial melting of UHP rocks. Two types of leucosome indicative of partial melting are widely distributed in

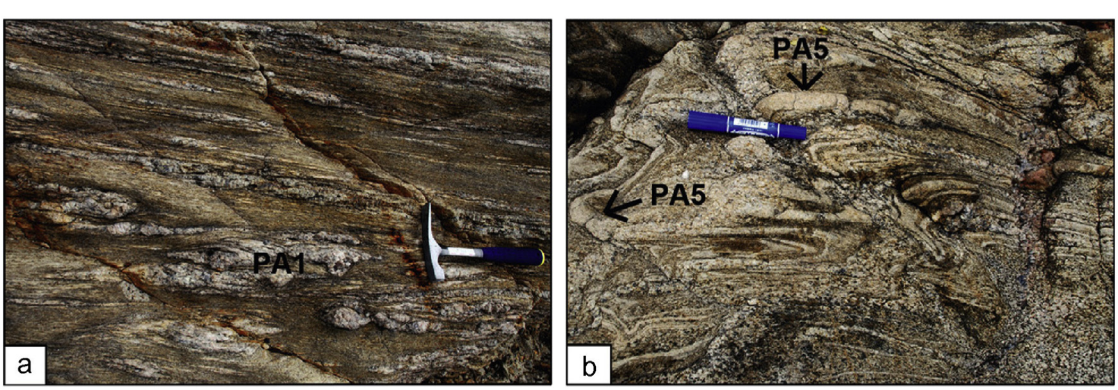

Figure 1. Field occurrences of migmatites in the Sulu UHP terrane (modified from Liu et al., 2012). (a) Epidote- and biotite-bearing paragneiss with deformed granitic leucosomes (PA1); (b) biotite-bearing paragneiss with deformed granitic leucosomes (PA5).