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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 R T I C L E I N F O

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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).

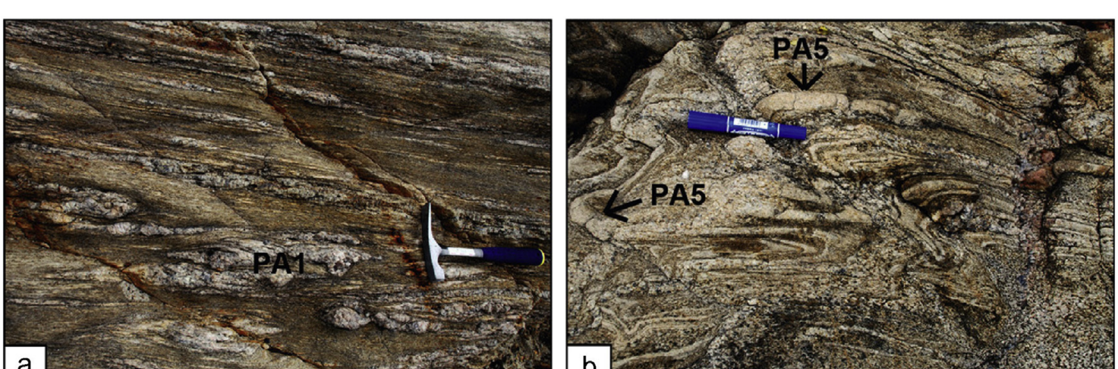

Figure 1. Field occurrences of migmatites in the Sulu UHP terrane (modified from Liu et al., 2012). (a) Epidote- and biotite-bearing paragneiss with deformed granitic leucosomes (PA1); (b) biotite-bearing paragneiss with deformed granitic leucosomes (PA5).

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 the northern Sulu terrane: (1) localized patches with an igneous texture within gneiss (Fig. 1a) and (2) granitic dikes weakly or strongly deformed (Fig. 1b) (Wallis et al., 1999, 2005; Liu et al., 2012; Xu et al., 2012, 2013; Wang et al., 2014). Anatectic zircons from the leucosomes retain U-Pb ages just slightly younger than peak UHP metamorphism, indicating decompression melting of the UHP rocks. According to the outcrop and microscale structures, Wang et al. (2014) classified the leucosomes into three typical stages representing the different processes of partial melting, demonstrating how melt starts to form from small scale droplets and then evolve to eventually form migmatites (Fig. 2). Similar leucosomes are also distributed in other UHP terranes as for instance the Caledonides in Greenland (Lang and Gilotti, 2007), Rhodope orogen in Greece (Baziotis et al., 2008) and North Qaidam terrane in China (Yu et al., 2015).

Leucosomes within UHP terranes are mainly composed of feldspar + quartz + mica, have low color index and are tonalitic-trondhjemitic-granitic in composition. Feldspar is a key phase to help distinguish leucosomes from fluid-induced metamorphic

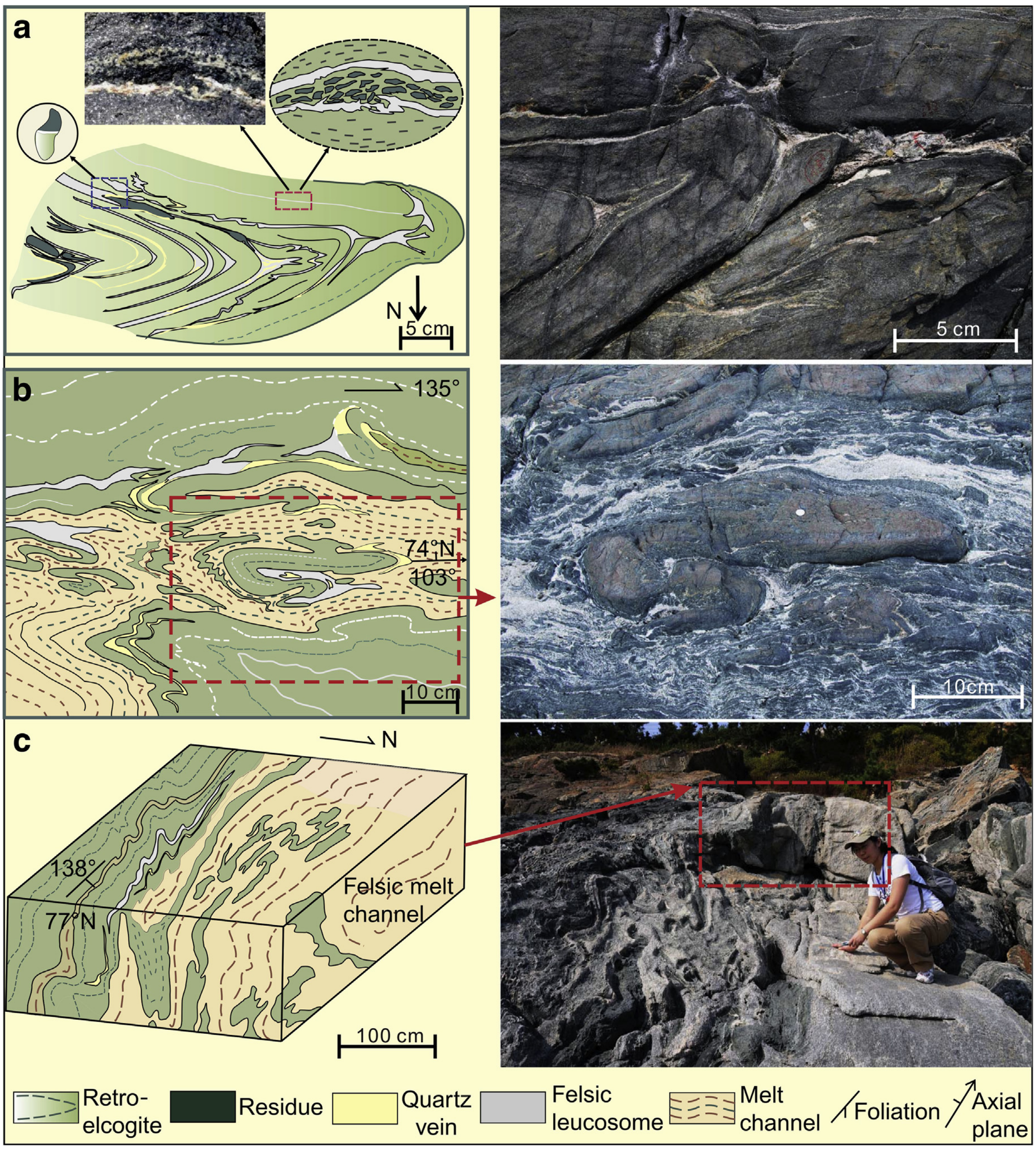

Figure 2. Sketches and associated field occurrences showing the partial melting processes in the Sulu UHP terrane (cited from Wang et al., 2014). (a) Stage-I. Early stage of partial melting; finger-shaped leucosome starts to aggregate within the hinge of the isoclinal eclogite fold. Field photograph connected to the red box by the black arrow shows the irregular boundary between leucosome and residue supporting a partial melting genesis. The scale bars are 5 cm. (b) Stage-II. Medium stage of partial melting; melt channels (leucosome) interlayered and flowing surrounding the sheared folded eclogite. The scale bars are 10 cm. (c) Stage-III. Mature stage of partial melting; melt aggregates into larger veins and then into felsic dikes. The scale bar is 100 cm.

veins in UHP rocks, such as the quartz veins and omphacite-rich veins in eclogites or gneisses in the Dabie-Sulu orogen (Zheng et al., 2007; Zhang et al., 2008; Guo et al., 2012).

2.2. Microtextural evidence

Partial melting is not always easy to be recognized in the field, especially when the volume of melt is very small, and/or the lithologies have been intensely retrogressed and deformed after anatexis. In the North Dabie Zone (NDZ – an UHP terrain within the Dabie orogen in China) for example, no clear field evidence of UHP partial melting have been reported so far, mainly because: (1) protoliths of the UHP rocks in the NDZ are "dry" and unfertile, resulting in very small amounts of melt produced at UHP conditions; (2) the UHP rocks in the NDZ experienced a long-lived and complex retrograde evolution coupled with intense deformation (Liu et al., 2007a, 2011a,b, 2015). In this case, microstructural evidences such as nanogranite inclusions within peritectic minerals and/or melt pseudomorphs as for instance mono- and/or polymineralic thin films, often with cuspate shape, concentrated at mineral grain boundaries (Holness and Sawyer, 2008; Cesare et al., 2009; Holness et al., 2011; Ferrero et al., 2012, 2015; Zhang et al., 2015) are relevant to recognize the occurrence of partial melting.

Melt inclusions in garnet or other peritectic minerals are not only key evidence of partial melting but also of crucial significance in retrieving the composition of primary melt. These inclusions in garnet within migmatite or granulite have been documented in a number of localities. They occur as glass or polyphase inclusions called "nanogranite" (Cesare et al., 2009), mainly composed of Pl + Kfs + Qz ± mica ± other minerals. The compositions of crystallized melt inclusions commonly range from granitic to granodioritic, tonalitic and trondhjemitic. A typical feature of these melt inclusions is the negative crystal shape of its host mineral, which is ascribed to the microstructrural equilibrium between melt and the host (Acosta-Vigil et al., 2007, 2010, 2012, 2016; Cesare et al., 2009; Ferrero et al., 2012, 2015; Bartoli et al., 2013, 2016; Fig. 3a and b).

Holness and Sawyer (2008) made a very significant contribution on the study of microstructures of melt-filled pools during crystallization. Microstructures indicative of partial melting include: cuspate grains and pockets on grain boundaries, thin feldspar films between primary minerals, granophyric intergrowths of quartz and feldspar nucleating on quartz or feldspar, network of feldspar-filled pores, etc. Vernon (2011) summarized a wide variety of microstructrural criteria to infer the former presence of felsic melt in a migmatite, and discussed their reliabilities, therein a three-mineral (quartz, K-feldspar, and sodic plagioclase) aggregate in veinlets was considered to be the most reliable. These microstructures are frequently used to identify partial melting of high-grade metamorphic rocks, though caution should be taken in practice.

Melt inclusions in garnet also occur in UHP rocks, for example the UHP metacarbonates of the Kokchetav massif, northern Kazakhstan (Korsakov and Hermann, 2006; Fig. 3c and d). These inclusions are dominated by intergrowths of Bt + Kfs with additional phases, and many of them have negative crystal shape of the host minerals (garnet, clinopyroxene or dolomite). UHP conditions of the trapping stage of the melt inclusions were demonstrated by their association with polyphase inclusions of diamond + graphite. Another noteworthy case study with clear petrographic evidence of UHP partial melting was described by Lang and Gilotti (2007), wherein a polyphase pocket in garnet was recognized in the UHP metapelities from the Greenland Caledonides (Fig. 3e and f). The pocket contains phengite, quartz, kyanite, rutile, K-feldspar, biotite and plagioclase. These minerals were interpreted to be reactants and products of the fluid-absent melting of phengite at UHP conditions (Hermann and Green, 2001).

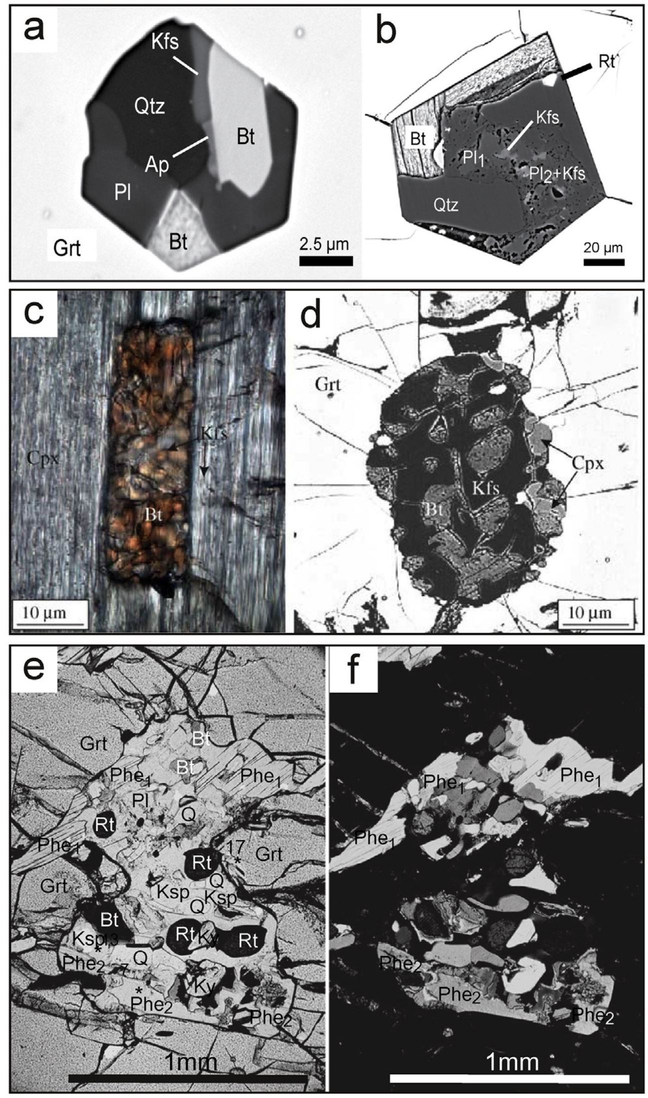

Figure 3. Polyphase inclusions in garnet from selected UHP lithologies indicating partial melting. (a, b) Inclusions of Bt + Pl + Kfs + Qz in garnet within high-pressure leucogranulites of the Orlica-Śnieżnik Dome, Bohemian Massif (Ferrero et al., 2015). (c, d) Inclusions dominated by Bt + Kfs intergrowths within clinopyroxene and garnet in the UHP metacarbonate of the Kokchetav massif, Kazakhstan (Korsakov and Hermann, 2006). (e, f) Polyphase inclusion of Phe + Bt + Ksp + Q + Rt + Ky in garnet from the UHP metapelites of the Greenland Caledonides (Lang and Gilotti, 2007). Phe, phengite; Bt, biotite; Kfs and Ksp, K-feldspar; Q, quartz; Cpx, clinopyroxene; Grt, garnet; Rt, rutile; Ky, kyanite.

2.3. Zircon evidence

Zircon is the most important accessory mineral in U-Pb geochronology. In metamorphic rocks, zircon growth or recrystallization is often deduced by fluid or melt activities (Rubatto et al., 1999; Williams, 2001; Tomaschek et al., 2003; Dempster et al., 2008; Kelsey et al., 2008; Kelsey and Powell, 2011). Dating anatectic zircons grown from the melt is one of the most popular methods in dating anatexis events (e.g. Rubatto et al., 2009; Imayama et al., 2012; Hansen et al., 2015), including those in UHP rocks (e.g. Wallis et al., 2005; Liu et al., 2007b, 2012; Xu et al., 2013). Anatectic zircons can be distinguished with good confidence from magmatic and metamorphic types, on the base of their distinct cathodoluminescence (CL) images and trace-elemental features (e.g. Hermann et al., 2001; Hoskin and Schaltegger, 2003; Liu et al., 2007b; Chen et al., 2013, and references therein).

Magmatic zircons generally have well developed growth zoning (including typical oscillatory zoning), euhedral and prismatic shape (Pidgeon, 1992; Mattinson et al., 1996; Hoskin, 2000), Th/U ratios higher than those of metamorphic zircons, which in turn have subrounded or highly resorbed shapes, no zoning or various types of amoebic zoning (Corfu et al., 2003). Magmatic zircons are also strongly enriched in HREE with respect to MREE, relatively depleted in LREE, and usually have a negative Eu anomaly (e.g., Heaman et al., 1990; Hinton and Upton, 1991; Hoskin and Schaltegger, 2003). In contrast, metamorphic zircons have variable REE patterns, which are to some extent related to the petrogenetic environments in which they evolved (Hoskin and Schaltegger, 2003). Zircon growths on inherited cores have been recognized in partially melted rocks (e.g. Vavra et al., 1996; Rubatto et al., 2006; Song et al., 2010; Chen et al., 2013); these zircon domains are homogeneous or have radiating sector zoning, euhedral and near isometric in shape, and generally have low Th/U ratios and variable REE patterns. Based on these features, they can be distinguished from both magmatic and metamorphic zircons, and are thus regarded to be anatectic zircons crystallized from partial melts.

2.4. Bulk-rock geochemical evidence

Chemical compositions, particularly trace element and isotope contents of rocks can be significantly modified by patial melting (e.g. Zheng et al., 2011), and thus can be used to infer its occurrence. As an example, Gu et al. (2013) analyzed two types of eclogite in the NDC: type I has a trace element pattern typical of lower continental crust, while type II is depleted in LILE and LREE (Fig. 4a). To confirm whether fluid or melt extraction resulted in the discrepance of REE patterns, the REE partitioning data provided by Kessel et al. (2005) were applied to model the REE patterns of the residual of type I eclogite after UHP fluid flux or melt extraction (Fig. 4b and c). As shown in Fig. 4, the residual after fluid flux (Fig. 4b) exhibits REE patterns significantly different from type II eclogite, while the residual after melt extraction (Fig. 4c) exhibits REE patterns nearly parallel with type II eclogite. Hence, the depletion nature of type II eclogite most likely resulted from melt extraction rather than fluid flux. Stepanov et al. (2014) published data on a series of UHP gneisses with various degrees of depletion in LREE, Th and U from the Kokchetav massif in northern Kazakhstan, and attributed these features to complete dissolution of monazite/allanite in the melt and to variable degrees of melt extraction. Moreover, in a number of case studies on leucosome-bearing metamorphic terrains, the leucosomes commonly exhibit enrichment of LILE, higher Th/U and LREE/HREE compared to adjacent melanosomes or paleosomes (Baziotis et al., 2008; Rubatto et al., 2009; Reichardt and Weinberg, 2012; Wang et al., 2014).

2.5. Phase equilibrium modeling

Phase equilibrium modeling on a given bulk-rock composition (pseudosection) can reveal stable mineral assemblages and their evolution in P-T-X space. This approach is a very important tool in petrological research and can provide constrains on the solidus curve of a certain bulk rock composition. Several softwares have been developed to perform the modeling, including the two most popularly applied: THERMOCALC (Powell and Holland, 1988) and Perple_X (Connolly, 1990, 2009). Given the P-T path, this method can predict if, when and under what P-T conditions the rock experienced partial melting, together with the detailed information of the melt-producing and consuming reactions, and even the melt compositions (e.g. Bartoli et al., 2013, 2016; Elvevold et al., 2014; Yin et al., 2014; Lang and Gilotti, 2015). Taking the UHP

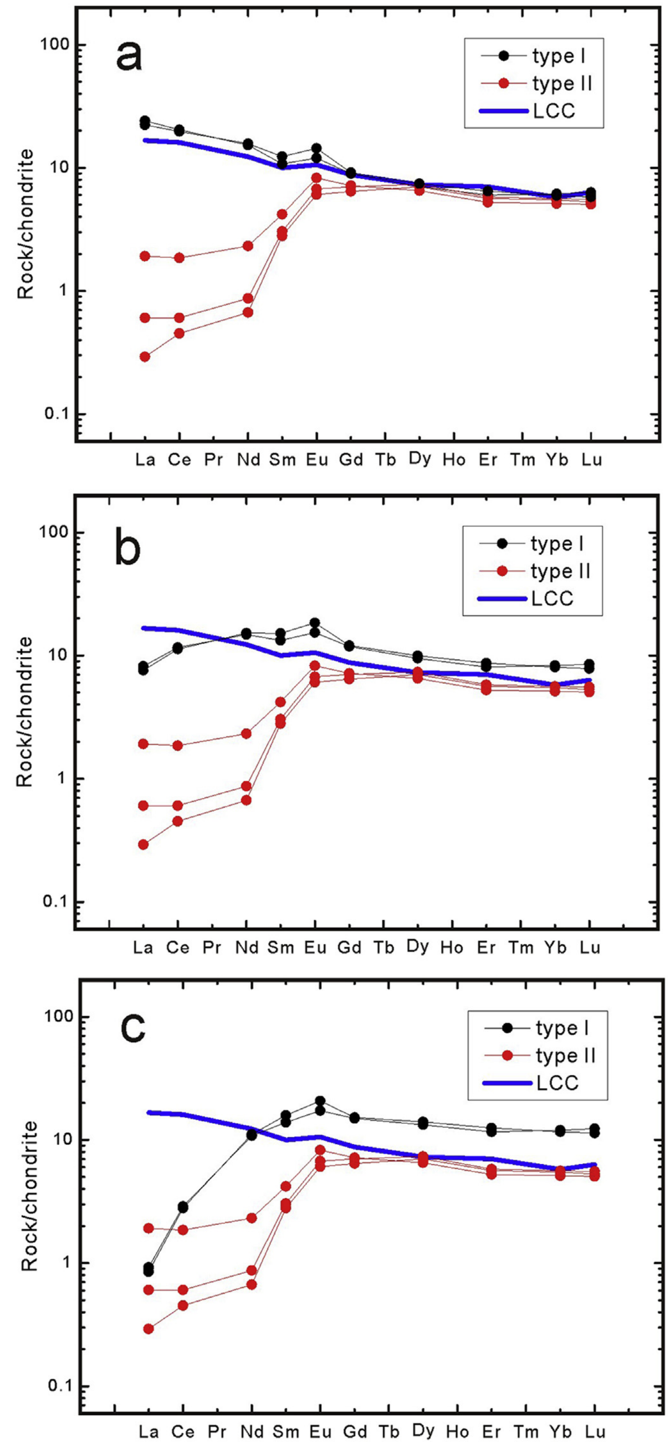

Figure 4. REE patterns after UHP fluid flux or melt extraction on UHP eclogites. (a) Two types of eclogite collected from the same outcrops in the North Dabie Complex Zone, with type I REE patterns typical of lower continental crust, and type II depleted in LREE (data from Gu et al., 2013). (b) REE patterns of type II and modeled residuals of type I after UHP fluid extraction. (c) REE patterns of type II and modeled residuals of type I after UHP melt extraction. Composition of chondrite is from Evensen et al. (1978); compositions of LCC and UCC are from Rudnick and Gao (2003); REE mobilities in UHP fluid and melt are from Kessel et al. (2005).

metapelites in northeastern Greenland as an example, Lang and Gilotti (2015) inferred the decompression melting reactions by intersecting the melt-in curve in the P-T pseudosections with the P-T path of the rocks. These melting reactions are consistent with the polyphase inclusions in garnet (Fig. 3e and f) reported by Lang and Gilotti (2007). It is worth noting that comparing experimental and natural melts (Grant, 2009; Bartoli et al., 2013) with modeled melts suggests that a departure of composition between them may exist in some cases.

Summing up, field, petrographic, bulk-rock and zircon geochemical investigations as well as phase equilibrium modeling are often combined to identify the occurrence of partial melting, and to constrain its timing, genesis and P-T conditions.

3. Compositions of HP-UHP melts

3.1. Major element compositions

Here, various examples of partial melts from different HP-UHP terranes are considered. The leucosomes in the Sulu UHP terranes are mainly composed of quartz + albite + plagioclase + K-feldspar and have slightly peraluminous granitic bulk compositions (e.g. Liu et al., 2012; Xu et al., 2012, 2013; Wang et al., 2014), with high SiO_2, low FeO, MgO, MnO and TiO_2 contents. Trace element patterns of these leucosomes are characterized by enrichment of LILE, depletion of HFSE and HREE and large LREE/HREE ratios (Xu et al., 2013; Wang et al., 2014). The leucosomes in the Qaidam UHP terrane have similar assemblages and major element compositions with those of the Sulu orogen (Yu et al., 2015). HREE and HFSE are depleted, while LILE are enriched (Yu et al., 2015). In the Bohemian massif, HP leucogranulites (Kotková and Harley, 1999) are weakly to moderately peraluminous (ASI = 1.05–1.20), with high SiO_2 (71–77 wt.%), low FeO, MgO and TiO_2 (below 2.6, 1.0 and 0.4 wt.%) contents. They have moderate LREE enrichments, negative Eu anomalies and flat HREE. According to the major element features, felsic components prefer to enter the liquid phase than ferromagnesium minerals during HP-UHP melting. Trace element patterns suggest the presence of garnet and rutile in the residual, which are the major sinks of HREE and HFSE in HP-UHP lithologies, respectively.

Although leucosomes are formed from melts, they are involved in a variety of processes including melt generation, segregation, migration, mineral accumulation and fractionation. As a consequence, the compositions of leucosomes cannot truly reflect those of the primary melt droplets. Glass or nanogranitoid inclusions in peritectic minerals such as garnet are commonly considered to be the equivalents of the primary melts, which provide the possibility to directly obtain the melt compositions.

Nanogranites composed of Pl + Kfs + Qz + Bt in garnet were identified within high-pressure leucogranulites of the Orlica-Śnieżnik Dome (Bohemian Massif, central Europe). The nanogranites were re-homogenized at nearly UHP conditions and yielded slightly peraluminous (ASI = 1.03) granitic compositions by EMP analyses, with Na_2O = 4.24 wt.%, K_2O = 4.50 wt.%, CaO < 1 wt.%, and FeO ≈ 2 wt.% (Ferrero et al., 2015). The plagioclase is albite-rich, with low CaO and relatively high Na_2O contents. Similar inclusions in garnet, with typical Pl + Kfs + Qz assemblages, were also recognized in the eclogites within the Dabie UHP terranes (Gao et al., 2012). Mineral compositions were detected by EMP, and all the Pl grains in a number of inclusions gave albite-rich (An_{3-18}) compositions. Polyphase inclusions in garnet within the khondalites from the Kerala Khondalite Belt in southern India yielded a peraluminous (ASI = 1.16–1.43) leucogranitic composition, with $SiO_2 \geq 68$ wt.%, Al_2O_3 12–13 wt.%, FeO ≤ 3 wt.%, CaO and MgO < 1 wt.% and variable K_2O and Na_2O (Ferrero et al., 2012). These inclusions were re-melted at pressures between 0.5 and 0.8 GPa. In terms of CIPW normative values, the inclusions have low An (≤4%) contents. Ab contents decrease with the increasing re-melting temperature, while no correlations between composition and pressure were identified (Ferrero et al., 2012).

Based on the above examples, partial melts in HP-UHP rocks have narrow peraluminous granitic composition ranges, and are characterized by high SiO_2 and low MgO, FeO, MnO and TiO_2 contents. Assemblages crystallized from the melts mainly contain Pl + Kfs + Qz with or without other silicates like micas. The plagioclase is albite-rich, consistent with the fact that albite component prefers to enter the liquid during partial melting of plagioclase (Bowen, 1913).

Leucogranitic compositions were reported from glass analyses in fluid-absent anatexis experimental studies via the incongruent melting of micas (e.g., Vielzeuf and Holloway, 1988; Patiño Douce and Johnston, 1991; Patiño Douce and Beard, 1996; Montel and Vielzeuf, 1997; Patiño Douce and Harris, 1998; Hermann and Green, 2001; Schmidt et al., 2004; Auzanneau et al., 2006). In these experimental glasses, CaO concentrations are always ≤1.5 wt.% and commonly between ≈0.5 wt.% and 1.0 wt.%. On the contrary, those from H_2O added (either high aH_2O or H_2O-saturated) experimental partial melting of metapelites and peraluminous metagreywackes (Conrad et al., 1988; Patiño Douce and Harris, 1998; García-Casco et al., 2003; Hermann and Spandler, 2008; Ferri et al., 2009) are granodioritic, trondhjemitic and tonalitic peraluminous (ASI = 1.10–1.55) melts, rich in Na_2O and CaO (up to 6.7 and 3.9 wt.%, respectively), poor in K_2O (1.2–2.7 wt.%) and low in K# [0.14–0.55; K# = mol. $K_2O/(K_2O + Na_2O)$] and FeO^t + MgO + TiO_2 (≈1.0–2.7 wt.%). These studies indicate that peraluminous granodioritic, trondhjemitic and tonalitic melts are produced during anatexis of peraluminous metasedimentary protoliths at high aH_2O to H_2O-saturated conditions, while peraluminous leucogranitic melts can be produced by fluid-absent melting of metasedimentary rocks, at moderate-to-low H_2O activities, within a wide range of crustal P-T conditions (≈750–900 °C, 0.1–1.5 GPa; i.e. at the solidus or even well above it) and also at mantle conditions (up to 1000 °C, 2.5–5 GPa). High pressure melts tend to be less calcic and somewhat more sodic than their lower-P counterparts, as a consequence of the lower Na_2O and higher CaO contents in the high pressure grossular + omphacite residual assemblage, compared to the low-pressure amphibole + plagioclase assemblage (Patiño Douce, 1996; Moyen, 2011). Examples of melt-producing phase diagrams are shown in Fig. 5.

Phengite is one of the most abundant hydrous minerals in UHP rocks, and it is vital for the occurrence of fluid-absent partial melting of UHP rocks during decompression (e.g. Hermann and Green, 2001; Auzanneau et al., 2006). In HP-UHP rocks, dehydration of hydrous phases and subsequent fluid release occurs during prograde metamorphism along a high P/T slope (Zheng et al., 2007; Zhang et al., 2008; Guo et al., 2012), thus fluid-absent melting of phengite is commonly expected during exhumation of UHP rocks (e.g. Hermann, 2002; Hermann et al., 2006). Therefore, HP-UHP melts with leucogranitic compositions are frequently reported, and are consistent with the results of the fluid-absent melting experiments.

The composition of the source rock is also significant; for example, K-rich sources yield potassic melts, granites and granodiorites rather than trondhjemites and tonalites (Sisson et al., 2005; Martin and Sigmarsson, 2007). Fe/Mg ratio as well as pressure control whether garnet or orthopyroxene are the dominant residual phases during melting of metagreywackes, and affect the

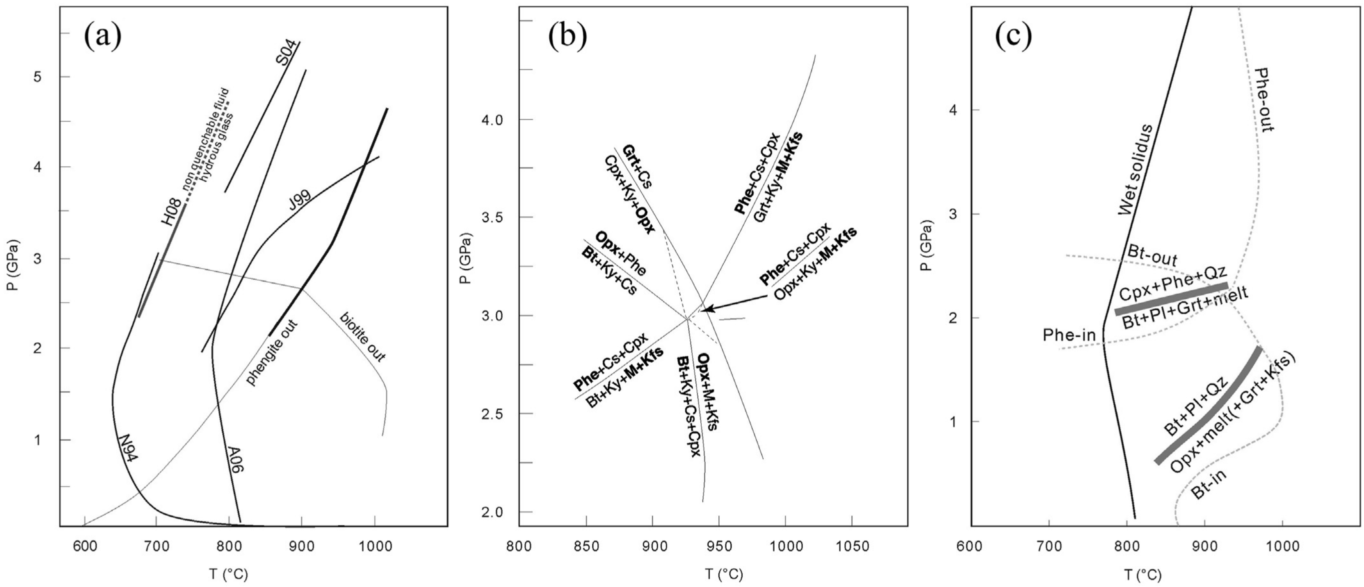

Figure 5. Fluid-present and fluid-absent melting phase diagrams. (a) The locations of wet solidus in metapelite and metagreywacke compositions in P-T space. H08, Hermann and Spandler (2008); N94, Nichols et al. (1994); J99, Johnson and Plank (1999); S04, Schmidt et al. (2004); A06, Auzanneau et al. (2006). (b) Experimental fluid-absent melting reactions in the K_2O-CaO-MgO-Al_2O_3-SiO_2-H_2O (KCMASH) synthetic system (modified from Hermann and Green, 2001). (c) Experimental decompression melting reactions for metagreywacke during exhumation (modified from Auzanneau et al., 2006).

compositions of the coexisting melts, and the melt fractions (e.g. Patiño Douce, 1992; Patiño Douce and Beard, 1996). The protolith composition affects not only melt compositions, but also melting processes. As an example, for given pelitic protoliths of comparable Fe/Mg ratios and TiO_2 and F contents, the fluid-absent solidus temperature is lower than that of less aluminous metapelites by at least 100 °C (e.g. Vielzeuf and Montel, 1994). Metagreywackes, however, produce greater volumes of granitic melts than metapelites, owing to their higher Na_2O contents (Patiño Douce and Johnston, 1991; Thompson, 1996).

3.2. *Trace element compositions*

Experiments and natural rock studies show that under UHP conditions, melts are much more capable than fluids to dissolve most of the rock-forming elements (Kogiso et al., 1997; Kessel et al., 2005; Hermann et al., 2006; Zheng et al., 2011; Fig. 6), thus partial melting of UHP rocks is crucial for element transfer in subduction zones. Silicate melts are generally rich in LILE, LREE and HFSE with respect to their source rocks (Hermann et al., 2006); therefore melt extraction can decrease the content of these elements in the residues. Moreover, partial melting can lead to significant REE fractionation and to Nd-disequilibrium (Ayres and Harris, 1997; Suga et al., 2015). Garnet is strongly enriched in HREE, thus the partition of HREE between melt and residue depends significantly on the presence or absence of garnet (Martin, 1987). Accessory minerals influence profoundly trace-element partitioning between melt and solid, because several important trace elements are controlled by these minerals (Nb and Ta by rutile, Sm and Nd by apatite, Zr and Hf by zircon, Th and LREE by monazite/allanite) (Hermann, 2002; Zeng et al., 2005a; Hermann and Rubatto, 2009). The solubility of accessory minerals (together with their controlled elements) in melt significantly increases with temperature for a given composition (Watson and Harrison, 1983; Rapp and Watson, 1986; Montel, 1993; Miller et al., 2003). Rutile and garnet commonly occur in the residual during partial melting of subducted oceanic crust or of thickened lower continental crust, leading to the depletion of HFSE and HREE in arc magmas or adakites (Schmidt and Poli, 1998; Foley et al., 2000; Martin et al., 2005; Xiong et al., 2009; Qian and Hermann, 2013; Ding et al., 2016). Likewise, partial melts under UHP conditions are depleted in Nb, Ta, Ti and HREE (Stepanov et al., 2014; Wang et al., 2014; Yu et al., 2015; Zhang et al., 2015).

4. When and where do UHP rocks melt?

In order to investigate the mechanisms and effects of partial melting of UHP lithologies, it is of critical importance to clarify when and where UHP rocks melt. However, this is not an easy task, because UHP rocks have commonly experienced extensive retrogression during exhumation.

In principle, partial melting of subducted continental crust may occur during prograde, peak or decompression stages (e.g. Prince et al., 2001; Whitney et al., 2004; Korsakov and Hermann, 2006; Groppo et al., 2012; Liu et al., 2013; Ferrero et al., 2015), as a consequence of heating, decompression or water infiltration.

Partial melting during prograde to peak UHP metamorphism requires dehydration reactions to supply water. Dehydration of zoisite in Ca-rich intermediate rocks occurs at P-T conditions close to the quartz–coesite transition (Poli and Schmidt, 2002). Thus, fluid released by the breakdown of zoisite and related minerals can be potentially involved in melting in the early stages of UHP metamorphism (e.g. Patiño Douce, 2005). Dehydration of chlorite or talc in rocks of appropriate composition is an alternative way to provide the fluids necessary for partial melting during prograde evolution (Fumagalli and Poli, 2005).

Decompression melting during the initial stages of exhumation is more common in continental collision belts (e.g. Korsakov and Hermann, 2006; Liu et al., 2013), and is consistent with the experimental studies (Hermann and Green, 2001; Auzanneau et al., 2006; Hermann et al., 2006) suggesting phengite dehydration HP-UHP melting to occur during decompression of various rock types. As an example, during decompression K-rich mafic UHP rocks may cross the melting reaction Phe + Cpx + Coe = Grt/Bt/Opx + Ky + Melt + Kfs (Hermann and Green, 2001), and UHP metagreywackes may cross the

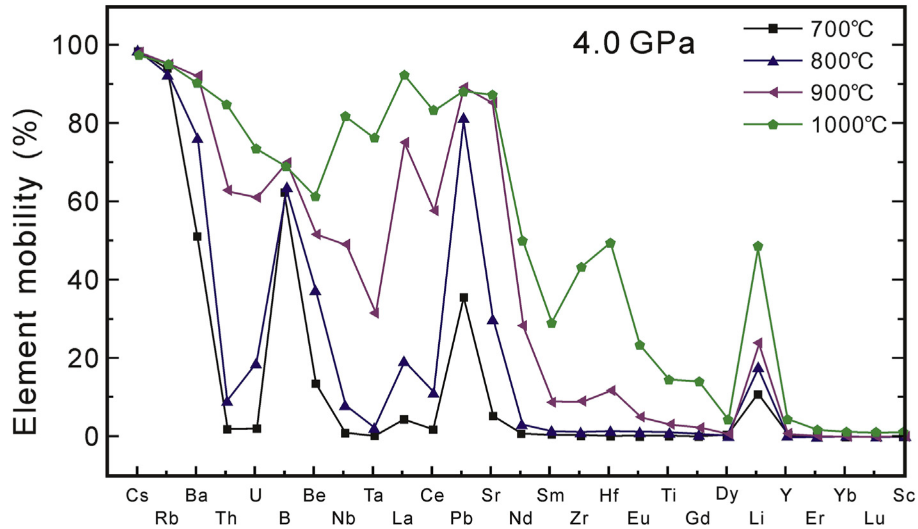

Figure 6. Mobilities of incompatible trace elements in aqueous fluids (700–900 °C) and hydrous melts (1000 °C) at 4.0 GPa (modified from Zheng et al., 2011). "Element mobility" as defined in Kogiso et al. (1997). Fluid-solid partition coefficients from Kessel et al. (2005).

curve Phe + Cpx + Qz = Bt + Pl + Grt + Melt (Auzanneau et al., 2006). The initial exhumation segments of the P-T paths of several UHP terrains are illustrated in Fig. 7; the peak UHP conditions of Erzgebirge, Dabie, Kokchetav and Rhodope were inferred by the occurrences of diamond (Xu et al., 1992, 2003, 2005; Nasdala and Massonne, 2000; Dobretsov and Shatsky, 2004; Mposkos and Krohe, 2006), while the UHP peak of Greenland was determined by geothermobarometric calculations for the assemblage garnet + clinopyroxene + kyanite + phengite + quartz/coesite (Gilotti and Ravna, 2002). Peak conditions of the UHP terrains plot

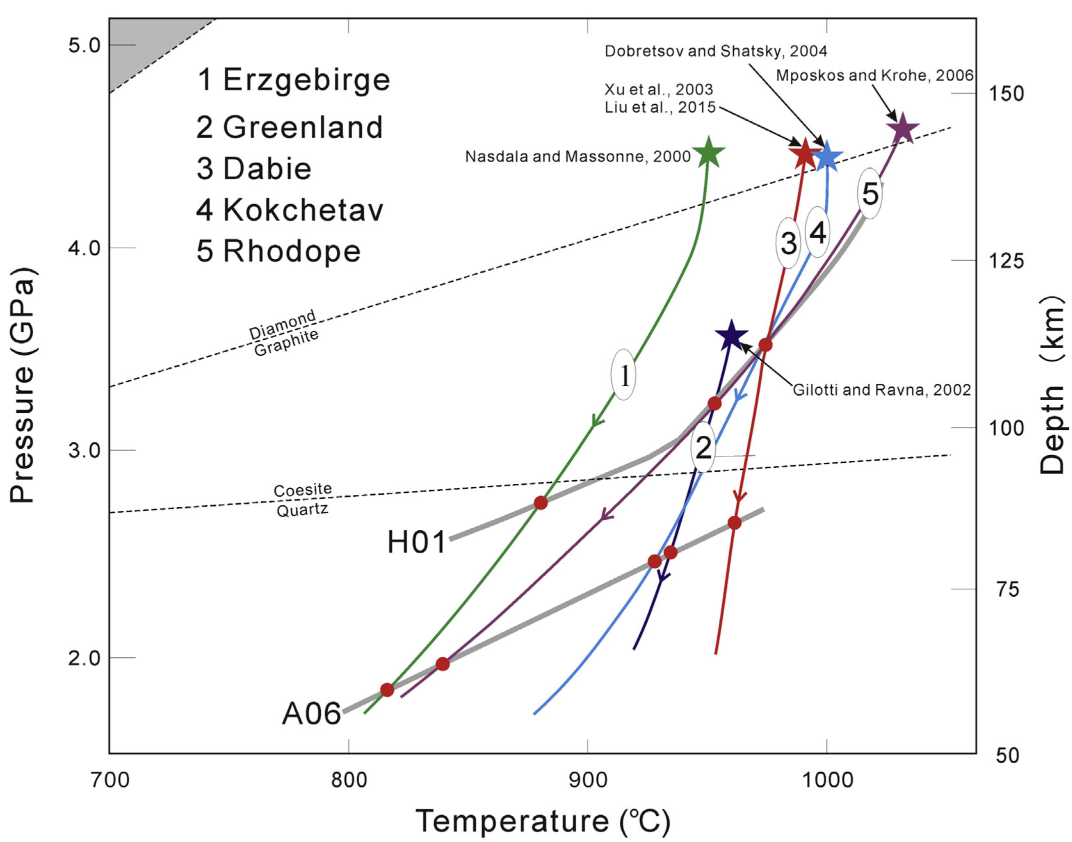

Figure 7. UHP to HP decompression segments of P-T paths of selected UHP slices and melting reaction curves showing partial melting of UHP rocks during exhumation. The P-T paths of the UHP slices in Dabie, Greenland, Rhodope, and Erzgebirge terranes are modified from Liu et al. (2015), Gilotti and McClelland (2007), Mposkos and Krohe (2006), and Rötzler and Kroner (2012), respectively, while that of Kokchetav is modified after Hermann et al. (2001), Dobretsov and Shatsky (2004), and Ragozin et al. (2009). Peak P-T conditions of each UHP terrane are marked by stars and reported in the references marked beside. The diamond-graphite transformation curve is from Kennedy and Kennedy (1976), coesite-quartz transformation curve is from Hemingway et al. (1998), and the melt producing reaction curves are from Auzanneau et al. (2006). The gray area above the 5 °C/km geotherm is the so-called "forbidden zone" that is not found on Earth.

above the two melting reaction curves, indicating that their P-T paths may well traverse across the melting reactions during exhumation, leading to phengite-controlled partial melting. Polyphase inclusions composed of Phe + Bt + Ky + Qz + Kfs + Ru within garnet were reported in the UHP metapelites in the Greenland Caledonides (Lang and Gilotti, 2007), thus also demonstrating the phengite-controlled melting as suggested by the figure.

Although the P-T paths and the melting reaction curves suggest melting occurred at similar stages of exhumation, the ages of partial melting recorded by the UHP terranes reported in Fig. 7 are extremely variable. Sm-Nd isochronal age and U-Pb age of an anatectic zircon from the NDZ in the Dabie orogen show that the decompression partial melting occurred during the granulite-facies retrograde stage (Gu et al., 2013); U-Pb ages of zircons in migmatites in the Kumdy-Kol area of Kokchetav indicate that partial melting took place during exhumation of UHP rocks from mantle depths to the mid-crustal levels (Ragozin et al., 2009); the ages of felsic veins cross-cutting eclogites in the Kimi Complex Zone of Rhodope suggest partial melting during subduction/accretion at the base of a thickened crust (Liati et al., 2002; Baziotis et al., 2008).

For a given bulk-rock composition, phase equilibrium modeling may be a better way to infer the starting point of partial melting. In addition, it can provide additional informations, including the P-T conditions at which melting starts, the reactants and products of the melting reactions as well as their compositions. In some case studies (e.g. Yin et al., 2014; Lang and Gilotti, 2015), melting reactions were constrained by phase equilibrium modeling, by identifying in thin section the assemblages involved in the reactions. However, it is almost impossible to precisely date the modeled melting start point, because datable minerals as for instance zircon and monazite usually dissolve in melt and grow again when melt crystallizes (Kelsey et al., 2008; Kelsey and Powell, 2011; Kohn et al., 2015). In other words, the ages recorded by anatectic zircon or monazite reflect the time of melt crystallization rather than that of melt production.

5. Physical effects and dynamic implications

Partial melting is an endothermic process that has the important effect of buffering the temperature of metamorphism (Vielzeuf and Holloway, 1988; Stüwe, 1995; Clark et al., 2011), depending on the proportion of melt produced. If melt is sufficiently abundant to equilibrate with the residual solid, the P-T path of the partially molten rocks would then coincide with the melting reaction curve; on the contrary, if there is not enough melt, the thermal equilibration between melt and solid could not be achieved, and thus the temperatures of the rocks would be higher than the melting reaction curve. On the other hand, because melt loss decreases the melt fertility of rocks, UHP terranes that have experienced melt extraction can achieve higher metamorphic temperatures, although this effect could be offset by the simultaneous depletion of heat-producing elements, given that U, Th and K partition into the melt (Clark et al., 2011).

Another important physical effect of partial melting is volume change, which affects the slope of the solidus curves. The bulk volume (total volume of solids, melts and pore-filling fluid if present) change during partial melting is controlled by the presence or absence of a fluid phase: fluid-present melting reactions are generally accompanied by bulk volume reductions (over the P range 0.1–1 GPa), whereas fluid-absent melting reactions increase the bulk volume (Clemens and Droop, 1998 and references therein; Fig. 8). Therefore, during exhumation of UHP rocks, fluid-absent dehydration melting may lead to an increase in the bulk volume and the corresponding pressure. If the rate of melt production exceeds the rate of melt segregation, the increased pressure may result in melt-enhanced embrittlement of the crust (Brown et al., 1995; Rutter and Neumann, 1995) and melt extraction driven by buoyancy (see Droop and Brodie, 2012 for an example). There is a natural feedback between volume change by melting and the evolution of anatexis (Powell et al., 2005). During the decompression melting of UHP rocks, increased pressure during melting inhibits further melting by moving the system away from the solidus curve, while the ascent of the rock bodies can relax such overpressures and thus permit further melting.

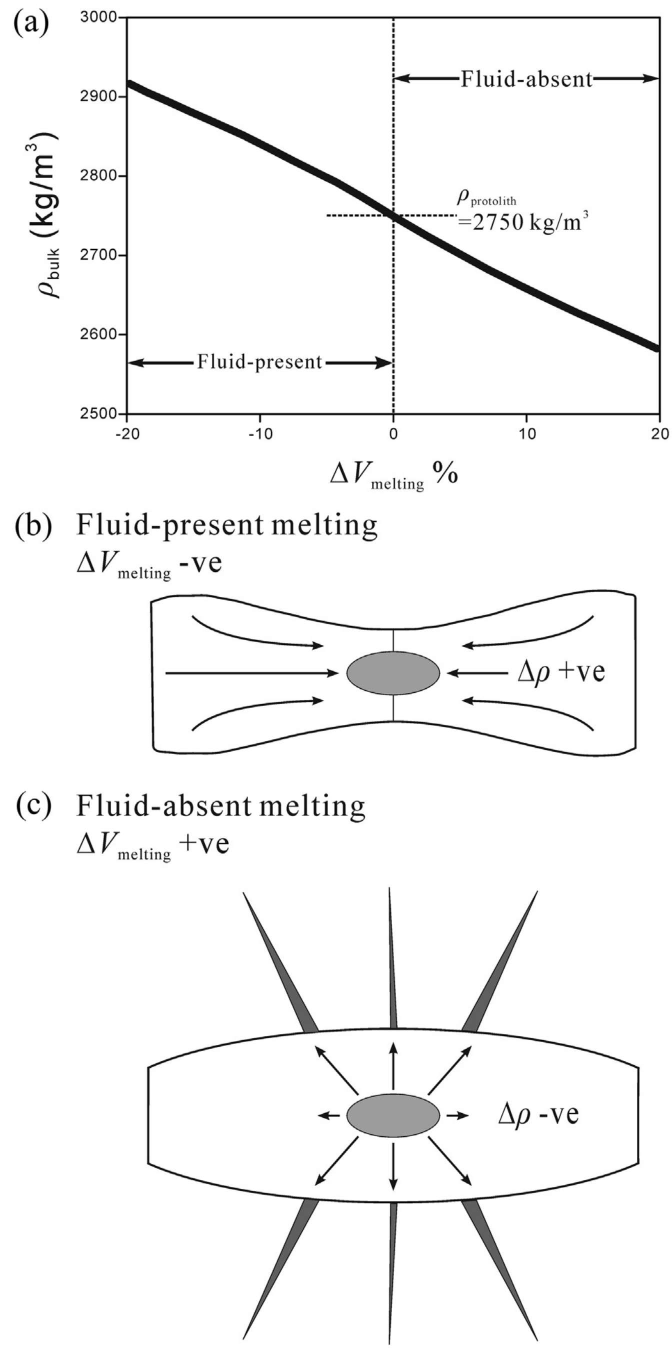

Figure 8. Bulk volume change during fluid-present and fluid-absent melting (Clemens and Droop, 1998). (a) Graph showing how the bulk density of a rock mass changes during partial melting. (b) Fluid-present melting results in a negative volume change, an increase in density and melt flow focused into the rock mass. (c) Fluid-absent melting leads to a positive volume change, a decrease in density and melt expulsion focused into external fractures.

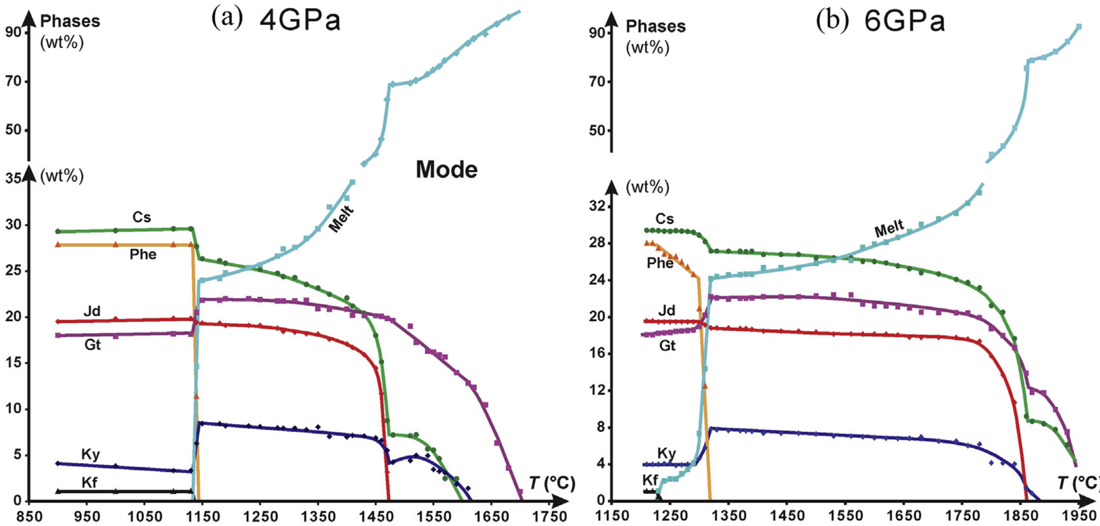

Figure 9. Modal composition changes for diamondiferous quartzofeldspathic rocks at 4 GPa (a) and 6 GPa (b) as a function of temperature (T) (Massonne and Fockenberg, 2012). Cs, coesite; Phe, phengite; Jd, jadiete; Gt, garnet; Ky, kyanite; Kf, K-feldspar.

Physical changes of UHP rocks have great effects on the dynamic behaviors of the subducted slabs. The continental crust is typically dominated by rocks of felsic composition such as granitic gneisses, which are buoyant relative to the mantle at UHP conditions (e.g. Cloos, 1993; Gilotti, 2013), thus it cannot sink to mantle depths without the involvement of external forces. The drag of fore-end oceanic crust, which is even denser than the mantle at UHP conditions (e.g. Cloos, 1993; Gilotti, 2013) is generally considered to be the predominant driving force for continental subduction. As a result, the subducted continental lithosphere will sustain opposing pulling forces leading to extensional deformation. A narrow rifting mode of deformation will result if there is strain localization, followed by slab break-off (e.g. Davies and von Blanckenburg, 1995). Afterwards, the subducted continental crust will be exhumed under positive buoyant force. This implies that the continental subduction and exhumation processes are dynamically controlled by the mean density of the involved slab.

As partial melts are rich in silica and alkalis, the residues will be depleted in these elements and enriched in FeO, resulting in a modal increase of denser minerals such as garnet and in a decrease of lighter minerals such as phengite and coesite. The extraction of partial melts will thus result in an increase of the bulk rock density (see Hermann and Rubatto, 2014). Experiments and numerical calculations (Hermann and Green, 2001; Hacker et al., 2011) have confirmed that melt extraction can increase the density of UHP rocks, depending on the rock composition and melt proportion. Following this reasoning, syn-exhumation partial melting of UHP rocks will likely slow down the exhumation rate.

On the other hand, partial melting can dramatically decrease the rheological strength of rocks (e.g. Faure et al., 1999; Hermann and Green, 2001; Vanderhaeghe and Teyssier, 2001; Zhong et al., 2001; Labrousse et al., 2002, 2011; Chopin, 2003; Rosenberg and Handy, 2005; Wallis et al., 2005; Whitney et al., 2009; Brown, 2010) and thus promote/trigger the intra-crustal decoupling and subsequent exhumation of UHP slices. Besides, melts might also lubricate the contact surfaces between the rock slices during exhumation, thus promoting the exhumation process. Therefore, a natural feedback exists between exhumation and partial melting of UHP rocks: exhumation decreases pressure and promotes dehydration melting, while melting promotes exhumation by decreasing the viscosity of the crust.

6. Outlook

Partial melting is a major process involved in modifying the composition of subducted continental crust in collisional orogens, and is therefore relevant for continental crust differentiation (e.g. Brown, 2010). Currently, partial melting of UHP rocks of pelitic and granitic compositions is reported in several collision terranes (e.g. Hermann et al., 2006; Liu et al., 2010; Zhang et al., 2015); however, occurrences of UHP eclogites are much less well-known. Thus the investigation of partial melting in eclogites will likely be a hot topic in future studies of continental collision. Solution models for the melt derived from partial melting of eclogites are still lacking, hampering the reliable thermodynamic modeling of mafic rocks at supra-solidus conditions. Experimental studies are therefore needed to acquire these thermodynamic parameters.

Partial melting plays also a significant role in the decoupling of subducted continental crust and the subsequent exhumation of UHP slices, by decreasing their mechanical strength and viscosity. However, to what extent this effect can attain still remains ambiguous. Experimental and numerical modeling investigations will help to understand if partial melting is the urge of decoupling of subducted continental crust, or is the result of decoupling because of stress released in ductile shear zones.

Trace elements partitioning between solids and melts has been studied since long time (see Zheng et al., 2011 for a review), whereas the behavior of isotopes (especially the non-traditional isotopes) during partial melting is so far poorly understood. With a large relative mass difference (8%) between ^{26}Mg and ^{24}Mg, Mg isotopes are potentially prominent geochemical tracers. So far, few investigations of the Mg isotope fractionation processes during magma differentiation, surface weathering and low- to mid-temperature metamorphism have been performed (Galy et al., 2002; Tipper et al., 2006; Teng et al., 2007; Bourdon et al., 2010; Li et al., 2011), whereas the fractionation processes between different minerals in UHP rocks are not clearly known. Li et al. (2011) reported significant Mg isotope fractionation between garnet and omphacite/phengite (^{26}Mg preferably enters omphacite/phengite rather than coexisting garnet) in medium-T eclogites, which have bulk rock Mg isotopic compositions undistinguishable from their protoliths. Accordingly, if partial melting and subsequent melt extraction occurred in analogous lithologies, considerable Mg isotope fractionation between the melts and solid residuals should be expected since phengite is much easier to be melted than garnet.

Phase equilibrium modeling is an effective tool to predict modal changes during metamorphism and partial melting. Massonne and Fockenberg (2012) modeled these changes in metasedimentary rocks during heating at UHP conditions (Fig. 9). As shown in this figure, the modeled rocks contain two Mg-bearing phases, garnet and phengite, under subsolidus conditions. As long as the rocks start to melt, the modal amount of phengite decreases very quickly while that of garnet slightly increases. In this way, the residual will be poorer in δ^{26}Mg than the protolith if melt extraction occurred. As a result, by integrating phase equilibrium modeling with related Mg isotope fractionation coefficients, it would be possible to predict Mg isotopes evolution during partial melting, and Mg isotopes in turn could be used as indicators of partial melting. Certainly, Mg-isotope fractionation coefficients between minerals and melt are also essential to calibrate this method.

In summary, the study of UHP partial melting is just unfolding, and will possibly be in the close future one of the hottest topics in the field of Earth Science research.

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