Dehydration melting of UHP eclogite and paragneiss in the Dabie orogen: Evidence from laboratory experiment to natural observation

LIU Qiang^{1*} & WU Yao²

¹ Faculty of Earth Sciences, China University of Geosciences, Wuhan 430074, China;

² State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences, Wuhan 430074, China

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Dehydration melting of subducted continental crust is significant during exhumation, and its study from both experimental and petrological observations is of great importance to our understanding of continental geodynamics. Dehydration melting experiments were carried out on ultrahigh-pressure (UHP) eclogite from Bixiling in the Dabie orogen using a piston cylinder at 1.5–3.0 GPa and 800–950°C to investigate partial melting of eclogite induced by phengite breakdown. The phengite-bearing eclogite started to melt at $T \leq 800$ –850°C and $P = 1.5$ –2.0 GPa and produced about 3% granitic melt. The products of dehydration melting vary with temperature and pressure. Such results provide valuable constraints on the micro-texture related to partial melting of UHP rocks in the Dabie-Sulu orogenic belt. Three types of polyphase inclusions were identified in garnet from the Shuanghe UHP eclogite. K-feldspar and quartz inclusions are interpreted to represent the products of segregation and crystallization of minor amounts of melt that formed during dehydration melting of phengite by the inferred reaction $\text{Phengite} + \text{Omphacite} \pm \text{Quartz} \rightarrow \text{Amphibole} \pm \text{Garnet} + \text{Melt}$ ($\text{K-feldspar} + \text{Quartz} \pm \text{Plagioclase}$). Polyphase inclusions of phengite and K-feldspar+Quartz inclusions were also found in zoisite/clinozoisite and garnet from the Shuanghe garnet-bearing paragneiss. These polyphase inclusions provide evidence for a continuous process from sub-solidus dehydration to partial melting within the UHP gneissic rocks. The compositional variation of garnets demonstrates that breakdown of epidote-group minerals may have played a crucial role during dehydration melting reaction of phengite. The Ti-in-zircon thermometry and Si content of phengite in zircon suggest that partial melting would occur at 783–839°C and 2.0–2.5 GPa. Therefore, both experimental results and petrological observations indicate that dehydration melting and fluid activity within the Dabie UHP rocks at micro-scale are controlled by the breakdown of phengite.

dehydration melting, phengite, experimental petrology, polyphase inclusions, ultrahigh-pressure metamorphism, Dabie orogen

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Recent studies from experimental petrology [1–3], geochemical analyses [4–6] and geochronological data [7–9] have indicated that deeply subducted continental crust experienced partial melting during exhumation. Such anatexis can change mechanical and chemical behaviours of ultrahigh-pressure (UHP) metamorphic rocks. It has significant effects on facilitating the deformation mechanisms (or strain localization) of UHP rocks [10,11], increasing the buoyancy

of melted rocks and promoting the segregation of partial melts. Thus, partial melting of subducted continental crust is of great significance for understanding the melting event and fluid activity at great depths as well as the rheological property of UHP rocks in collisional orogenic belts [12–14]. So far, some aspects related to dehydration melting of UHP rocks are still open to discussion, including petrological evidence [15–20], conditions and degrees of melting, the differences among various rock units, element partitioning and coupling of lithological strength during melting.

*Corresponding author (email: liuqiang@cug.edu.cn)

It is widely accepted that the breakdown of phengite and zoisite play a key role in partial melting of UHP rocks [14]. Thus, it is important to investigate the dehydration melting of hydrous minerals under various P - T conditions and their implications for initial melting of host rocks. The results can also shed light on understanding of anatexis processes and changes in mineral assemblages preserved in UHP rocks. High P - T experiment can straightforwardly simulate the partial melting of rocks, and thus provide important constraints on the formation and evolution of partial melts in natural UHP rocks. In particular, polyphase inclusions in some eclogite minerals such as garnet and omphacite are the potential natural record of partial melting in deeply subducted crust [17–21] and can further test the experimental results. Therefore, the combination of laboratory experiments with natural observations could be an essential way to explore partial melting of UHP rocks. In this paper we highlight previous experimental results from dehydration melting of phengite-bearing eclogite [22] and report new observations for textural and compositional characteristics of different types of polyphase inclusions in the Shuanghe UHP eclogite and paragneiss. These results provide important insights into the mechanism, evolution and related effects of partial melting that occurred during the exhumation of UHP rocks in the Dabie orogen.

Abbreviations for minerals in this paper are from Whitney & Evans [23].

1 Experimental constraint on dehydration partial melting of phengite-bearing eclogite

Phengite-bearing UHP eclogite collected from Bixiling in the Dabie orogen were used as starting materials and aimed to systematically study the dehydration melting of phengite-bearing eclogite at pressures of 1.5–3.0 GPa and temperatures of 800–950°C [22].

The experimental results indicate that phengite and zoisite release fluid under sub-solidus conditions at 1.5–2.0 GPa and 800–850°C. The eclogitic rock subsequently started melting with the assistance of fluid. The less refractory components preferentially enter the melt, which reacts with kyanite to form reaction rim of plagioclase. Zoisite starts to melt at 800°C through the reaction $Zo + Omp + Qz \rightarrow Pl + Melt$ (Figure 1(a)), whereas phengite begins to melt at 850°C by the reaction of $Ph + Qz \rightarrow Ky + Melt$ (Figure 1(b)). The melt fraction increases gradually with increasing temperature. The melt is distributed adjacent to hydrous minerals or at grain boundaries of different minerals. The phase relations indicate the melting reaction of $Ph + Omp + Qz \rightarrow Pl + Ky + Melt$ at 1.5–2.0 GPa and 850–900°C. Oligoclase is the primary reaction product of melting of phengite in natural eclogite. At elevated temperatures, phengite is dissolved completely through the reaction $Ph + Omp + Qz \rightarrow Pl + Grt + Ky + Melt$ at 2.0

GPa and 950°C to produce garnet (Figure 1(c)). On the basis of phase relation and texture, the dehydration melting reaction of phengite under 2.4–3.0 GPa and 900–950°C can be written as the reaction of $Ph + Omp + Qz \rightarrow Jd + Grt + Kfs + Ky + Melt$ (Figure 1(d) and (e)).

Our experimental results suggest that pressure and temperature have significant influence on dehydration melting of phengite-bearing eclogite. The melting of eclogite can generate granitic melt which is of significance for fluid mobility especially for transporting K and LILE. According to the experimental results and field observations, we concluded that the most appropriate P - T condition for partial melting of phengite-bearing eclogite from the Dabie-Sulu orogen is 1.5–2.0 GPa and 800–850°C. In comparison, dehydration partial melting experiments were performed on biotite gneiss and phengite-bearing eclogite at 2.0 GPa and 800–950°C. The results showed that the larger volume of melt was produced in biotite gneiss than that in phengite-bearing eclogite under similar conditions. For example, the dehydration melting of gneiss generated more granitic melts (about 10%) compared with eclogite at 2.0 GPa and 950°C (Figure 1(f)). Melt from gneiss infiltrated eclogite at the contact zone and may cause eclogite composition rich in silica and alkali contents [24].

2 The low-degree partial melting of UHP eclogite: Evidence from polyphase inclusions within garnet

The melting texture of hydrous minerals such as phengite and zoisite preserved in UHP eclogite may provide important information about their origin and evolution during dehydration melting. It also should be considered as the reliable evidence for partial melting of UHP eclogite. The Shuanghe UHP eclogites in the Dabie orogen consist of coesite-bearing homogeneous eclogite and layered eclogite. Rutile in homogeneous and layered eclogite has Zr contents of 80 to 138 ppm, yielding Zr-in-rutile temperatures of 640 to 690°C using the thermometer of Tomkins et al. [25]. The Fe-Mg thermometry of Grt-Omp on the homogeneous eclogite yields a comparable temperature range at pressures of 3.5–4.0 GPa. Therefore, our new data provide peak UHP conditions of 650–700°C and 3.5–4.0 GPa for the Shuanghe UHP rocks. The previous study on the metamorphic evolution of the Shuanghe eclogite suggested a significant heating stage (780–840°C) at 2.0–2.5 GPa during exhumation [26], making the partial melting of eclogite highly possible. In comparison with the homogeneous eclogite, the layered eclogite that may experience shear deformation should preserve micro-evidence related to partial melting. Based on a previous investigation [17], we have identified three types of polyphase inclusions hosted within garnet from the Grt-rich zones and Grt+Qz zones of the layered eclogite (Figure 2(a)–(d)). These inclusions can provide new constraints on

Figure 1 Backscattered electron (BSE) images of dehydration melting experiments of phengite-bearing eclogite at 1.5–3.0 GPa and 800–950°C (data from [22,24]). (a) Dehydration melting of zoisite leads to the formation of thin melt film and plagioclase ($P=1.5$ GPa, $T=800^{\circ}\text{C}$). (b) The initial melt occurs as a ring surrounding phengite. New kyanite was crystallized from melt pools ($P=2.0$ GPa, $T=850^{\circ}\text{C}$). (c) Phengite was completely consumed and replaced by oligoclase and garnet ($P=2.0$ GPa, $T=950^{\circ}\text{C}$). (d) Dehydration melting of phengite produced jadeite, K-feldspar and kyanite ($P=2.4$ GPa, $T=950^{\circ}\text{C}$). (e) Dehydration melting of phengite produced jadeite, K-feldspar and garnet ($P=3.0$ GPa, $T=950^{\circ}\text{C}$). (f) Melt (melt1) from biotite gneiss (left) infiltrating eclogite (right), as shown by the arrow ($P=2.0$ GPa, $T=950^{\circ}\text{C}$).

the process of dehydration melting of UHP eclogite at an advanced stage of exhumation.

The first type of polyphase inclusions mainly consist of phengite and epidote. Phengite within inclusions has a high Si-content ($\text{Si}=3.58$ p.f.u., $\text{O}=11$) and shows an intergrowth rim of amphibole+muscovite (Figure 2(e)), indicating that breakdown of phengite occurred to generate minor amphibole and muscovite as reaction products. Epidote inclusions that are associated with a tight intergrowth of zoisite, amphibole and quartz contain some small omphacite ($\text{Jd}_{60}\text{Aug}_{40}$) grains with high jadeite content (Figure 2(f)). Such epidote inclusions are interpreted to have formed as pseudomorphs after prograde to peak lawsonite. The breakdown of lawsonite during initial decompression of the UHP rocks would occur along the reaction: $\text{Lws}+\text{Omp}=\text{Ep}/\text{Zo}+\text{Qz}+\text{Amp}+\text{Fluid}$.

The second type of polyphase inclusions consisting of approximately equal amounts of K-feldspar and quartz occur in the core and rim of garnet in the Grt-rich zone and

Grt+Qz zones (Figure 2(g)). K-feldspar and quartz within these inclusions are intermingled with a mosaic texture. Irregular voids in variable sizes have been observed in these inclusions. Most inclusions are surrounded by radial fractures, some of them exhibit regular shapes in the host garnet and have well-developed off-shoot structure (Figure 2(h)). These textural features (i.e. negative-crystal shapes, radial fractures) suggest that this type of inclusion derived from a trapped hydrous felsic melt. The radial fractures of host garnet were interpreted to have formed by the segregation and crystallization of melt and act as the channel for infiltration of retrograde fluid. This conclusion is supported by the presence of relic phengite within polyphase inclusion (Figure 2(i)). The relic phengite in such inclusion has a high Si-content together with an intergrowth of plagioclase, K-feldspar, quartz and minor amphibole, indicating that the dehydration partial melting of phengite occurs in the Shuanghe eclogite by the reaction of $\text{Ph}+\text{Omp}+\text{Qz}\rightarrow\text{Amp}+\text{Grt}+\text{Melt}$.

Figure 2 Different types of polyphase inclusions within garnet from the Shuanghe UHP eclogite. (a) Scanning thin sections showing the different compositional zones of layered eclogite (Grt-rich zones, Grt+Qz zones and Amp-rich zones). (b)–(d) Photomicrographs of inclusions hosted by garnet from Grt-rich zones and Grt+Qz zones. BSE images of representative polyphase inclusions within garnet. (e) Phengite inclusion is rimmed by amphibole and muscovite. (f) Epidote inclusions are associated with an intergrowth of zoisite, amphibole and quartz and tiny omphacite inclusions occur within the epidote. (g)–(h) Kfs+Qz inclusions are hosted by garnet, which are surrounded by radial fractures and have well-developed off-shoot structure. (i) Polyphase inclusion consists of relic phengite, K-feldspar, plagioclase, quartz and amphibole, indicating melting of phengite in host eclogite. (j) Mineral assemblage of K-feldspar, plagioclase, biotite, quartz and amphibole was preserved in garnet, showing the retrograde metamorphism in host eclogite.

Interestingly, the Kfs+Qz inclusions as well as the Pl+Kfs+Qz inclusions have major element compositions compatible with a granitic melt origin. Such bulk compositions with high SiO_2 and K_2O , low Al_2O_3 and Na_2O are similar to hydrous felsic melt observed in experiments of low-degree melting of phengite in eclogite [22]. Thus, the observed gradual breakdown of phengite resulting in these types of inclusions suggests phengite melting at 1.5–2.0 GPa and 750–800°C during exhumation.

The third type of polyphase inclusions mainly preserves the retrograde mineral assemblage of amphibole and plagioclase (similar in chemistry to the amphibole and plagioclase symplectites in the matrix), including biotite, K-feldspar and chlorite (Figure 2(j)). These inclusions display oval

shapes and are occasionally surrounded by radial cracks, which likely formed during late stage fluid influx that is also responsible for the replacement of phengite by biotite as well as omphacite by amphibole and plagioclase.

The trace element compositions of Kfs+Qz inclusions were determined by a laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) to better constrain the chemical features of minor melt existing in eclogite. The results showed that almost all of the Kfs+Qz inclusions display enrichment in LILE, LREE and depletion in HREE and have a negative Ce anomaly with REE contents of 6.6–60 ppm and $(\text{La}/\text{Sm})_{\text{N}}=1.1\text{--}5.1$. Thus, trace element characteristics of Kfs+Qz inclusions are similar to those of granitic melt [27], suggesting that these melt likely derived from

Figure 3 Polyphase inclusions of phengite and Kfs+Qz inclusions from the Shuanghe UHP paragneiss. (a) and (b) Transmitted light image (crossed polarized light) and BSE image of allanite core and zoisite mantle with phengite+kyanite inclusions and garnet+biotite inclusion. (c) and (d) transmitted light image (crossed polarized light) and BSE image of phengite inclusions and rutile inclusion in coarse-grained clinozoisite. Phengite is partly replaced by kyanite and K-feldspar within inclusion. (e) BSE image of polyphase inclusion consisting of new-born garnet, relic phengite and K-feldspar in garnet. (f) BSE image of inclusions of K-feldspar+quartz coexisting with biotite inclusion in garnet.

trapped melt that was produced during incongruent phengite melting. It is consistent with a previous investigation [28]. However, field observations showed that melting of host eclogite is very limited. We proposed that such low-degree partial melting did not result in a chemical differentiation of the subducted rocks but influenced the rheology of the eclogite during exhumation, as exemplified by the formation of Grt-rich zones and Grt+Qz zones.

3 Subsolidus dehydration and melting in UHP paragneiss: Evidence from polyphase inclusions within zoisite/clinozoisite and garnet

The garnet-bearing paragneiss interlayered with layered eclogite from the Shuanghe UHP slab was collected for detailed petrological study under microscope to investigate the differences between dehydration melting of eclogite and gneiss. As a result, three types of phengite inclusions identified within zoisite, clinozoisite and garnet in this gneissic rock. These inclusions mainly contain relic phengite with related new phases, such as kyanite, K-feldspar and fine-grained garnet. Another type of inclusions, Kfs+Qz inclusion, is commonly preserved in coarser-grained garnet.

The first type of phengite inclusions is single phase phengite inclusions and distributed in zoisite mantle surrounding an allanite core (Figure 3(a) and (b)). Kyanite occasionally coexists with phengite within this type of inclusion and phengite in this kind of inclusion has a high Si content of 3.55 p.f.u.(O=11). The second type of phengite inclusions occurring at the rim of clinozoisite contains relic phengite, K-feldspar and quartz (Figure 3(c) and (d)). The relic phengite with a Si content of 3.49 p.f.u.(O=11) is partially replaced by kyanite and K-feldspar. No melt phase occurs within this kind of inclusion. According to our studies (i.e. Figure 1(d)) [22], such kind of texture indicates a subsolidus dehydration of phengite by the reaction of $\text{Phe} \rightarrow \text{Kfs} + \text{Ky} + \text{fluid}$. The third type of phengite inclusions in garnet consist of relic phengite, K-feldspar and fine-grained garnet. This type of inclusion has equiaxed shape. The relic phengite contains a Si content of 3.37 p.f.u.(O=11). The fine-grained garnet displays higher grossular contents than the host garnet ($\text{Alm}_{54.5}\text{Grs}_{33.0}\text{Pyr}_{9.2}\text{Sp}_{2.1}$) in the matrix. K-feldspar within inclusion has a feature of melt crystallization (Figure 3(e)), indicating that it may have crystallized from melt in inclusion. Since garnet is generally the reaction product of dehydration melting of phengite [1,22] (Figure 1(c) and (e)), therefore, the third type of inclusion suggests that the initial melting reaction of phengite should occur in the UHP gneiss by $\text{Ph} + \text{Grt-I} \rightarrow \text{Grt-II} + \text{Kfs} (\text{Melt})$.

Kfs+Qz inclusions and biotite inclusions are well preserved in coarse-grained garnet (Figure 3(f)). The host garnet has an average composition of $\text{Alm}_{50.3}\text{Grs}_{37.1}\text{Pyr}_{8.7}\text{Sp}_{2.5}$ with increasing grossular contents from core to rim. Such a

Figure 4 The region of dehydration partial melting of the Shuanghe UHP eclogite and paragneiss. *P-T* path of the Shuanghe eclogite is from [26]. The breakdown curves of phengite are after [30] (hydrous basalt), [31] (KCMASH), [1] (metagreywacke) and [22] (phengite-bearing eclogite), respectively.

mineral assemblage is consistent with the experimental results [1], demonstrating hydration melting event induced by phengite breakdown occurred at higher temperature in the UHP gneissic rock. Based on the composition of garnets and mineral assemblage in the matrix (Figure 3(e)), we inferred that such a melting reaction may be expressed as $\text{Ph} + \text{Qz} \pm \text{Ep} \rightarrow \text{Grt} + \text{Bt} + \text{Melt} (\text{Kfs} + \text{Qz})$. Generally, three types of phengite inclusions as well as Kfs+Qz inclusions may be formed during the dehydration, initial melting and complete melting of phengite in the gneiss, respectively. These stages may make up the continuous processes of dehydration melting of phengite in the Shuanghe gneissic rock.

Combining Si content ($\text{Si}=3.37\text{--}3.51$ p.f.u., $\text{O}=11$) of phengite in zircon with Ti-in-zircon thermometer [29] at $\text{Ti}=15.8$ to 27.7 ppm, we suggest that the dehydration melting of the Shuanghe paragneiss induced by phengite breakdown would occur at $783\text{--}839^\circ\text{C}$ and $2.0\text{--}2.5$ GPa, corresponding to the quartz eclogite facies. It also indicates that the dehydration melting triggered by the phengite breakdown is easy to take place in UHP paragneiss at relatively high pressure ($2.0\text{--}2.5$ GPa) with respect to eclogite ($1.5\text{--}2.0$ GPa) (Figure 4).

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