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Abstract: The studied eclogite is located in the Luotian dome in the southwestern part of the North Dabie Complex Zone (NDZ), central China, and is a portion of deeply subducted mafic lower continental crust of the South China Block. Petrologic analysis suggests that the eclogite underwent ultrahigh-pressure (UHP) and high-pressure eclogite-facies metamorphism, and subsequent HP granulite-facies overprinting and amphibolite-facies retrogression during continental subduction and exhumation. As a result, multiple decompression textures were produced, suggesting a multistage exhumation history from eclogite-, to granulite-, to amphibolite-facies conditions. A striking feature of this eclogite is the widespread exsolution of different phases: oriented needles of rutile + clinopyroxene + amphibole + apatite in garnet; quartz + amphibole + hyperthsene + sodic plagioclase in clinopyroxene; pyrrhotite in apatite. Most importantly, we provide for the first time conclusive evidence of quartz pseudomorphs after coesite in garnet and relic coesite (confirmed by in situ Raman spectroscopy) in zircon. In addition, there are two groups of apatite: one is fluor (F)-apatite and occurs as inclusion in garnet or in matrix, which is rich in F (□3 wt %) without any exsolutions and formed at UHP metamorphic conditions; the second is relatively poor in F (< 1 wt %) associated with the oriented pyrrhotite exsolution and formed during decompression. Microtextural and petrologic analysis suggest that the eclogites from southwestern segment of the NDZ are similar to eclogites from the northern segment of the NDZ (e.g., Huangweihe and Baizhangyan) and suffered UHP metamorphism with pressure peak ≥ 5-7 GPa. These results, combined with published geochronological data, imply that the NDZ wholly experienced Triassic UHP metamorphism as a coherent unit.

Ultrahigh-pressure metamorphism and multistage exhumation of eclogite from the Luotian dome, North Dabie Complex Zone (central China): Evidence from mineral inclusions and decompression texture

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ABSTRACT

The studied eclogite is located in the Luotian dome in the southwestern part of the North Dabie Complex Zone (NDZ), central China, and is a portion of deeply subducted mafic lower continental crust of the South China Block. Petrologic analysis suggests that the eclogite underwent ultrahigh-pressure (UHP) and high-pressure eclogite-facies metamorphism, and subsequent HP granulite-facies overprinting and amphibolite-facies retrogression during continental subduction and exhumation. As a result, multiple decompression textures were produced, suggesting a multistage exhumation history from eclogite-, to granulite-, to amphibolite-facies conditions. A striking feature of this eclogite is the widespread exsolution of different phases: oriented needles of rutile + clinopyroxene + amphibole + apatite in garnet; quartz + amphibole + hyperthsene + sodic plagioclase in clinopyroxene; pyrrhotite in apatite. Most importantly, we provide for the first time conclusive evidence of quartz pseudomorphs after coesite in garnet and relic coesite (confirmed by in situ Raman spectroscopy) in zircon. In addition, there are two groups of apatite: one is fluor (F)-apatite and occurs as inclusion in garnet or in matrix, which is rich in F (~3 wt %) without any exsolutions and formed at UHP metamorphic conditions; the second is relatively poor in F (< 1 wt %) associated with the oriented pyrrhotite exsolution and formed during decompression. Microtextural and petrologic analysis suggest that the eclogites from southwestern segment of the NDZ are similar to eclogites from the northern segment of the NDZ (e.g., Huangweihe and Baizhangyan) and suffered UHP metamorphism with pressure peak > 5-7 GPa. These results, combined with published

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1. Introduction

The oriented exsolution or lamellae is a common feature of minerals that derive from deep-seated sources such as kimberlites, diamondiferous rocks, as well as eclogites and related rocks from high-pressure (HP) to ultrahigh-pressure (UHP) metamorphic belts, and is interpreted as the result of cooling and decompression (e.g., Smith, 1984; Gayk et al., 1995; Zhang et al., 1995, 2002a, 2005; Katayama et al., 2000a; Tsai and Liou, 2000; Ye et al., 2000a; Dobrzhinetskaya et al. 2002; Song et al., 2003, 2005; Malaspina et al., 2006; Nakano et al., 2007 and references therein). This peculiar microtexture is generally used to infer the primary conditions under which eclogites and related metamorphic rocks were formed. Eclogites are considered to be the most important witnesses of continental subduction, collision and subsequent exhumation processes and thus provide important information on the geodynamics of orogens. The survival of coesite and other index minerals in UHP rocks has important implications for the exhumation of subducted crustal rocks and is most commonly attributed to rapid exhumation, continuous cooling during uplift, and inclusion in strong phases that can sustain a high internal over-pressure during decompression (Mosenfelder et al., 2005). However, peak metamorphic conditions and the pressure/temperature (PT) evolution of UHP rocks involved in multistage metamorphism are not always straightforward because their mineral assemblages have been re-equilibrated to various degrees during retrogression and decompression (e.g., Faryad, 2009).

The finding of coesite and micro-diamond in eclogites from the Dabie orogen in central China (Okay et al., 1989; Wang et al., 1989; Xu et al., 1992) led this area to be one of the most important targets for studying UHP metamorphism, documenting continental subduction to mantle depths. A great number of studies have contributed to the understanding of the geodynamics of subduction and exhumation resulting in the Dabie–Sulu orogenic belt (see Liu and Li, 2008 for a summary). This orogenic belt contains the largest exposure of UHP rocks in the world, which formed by Triassic continental collision between the South China and North China Blocks (e.g., Li et al., 1993, 2000; Chavagnac and Jahn, 1996; Hacker et al., 1998; Ayers et al., 2002; Liu et al., 2005, 2007a, 2007b).

The Dabie UHP metamorphic belt in central China consists of three eclogite-bearing UHP crustal slices from north to south: the North Dabie complex zone (NDZ), the Central Dabie UHP metamorphic zone (CDZ), and the South Dabie low-T eclogite zone (SDZ), which differ by rock association, protolith nature and metamorphic evolution (see Liu and Li, 2008, in detail). Moreover, Pb isotopic mapping on the Dabie UHP belt has revealed a clear detachment between deeply subducted upper continental crust (the CDZ) and felsic lower crust (the NDZ) (Zhang et al., 2002a; Li et al., 2003). This duality is also supported by their different termination ages of peak UHP metamorphism, which probably result from multistage detachment within deeply subducted crust at different depths and multi-slice successive exhumation of the UHP rocks during continental collision (Liu et al., 2007b; Liu and Li, 2008). However, because of the lack of critical UHP phases such as coesite or microdiamond in the southwestern part of the NDZ, whether or not the

NDZ as a whole underwent deep subduction and subsequent UHP metamorphism is still a controversial issue (Zhao et al., 2008; Zhang et al., 2009).

In order to clarify : (1) peak metamorphic conditions of the eclogite from the Luotian dome in the southwestern part of the NDZ; (2) if the NDZ wholly underwent UHP metamorphism, a petrologic study on the eclogite from the Luotian dome in the NDZ was carried out. This paper focuses on multiple decompression texture and UHP metamorphic evidence of these eclogites. The results not only provide direct evidence on UHP metamorphism and multistage breakdown processes on the eclogite in the area, but also provide new constraints on exhumation mechanism of the UHP rocks in the Dabie orogen.

2. Geologic background and sample

The Dabie orogen is located in the intermediate segment of the Qinling-Dabie-Sulu belt formed by the collision of the North China Block and South China Block (SCB) in the Triassic. It comprises several fault-bounded rock units with varying metamorphic grades and is generally subdivided into five major lithotectonic units from north to south (e.g., Okay et al., 1993; Xu et al., 2003, 2005; Li et al., 2004; Liu et al., 2005, 2007a, 2007b; Liu and Li, 2008): (1) the Beihuaiyang zone (BZ); (2) the North Dabie complex zone (NDZ); (3) the Central Dabie UHP metamorphic zone (CDZ); (4) the South Dabie low-T eclogite zone (SDZ); and (5) the Susong complex zone (SZ). These five zones are respectively separated by the Xiaotian-Mozitan fault (XMF), Wuhe-Shuihou fault (WSF), Hualiangting-Mituo fault (HMF) and

Taihu-Shanlong fault (TSF) (Fig. 1). Zone (1) is a low-grade composite unit comprising the Foziling (or Xinyang) Group and the Luzhenguan (or Guishan) complex, whereas Zones (2), (3), (4) and (5) belong to the subducted SCB.

UHP metamorphic rocks, including coesite-bearing eclogite, UHP gneiss, whiteschist, quartz jadeitite and marble with eclogite nodules, are observed in the CDZ and SDZ (e.g., Xu et al., 1992; Okay, 1993; Okay et al., 1993; Rolfo et al., 2000; Li et al., 2004). The occurrence of diamond and coesite in the UHP rocks from the CDZ indicates the UHP metamorphism occurred at 700–850 °C and >2.8 GPa (e.g., Okay et al., 1989; Wang et al., 1989; Xu et al., 1992; Okay, 1993; Rolfo et al., 2004), whereas the peak P-T conditions on the eclogites in the SDZ were estimated at 670 °C and 3.3 GPa (Li et al., 2004). Both the CDZ and SDZ units experienced UHP eclogite-facies, and subsequent HP eclogite- and amphibolite-facies retrograde metamorphism (e.g., Xu et al., 1992; Okay, 1993; Rolfo et al., 2004; Li et al., 2004).

The NDZ consists predominantly of banded tonalitic and granitic gneiss and post-collisional intrusions with subordinated meta-peridotite (including dunite, harzburgite and lherzolite), garnet pyroxenite, garnet-bearing amphibolite, granulite and eclogite. Although no coesite has not yet been discovered from the eclogite or gneiss in the NDZ, the occurrence of micro-diamond from eclogite and gneiss is a key evidence for UHP metamorphism (Xu et al., 2003, 2005; Liu et al., 2007b). In addition, quartz rods in clinopyroxene are widespread in the eclogite, and these exsolutions are commonly regarded as evidence of prior UHP metamorphism (e.g., Smith, 1984; Liou et al., 1998; Tsai and Liou, 2000; Liu et al., 2005, 2007a; Zhang et al., 2005). Therefore, also the eclogites from the NDZ underwent the UHP metamorphism at P >3.5–4.0 GPa (Xu et al., 2003, 2005; Malaspina et al., 2006). As concerning geochronology, Triassic zircon U-Pb (Liu et al., 2000) and Sm-Nd (Liu et al., 2005) ages of the eclogites from the NDZ suggest that they formed by subduction of the SCB in the Triassic, similar petrogenesis to those from the CDZ and SDZ. The Triassic metamorphic ages (Liu et al., 2000, 2007b; Bryant et al., 2004; Xie et al., 2004) and the occurrence of micro-diamonds in zircons (Liu et al., 2007b) from the banded gneisses in the NDZ suggest that also the gneisses surrounding the eclogites were involved in the continental deep subduction of the SCB. Following the UHP and HP eclogite-facies metamorphism, however, the eclogites from the NDZ were first subjected to granulite-facies overprinting, and later to amphibolite-facies retrogression (e.g., Liu et al., 2000, 2005; Xu et al., 2000). This peculiar P-T path suggests a different post-peak metamorphic evolution for different tectonic units (e.g., NDZ and CDZ) of the Dabie UHP belt. Therefore, although both the CDZ and NDZ units experienced UHP metamorphism, they had different exhumation histories, suggesting that CDZ and NDZ are two UHP slices decoupled after subduction (Xu et al., 2005; Liu et al., 2005, 2007a, 2007b; Liu and Li, 2008). As concerning the metamorphic history prior to the peak, Pb isotope investigations show that the UHP rocks from the CDZ are characterized by high radiogenic Pb while banded gneiss from the NDZ are characterized by low radiogenic Pb (Zhang et al., 2002a; Li et al., 2003); this suggests that the UHP rocks of the CDZ were derived from subducted upper crust, while the UHP rocks of the NDZ were derived from subducted felsic lower continental crust with minor mafic boudins or lenses (Li et al., 2003; Liu et al., 2007a, 2007b).

A peculiar geologic feature in the southwestern segment of the NDZ is the Luotian dome, which is a deeply eroded area with abundant felsic and mafic granulites around the Luotian county (Fig. 1). In the Luotian dome, unusual eclogites were found as lenses in garnet-bearing banded tonalitic gneisses (Liu et al., 2007a). These eclogites preserve early granulite-facies mineral relics and have been overprinted by regionally extensive HP granulite-facies metamorphism, followed by penetrative amphibolite-facies retrogression during exhumation. The eclogite-facies mineral assemblage is garnet and relict omphacite, with rutile, quartz, allanite and fluor-apatite as common constituents. While micro-diamonds were found in the northeastern part of the NDZ, no index UHP minerals such as coesite and micro-diamond were identified so far in southwestern part of the NDZ, i.e. in the Luotian dome area. Because of the lack of index UHP phases, it has been always difficult to determine accurately the peak conditions under which the eclogites were formed, thus feeding a number of arguments on the tectonic affinity and evolution of the NDZ.

The eclogites from the Luotian dome occur as bands, lenses and blocks, up to 3m thick (Fig. 2), and are often strongly retrogressed to (garnet) amphibolite. The studied samples were collected from Luotian (sample 03LT1-1), Jinjiapu (samples 03LT8-1, 06LT3-2 and 06LT4-2) and Shiqiaopu (samples 07LT6-1 and 09LT2-1), respectively (Fig. 1). Details of the petrography and mineral chemistry of the studied samples were given in a separate paper (Liu et al., 2007a) and are only summarized here. However, samples were chosen because of their relative abundance of mineral inclusions in zircon and garnet, and oriented mineral exsolutions in garnet, clinopyroxene and apatite. Sample 03LT1-1 is a strongly retrogressed eclogite, which is mainly composed of garnet, rutile, hornblende and plagioclase with minor quartz, diopside, hypersthene and ilmenite. Other eclogite samples are less retrogressed and are composed of garnet, omphacite, diopside and rutile, and minor hypersthene, hornblende, plagioclase, quartz and ilmenite. Despite the strongly pervasive granulite- and amphibolite-facies overprint, five metamorphic stages have been recognized for the eclogite of the NDZ (Liu et al., 2005, 2007a, 2010): (1) a granulite-facies stage, with P ~ 0.8 GPa; (2) a UHP eclogite-facies stage, with P = 4.0 GPa and T = 900–960 °C, witnessed by the occurrence of diamond (Xu et al., 2003, 2005; Liu et al., 2007b) and oriented mineral exsolutions in garnet and clinopyroxene (Tsai et al., 2000; Xu et al., 2003, 2005; Liu et al., 2007a; Malaspina et al., 2006); (3) a HP eclogite-facies stage, with P = 2.0 GPa and T = 800–900 °C, characterized by the coexistence of garnet, sodic clinopyroxene or jadeite-poor omphacite and rutile with quartz; (3) a retrograde granulite-facies stage, with P = 1.1–1.4 GPa and T = 804–857 °C, indicated by the presence of hypersthene, plagioclase and diopside symplectite; (4) a retrograde amphibolite-facies stage, with P = 0.6–0.7 GPa and T = 706–777 °C.

3. Analytical methods

Mineral inclusions in zircon and oriented needles in garnet and clinopyroxene were identified using Raman spectroscopy at the Continental Dynamics Laboratory, Chinese Academy of Geological Sciences (CAGS) and confirmed using the electron microprobe analyzer (EMPA) at the Institute of Mineral Resources, CAGS in Beijing. Furthermore, minerals relevant for this study were analyzed with a JEOL JXA-8800R EMPA at the Institute of Mineral Resources, CAGS in Beijing, The analytical conditions on the Raman and EMPA were reported by Xu et al. (2005) and Liu et al. (2009). The representative mineral compositions are presented in Table 1. The representative Raman spectra of mineral inclusions in zircon are reported in Fig. 6. Mineral abbreviations in figures and tables are after Kretz (1983).

4. Decompression textures

4.1. Double symplectites

In the studied samples, garnets are characterized by peculiar kelyphytic rims with two distinct reaction stages here referred as "double symplectites" (Fig. 3a and b): the fine-grained inner one is composed of amphibole and plagioclase and is inferred to derive from the decomposition of garnet during the amphibolite-facies retrogression; the outer symplectite between garnet and clinopyroxene or omphacite is mainly composed of very fine-grained hypersthene, diopside and plagioclase, and formed between reacting garnet and clinopyroxene under granulite-facies conditions; this outer symplectite is restricted to a very narrow zone. Both symplectites show vermicular texture and are devoid of mica, suggesting that the retrogressive reaction or decompression breakdown developed under fast exhumation rates and anhydrous conditions, such that the neoblastic minerals had insufficient time for recrystallization and occurred as symplectite, *i.e.* a rapid retrograde metamorphic process from eclogite- via granulite- and amphibolite-facies conditions (Liu et al., 2005, 2007a).

4.2. Needle exsolutions

A most spectacular feature of the eclogite in the NDZ is the ubiquitous occurrence of oriented needle exsolutions of different phases in clinopyroxene, garnet and apatite (Figs. 4a-d and 5a).

Oriented rods or needles in clinopyroxene can be divided into three types depending on their mineral assemblage. Type 1 clinopyroxene contains quartz rods (Fig. 4a), which have been considered to be the evidence for the prior existence of a supersilicic omphacite stable at UHP conditions (≥ 2.5 GPa) (cf. Liou et al., 1998 for a review), and occur as discrete grains in the matrix or as inclusions in garnet. Type 2 clinopyroxene contains quartz + sodic plagioclase + orthopyroxene + amphibole needles (Fig. 4b). Type 3 clinopyroxene contains quartz + orthopyroxene lamellae (Fig. 4c). All these microtextures show that the precursor clinopyroxene was rich in Si and Na during the peak metamorphic conditions. Worth of note is that ultrahigh-temperature (UHT) conditions (> 900 ºC; Harley, 1998) may be suggested by orthopyroxene lamellae from clinopyroxene (type 3) as reported by Nakano et al. (2007). However, although UHT metamorphic conditions of 905–917 ºC can be inferred by applying Cpx-Opx geothermometry (Wood and Banno, 1973; Wells, 1977) to the hypersthene lamellae and the host clinopyroxene at their contact, more data are needed to better constrain this event and to define its geological significance.

Most of oriented rods or needles in garnet are rutile; few garnet crystals host rutile + clinopyroxene + amphibole + apatite needles (Fig. 4d), which attest to the presence of a Si-Ti-Na-P-rich precursor garnet phase (majorite) stabilized at UHP conditions (> 5–7 GPa) (Ye et al., 2000a; Mposkos and Kostopoulos, 2001; Song et al., 2005).

Needle exsolutions in apatite are made of pyrrhotite. The studied samples contain two types of apatite: type 1 is fluor (F)-apatite and occurs as inclusion in garnet or in the matrix, and is rich in F (~3 wt %) and devoid of any exsolutions; type 2 apatite is relatively poor in F (< 1 wt %) and is typically associated with the oriented pyrrhotite exsolution (Figs. 3d and 5a; Table 1). Type 1 apatite make a stable assemblage with the peak minerals such as garnet, omphacite, rutile and coesite (see below) and hence formed at UHP metamorphic conditions. The UHP origin of type 1 apatite is also supported by its high F contents because it has been demonstrated that F in apatite increases with metamorphic grade and pressure (Spear and Pyle, 2002). In contrast, type 2 apatite may be the result of breakdown during decompression.

4.3. Quartz inclusions

Quartz inclusions in garnet from the studied eclogites always show sub-rounded to elliptical shapes and occur both as single crystals, and as polycrystalline aggregates 50 to 150 μm in size (Figs. 3c and 4f). Around single large monocrystalline and polycrystalline quartz inclusions (> 30 μm), tensional cracks are typically developed radiating into garnet (Fig. 3c), whereas only a few irregular joints are present around very small (< 10 μm) quartz inclusions. For other mineral inclusions, radial fracturing of garnet is much less common. The observed textural characters of the quartz inclusions are commonly indicated as decompression features and are often considered as diagnostic for the identification of quartz pseudomorphs after coesite within a rigid host (Chopin, 1984).

4.4. Coesite relics

Zircon is probably the best container for relict UHP metamorphic phases because of its chemical inactivity and extreme stability over a wide P–T interval (e.g., Chopin and Sobolev, 1995; Liou et al., 1998; Tabata et al., 1998; Parkinson and Katayama, 1999). It has been widely used to determine the presence of UHP phases, including coesite and diamond in country rock gneisses and to establish the P–T path of deeply subducted terranes (e.g., Tabata et al., 1998; Katayama et al., 2000b; Ye et al., 2000b; Liu et al., 2001, 2002, 2007b).

Recently Liu et al. (2010) analyzed by Raman spectroscopy, a number of quartz inclusions in zircon from one of the retrograded eclogite studied in this paper (sample 03LT1-1) and found a strong peak of quartz at 466 cm^{-1} but also a weak peak of coesite at 521 cm^{-1} (Fig. 6). Such peaks represent fundamental vibrations of coesite along with the typical quartz vibration as reported from quartz-transformed coesite in UHP rocks (Ghiribelli et al., 2002; Liu et al., 2002; Zhang et al., 2005). This spectral feature strongly support the presence of trace relic coesite in quartz, which might have escaped its complete transformation during decompression.

5. Discussion and interpretation

5.1. Coesite and other indicators of UHP metamorphism

The discovery of coesite in crustal rocks (Chopin, 1984; Smith, 1984) first introduced a very powerful indicator of UHP metamorphism. Unlike diamonds, the presence of only one coesite inclusion undoubtedly provides evidence for an UHP origin of the host mineral (Korsakov et al., 2009). However, due to the reaction kinetics of the coesite to quartz transformation (Mosenfelder and Bohlen, 1997; Perrillat et al., 2003 and references therein), fresh coesite rarely survives even when it is included in robust minerals. In most cases, relics of coesite are present in the core of polycrystalline quartz aggregates, surrounded by a radial crack pattern (e.g., Mosenfelder et al., 2005). These partial or complete pseudomorphs of quartz after coesite are ubiquitous over a wide range of lithologies in various orogens of different ages, and are typically involved in a multistage metamorphic history related to exhumation. These pseudomorphs are also typically used together with other mineralogical indicators to prove that the rocks experienced UHP metamorphic conditions.

In contrast to other sectors of the NDZ, micro-diamonds have not been found in the Luotian dome in the southwestern part of the NDZ; however, there are other clues supporting the UHP metamorphism over the whole unit.

Firstly, the occurrence of mineral quartz exsolutions. Although Page et al. (2005) suggested that the presence of quartz rods in clinopyroxene does not require UHP metamorphism, relic coesite rods in eclogites of Tianshan in China (Zhang et al. 2005) clearly demonstrated that SiO_2 exsolution in clinopyroxene occurred in the coesite stability field and that most exsolved coesite rods in clinopyroxene transformed to quartz during retrograde metamorphism with only minor amounts of remnant coesite being present. Dobrzhinetskaya et al. (2002) proposed that oriented SiO_2 precipitation in omphacite from eclogite in the Alpe Arami garnet peridotite massif, Swizerland, occurred at P-T conditions of 7.0 GPa and 1100 °C. Experimental studies also indicated that supersilicic clinopyroxene formed under HP–UHP and HT conditions of 2.5–3.2 GPa at 1400–1500 °C (Wood and Henderson 1978), 3.5–7.0 GPa at 1200 °C (Zharikov et al. 1984), and 2–3 GPa at 1200–1400 °C (Gasparik 1986). Mao (1971) found that at 4 GPa and 1100–1700 °C, clinopyroxene contains 7.5 wt% excess SiO_2, and its excess SiO_2 increases with pressure. Therefore, based on natural and experimental data, quartz exsolution in clinopyroxene are fully compatible with, and strongly suggest, UHP and HT conditions because natural rocks containing clinopyroxene with quartz rods usually coexist with garnet or zircon containing coesite, or its quartz pseudomorph, or micro-diamond inclusions (e.g., Xu et al., 1992, 2005; Zhang et al., 1995; Liou et al., 1998; Katayama et al. 2000; Liu et al., 2007b). In this regard, oriented rods or needles in clinopyroxene from the eclogites in the Luotian Dome most likely witness a former UHP stage as suggested by Tsai and Liou (2000), and this microtextural evidence is fully consistent with the presence of relic coesite in zircon from one of the studied samples. Additionally, garnet from the studied eclogites contains rutile + clinopyroxene + amphibole + apatite oriented needles, which were ascribed by a number of authors (Ye et al., 2000a; Mposkos and Kostopoulos, 2001; Song et al., 2005) to be precursors of UHP condition at P > 5–7 GPa.

Another important evidence for UHP metamorphism in the studied area is the occurrence of quartz and relic coesite inclusions. Among all studied quartz inclusions in garnet, the majority is of the monocrystalline type (Fig. 3c), some are of the polycrystalline type (2 to 5 grains per inclusion, Fig. 4e and f), and only one inclusion within a zircon of sample 03LT1-1 gives Raman evidence of relic coesite based on the presence of an additional band at 521 cm^{-1} in the spectrum (Fig. 6c), corresponding to the most intense fundamental vibration in coesite. Numerous studies on natural coesite samples have documented that fundamental coesite and quartz frequencies can be present in single coesite spectra (Boyer et al., 1985; Ghiribelli et al., 2002; Liu et al., 2002; Zhang et al., 2005). This apparent discrepancy can be easily explained when the coesite grains are smaller than the laser beam to include some of the surrounding quartz, or because of incipient coesite transformation to quartz, although in some cases this effect can be induced by the laser itself. Moreover, a fracture goes through the coesite/quartz inclusions in zircon from sample 03LT1-1 (Fig. 6a), most likely resulting in the transformation of coesite to quartz.

In addition, a number of monocrystalline and polycrystalline quartz inclusions are enclosed in garnet with well-developed radial fractures (Figs. 3c and 4e), which are indicated as decompression features and are often considered to be diagnostic for the identification of quartz pseudomorphs after coesite within a rigid host (e.g., Chopin, 1984; Smith, 1984). However, although the presence of such textural features should be treated with caution because they are not unique to coesite transformation as suggested by Chopin & Sobolev (1995), the finding of relic coesite in the same rock samples supports the possibility that polycrystalline and monocrystalline quartz inclusions in garnet with radial cracks were formerly coesite, now inverted to quartz.

Therefore, the studied eclogites show radial fractures within garnet around quartz pseudomorphs and rare coesite relics documenting that they underwent UHP metamorphism, whereas multiple-phase needles in garnet show that the eclogites suffered UHP metamorphism with a possible pressure > 5–7 GPa. Other mineralogical and microtextural indicators, such as exsolved needles in clinopyroxene and F-apatite, are also present in the eclogite from the studied area and support peak UHP conditions.

5.2. Factors helping the poor preservation of UHP traces

Rapid exhumation for most UHP terranes has now been confirmed with geochronological data (e.g., Gebauer et al. 1997; Rubatto and Hermann 2001; Carswell et al. 2003; Mosenfelder et al., 2005 and references therein) and stable isotope data (Zheng et al., 2003). This geodynamic mechanism also help to some extent the preservation of coesite and related UHP phases. However, according to many authors (e.g., Liou and Zhang, 1996; Liou et al., 1997; Mosenfelder et al. 2005 and references therein), the preservation of coesite and other UHP evidences may depend on many factors including the rigidity of the host mineral, the P-T conditions and path of metamorphic crystallization, the rate of exhumation, continuous cooling during decompression, and prevention of fluid infiltration into the host mineral until fracturing at low temperatures or the presence of fluids during retrogression. Perhaps the most vital factor for the survival of coesite is its inclusion in strong host phases, such as garnet and zircon, which can act as “pressure vessels” and sustain an overpressure on the inclusion, inhibiting the volume increase necessary to transform it to quartz. That is to say, mineral inclusions in zircon or garnet may witness peak metamorphism or earlier stages of metamorphism (Chopin, 2003).

The petrologic observations described in this paper clearly reveal that the studied eclogites suffered a complex metamorphic evolution resulting in multistage decompression related to exhumation, which most likely obliterated almost all of the earlier evidence for coesite and UHP metamorphism. As a consequence, so far few evidence for UHP metamorphism has been found in the NDZ. The poor preservation of UHP conditions in the eclogites and orthogneisses of the NDZ might be also favored by the presence of partial melts during decompression from coesite- or diamond- to granulite-facies conditions as experimentally documented by Hermann et al. (2001), which is supported by the evidence for partial melting of the eclogites (Liu Y.-C. et al., unpublished data). Unfortunately, the textures of the orthogneisses cannot be used to prove this hypothesis because of their felsic composition and the subsequent, pervasive granulite- and amphibolite-facies overprint.

The P-T path followed by the eclogites of the NDZ (Fig. 7) maintained high- to very-high-temperature conditions for a long way from the early stages of uplift at

UHP conditions to HP granulite-facies overprinting. This peculiar P-T evolution, together with the influx of later abundant fluid circulation during the amphibolite-facies retrogression, may contribute to explain the extremely rare preservation of coesite and related UHP relics (Liou and Zhang, 1996; Mosenfelder et al., 2005). The early post-peak P-T history of the NDZ eclogites (Liu et al., 2000, 2007a; Xu et al., 2000), allowed to retain equilibration temperatures exceeding 850 °C during exhumation up to lower crustal levels (1.1-1.4 GPa and 804–857 °C); the following evolution is marked by both temperature and pressure decrease (Fig. 7). In such a P-T path, characterized mainly by isothermal decompression, the difference between internal and external pressure of garnet reaches its maximum at the end of isothermal decompression, and garnet fracturing would occur at high temperatures (> 800°C), leading to rapid diffusion (Nakano et al., 2007) and slow cooling with a complete breakdown of coesite (Ghiribelli et al., 2002; Faryad et al., 2010) or even the possibility that in most cases coesite would have been consumed (Tsai and Liou, 2000) at such HT condition during the granulite-facies overprint.

5.3. Implications for the exhumation of UHP rocks

The data presented in this paper show that the eclogites from the Luotian dome in the NDZ experienced a multistage and relatively slow cooling process at high-T conditions after peak UHP metamorphism, with a widespread HP granulite-facies overprinting. In contrast, the CDZ and SDZ underwent rapid exhumation and cooling from the eclogite-facies to the amphibolite-facies metamorphic stage without any granulite-facies overprinting. As a result, the eclogites in the NDZ are characterized by peculiar multiple decompression microtextures, and do not preserve almost any evidence of UHP metamorphism because of complete retrogression of UHP minerals due to action of fluids during the late amphibolite-facies overprinting and/or to the complete decomposition of coesite and related minerals during high-T exhumation. Therefore, the Dabie orogen comprises three eclogite-bearing terranes (i.e., the NDZ, CDZ and SDZ), all subjected to UHP metamorphism, characterized by different evolutional processes and exhumation histories. This conclusion further supports the model for multi-slice and multistage successive exhumation of UHP metamorphic rocks proposed by Liu et al. (2007b).

6. Conclusions

The eclogites from the NDZ underwent a prolonged exhumation history from eclogite- via granulite- and amphibolite-facies conditions, resulting in the common formation of peculiar multistage decompression textures and the extremely rare preservation of former UHP metamorphic evidence. The studied eclogites were strongly affected by multiple recrystallization processes during exhumation, thus making the determination of peak metamorphic conditions particularly difficult. However, the occurrence of radial cracks around quartz inclusions and of polycrystalline quartz inclusions in garnet, most likely suggests that these inclusions formerly were coesite, now inverted to quartz. This hypothesis is also supported by the presence of relic coesite which has been confirmed by Raman spectroscopy.

Moreover, the occurrence of rutile + clinopyroxene + amphibole + apatite oriented needles in garnet open the possibility of peak pressure exceeding 5-7 GPa in the NDZ. An important consequence of this study is that if the eclogites from the Luotian dome suffered UHP metamorphism, they are perfectly comparable to those from the northeastern part of the NDZ; in this respect, the NDZ wholly experienced Triassic UHP metamorphism as a coherent unit.

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Figure captions

Figure 1 Schematic geological map of the Dabie orogen. Sample localities with sample numbers are described in detail in the text. BZ = Beihuaiyang zone, NDZ = North Dabie complex zone, CDZ = Central Dabie UHP metamorphic zone, SDZ = South Dabie low-T eclogite zone, SZ = Susong complex zone, HMZ = Huwan mélange zone, HZ = Hong'an low-T eclogite zone, DC = amphibolite-facies Dabie complex, XMF= Xiaotian-Mozitan fault, WSF= Wuhe-Shuihou fault, HMF = Hualiangting-Mituo fault, TSF= Taihu-Shanlong fault, TLF = Tan-Lu fault. The inset shows the location of Fig. 1 within the Triassic Qinling—Dabie—Su-Lu collision orogen in central China.

Figure 2 Field occurrence of eclogite band (a) and lens (b) from the Luotian dome in the southwestern part of the North Dabie complex zone.

Figure 3 Photomicrographs of eclogite from the Luotian dome in the Dabie orogen. a. Omphacite inclusion in garnet with two generations of symplectites (Hy+Di+Pl and Hbl+Pl+Mt), sample 06LT4-2; b. Omphacite, rutile and quartz inclusions in garnet, rimmed by distinctive double symplectites, sample 07LT6-1; c. quartz inclusion in garnet with well-developed radial fractures, sample 07LT6-1; d. Apatite (Ap) occurs as inclusion in garnet and in the matrix, the former is fluor-apatite (F-Ap) and the latter contains oriented pyrrhotite exsolutions (Po), sample 06LT4-2.

Figure 4 Photomicrographs (a and d–f) and Back scattered electron (BSE) images (b and c) of eclogite from the Luotian dome showing multiple decompression textures. a. Diopside inclusion with quartz rods in garnet, sample 03LT1-1; b. Qtz + Pl + Hbl + Hy oriented needles in clinopyroxene, sample 03LT8-1; c. Qtz + Hy oriented needles in clinopyroxene, sample 06LT3-2; d. Cpx + Rt + Hbl + Ap oriented needles in garnet, sample 03LT1-1; e. Quartz after coesite in garnet, sample 09LT2-1; f. Cross-polarized light image of (e), showing polycrystalline quartz inclusions in garnet.

Figure 5 a. Photomicrograph showing needle pyrrhotite (Po) exsolutions in apatite (Ap) and Cpx with quartz needles, sample 06LT3-2; b. The EDS spectra of exsolution rods in apatite from (a).

Figure 6 Photomicrographs (a and b) of coesite (Cs) and quartz (Qtz) inclusion in zircon (Zr) and their mixed Raman spectra (c); zircon separated from the eclogite sample 03LT1-1 from the Luotian dome. The black circle in (a) is LA-ICPMS dating analysis with available $^{206}Pb/^{208}U$ age shown.

Figure 7 Multistage exhumation P-T trajectory of the NDZ eclogites, based on available data from the north-eastern portion of the NDZ (Malapina et al., 2006) and from the Luotian dome (Liu et al., 2007a).

Table captions

Table 1 Electron microprobe analyses of representative minerals from the eclogites in the Luotian dome (wt%)

Figure 1

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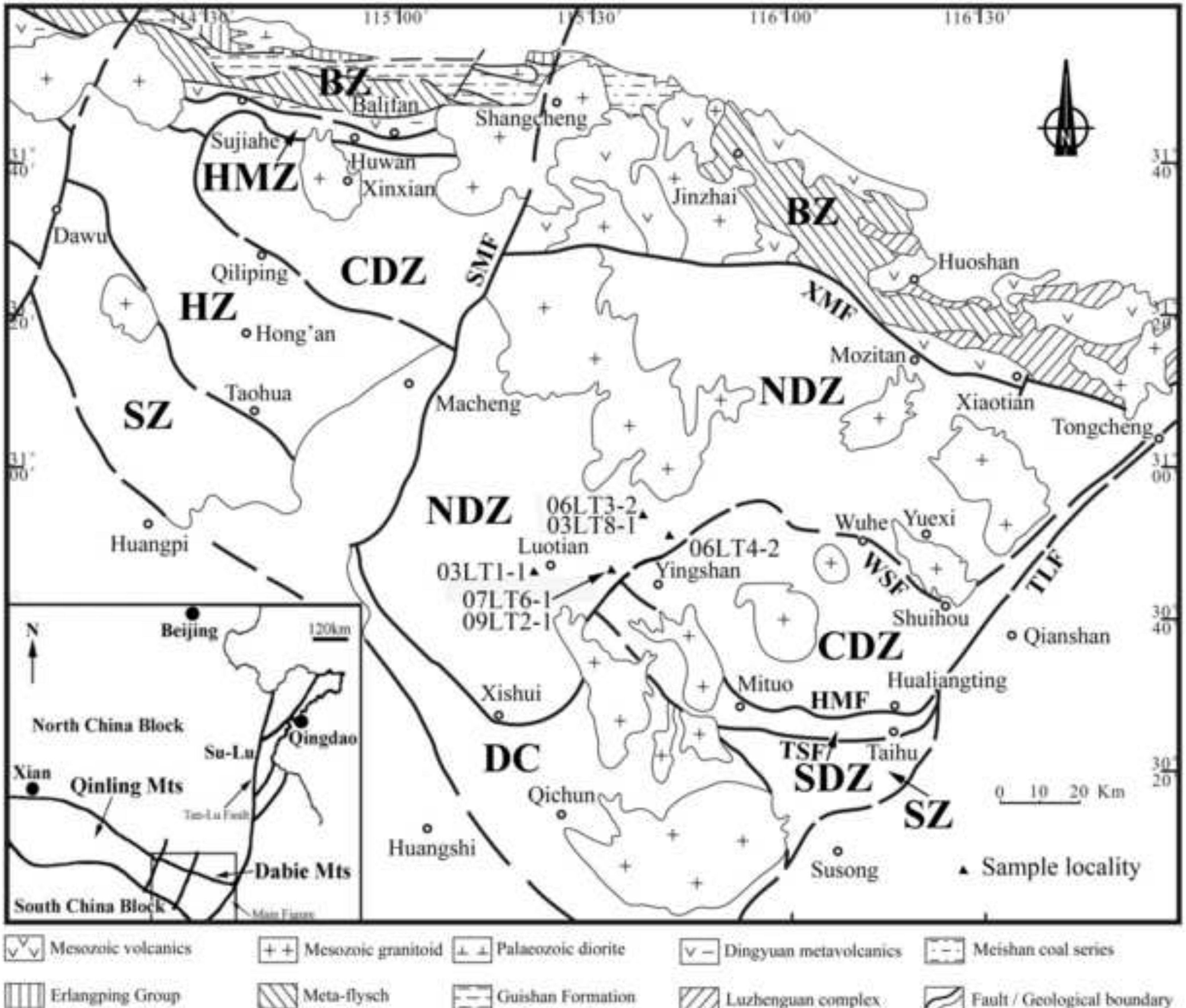

Figure 1

Figure 2
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Figure 2

Figure 3
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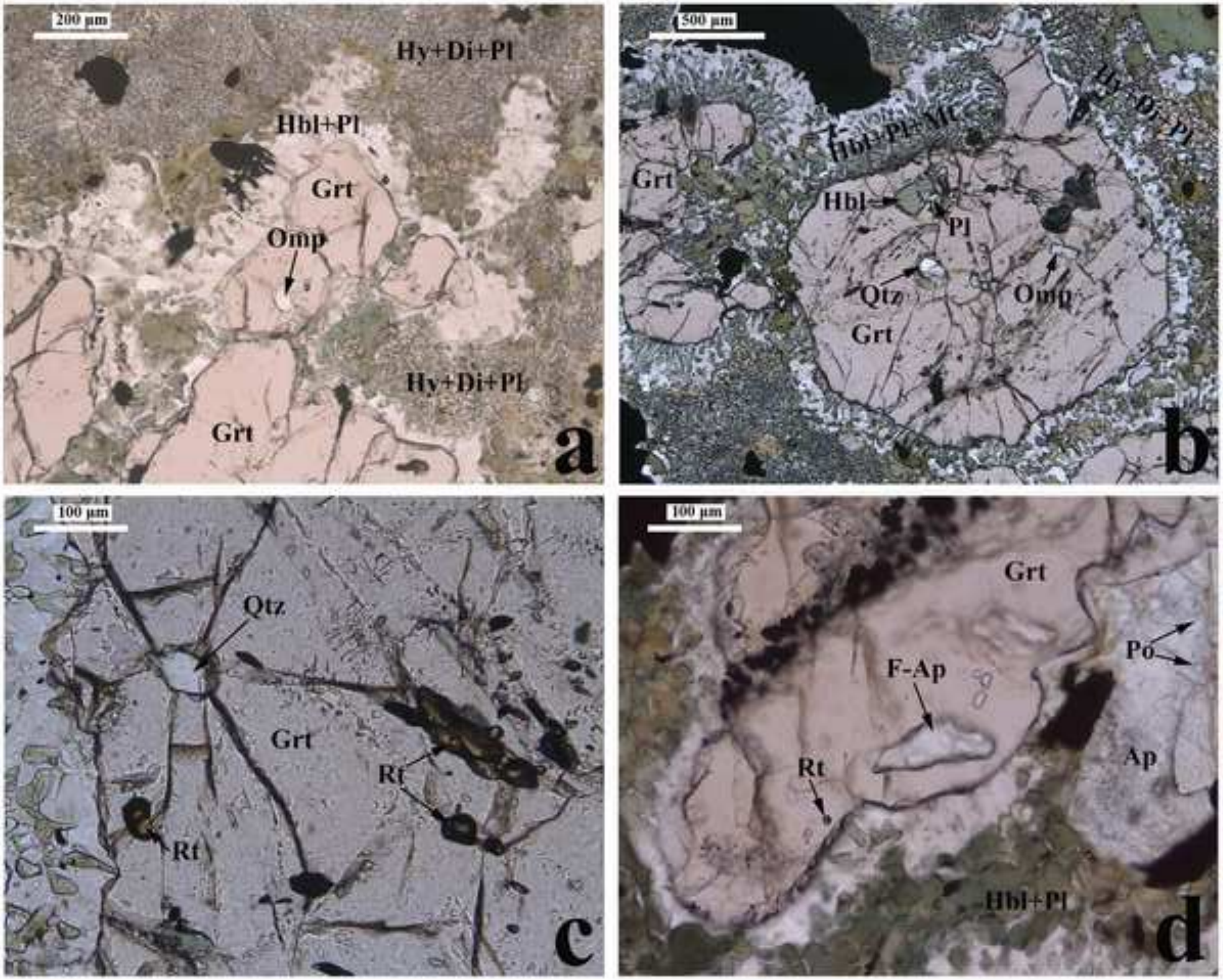

Figure 3

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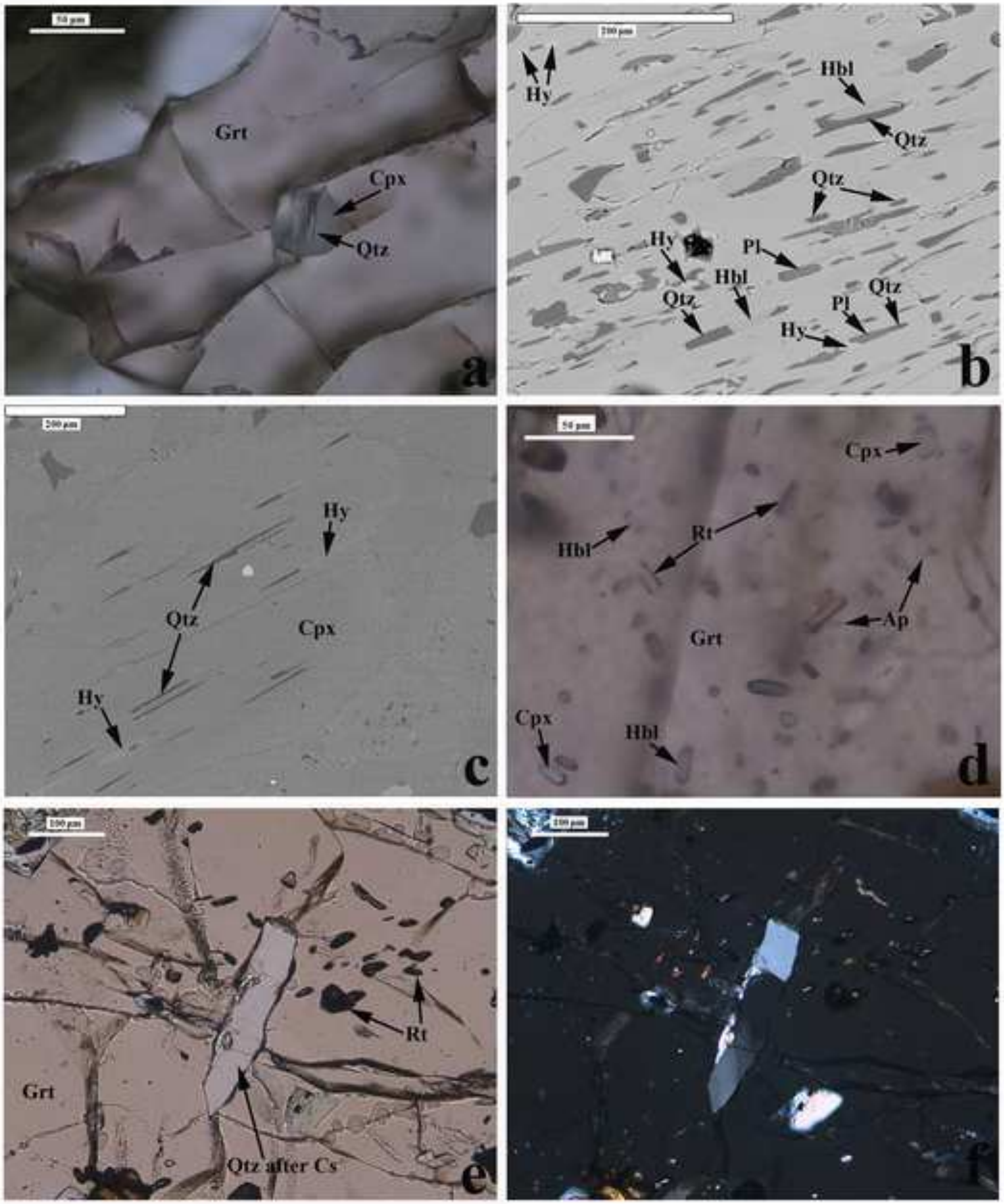

Figure 4

Figure 5
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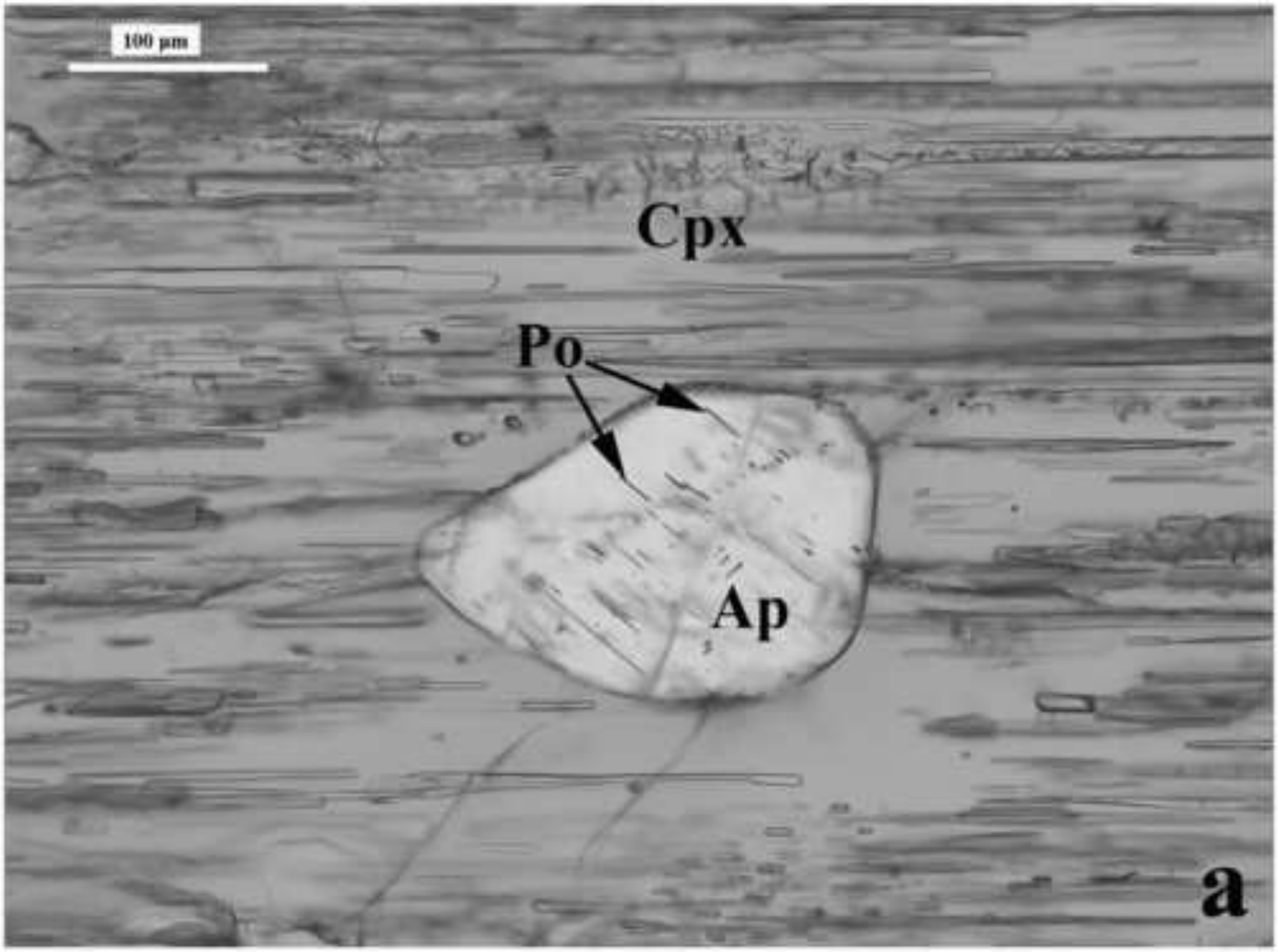

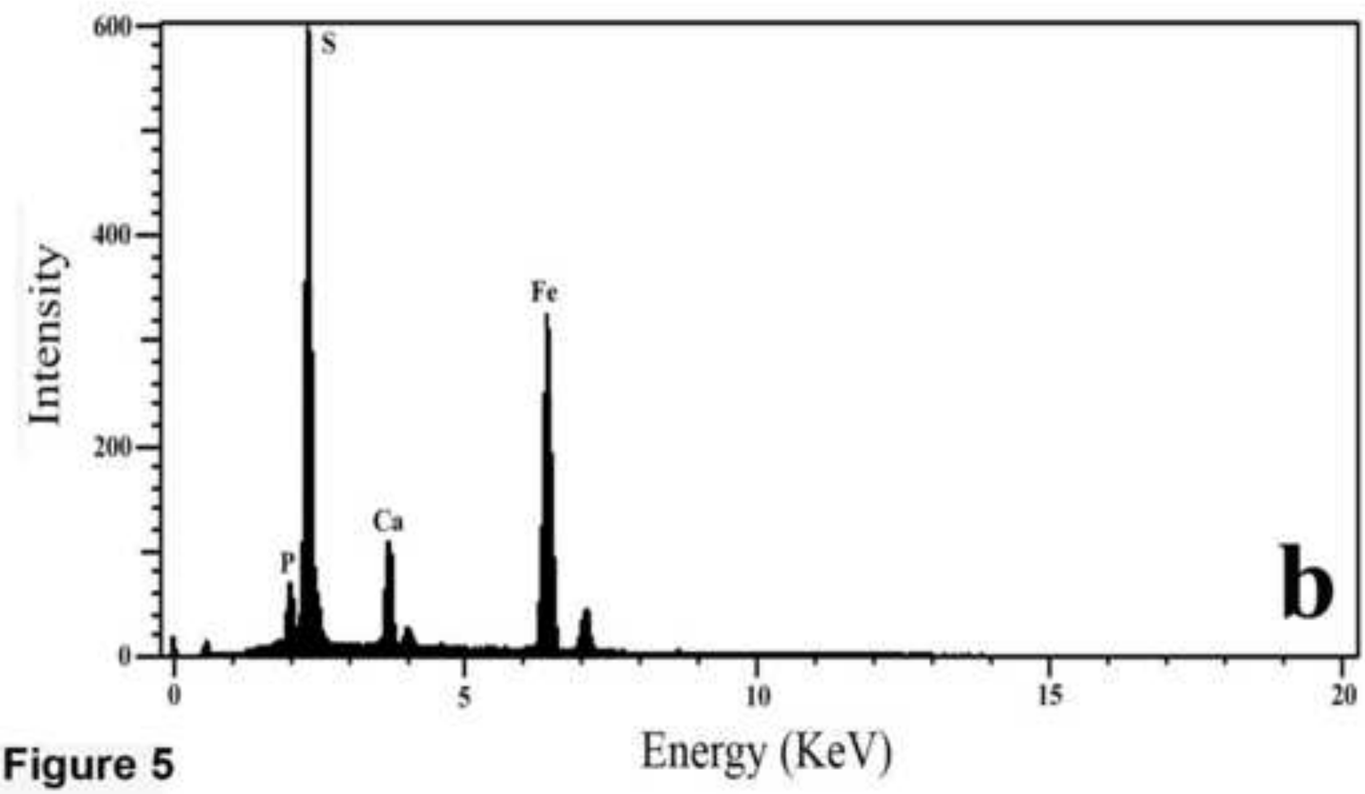

Figure 5

Figure6
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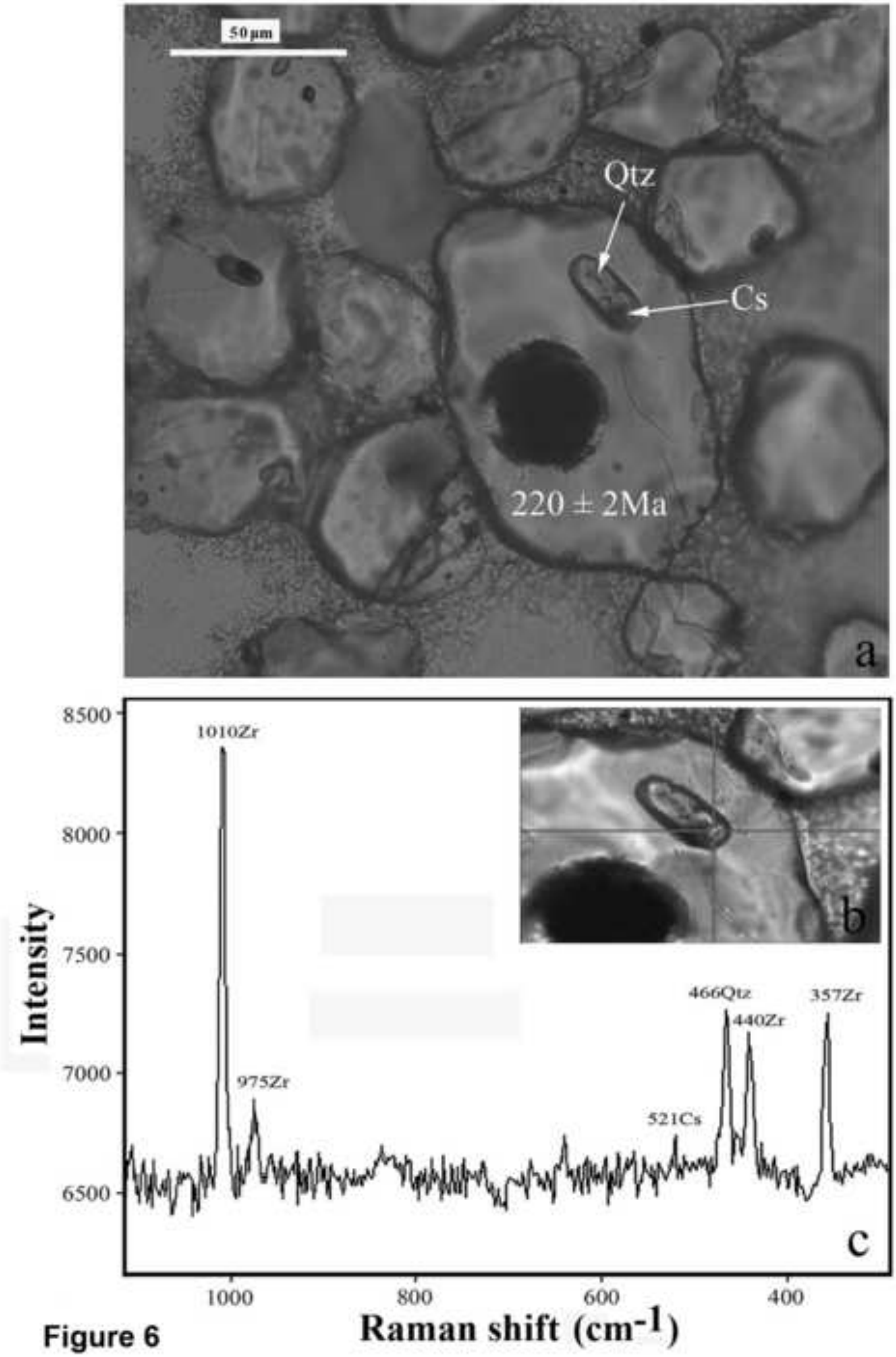

Figure 6

Figure 7
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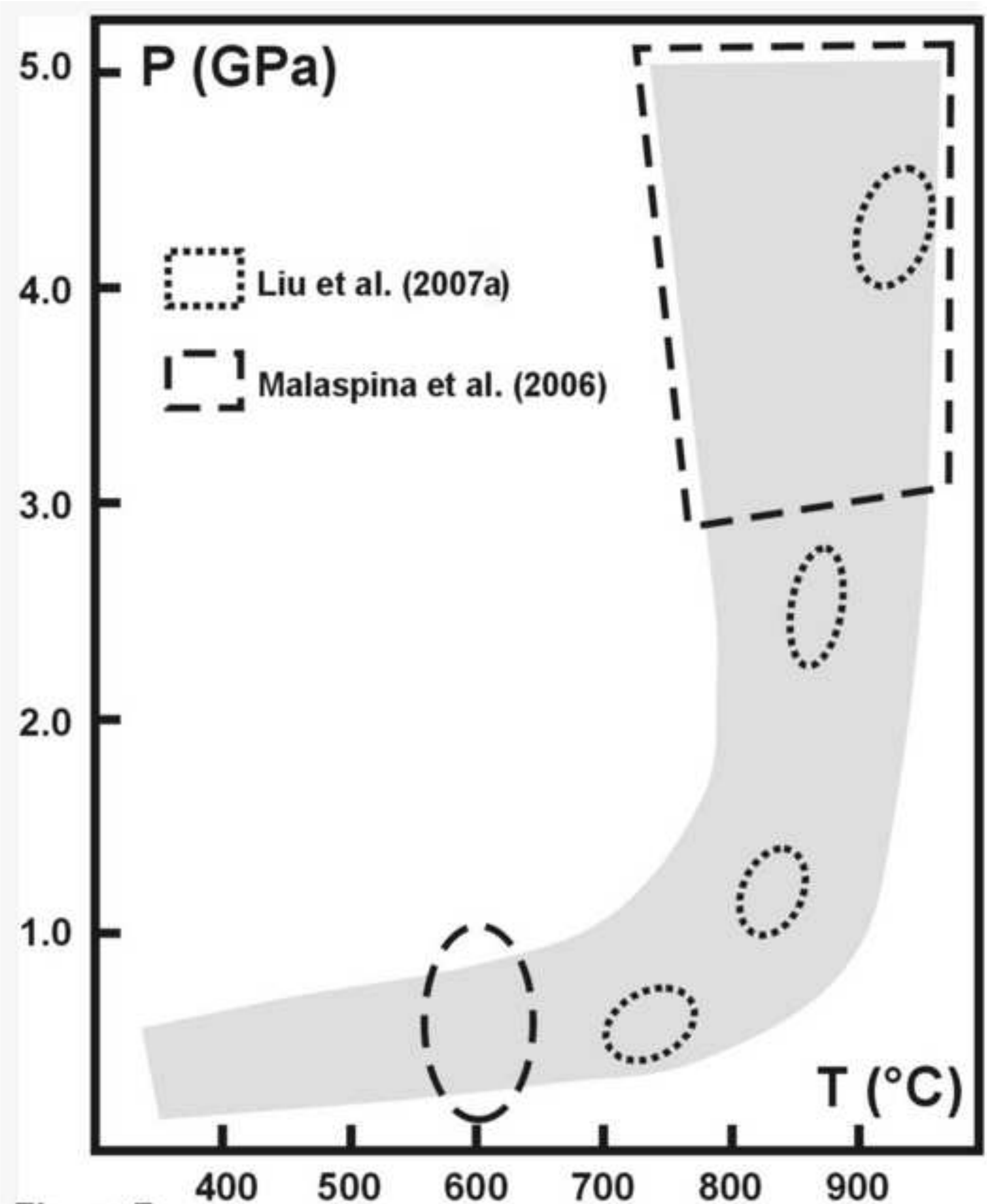

Figure 7

Table

Table 1

Mineral	Garnet		Omphacite		Diopside	Hornblende		Plagioclase	
No.	06LT3-2	06LT4-2	06LT3-2	06LT4-2	06LT3-2	06LT3-2	06LT3-2	03LT1-1	06LT3-2
Locality	m	m	i	i	ng	nc	ng	nc	nc
SiO_2	38.88	38.43	54.45	55.28	52.7	45.12	38.65	61.2	61.46
TiO_2	0.02	0.07	0	0.04	0.1	0.08	0.73	0	0
Al_2O_3	21.24	21.88	4.84	11.03	3.5	12.21	18.36	24.11	23.55
FeO	24.1	24.84	6.15	6.86	6.38	9.2	12.07	0	0.23
Cr_2O_3	0	0	0.02	0	0.04	0.04	0	0	0
MnO	0.52	0.38	0.02	0.02	0.05	0.04	0.02	0.24	0.02
MgO	8.14	5.78	12.71	7.38	14.05	15.13	11.45	0	0.01
CaO	7.07	8.91	18.34	12.24	22.28	11.53	11.39	5.7	4.92
Na_2O	0	0.12	2.95	7.33	0.83	2.27	2.89	8.71	9.05
K_2O	0	0	0	0.01	0.01	0.03	0.02	0.01	0.02
Total	99.97	100.41	99.48	100.19	99.94	95.65	95.58	99.97	99.26
O	12	12	6	6	6	23	23	8	8
Si	2.985	2.964	1.986	1.967	1.938	6.526	5.71	2.723	2.749
Al^{IV}	0.015	0.036	0.014	0.033	0.062	1.474	2.29	1.263	1.241
Al^{VI}	1.905	1.951	0.194	0.430	0.09	0.606	0.904		
Fe^{3+}	0.102	0.09	0.028	0.106	0.025	0.626	0.787	0	0
Ti	0.001	0.004	0.000	0.001	0.003	0.009	0.081	0	0
Fe^{2+}	1.445	1.512	0.160	0.098	0.171	0.484	0.704	0.009	0.009
Cr	0	0	0.001	0	0.001	0.005	0	0	0
Mg	0.932	0.664	0.691	0.392	0.77	3.263	2.522	0	0.001
Mn	0.034	0.025	0.001	0.001	0.002	0.005	0.003	0	0.001
Ca	0.581	0.736	0.717	0.467	0.878	1.787	1.803	0.272	0.236
Na	0	0.018	0.209	0.506	0.059	0.637	0.828	0.751	0.785
K	0	0	0	0	0	0.006	0.004	0.001	0.001

Note: m, matrix; ng, oriented needle in garnet; nc, oriented needle in clinopyroxene; i, inclusion; sy, symplectite.

Continued Table 1

Mineral	Apatite		Diopside		Hypersthene		Hornblende	Plagioclase	
No.	06LT3-2	06LT4-2	07LT6-1	06LT3-2	06LT3-2	07LT6-1	07LT6-1	07LT6-1	07LT6-1
Locality	m	i	sy	m	nc	sy	sy	sy	sy
SiO_2	0.00	0.00	53.28	54.39	54.89	51.22	42.26	58.82	55.19
TiO_2	0.02	0.00	0.18	0.03	0.00	0.08	0.86	0.02	0.04
Al_2O_3	0.01	0.00	1.33	3.90	2.10	0.36	14.94	25.93	28.5
FeO	0.17	0.37	7.10	6.59	18.9	29.73	13.53	0.36	0.54
Cr_2O_3	0.01	0.01	0.11	0	0.01	0.01	0.16	0.00	0.00
MnO	0.02	0.00	0.10	0.03	0.13	0.47	0.06	0.02	0.01
MgO	0.08	0.04	14.81	13.99	23.42	17.75	11.15	0.02	0.02
CaO	55.69	54.45	22.61	20.35	0.50	0.59	9.33	6.98	10.15
Na_2O	0.06	0.00	0.42	1.52	0.01	0.02	4.12	7.42	6.02
K_2O	0.00	0.01	0.01	0.00	0.02	0.00	0.08	0.01	0.02
P_2O_5	41.13	41.81							
F	1.00	3.09							
Total	98.19	99.78	99.95	100.86	99.98	100.23	96.49	99.58	100.49
O			6	6	6	6	23	8	8
Si			1.969	1.974	2.018	1.968	6.200	2.635	2.480
Al^{IV}			0.031	0.026	0.000	0.016	1.800	1.368	1.508
Al^{VI}			0.027	0.141	0.091	0.000	0.781		
Fe^{3+}			0.022	0.000	0.000	0.045	0.691	0.000	0.000
Ti			0.005	0.001	0.000	0.002	0.095	0.001	0.001
Fe^{2+}			0.198	0.098	0.581	0.911	0.968	0.013	0.020
Cr			0.003	0	0.000	0.000	0.019	0.000	0.000
Mg			0.816	0.757	1.284	1.017	2.438	0.001	0.001
Mn			0.003	0.002	0.004	0.015	0.007	0.001	0.000
Ca			0.895	0.791	0.020	0.024	1.466	0.335	0.489
Na			0.030	0.107	0.001	0.001	1.172	0.645	0.524
K			0.000	0	0.001	0.000	0.015	0.001	0.001

Note: m, matrix; ng, oriented needle in garnet; nc, oriented needle in clinopyroxene; i, inclusion; sy, symplectite.