

Multiphase solid inclusions in ultrahigh-pressure metamorphic rocks: a petrographic approach

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ABSTRACT. — The study of fluid inclusions in ultra high-pressure (UHP) rocks does not represent an easy task, since most peak inclusions are destroyed during post-metamorphic uplift. Peak metamorphic conditions are in fact largely outside the isochore fields even for the densest fluid solutions, and the exhumation P-T paths of the host rocks strongly favour chemical interaction with the host mineral. Despite these difficulties, a number of documented examples show that inclusions in these metamorphic rocks might be preserved, providing valuable information on the composition of fluids at UHP, which are precursor to subduction fluids. Most peak inclusions in UHP rocks are multiphase solid (MS), containing different silicates \pm salts, and no or very subordinate amount of water. A petrographic approach to MS inclusion studies in UHP rocks is proposed, consisting of a number of successive investigation steps (i.e. identification, chronology, selection, and interpretation). Since MS inclusions represent an integral part of UHP metamorphic phase assemblages, they should be systematically investigated during any petrographic study of such rocks.

RIASSUNTO. — Lo studio delle inclusioni fluide in rocce metamorfiche di pressione molto alta è

complesso in quanto la maggior parte delle inclusioni sono state distrutte durante il sollevamento post-metamorfico. Infatti, anche considerando le soluzioni fluide più dense, le condizioni di picco sono molto lontane dalle condizioni P-T attraversate dalle isocore dei fluidi. Inoltre, le traiettorie P-T di esumazione di queste rocce favoriscono l'interazione chimica tra l'inclusione ed il minerale ospite. Nonostante queste difficoltà, numerosi esempi documentano la possibilità che si preservino inclusioni fluide anche in rocce metamorfiche di pressione molto alta. Queste inclusioni forniscono preziose informazioni sulla composizione dei fluidi in condizioni di pressione estrema. Molte delle inclusioni di picco in rocce di pressione molto alta sono inclusioni solide multifase, cioè inclusioni che contengono vari silicati \pm sali e sono prive di acqua, o ne contengono in quantità decisamente subordinata. Il presente articolo propone un approccio petrografico allo studio delle inclusioni solide multifase che consiste in una serie di indagini successive: riconoscimento, cronologia, scelta e interpretazione. Poiché le inclusioni solide multifase rappresentano una parte integrante della paragenesi metamorfica di pressione molto alta, dovrebbero essere sistematicamente indagate in tutti gli studi petrografici che si effettuano su questo tipo di rocce.

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KEY WORDS: *petrography, ultrahigh-pressure metamorphism, fluid inclusions, multiphase solid inclusions.*

INTRODUCTION

Ultrahigh-pressure (hereafter UHP) metamorphic rocks represent an excellent natural laboratory to study the nature and evolution of fluid phases in deep subduction zones. They have been carried down to a depth of at least 100 - 150 km and converted to eclogite-facies rocks, but have retained a number of original features, such as fluid inclusions in peak metamorphic minerals. These may have formed at UHP conditions, in the stability field of coesite and/or diamond (e.g. Philippot *et al.*, 1995; Carswell and van Roermund, 2005).

In UHP rocks, three main types of fluid inclusions might be considered representative for the composition of peak fluids (see the reviews by Scambelluri and Philippot, 2001; Touret and Frezzotti, 2003): 1) "gaseous" (N_2 - CO_2 - CH_4), 2) chloride-bearing aqueous, and 3) multiphase solid, containing different silicates \pm salts, and no or very subordinate amount of liquid water. The two first types - gaseous and brine fluid inclusions - have been extensively studied, allowing to identify H_2O - N_2 mixtures of variable salinities \pm CO_2 as typical peak fluids in UHP rocks from different metamorphic belts (e.g. Klemm and Bröcker, 1999; Xiao *et al.*, 2000, 2002, 2006; Franz *et al.*, 2001; Fu *et al.*, 2001, 2002, 2003a, 2003b; Fan *et al.*, 2002, 2003; Zhang *et al.*, 2005; Xu *et al.*, 2006).

Multiphase solid (hereafter MS) inclusions in UHP rocks were first reported by Philippot (1993) in pyrope from Dora-Maira whiteschists, and since then, they have received a progressively growing interest, because of their very common occurrence and peculiar characteristics. They testify for the presence of solute-rich aqueous fluids at peak conditions (e.g. Philippot and Selverstone, 1991). In all UHP belts where they have been observed, MS inclusions are constantly characterized by the presence of many different solid phases \pm a fluid. Although it is not always clear if all minerals contained within single MS inclusions are precipitated from the fluid (daughter minerals, Roedder, 1984), some general

trends were recognized (cf. Ferrando *et al.*, 2005a, 2005b; Frezzotti *et al.*, 2007, and references therein): i) most abundant daughter minerals are hydrous alkali-alumino-silicate phases; ii) phosphates, carbonates, sulfates, and chlorides occur in subordinate amounts; (iii) fluids are dominantly aqueous in composition, although their preservation is rare.

The present paper discusses some of the difficulties involved in the study of MS inclusions in UHP metamorphic rocks and proposes a petrographic approach to address correctly this issue. It involves both a discussion of the organization of MS inclusion studies and what data so far obtained can tell us about fluid evolution at extreme pressures. Although the study of MS inclusions is not straightforward, ongoing research confirms that they are worth to be investigated (see Hermann *et al.*, 2006, for a review).

THE STUDY OF FLUID INCLUSIONS IN METAMORPHIC ROCKS

The first description of fluid (and melt) inclusions in rock minerals occurred in the nineteenth century. H.C. Sorby (1858) first understood that "bubbles" in fluid and melt inclusions were formed due to shrinkage of the enclosed fluid, and he used these microsystems as tracers for the growth environment of minerals. It is not surprising that the founder of petrography (i.e. the description of rocks) paid attention to these tiny little features within single minerals. He was the first to look critically at rock sections (0.03 mm thickness) and at polished sections of metals with the microscope: "*In those early days people laughed at me. They quoted Saussure who had said that it was not a proper thing to examine mountains with microscopes, and ridiculed my action in every way. Most luckily I took no notice of them*" (Sorby, 1858).

But the "father" of fluid and melt inclusion study concentrated his effort mainly on the genesis of plutonic rocks (granites), paying, as a consequence, more attention to the melt- than to the fluid-inclusions. His scholar Vogelsang should be better considered as the pioneer for fluid inclusion studies in metamorphic rocks (Fig. 1a, Touret, 2004). He was the first scientist able to recognize CO_2 within inclusions in Saxonian

granulites, described as “*relatively small (a few tens of micrometers in diameter) and grayish inclusions, showing stunning ‘negative crystal’ shapes, and a gas bubble, the size of which rapidly decreased and disappeared upon heating to 30°C*” (Vogelsang, 1867). With the technical help of T. Geisler, he anticipated a very simple and efficient model of heating stage, a simple thermometer with an annular reservoir, heated by an electric resistance (Fig. 1b, Vogelsang and Geisler, 1869). Fundamentally, a similar system is used today for microthermometric measurements, recording the temperatures of the main phase transitions within single inclusions. The fluid composition is expressed by a number of microthermometric parameters: final melting temperatures for aqueous systems or non-permanent gases (CO₂), homogenization temperatures for low-critical temperature gases (CH₄, N₂).

The modern petrographic approach of fluid inclusions in metamorphic rocks was initiated with Jacques Touret’s investigations a hundred year later, in similar granulites from southern Norway (Touret, 1971). From Touret’s ground-

breaking work, he and many other authors have been showing the potentiality, but also the complexity of fluid inclusion studies in such rocks. The difficulties of such studies rely mainly on the large number (“*at least thousands*”) of fluid inclusions occurring within single rock-forming minerals, as well as to the fact that these inclusions may have been formed at different stages of the rock history (Touret, 1984, 2001, and references therein). An additional problem arises in HP and UHP metamorphic environments from the fact that peak inclusions have experienced the large pressure - and eventually temperature - differences applied to the host rock, with conspicuous chance of extensive post-trapping modifications (i.e. decrepitation and stretching and/or chemical re-equilibration; Sterner and Bodnar, 1989; Vityk *et al.*, 1994; Romer *et al.*, 2006, see below).

Thus, the study of MS inclusions in UHP rocks should follow in a very precise and rigorous way the procedure used for any other fluid inclusions in metamorphic rock, as described in Touret (1977, 2001), and Touret and Frezzotti (2003). A correct *modus operandi* involves four successive steps, which should precede any petrological interpretation (i.e. fluid origin, fluid migration through the rock system, fluid/rock interaction, etc.): 1) identification of the different preserved fluid types, 2) chronology of the successive inclusion generations, 3) selection of few representative inclusions for each fluid type, and 4) comparison between independent fluid inclusion and mineral P-T data. It is noteworthy to point out that most investigation steps are rigorously of petrographic nature, making such a study an integral part of conventional petrographic studies of rocks.

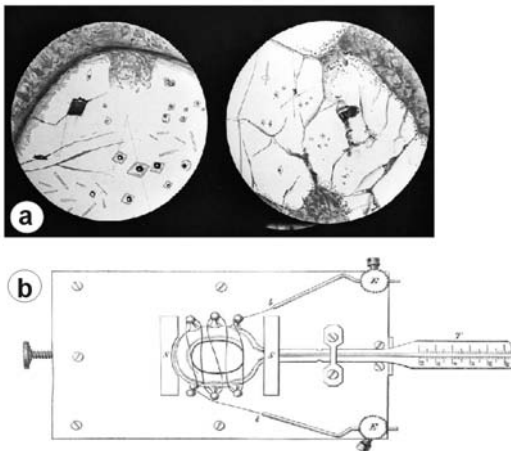


Fig. 1 - a) Original drawings of melt inclusions by Vogelsang, from the Philosophie der Geologie (1867, Tafel X). The left drawing illustrates the negative crystal shapes of inclusions in a porphyry from Bolivia (300x magnification). The right drawing shows the relationships between the inclusions and their host crystal (quartz) in a porphyry from Halle, Germany (100x magnification) (from Touret, 2004). b) Model of the heating stage designed by Vogelsang and Geisler (1869) where a thermometer with an annular reservoir is heated by an electric resistance.

THE PETROGRAPHIC APPROACH TO MS INCLUSIONS IN UHP METAMORPHIC ROCKS

Although the study of fluid inclusions in metamorphic rocks is already a well established technique, the study of MS inclusions in UHP rocks requires some specific additional skills, because of the high amount of solids present, and of the nature of such solids (i.e., most of these minerals are silicates instead of salts, as commonly observed in fluid inclusions from metamorphic environments). In many aspects, a correct petrographic approach

to MS inclusions should be more akin to melt inclusion investigations, than to fluid inclusion ones.

Identification and chemical characterization of MS inclusions

Multiphase solid inclusions are quite common in eclogitic rocks of both crustal and mantle origin, and are always found within peak mineral phases (e.g. garnet, omphacite, and kyanite; Fig. 2). They consist mainly of aggregates of two or more silicate minerals \pm carbonates, phosphates, and sulfates, and an aqueous fluid or empty cavities (Fig. 2b). Right from the first studies in the early 90's in Dora-Maira UHP whiteschists (Philippot, 1993; Philippot *et al.*, 1995), it was clear that they did not represent a minor feature. As an example, in some zones of the large garnets of Dora-Maira, MS inclusions can represent up to 5 -10 % of the total volume (Fig. 2c) of the mineral. As illustrated in Fig. 2, MS inclusions might be distributed either regularly or unevenly in the cores and/or the rims of the host minerals, with textural characteristics archetypal for primary fluid inclusions (Lemlein, 1929; Roedder, 1984).

The petrographic analysis of single MS inclusions should begin with the observation under plane polarized light (Figs. 2b, 3a, and 3d); their basic features, such as dimension, shape, degree of filling, etc, are identified. MS inclusions might have variable size, in some cases exceeding 100 μm , which is quite remarkable for inclusions formed in high pressure environments. Some inclusions may show negative crystal shape, and decrepitation features are commonly observed. In some cases, the identification of the mineral phases contained within a single MS inclusion can be obtained at crossed polarizers (e.g. compare Figs. 3a and 3b): in these conditions, the presence of multiple phases entrapped results clear from the difference in birefringency among the different minerals (Figs. 3b and 3e). MS inclusions can be readily analyzed at the SEM-EDS, by choosing those representative MS inclusions open at the surface (Figs. 3c and 3f). The two inclusions reported in Fig. 3 are from pyrope of the Dora-Maira whiteschist and contain intimate equilibrium intergrowths of chlorite and white mica.

A precise chemical characterization of the phases contained within MS inclusions, however, involves observation at the scanning electron microscope, measurements of major element composition by electron microprobe (Ferrando *et al.*, 2005a, 2005b), non-destructive Raman measurements (Philippot, 1993; Frezzotti *et al.*, 2007), trace element analysis by laser ablation ICP-MS (Malaspina *et al.*, 2006), and observation at the transmission electron microscope (e.g. Hwang *et al.*, 2001; Dobrzhinetskaya *et al.*, 2003a).

In contrast to "normal" fluid inclusions, the presence of a fluid phase, either aqueous or gaseous in nature, is often difficult to prove, due to the high amount of solid phases contained (Figs. 2 and 3). The identification of a fluid phase is further impeded by two factors: the high density of the trapped fluids, difficult to detect optically, and the possibility that fluids might have been lost from fluid inclusions during the retrograde evolution of the host rocks (Scambelluri *et al.*, 2001), as discussed below.

Selection of representative MS inclusions

After the initial formation of the inclusions in the host mineral at peak metamorphic conditions, density and chemical variation can occur within single inclusions, caused by the constant adaptation of the fluid system to changing P and T conditions, during retrograde exhumation path. This important conclusion is illustrated (and explained) in the pressure and temperature diagram in Fig. 4, the basic chart for the interpretation of inclusions in high-grade metamorphic rocks.

Density variations. Once the inclusion sealed at high pressure and temperatures, these variables are no longer independent, being related by the equation of state of the enclosed fluid. Any change in the inclusion volume will be determined by the pressure difference in and out of the inclusion cavity: it decreases if the metamorphic P-T path is more or less parallel to the temperature axis (the "c" nearly isobaric path of Fig 4) and increases in the case of strong decompression (paths "b" and "d"). When the strength of the host mineral is no longer able to accommodate to the pressure difference, inclusions will be burst, either by implosion (trajectory "c"), or by explosion (decrepitation:

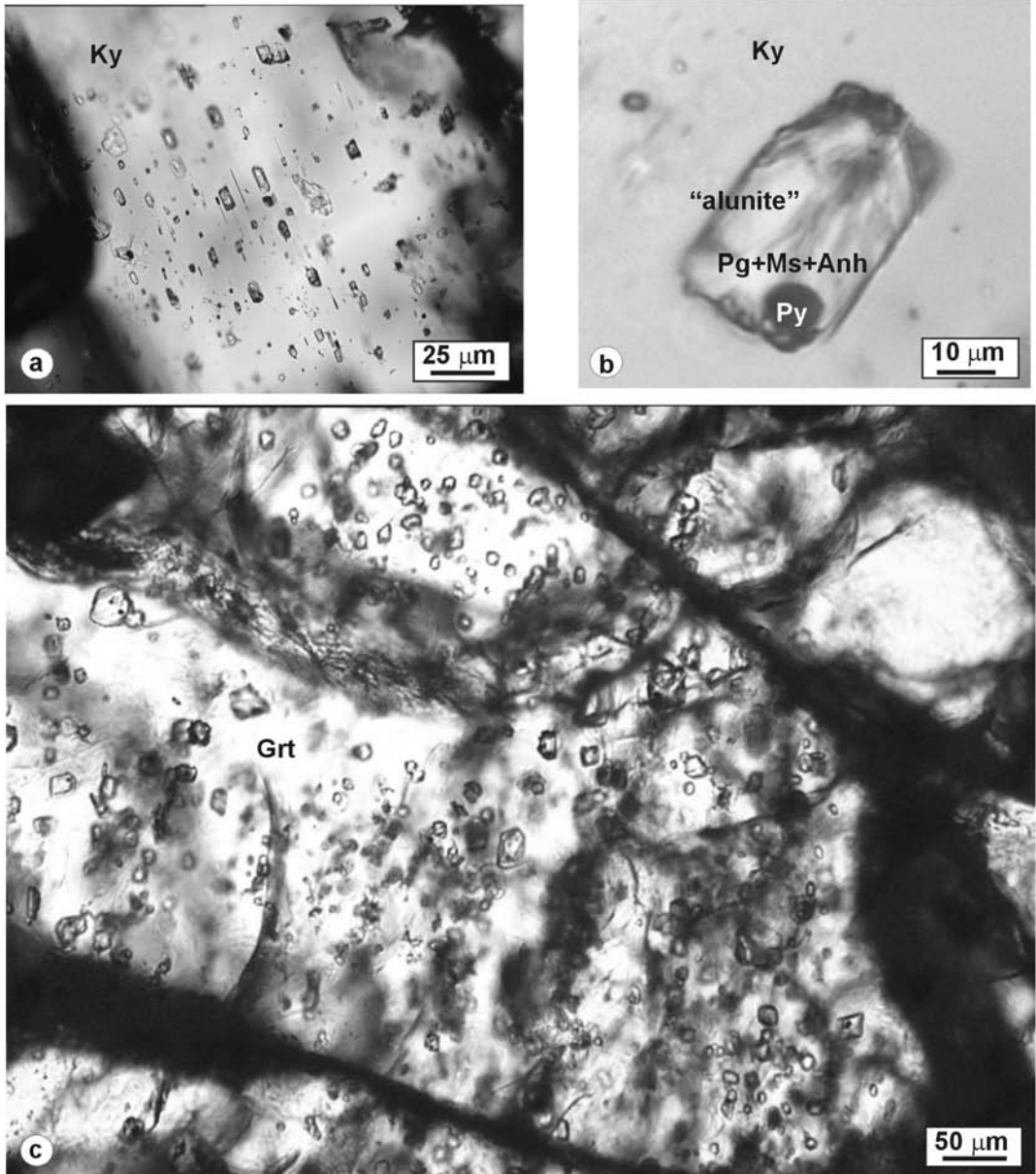


Fig. 2 - Photomicrographs showing the occurrence of MS inclusions in UHP minerals. (a) Primary MS inclusions in kyanite from OH-rich topaz – kyanite quartzite of Sulu (China). All the inclusions show the same dimensions and are oriented along the c axis of the host mineral. Sample RPC547, plane polarized light (PPL). (b) Detail of Fig. 2a. A single preserved MS inclusion showing negative crystal shape, characterized by the typical association of paragonite (Pg) + muscovite (Ms) + anhydrite (Anh) + “alunite”-type sulfate + pyrite (Py), without any visible fluid phase. Sample RPC547, PPL. (c) Primary MS inclusions regularly distributed within pyrope from whiteschists of the Dora-Maria Massif. Sample DM14, PPL. All the MS inclusions show tendency toward negative crystals shape and have the same dimensions.

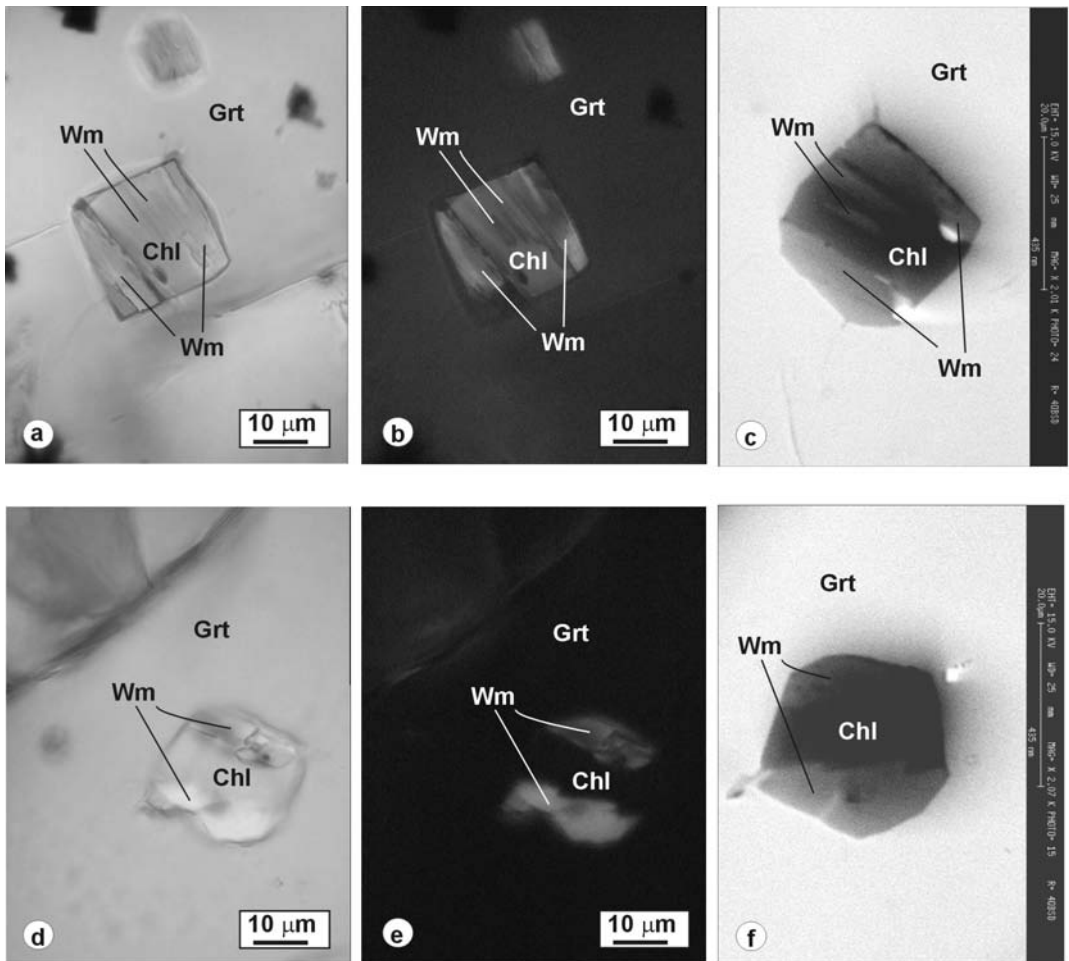


Fig. 3 - Photomicrographs (PPL: a, d; crossed polarizer: b, e) and back-scattered images (c, f) of two preserved primary MS inclusions in pyrope from a Dora-Maira whiteschist. a, b, and c: MS inclusion in sample DM1035; d, e, and f: MS inclusion in sample DM1042. Both MS inclusions consist of intimate equilibrium intergrowths of chlorite (Chl) and white mica (Wm) without any visible fluid phase. They show tendency toward negative crystal shapes.

paths “b” and “d”). New generations of inclusions can then be formed, with characteristics (smaller size, typical textures) extensively discussed in the fluid inclusion literature (e.g. Touret and Frezzotti, 2003, and references therein). Note that only if the metamorphic P-T path remains parallel to the fluid constant density line (isochore), no pressure difference is generated, and inclusions can then be preserved from the greatest depth until the surface (path “a”).

The main conclusion, arising from the above discussion, is that in UHP metamorphic rocks the preservation of the fluid phase would be almost impossible; all inclusions formed at UHP will be re-equilibrated to different extent, and may or may not still contain some fluid phase. However, the absence of reliable fluid density data is not hampering the study of MS inclusions in UHP rocks, since the absence of pressure and temperature indications can be overcome by the

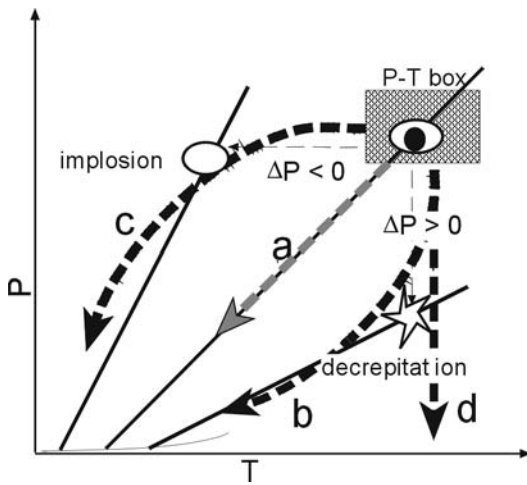


Fig. 4 - The fundamental principles of fluid inclusion interpretation in high-grade metamorphic rocks. Each fluid inclusion trapped at high P-T conditions (P-T box) defines its isochore (solid line), which has to be compared with the metamorphic P-T path (heavy broken lines) followed during retrogression (a: isochoric path; b and d: decompression path; c: nearly isobaric cooling path). Depending upon pressure difference (ΔP), the inclusion volume will change, until rupture either by implosion (c), or by explosion (decrepitation, b and d) will occur.

unambiguously primary nature of MS inclusions in peak minerals.

Chemical variations. In most metamorphic rocks, with a few exceptions (e.g. fluid inclusions in minerals of simple, not variable composition, like quartz and kyanite), chemical interaction between fluid and host minerals might occur along the retrograde path, and might deeply modify the chemical composition of the fluids (e.g. Romer *et al.*, 2006). Such a process severely hampers the petrographic study of MS inclusions, since the high amount of solids contained makes complicated to discriminate between minerals crystallized from the inclusion fluid (daughter-minerals) and those formed through retrograde reactions with host (i.e. step-daughter minerals). Those MS inclusions which decrepitated along the exhumation path are the “best candidates” for chemical reaction with host minerals. Decrepitation features can be often recognized without difficulty at the microscope, by formation of haloes or cracks around single MS inclusions (Figs. 5a and 5b), which should be

carefully avoided for chemical data analysis (i.e. open system).

In many cases, decrepitation processes in MS inclusions are not straightforward to recognize at the microscope, and require further chemical investigations. In the most simple case, MS inclusions react with the host mineral, forming new phases, that take away H_2O from the fluid. As an example, Frezzotti *et al.* (2007) found diaspore with relict corundum along the walls of some MS inclusions hosted in kyanite, and proposed that diaspore formed, during the last stages of host rock exhumation, at P-T conditions no more compatible with the stability of corundum.

If the host mineral has a more complex composition, like in the case of garnet, hydration might induce stronger fluid-host chemical exchanges. Relatively “large” grains of ferroan-pargasite along the walls of MS inclusions (Fig. 5c), were reported by Ferrando *et al.* (2005b) in garnet from eclogites from Sulu (China) and formed through the reaction of the inclusion fluid with garnet host. In garnet, chemical re-equilibration of MS inclusions has been recognized also without formation of hydrated phases (Ferrando *et al.*, 2005b). Scanning electron microscope chemical imaging of Ca distribution in garnet (Fig. 5d; Sulu eclogites) indicated that Ca-rich fluids were released from MS inclusions; around single decrepitated MS inclusions, the host garnet ($Alm_{45}Prp_{27}Grs_{26}Sps_{02}$) shows a Ca enrichment up to $Alm_{44}Prp_{23}Grs_{32}Sps_{01}$ (light gray area, in Fig. 5d).

Daughter vs. step-daughter phases.

In order to reconstruct the original composition of the fluid, it is fundamental to distinguish between solid phases precipitated upon cooling in the sealed cavity (daughter minerals; closed inclusion system), and those formed through the reaction of the enclosed fluid with the host mineral (step-daughter minerals; open inclusion system). The formation of step-daughter phases modifies considerably the original composition of the fluid solutes, hampering a correct determination of the fluid chemistry - in terms of original concentration - of dissolved major and trace element ions.

Experience shows that the best way to approach this problem is by detailed petrography. A clear

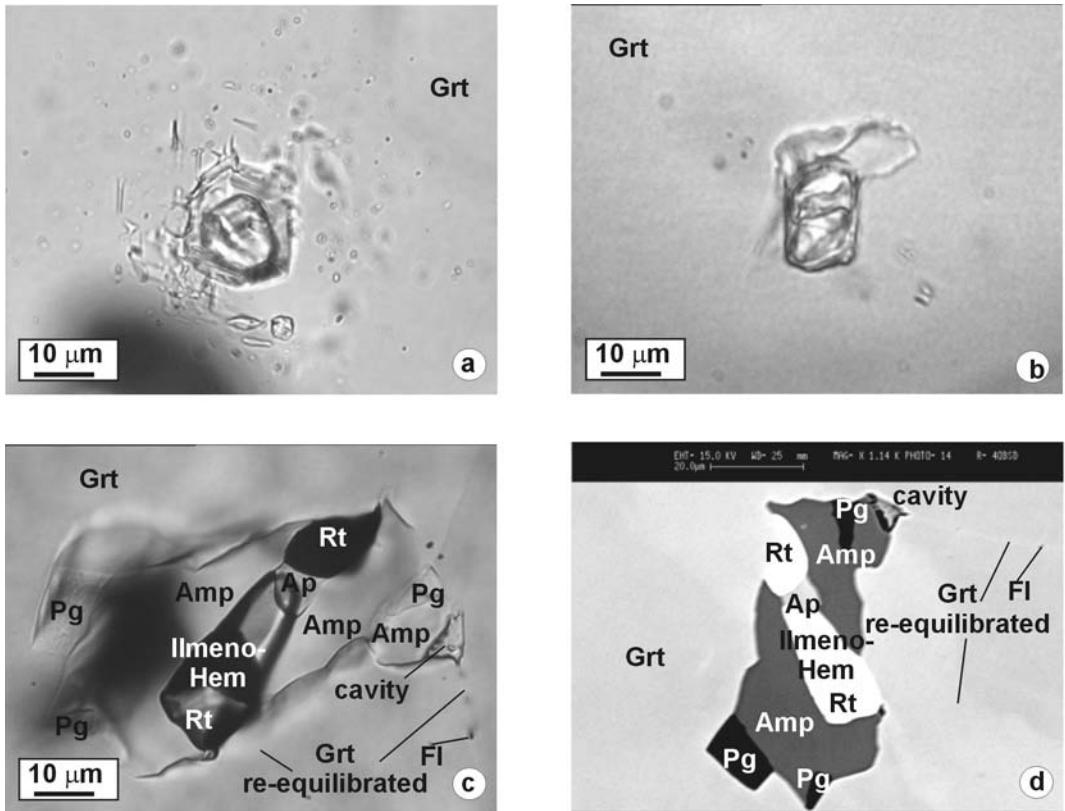


Fig. 5 - Photomicrographs showing decrepitation features in MS inclusions. (a) Haloes of very small fluid inclusions, distributed around single decrepitated MS inclusions within pyrope (Dora-Maira whiteschist, sample DM1598, PPL); (b) Post-trapping chemical re-equilibration between a decrepitated MS inclusion and the host pyrope (Dora-Maira whiteschist, sample DM1598, PPL); (c-d) Photomicrograph (PPL: c) and back-scattered image (d) of a single decrepitated MS inclusion within peak garnet of Ky-Phe-Ep eclogite from Sulu orogen (sample RPC 778), consisting of amphibole (Amp), paragonite (Pg), rutile (Rt) with ilmeno-hematite lamella (Ilmeno-Hem), and apatite (Ap). Cavities and tiny fluid inclusions (FI) formed by decrepitation are also present. Note that the garnet composition changes in the region of MS inclusions, and of tiny secondary fluid inclusions trails (i.e. Ca-enrichment, see text).

distinction among true daughter phases and step daughter minerals might in some cases be rather difficult. However, some differences are present and may help to identify chemically re-equilibrated inclusions. Daughter minerals are precipitated from the inclusion fluids, and because of this, they should constitute a constant and statistically representative association within inclusions. Daughter minerals will have constant proportion in the fluid inclusions since they precipitate from the same fluid. Conversely, step-daughter phases, resulting from local interaction of MS inclusions

with the host mineral, should not be systematically observed in all MS inclusions, and their volume should not be constant within the different inclusions. Further, step-daughter minerals are preferentially distributed along the cavity walls (Fig. 5c), and they typically consist of hydrous phases. Symplectitic textures and relict anhydrous minerals may be also locally observed.

In conclusion, a good petrographic study of MS inclusions should be aimed at recognizing any possible density, and, most importantly, chemical variation, in order to select the representative

MS inclusions to bring to chemical analysis. A random selection of MS inclusions might lead to non representative chemical data, especially if inclusions are contained in host phases having a complex chemical composition (e.g. garnet; cf. Perchuk *et al.*, 2005).

WHAT KIND OF “FLUIDS” ARE CONTAINED WITHIN MS INCLUSIONS?

In UHP rocks, primary MS inclusions permit to identify aqueous fluids present at peak metamorphic conditions. Hence, their chemical study allows an in depth view of the characteristics of the fluids that begins the process of material transfer in subduction zones. Table 1 summarizes major daughter mineral phase associations present in MS inclusions from different UHP metamorphic rocks, as reported in the relevant literature. Most mineral phases are hydrous (alkali-alumino)-silicate in compositions. Sulfates, carbonates and phosphates are also present in subordinate amounts. Chlorides are rare. CO₂ has never been reported, while carbon might be present either as graphite or diamond. Further, comparing the different daughter mineral associations within single MS inclusions, one aspect is unmistakable: the chemical composition of the inclusions replicates the chemistry of host rocks. As an example, the association of phlogopite, spinel, amphibole, sulfides, chlorite and talc is common in ultramafic rocks, whereas paragonite, amphibole, sulfides, rutile and magnetite are observed in mafic rocks, and muscovite, paragonite and quartz dominate in felsic rocks (cf. Table 1).

It is not easy to understand how the complicated MS inclusions are generated and, since their discovery, this question has been the subject of much discussion and debate (cf. Ferrando *et al.*, 2005a; Hermann *et al.*, 2006, for a review). Since the earliest report by Philippot (1993), a number of hypotheses have been proposed to explain the characteristics of these solute-rich fluid systems: 1) residual Mg-rich aqueous and carbonic fluids (up to 68 wt% NaCl equivalent), derived from partial melting (Philippot, 1993; Philippot *et al.*, 1995), 2) residual aqueous fluid produced by peridotite/felsic hydrous melt reaction (Malaspina *et al.*, 2006), 3) silicate melts with variable silica and

alkali contents (Hwang *et al.*, 2001); 4) residual hydrous carbonate melt derived by reaction between hydrous granitic melts and dolomite (Korsakov and Hermann, 2006); 5) alkali-alumino-silicate aqueous solutions, intermediate between solute-rich aqueous fluids and silicate melts (Frezzotti *et al.*, 2007); 6) supercritical C-O-H + silicate fluids of crustal or mantle origin (Stöckhert *et al.*, 2001; Carswell and van Roermund, 2005; Dobrzhinetskaya *et al.*, 2003b; Hwang *et al.*, 2003).

A similar variety of mechanisms shows that probably more than one process is involved, and that each case must be discussed separately, depending on the nature of the protolith, metamorphic P-T conditions, etc. One result is however certain: in UHP rocks, aqueous fluids are able to dissolve and transport substantial amounts of silica, alumina, and alkalies. These last ones (notably Na) are also found in medium-low pressure metamorphic fluids, but mostly if not exclusively, in the form of salts (chlorides and sulfates; Touret, 2001).

UHP enormously increases the solubility of silicon and alumina by complexing as polymers, comparable to those found in silicic melts (Manning, 2004). Polymerization of silica enhances the transport of Ca, Na, K, and of those metal components (e.g. Al and Ti) that generally have low solubility in aqueous fluids (Antignano and Manning, 2005; Tropper and Manning, 2005), and turns these fluids to silicate aqueous solutions intermediate between concentrated aqueous solutions and hydrous silicate melts. In a rock-H₂O system, the fluid-melt miscibility gap closes down with increasing pressure, until the apex of the miscibility gap intersects the wet solidus of the system (see Fig. 4 of Ferrando *et al.*, 2005a) in the so called “second critical endpoint” (e.g. Manning 2004; Hermann *et al.*, 2006). Above this pressure, a single supercritical liquid with H₂O = 70-30 wt % is present, and its chemical and physical properties vary with temperature (Niggli, 1920; Kessel *et al.*, 2005). It is quite likely that this change with increasing depth in subduction zones simply reflects the ability of alkali alumino-silicate components to form aqueous polymers at high pressure and temperature.

TABLE 1 — Composition of MS inclusions, with or without fluid preserved, consisting of abundant crystals and found within UHP minerals

| Metamorphic Belt | MS INCLUSIONS OCCURRENCES | | | | SOLID PHASES | | | | | | | |
|-----------------------|--|--------------------|---|--|------------------------------------|----------------------------------|----------------------|------------------------|---|-----------|-------|---------|
| | Rock | Host mineral | silicates (hydrous) | silicates | carbonates | sulphates | sulphides | phosphates | oxides | chlorides | water | diamond |
| Dora Maira | pyrope quartzite ^{1,2} | Grt | talc Mg-chlorite | zircon | magnesite | | opaque minerals | Mg-phosphate | opaque minerals | NaCl | no | no |
| Western Gneiss Region | garnet websterite ³ | Spl, Opx, Cpx, Grt | phlogopite kalsilite | zircon | magnesite (BaCa)CO ₃ | | iron-nickel sulphide | Cl-apatite monazite | Cr-spinel rutile | | no | yes |
| Erzgebirge | quartz-feldspathic rocks ⁴ | Grt | phlogopite paragonite | quartz zircon | | | ZnS | apatite | rutile | | no | yes |
| | garnet gneiss ⁵ | Grt | phlogopite paragonite phengite | quartz | | | | apatite | rutile | | no | yes |
| Kokchetav | felsic gneiss ⁶ | Grt, Zrn | phengite phlogopite chlorite biotite | quartz K-feldspar albite titanite | | | | apatite | rutile | | no | yes |
| | Grt-Cpx-Qtz rocks ⁷ | Grt | phlogopite chlorite paragonite | | calcite | | metal sulfides | | | | no | yes |
| | carbonate rocks ⁸ | Grt, Cpx, Ttn | biotite zoisite | K-feldspar Cpx garnet titanite | Mg-calcite | | | | | | no | yes |
| | OH-rich Toz - Ky quartzite ^{9,10} | Ky | paragonite muscovite chlorite | SiO ₂ zircon | calcite | anhydrite "alunite" barite | pyrite | | corundum | | no | no |
| Dabie-Sulu | Ky-Phe-Ep eclogite ¹¹ | Grt, Ky | paragonite amphibole Zn-staurolite | plagioclase | "alunite" | | pyrite | apatite | rutile magnetite Zn-Mg-Al-Fe-Ti spinel | | no | no |
| | Garnet orthopyroxenite ¹² | Grt | amphibole chlorite talca mica | | | | sulfide | apatite | spinel | | no | no |

(1) Philippot (1993), (2) Philippot *et al.* (1995), (3) Carswell and van Roermund (2005), (4) Hwang *et al.* (2001), (5) Stöckhert *et al.* (2001), (6) Dobrzhinetskaya *et al.* (2003a), (7) Hwang *et al.* (2003), (8) Korsakov and Hermann (2006), (9) Ferrando *et al.* (2005a), (10) Frezzotti *et al.*, 2007; (11) Ferrando *et al.* (2005b); (12) Malaspina *et al.* (2006).

CONCLUDING REMARKS

We have given a few guide-lines for the interpretation of complex MS inclusions, illustrating some basic principles of this technique, and reporting some major chemical data from literature, that may be useful to understand the significance of these UHP metamorphic inclusions.

A correct approach to the study of MS inclusions is based on the petrographic study of these microsystems, aiming at the selection of preserved inclusions (ideally a closed system). Particular attention should be given to distinguish daughter minerals from step-daughter and other incidentally trapped phases within single MS inclusions. In fact, an imprecise identification of the true daughter mineral association may bring to major shortcomings in the reconstruction of the chemical composition of originally trapped fluids.

With this in mind, a petrographic microscope is sufficient to characterize UHP MS inclusions, and their detailed petrographic study should precede any chemical data obtained through various analytical methods. Although MS inclusions are difficult to interpret due to their reaction with the host minerals during the retrograde evolution, they might represent better indicators of the geochemical evolution of major, trace and incompatible elements in UHP fluids, than data obtained from host rocks or with experimental techniques.

For these reasons, we expect a great increase of interest in the forthcoming years by metamorphic petrologists. This tendency has already started, as shown by the fast increasing number of papers published on this subject in the last 5 years, which ultimately indicates that this kind of studies is not anymore confined to fluid and melt inclusion specialists.

ACKNOWLEDGMENTS

Authors are grateful to D. Castelli and R. Compagnoni for invitation to write for this special issue in honor of E. Callegari. Reviews by J. Hermann and J.L.R. Touret are gratefully acknowledged. Present research was funded by MURST and CNR, by "Convenzioni Interuniversitarie" and "Fondi Scambi Culturali" - University of Torino, PAR - University of Siena (2004).

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