FLUID AND MELT INCLUSIONS IN UPPER MANTLE XENOLITHS

by

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The chemical modification or „metasomatism" induced by migrating fluids or melts has been recognised as a key process in the evolution of upper mantle rocks. However, the origin of these melts is still an uncertain topic.

Several studies of fluid and melt inclusions in ultramafic xenoliths (ROEDDER 1984; LIN QUI XIA et al. 1984; ANDERSEN et al. 1984; PASTERIS, 1987; DE VIVO et al. 1988; HANSTEEN 1991; FREZZOTTI et al. 1992; SCHIANO et al. 1992; SCHIANO & CLOCCHIATTI, 1994; SCHIANO et al, 1994; SCHIANO et al. 1995; SZABO & BODNAR, 1996; SZABO et al. 1996, ANDERSEN et al. 1996) documented the presence of a fluid phase in the upper mantle.
The melt inclusions have been interpreted as aliquots of a metasomatic melt phase migrating through the sub-oceanic and sub-continental upper mantle (SCHIANO & CLOCCHIATTI, 1994). Thus, the composition of the metasomatic agent can be studied more directly by examining trapped fluid and melt inclusions in ultramafic xenoliths

Fluid Inclusions

Fluid inclusions in ultramafic xenoliths represent the only direct samples of fluid in upper mantle, therefore, they provide a rich source of data necessary to understand the relationships with other types of fluids and to constrain their P-T-history. They are important for our understanding of the physico-chemical conditions, e.g. the temperature, pressure, density and composition of fluids percolating in the upper mantle rocks.
Phase transitions observed in monophase (CO_2 liquid) (Fig.1a) or biphase (CO_2 liquid + CO_2 vapour) inclusions with heating-freezing stage allow quantitative estimations of the composition and densities of these fluids. However, the interpretation of the phase transitions in fluid inclusions depends in one important assumption:

„Any fluid inclusion is a closed system of constant volume and compostion (BURRUS 1981)".

The existence of pure CO_2 fluid in upper mantle has been documented in several studies of fluid inclusions (ROEDDER, 1984), but the presence of additional components has to be considered. The homogenization behaviour and temperature range are useful for the identification of CO_2. The triple point for pure CO_2 at -56.6°C is an excellent diagnostic criterium. Melting temperatures values (Tm) around -56.6°C suggest a nearly pure CO_2 system. A skewed distribution of melting points towards lower temperatures, due to a depression of $Tm\,CO_2$ and/or the observation of some phase transitions while freezing to -180°C, suggest the presence of additional components in a CO_2-rich inclusion (e.g., SOLOVOVA et al. 1990; FREZZOTTI et al.1992 ; ANDERSEN et al. 1996).

The lack of water in the fluid inclusions has been taken as evidences for dry conditions in upper mantle sources. However, due to the rapid rate of diffusion of water-derived species in olivine (MACKWELL et al. 1985) the low hydrogen concentration within fluid inclusions in olivine is not indicative of low water content in the mantle (MACKWELL & KOHLSTEDT, 1990). Recently ANDERSEN et al., (1996) showed that nitrogen can also be present as a major component in fluid inclusions in olivine from upper mantle xenoliths.

If the composition of the fluid can be determined and the liquid vapour curve of that fluid is known, then the **density** can be obtained from the temperature of homogenization of the vapour and liquid phase.

Fluid inclusions may be used to estimate the pressure of trapping. If the temperature of trapping is known , then the pressure of trapping is given by the intersection of the fluid inclusion *isochore* (BURRUS, 1981:„*line that represent the range of P-T conditions over which a fluid of that density was trapped*"). with the isotherm.

In upper mantle xenoliths the co-genetic relationship between fluid and melt inclusions allow to constrain the P-T trapping conditions. The homogenization temperature of the melt inclusions, genetically related to the fluid inclusions, can be considered being close to the trapping temperature. This assumption and the estimated density at the time of trapping allow an estimation of the pressure prevailing at the time of trapping.

The density of CO_2 inclusions and trapping **depth** can be related if the pressure regime regulating the considered system is established. The inclusions can be trapped under hydrostatic pressures (regime resulting from a liquid lava column of $\rho = 2.7$ g/cm^3) or lithostatic pressures (if one assumes that the magma at the place of entrapment was an isolated pocket surrounded by rocks with $\rho = 3.3$ g/cm^3). As it is difficult to determined which of the two pressures regimes were active at the moment of trapping of the fluid inclusion, and considering that each of them can have prevailed at different stages, then, the **depth** equivalent to a given CO_2 density has to be calculated in terms of both regimes.

A common phenomenon affecting fluid inclusions in upper mantle is total or partial *decrepitation* (Fig. 1c). The effect of decrepitation is to increase the volume available to the fluid, thereby reducing the density. If the fluid is homogeneous the composition will be unaffected by this process (ANDERSEN et al., 1984).

Decrepitation „*This phenomenon takes place when the internal pressure in the inclusion exceeds the lithostatic pressure acting on the host mineral by more than the mechanical strengh of the solid at the given temperature (ROEDDER, 1984)*".

Considering the necking-down processes commonly observed in these inclusions (Fig. 1h), the partial decrepitation phenomenon and the re-equilibration of the inclusions with the host mineral (re-equilibration probably occurred as a result of a slight heating of the xenolith by the host magma or by decompression (GREEN & RADCLIFFE, 1975), therefore, the estimated trapping pressure for a given temperature can only be considered as „*minimum values*". Thus, inclusions cannot be used to determined original trapping conditions, but can provide information concerning the minimal trapping and changing P-T conditions during transport of the xenoliths to the surface.

Melt Inclusions

Melt inclusions present in the mineral phases of ultramafic xenoliths can contain a mixture of glass + CO_2 bubble (biphase melt inclusion) (Fig.1d, 1e, 1f) or glass + bubble + crystals (multiphase melt inclusions) (Fig.1g). Two types of spatial associations between CO_2 fluid inclusions and melt inclusions are observed in ultramafic xenoliths:
1) melt inclusions and fluid inclusions occur in the same secondary trail and
2) fluid and melt inclusions are joined by necks. Such co-genetic features are typical of CO_2 fluid and melt inclusions in mantle xenoliths (SCHIANO & CLOCCHIATTI, 1994).

The data obtainable from melt inclusions are:
1) the chemical composition of the glass at the moment of entrapment,
2) the temperature of homogenization of the melt inclusions and
3) an estimation of the level of saturation of the volatile phase in the glass.

Thermometry experiments allow to reverse the phenomena that occurred inside the inclusion during natural cooling. These phenomena are due to a differential contraction between the host and the inclusion that are visible by the formation of a „shrinkage" bubble. Cryometric experiments undertaken on the shrinkage bubbles of the melt inclusions in xenoliths revealed the presence of a nearly pure CO_2 volatile phase (Fig. 1d).

In order to estimate the trapping temperature and the initial composition of the melt, high thermometric experiments are conducted on melt inclusions with different degree of crystallization. The complete homogenization, that is the disappearance of the shrinkage bubble, will not be achievable. This results in the systematic presence of a CO_2 bubble in the melt during the experiments (even at temperatures > 1300°C) attesting to a CO_2 oversaturation of the melt at the moment of entrapment.

An alternative method to obtain the trapping temperature is to heat multiphase melt inclusions. During such experiments, each phase will dissolved in the melt, thus, knowing that the disappearance of the bubble will not occur, the final melting temperature of the last crystalline phase can be considered „close to" the homogenization temperature of the inclusion , and thus to the „liquidus" temperature of the melt (CLOCCHIATTI et al., 1992; SOBOLEV& NIKOSIAN, 1994).

After heating a multiphase melt inclusion with „daughter crystals" (the most common daughter crystals in upper mantle xenoliths are: kaersutite, clinopyroxene, rutile, ilmenite, and apatite) occur; the inclusion will be quenched and the initial chemical composition of the melt can be obtained. If the chemical composition of these types of inclusions (heated multiphase inclusions) is similar to those of heated and unheated biphase glass inclusions then the glass inclusions do not contain residual liquids. Thus, post-entrapment processes that could change the chemical composition of glasses can be excluded.

Also, the chemical composition of glass inclusion hosted by different minerals (olivine, orthopyroxene, clinopyroxene, etc.) from the same xenolith have to be compared. If the chemical composition of glass inclusions hosted by olivine is similar to that hosted by orthopyroxene and clinopyroxene then, any possible genetic relationship between glass inclusion and the host mineral can be discharged.

The chemical composition of glass inclusions in mantle xenoliths is characterized by high contents of SiO_2, Al_2O_3, K_2O and Na_2O and low contents of CaO, FeO and MgO. Regarding volatile elements, Cl contents can vary between 1000 - 9000 ppm, oversaturation of the melt in CO_2 is suggested by the persistence of a CO_2 bubble during heating experiments and the presence of H_2O in the trapped melt can be inferred from the crystallization of hydrous daughter minerals.

Considering the chemical composition of the inclusions, their high volatile content, their secondary origin and the paragenesis of the daughter minerals, SCHIANO & CLOCCHIATTI (1994) have concluded that: *„melt inclusions are not generated by melting of the peridotite assemblage in which they have been trapped. They represent a migrating exotic phase in the upper mantle".*

Recent studies of Patagonian ultramafic xenoliths (VARELA et al., 1996) give additional support to this hypothesis. Melt inclusions trapped in Patagonian xenoliths are the metasomatic expression of a melt rich in SiO_2, Al_2O_3, Na_2O, K_2O and volatiles (CO_2, Cl, H_2O). Chemical variations in the composition of these melts suggest at least two stage in the evolution of these melts. The presence of melt inclusions in fractures crosscutting minerals and decorating deformation lamellae in olivines suggest that infiltration of these melts may be related to a deformation process, that is, a pre eruptional uprise of the upper mantle (VARELA et al.,1996) that could have affected this area.

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Fig.1 (next page)

Fig. 1a)   Monophase inclusions (liquid CO_2) parallel to orthopyroxene cleavage.
                Sample So 0312, (Rio Negro), Patagonia , Argentina.

Fig.1b)   Relationship between monophase inclusions (older generation) and
^   biphase inclusions (younger generation) occurring in secondary trails.
                Sample So 0312, (Rio Negro), Patagonia, Argentina.

Fig. 1c)   Decrepitation in fluid inclusions.
                Microcracks and halos of tiny inclusions surround empty inclusions.
                Sample 26C, Avalos, La Gomera, Canary Islands.

Fig. 1d)   Biphase glass + CO_2 -inclusion.
                Note the presence of liquid and vapour CO_2 in the bubble.
                Sample Mt. Sh. 103, Victoria, Australia.

Fig. 1e)   Primary glass inclusion in olivine neoblast.
                Sample 27-09 , Comores Islands.

Fig 1f)   Secondary melt inclusions along fractures in olivine.
                Note the variable vapour/glass ratios indicative of trapping of a
                possible heterogeneous fluid.
                Sample Co 0320, (Chubut), Patagonia, Argentina.

Fig. 1g)   Multiphase glass inclusions with Ti-rich clinopyroxene, spinels and a bubble (b).
                Sample 26C Avalos, La Gomera, Canary Islands.

Fig. 1h)   Necking down of a melt inclusion.
                Note the place where the inclusion starts to neck down (arrow).
                Sample Co 0320 (Chubut), Patagonia, Argentina.

All scale bars in μm.

a

b

c

d

e

f

g

h