

Melt inclusions trapped in mantle minerals : a clue to identifying metasomatic agents in the upper mantle beneath continental and oceanic intraplate regions

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Rock samples derived from the Earth's upper mantle commonly show indirect evidence for chemical modification induced by migrating fluids or melts. Such modification, or 'metasomatism', can be recognized by the precipitation of exotic minerals such as phlogopite, amphibole, or apatite, and by the overprinting of the bulk compositions of the mantle rocks by a chemical signature involving the enrichment of incompatible elements. However, identification of the metasomatic agents occurring in the upper mantle is still a controversial topic. Here, we study the composition of the metasomatic agents more directly by examining trapped melt inclusions in mantle minerals from ultramafic peridotites from both continental and oceanic intraplate regions.

The xenolith samples come from Society islands (Tahaa, Tahiti), Canary islands (Lanzarote, Hierro), Kerguelen island (Jeanne d'Arc Peninsula), Comores island (La Grille), New Mexico (Kilbourne Hole), Arizona (San Carlos), Germany (Dreiser Eifel), Italy (Mt Iblei), France (Massif Central), Mongolia (Dariganga), Russia (Vitim Highland) and Vietnam. They are massive anhydrous spinel-lherzolites and harzburgites, with 60-81% olivine, 10-21% orthopyroxene, 0.5-11% clinopyroxene and 0.5-3% spinel. Textures vary from protogranular to porphyroclastic, often with a transition between the two.

The xenoliths contain three types of genetically related inclusions hosted by olivine, clinopyroxene and orthopyroxene: silicate melt inclusions, carbonate-rich inclusions, and CO₂ fluid inclusions. The inclusions are secondary in nature and form trails along annealed fracture planes in the sheared peridotites. CO₂ inclusions and silicate melt inclusions joined by necks and multiphase inclusions consisting of both CO₂-rich fluid and silicate-carbonate melts are visible, indicating a

cogenetic relationship between fluid and melt inclusions.

Silicate melt inclusions

All the xenoliths contain secondary silicate melt inclusions. Their shape is irregular, round to sigmoidal, and the size is generally less than 30 µm. Most of the inclusions contain one or more gas (± liquid) bubbles. Some inclusions are composed only of glass, but generally they contain µm-size daughter minerals, crystallized from the trapped melt. The most common daughter minerals are K-rich amphibole (kaersutite), diopside, rutile, ilmenite and carbonate (magnesite), a paragenesis clearly different from the host peridotite paragenesis.

In order to estimate the temperature of melt entrapment, and the initial melt composition, heating stage experiments were conducted on silicate melt inclusions with different degree of crystallization, trapped in olivine and clinopyroxene crystals. The complete homogenization of the inclusions could not be obtained even at temperatures > 1350°C because of the systematic presence of dense CO₂ bubbles (liq/vap) in the melt during the experiments. The final melting of the enclosed minerals always occurs between 1220 and 1270°C.

The compositions of heated melt inclusions and unheated glass inclusions that contained no daughter minerals were determined using an electron microprobe. Unheated and heated inclusions have similar compositions, indicating that the heating experiment did not produce artefacts owing to the interaction between inclusions and host minerals. The major element compositions are homogeneous and characterized by high contents of SiO₂ (54.3-66.0%), Al₂O₃ (15.6-22.4%), Na₂O (2.2-7.4%), K₂O (1.0-6.9%), and

low values for TiO₂ (0.1–2.2%), FeO (0.7–5.0%) and MgO (0.6–4.1%). CaO contents vary from 1.4 to 11.0 wt%. No MgO-rich melt inclusions have been found, despite the high MgO contents of the surrounding peridotite minerals. Turning to volatile elements, chlorine concentrations in melts are always greater than 1000 ppm (up to 9500 ppm in Comores island), whereas sulphur contents never exceed 500 ppm. The occurrence of CO₂ in shrinkage bubbles of the melt inclusions, as indicated by cryometric experiments, and the persistence of CO₂ bubbles during the heating experiments, indicate a CO₂ oversaturation of the inclusions. Crystallization of numerous hydrous phases in melt inclusions indicates the presence of H₂O in the trapped melts (H₂O concentrations ≥ 1.2 wt% for melt inclusions trapped in Kerguelen spinel lherzolites were determined by ion microprobe (Nancy, CRPG)). Glass inclusions in different host minerals from the same xenolith have similar compositions. This rules out any hypothetical relationship between inclusions and host minerals. Ion probe trace element analysis (WHOI) of unheated glass inclusions trapped in Kerguelen spinel lherzolite indicate that trace element signature of silicate melt inclusions is characterized by LREE enrichment, negative HFSE (Ti and Zr) anomalies and a low Ti/Zr value (~ 17). These are typical metasomatic features generally related to carbonatitic melts.

Carbonate-rich inclusions

Less frequent than silicate melt inclusions, carbonate-rich inclusions show irregular, elongated shape. Their size ranges between 10 and 50 μm in the maximum dimension. Carbonate-rich inclusions contain aggregates of tabular calcite crystals. Large CO₂ bubbles, which can occupy more than half of the inclusion, appear in the melt during the heating experiments. Their specific features indicate that carbonate-rich inclusions result from the crystallization of a trapped carbonate melt. Moreover, the carbonate-rich inclusions are often physically connected with the silicate melt inclusions, indicating the former existence of a homogeneous melt separated subsequently by immiscibility.

Fluid inclusions

They are sub-spherical in shape, and less than 10 μm across, and contain dense CO₂ vapor and liquid. Melting temperatures for fluid inclusions on the cryometric stage are close to the CO₂ triple point of -56.6°C, indicating that the trapped fluid is nearly pure CO₂. This allows fluid density

determinations using the homogenization method based on the CO₂ vapour/liquid equilibrium. The maximum density for the CO₂ inclusions in oceanic xenoliths varies from 0.88 for Tahaa to 1.11 g/cm³ for Kerguelen, corresponding to homogenization temperatures into the liquid phase (Th^L) of +7°C and -37.5°C respectively. For continental xenoliths, density varies from 1.05 (Arizona with Th^L = -24°C) to 1.14 g/cm³ (Vitim with Th^L = -46°C). From the density values and the P-V-T equation, we obtain trapping pressures for CO₂ inclusions ranging from 0.7 GPa to 1.4 GPa at 1250°C. These values represent a lower limit for entrapment pressure, since fluid inclusions may have been reequilibrated. Evidently, trapping of CO₂ as inclusions, and thus of associated carbonate melt inclusions and silicate melt inclusions, occurred at upper mantle depths.

Conclusions

On the basis of their daughter mineral types, their very unusual major and trace element compositions and their high volatile element contents, melt inclusions trapped in ultramafic xenoliths are interpreted as small amounts of metasomatic melts originated from greater depths. Their compositions, which differ dramatically from those of erupted, mantle-derived magmas, are more akin to continental crust than to oceanic crust.

With regard to the origin of these melts, melt inclusions are unlikely to have been generated only by melting of the anhydrous peridotite assemblages in which they have been trapped. They must represent part of an exotic, migrating metasomatic melt phase in the lithosphere.

The distribution of melt inclusions, along fracture planes, suggests that injection of the trapped silicate-carbonate melt was prior to or synchronous with deformation of the peridotites, which allowed the metasomatic melt to invade the surrounding peridotites and form secondary melt inclusions.

The widespread presence of these metasomatic melt inclusions in ultramafic xenoliths indicates that mantle metasomatism is an ubiquitous mechanism related to world-wide occurrence of acidic melts in the lithosphere.

References

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