

The message in the bottle: “Melt” inclusions in migmatitic garnets

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Minute bubbles of fluid sealed inside crystals have long been studied for what they reveal about mineralizing, magmatic, and metamorphic fluids and the pressure-temperature (P - T) paths followed by the host rocks. The famous science-fiction author H.G. Wells, as a geology student, found these far more fascinating than the rocks in which they occur (Wells, 1934). More recently, melt inclusions have been used to constrain the chemistry of magmatic liquids and liquid-crystal element partitioning. Now, an exciting development is the discovery of what may be melt inclusions in peritectic garnets of migmatites (Cesare et al., 2009, p. 627 in this issue of *Geology*). These tiny “bottles” contain important messages for understanding metamorphic and partial melting conditions, reaction stoichiometry and kinetics, and clues to the riddles of crust formation and crustal differentiation. But what is the message in the bottle?

To answer this we need first to know what these inclusions are. The second thing we need is their composition. If the inclusions do represent melt, and can be reliably analyzed, the third requirement is that their present composition reflects that at the time of entrapment. Finally, the message will be unclear unless we know whether the phase in these inclusions was representative of the bulk composition of that phase in the system. Let us briefly examine these issues.

WHAT PHASE WAS ENTRAPPED?

Melt is the obvious answer, and this is what Cesare et al. conclude, because the compositions are broadly granitic/rhyolitic. However, the rocks in which the inclusions occur are medium- P granulites (600–800 MPa; e.g., Nandakumar and Harley, 2000). At high P , a supercritical, aqueous fluid can dissolve a substantial silicate component. Siliceous and ultrapotassic fluids have been produced experimentally at $P > 1500$ MPa (e.g., Massonne and Schreyer, 1987; Massonne, 1992) and also at $P < 200$ MPa, and T from 300 °C to at least 750 °C (Wilkinson et al., 1996). Such supercritical fluids were dubbed “silicothermal” by Wilkinson et al. (1996) who suggested that they are the main mantle metasomatizing agent. Granitic magmas might also evolve such fluids at the solidus.

The garnets in which Cesare et al. discovered the inclusions also contain CO_2 -rich fluid inclusions, and the rocks contain graphite. This evokes an old debate on the origins of such carbonic fluids: whether they were trapped at or after the metamorphic peak, whether they represent a pervasive phase, and whether their present composition represents that originally trapped. A fundamental fact concerning fluids, melting, and the granulite-facies is that partial melting involving biotite breakdown takes place in the absence of a pervasive fluid phase of any composition in the C-O-H system (Clemens and Watkins, 2001). Thus, if some inclusions represent a siliceous fluid, as for carbonic inclusions, they are most likely to have been either non-pervasive scraps of accessory fluid, or fluid introduced at post-peak, post-melting conditions. Nevertheless, let us assume that they are samples of former melt.

WHAT IS THE COMPOSITION OF THE PHASE IN THESE INCLUSIONS?

The inclusions were analyzed by electron probe with a focused beam and, as Cesare et al. note, there will have been Na counting losses. Using a standard glass, analyzed under the same conditions, an attempt

was made to correct for this. However, apparent Na loss scales with H_2O and Na_2O contents, and the analyses are still likely to contain significant errors. Nevertheless, the compositions are broadly granitic/rhyolitic and SEM images of the glassy inclusions (e.g., Cesare et al., 2009, their figures 2C and DR3b) suggest that there are no daughter crystals at their margins to render the inner, analyzable sections unrepresentative. The glasses (Cesare et al., 2009, their table DR2) are highly potassic, even more so than ultrapotassic rhyolites (Maheshwari et al., 1996) or melts formed in experiments on plagioclase-free pelites (Patiño Douce and Johnston, 1991). Such compositions are unlike the vast majority of felsic melts produced in experiments on metapelites (Villaros et al., 2009) and unlike most rhyolitic/granitic rocks that are interpreted as partial melts of metasediments. This unusual composition suggests caution in their interpretation.

Cesare et al. argue that the protoliths were plagioclase-free but the other type of “melt” inclusion (Cesare et al., 2009, their figures DR3c and DR3d) is crystalline, with quartz, plagioclase, K-feldspar, and biotite. Thus, it seems likely that the melting reaction exhausted a small sodic plagioclase component in these rocks. The compositions of these polycrystalline inclusions are not reported, nor are those of the leucosomes in the rocks. The absence of these data hampers assessment of what the compositions of the glassy inclusions mean. Whatever the case, and in contrast to the view of Cesare et al., it is not justified to conclude that melts in metapelitic migmatites have the highly potassic compositions of the glassy inclusions that they analyzed.

DO THE INCLUSIONS MIRROR THE ORIGINAL COMPOSITION OF THE TRAPPED PHASE?

For melt or fluid inclusions, the default assumption is that, if they appear primary, then they represent what was trapped initially. Many metamorphic minerals re-equilibrate as their host rocks travel down the retrograde P - T -fluid path. Cation diffusion is relatively rapid in biotite so, in crystallized inclusions, biotite would readily re-equilibrate. Cesare et al. mention the retrograde history of their rocks spanned 60 m.y. With the short diffusion paths between the garnets and the contents of the inclusions, extensive diffusional exchange seems likely, with loss of Fe, Mg, and Ca to the encasing garnets. Glasses also re-equilibrate readily—a possible explanation for the extremely low Mg and Ca in the glassy inclusions. However, herein lies a dilemma. The polycrystalline inclusions, inferred to be devitrified examples of the same phase, seem to have crystallized substantial amounts of plagioclase and biotite, suggesting a more normal rhyolitic composition. Were the crystalline and the glassy inclusions two distinct phases, perhaps even with different ages? Could the crystalline inclusions represent melt, and the glassy inclusions a siliceous fluid?

Cesare et al. report that the crystalline inclusions can be re-homogenized by heating and that their compositions are thereby contaminated with Fe and Mg from the garnet. Biotite in the crystalline inclusions is extremely magnesian, unlike any igneous mica in a felsic rock. This mica may have lost Fe to the garnet, by diffusional exchange, during retrograde cooling. Thus, provided that the homogenization T was similar to the trapping T , these inclusions may simply have been returning toward their original compositions. Whatever these inclusions were originally, their present compositions probably do not reflect their original entrapment compositions.

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WAS THE TRAPPED PHASE REPRESENTATIVE OF THAT PHASE IN THE ROCK?

Another assumption in inclusion work is that the trapped phase reflects the bulk composition of that phase in the rock. Small equilibration volumes and disequilibrium melting could result in spatially variable melt compositions. Mounting evidence suggests that partial melting and melt segregation are commonly rapid enough to preclude trace-element equilibrium between coexisting phases (e.g., Sawyer, 1991; Watt and Harley, 1993; Barbero et al., 1995; Bea, 1996; Davies and Tommasini, 2000; Janák et al., 2001). Also, experimentalists have noticed that melt compositions in run products are not homogeneous throughout, even though the compositions of crystals may be. Patches of melt (microns to hundreds of microns) have compositions that depend on the crystalline phases with which they are in contact. If these melt fractions were aggregated and homogenized, the phase would match the composition of the segregated and extracted melt in a natural partially melted system.

Rapid partial melting and growth of peritectic phases (e.g., garnets) could trap melt inclusions with compositions determined by transient, local, disequilibrium. One cause of this could be that the reaction requires the presence of biotite and quartz as reactants while, depending on the degree of reaction overstepping, the presence of plagioclase may be nonessential. Thus, melts might have low Na where biotite and quartz were not in mutual contact with plagioclase and v.v. Highly potassic, glassy inclusions and polycrystalline, plagioclase-bearing rhyolitic inclusions could represent these contrasting situations. However, the fact that the two kinds behaved differently (one crystallizing and one remaining glassy) and the large contrast in composition, together suggest that they were two distinct phases. Nevertheless, it is worth considering whether a trapped melt would be representative of the bulk composition of the melt in a rock. A related question concerns the composition of a melt in a granulite-facies metapelite.

In view of the potential problems related to accidents of entrapment and compositional changes, melt inclusions are not the most direct way of observing melt composition. That status belongs to analysis of glasses (quenched melts) formed in well-designed and carefully executed experiments. Such work has been carried out on a wide variety of natural metapelites (e.g., Vielzeuf and Holloway, 1988; Patiño Douce and Johnston, 1991; Pickering and Johnston, 1998; Patiño Douce and Harris, 1998) and shows that biotite breakdown produces peraluminous melts with ordinary, granite-like compositions. The compositions of the inclusions identified by Cesare et al. need to be interpreted in this context.

CONCLUSION

Melt inclusions trapped inside peritectic phases in migmatites promise to send us an important message about the nature of the melting reactions, the compositions of the melts, and their meaning for the formation of felsic magmas. Sadly, however, the message in this bottle is written in a language that we have yet to properly decipher. More work is needed before we can even answer the most basic question of whether all these inclusions actually contained melt, and what its composition was. Analysis of the glassy or re-homogenized inclusions by electron probe, using a freezing stage, would virtually eliminate analytical uncertainties (see e.g., Vielzeuf and Clemens, 1992). An interesting line of study would be to look for similar inclusions in low-*P*, granulite-facies migmatites, where the question of the melt or fluid nature of the inclusions might be simpler. This could provide us with the equivalent of the Rosetta Stone, and unlock the secrets of these fascinating and potentially important little data repositories.

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