Experimental constraints on partial melting in the crust

D. Vielzeuf
J.M. Montel

Département de Géologie, URA 10 du CNRS, Université Blaise Pascal, 5 rue Kessler 63038, Clermont-Fd, France

Partial melting and the ascent of granitoid magma are among the main processes leading to differentiation of the continental crust. In order to constrain models for crustal melting, a series of experiments has been undertaken under fluid-absent conditions on pelites and metagreywackes.

Partial melting of pelites

Vielzeuf and Holloway (1988) experimentally studied the melting of a metapelite under fluid-absent conditions. At 10 kbar, three main stages of melting were distinguished :

1) The first melting occurs below 800°C and corresponds to the breakdown of muscovite via reactions such as Ms + Bt + Pl + Qtz + V = M + Als; Ms + Pl + Qtz = Bt + Als + Kfs + M. The proportion of melt was small (10–15 vol.%).

2) Between 850 and 875°C there was a dramatic increase in the proportion of melt, changing from about 10% to 50–60%. This step corresponded to the breakdown of biotite (Bt + Als + Pl + Qtz = Grt + Kfs + M) and was followed by a plateau along which garnet and sillimanite progressively dissolved in the liquid.

3) The last stage represented the melting of garnet and spinel at very high temperatures (above 1100°C). In this scheme, the reaction

$$\text{Bt} + \text{Als} + \text{Pl} + \text{Qtz} \rightleftharpoons \text{Grt} + \text{Kfs} + \text{melt} \quad (1)$$

plays a major role. Vielzeuf and Holloway (1988) considered that, at 10 kbar, this reaction occurred at about 850–875°C, over a small temperature interval. These experiments indicate a very steep slope for that reaction in the range 7 to 12 kbar.

Experimental investigation on related lithologies at 10 kbar by Le Breton and Thompson (1988) indicated that melting began between 780 and 800°C and was extensive at 850°C.

Patiño-Douce and Johnston (1989) performed experiments on a natural metapelite. They observed biotite, sillimanite and quartz coexisting with melt at temperatures up to 975°C and a very progressive increase of the proportion of melt. This is significantly different from the findings of Vielzeuf and Holloway but can be explained by the low amount of plagioclase (4 wt%) in Patiño-Douce and Johnston's starting material.

Thus, temperatures between 850 and 900°C seem sufficient to produce a significant proportion of liquid in pelites. Such silicate liquids, or at least a proportion of them, are potentially able to segregate from the source, leaving behind a residue of quartz, garnet, sillimanite, feldspar, and rutile. Such a restitic residue has the characteristic mineral assemblage of silicic aluminous granulites.

Partial melting of peraluminous metagreywackes

Island arcs, active and passive margins are the best tectonic settings to generate fertile (water-rich) reservoirs likely to be involved in subsequent granitoid genesis. In such environments, greywackes are abundant crustal rock types and thus are good candidates to generate granitoid magmas. We performed a series of experiments, between 1 and 20 kbar, on the fluid-absent melting of a quartz-rich aluminous metagreywacke composed of 32wt% plagioclase (An_{22}), 25wt% biotite ($X_{Mg}45$), and 41wt% quartz (Vielzeuf and Montel, 1994). Experiments were carried out using both a powder of minerals and a glass of the same composition. The multivariant field of the complex reaction

$$\text{Bt} + \text{Pl} + \text{Qtz} \rightleftharpoons \text{Grt/Crd/Spl} + \text{Opx} + \text{Kfs} + \text{melt} \quad (2)$$

limited by the Opx-in and Bt-out curves, is located between 810–860°C at 1 kbar, 800–850°C at 2 kbar, 810–860°C at 3 kbar, 820–880°C at 5 kbar, 860–930°C at 8 kbar, 890–990°C at 10 kbar, and at a temperature lower than 1000°C at 15 and 17 kbar. The melting of biotite + plagioclase + quartz produced melt + orthopyroxene + cordierite or spinel at 1, 2 and 3 kbar, and melt + orthopyroxene + garnet from 5 to 17 kbar (+ Qtz, Pl, Fe-Ti Ox. at all pressures). K-feldspar was found as a product of the reaction in some cases and we observed that the residual plagioclase was always strongly enriched in orthoclase component. The P-T surface corresponding to the multivariant field of this reaction is about 50 to 100°C wide.

At temperatures below the appearance of orthopyroxene, biotite is progressively replaced by garnet with increasing P. At 850°C, we observed that (1) the modal proportion of garnet increases markedly with P and (2) the grossular content of the garnet increases regularly from about 4 mole % at 5 kbar to 15 mole % at 20 kbar. These changes can be ascribed to the reaction

$$Bt + Pl + Qtz \rightleftharpoons Grt + Kfs + melt \quad (3)$$

with biotite + plagioclase + quartz on the low-P side of the reaction. As a result, at 20 kbar, we observed the progressive disappearance of biotite without production of orthopyroxene. These experiments emphasize the importance of reaction (3) for the understanding of partial melting processes and evolution of the lower continental crust.

Thin layers of gneisses composed of orthopyroxene, garnet, plagioclase, and quartz (± biotite), interbedded within sillimanite-bearing paragneisses, are quite common in granulite terrains. They may result from partial melting of metagreywackes and correspond to recrystallized mixtures of crystals (+ trapped melt) left behind after removal of a major proportion of melt.

Discussion

Available experimental constraints indicate that the beginning of melting for both lithologies (pelites and greywackes) coincide and corresponds to a fluid-absent melting reaction involving muscovite, such as Ms + Pl + Qtz = Bt + Als + Kfs + M. However, extensive melting of pelites takes place at a significantly lower temperature (850°C ± 20) than the melting of Al-metagreywackes (950°C ± 30), at 10 kbar. In addition, the experimental melting curve of greywackes is much less steep than the one for the pelites : at 2 kbar, biotite disappears at about 850°C while it disappears between 980 and 1000°C at 10 kbar. Thus, Ca-poor Al-metagreywackes represent fertile rocks at commonly attainable temperatures (i.e. 800–900°C), only below 7 kbar. There, 30 to 60 vol% of melt can be produced. Above this pressure, temperatures above 900°C are required, making the production of granitoid magmas more difficult from these source rocks. These facts have interesting implications :

1) The positive slope of reaction (2) Bt + Pl + Qtz $\rightleftharpoons$ Grt/Crd/Spl + Opx + Kfs + melt points out the high thermal stability of biotite + plagioclase + quartz at high pressure. This is an explanation for the field observation that orthopyroxene is relatively rare in high pressure quartzo-feldspathic granulites while this mineral is characteristic of medium- to low-pressure quartzo-feldspathic granulites throughout the world. This is nicely exemplified by reference HP-HT rocks from the Hercynian belt of Europe.

2) The P-T stability field of the assemblage Bt + Pl + Qtz + Opx + Grt (+ Kfs) determined by Vielzeuf and Montel (1994) can be used for geothermobarometric purposes. The common observation that biotite is no longer stable in aluminous paragneisses (pelitic protolith) while it still coexists commonly with orthopyroxene, garnet, plagioclase and quartz (greywacke protolith), provides rather tight temperature constraints for granulitic metamorphism.

3) The melting curves of reactions (1) and (2) converge towards 6 kbar and 850°C. There, extensive partial melting of both lithologies coincide making this P-T domain particularly important for granitoid genesis.

Some geodynamic considerations

Comparative studies of orogenic belts show a marked contrast between orogens with abundant granitoids and those with only scarce granitoids. Examples of granite-rich ('fertile') orogens include the European Hercynides, the Lachlan Fold Belt of SE Australia, and the High-/ and North Himalaya belts. Granite-poor, ('sterile') orogens include the Scandinavian Caledonides, the Mauritanides, or the Central-Western Alps, and the Mesozoic-Cenozoic Pyrenean Belt. This contrast in granitoid abundance does not appear to be the result of (i) greatly different evolutionary stages, (ii) different levels of erosion, or (iii) contrasting orogenic processes. Rather, the markedly different amounts of granitoids might be simply interpreted in terms of the contrasting fertility of the major rock types involved in the different orogens. Where orogenic processes mainly rework an older basement, composed of cratonized, thoroughly differentiated crust, no significant granite magmatism should be anticipated. In contrast, orogenic segments involving large quantities of 'wet' sediments and low-grade metamorphic rocks would offer excellent prospects for voluminous granitoid magma production, during and after tectonic thickening. We believe that low-P/high-T metamorphism in the medium to upper parts of the crust, such as the one observed in the Hercynian Pyrenees, is another important consequence of the ability of the lower crust to melt and differentiate.

In conclusion, the abundances, types, and ages of crustally-derived granitoids reflect the compositions, ages and metamorphic states of their source regions, both prior to and following the magmatic events.

References

Le Breton, N. and Thompson, A.B. (1988) *Contrib. Mineral. Petrol.*, **99**, 226–37.