Melt generation in the continental crust: answered and unanswered questions

A.E. Patiño Douce

Department of Geology, University of Georgia, Athens GA 30602, USA.

A comparison of results of experimental studies of the melting behavior of crustal rocks to numerical models of the thermal structure of the continental crust (Fig. 1) suggests that Al-rich metamorphic rocks ('metapelites') can undergo extensive melting (20 to 60 %) during episodes of crustal thickening, even in the absence of intrusion of hot basaltic liquids. Under the same conditions, other metamorphic lithologies, such as orthogneisses and metabasalts, would generate melt fractions well below 20 % or even remain below their solidi. Similarities between common types of silicic igneous rocks and melts generated experimentally from crustal lithologies are limited (Fig. 2). The strongly peraluminous, potassic and Ca-poor melts generated from biotite-rich protoliths are analogous to leucogranitic rocks associated with intracontinental metamorphic belts (e.g. the Himalayan leucogranites, Inger and Harris, 1993). Dehydration-melting of amphibolites gives rise to low-K tonalitic-trondhjemitic melts, which are often strongly peraluminous owing to crystallization of restitic clinopyroxene (Patiño Douce and Beard, m.s. in review), and which differ from most Phanerozoic silicic igneous rocks, with the possible exception of low-K rhyolites and rhyodacites erupted in oceanic environments. The compositions of other important groups of silicic igneous rocks differ from melts generated experimentally from crustal protoliths (Fig. 2). Among such rocks are: the calc-alkaline granitoids and rhyolites characteristic of continental-margin batholiths and ash-flow tuffs; the peraluminous granitoids of the continental interior of Western North America such as those of the Idaho batholith (e.g. Hyndman, 1983); and the strongly peraluminous and somewhat mafic 'S-type' granitoids from SE Australia (e.g. Chappell and White, 1992).

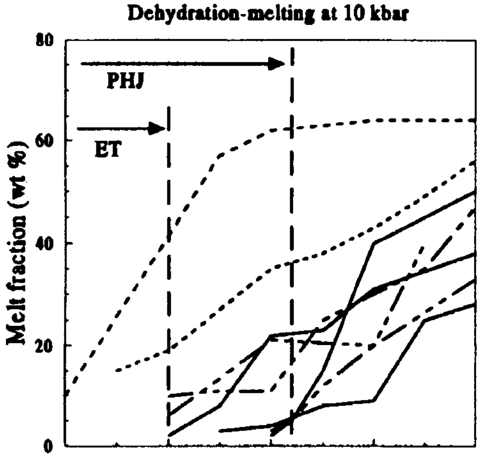

FIG. 1. Vapor-absent melt productivities (at 10 kbar) of: metapelites (dots, after Vielzeuf and Holloway, 1988 and Patiño Douce and Johnston, 1991); biotite gneisses (solid, after Rutter and Wyllie, 1988; Skjerlie and Johnston, 1993 and Patiño Douce and Beard, submitted); and amphibolites (dot-dash, after Beard and Lofgren, 1991; Wolf and Wyllie, 1994 and Patiño Douce and Beard, submitted). Arrows and vertical lines show maximum temperatures during crustal thickening after England and Thompson (1986) and Patiño Douce *et al.*, (1990).

A possible interpretation of these observations is that: (i) only Ca-poor and strongly peraluminous leucogranites represent pure crustal melts, derived from the only kind of protoliths (aluminous mica schists) which can melt extensively in a chemically-closed crust, and (ii) generation of most other types of silicic igneous rocks requires participation of hot mafic melts, and this participation entails both heat and mass transfers. An important question is, then, whether interaction between basaltic magmas and metamorphic rocks can explain the compositions of silicic rocks which do not resemble 'pure' crustal melts (Fig. 2).

In an attempt to help elucidate this issue, I conducted two series of piston-cylinder experiments with 1:1 mixtures of different crustal components (a biotite gneiss and a metapelite) and the same mantle component (a synthetic high-Al olivine tholeiite glass, HAOT). Experiments were done at a uniform temperature of 1000°C, f(O_2) about one log unit more reducing than QFM, and pressures between 5 and 15 kbar. A temperature of 1000°C was chosen because this is a reasonable final

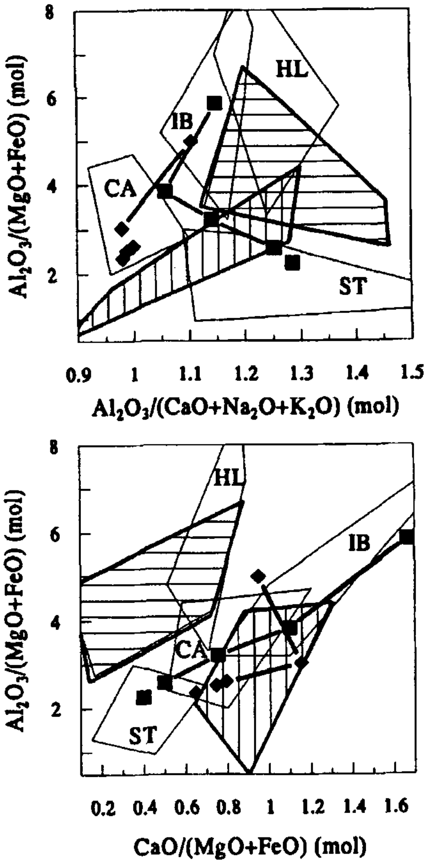

FIG. 2. Comparison of experimental melt compositions to natural silicic rocks. Open polygons are for calc-alkaline granites and rhyolites (CA), granites from the Idaho batholith (IB), Himalayan leucogranites (HL) and Australian S-type granites. Ruled areas are for melts produced experimentally: horizontal from metapelites (Patiño Douce and Johnston, 1991) and biotite gneisses (Skjerlie and Johnston, 1993; Patiño Douce and Beard, submitted); vertical from amphibolites (Beard and Lofgren, 1991; Patiño Douce and Beard, submitted). Trends are for melts generated experimentally by reaction between HAOT and biotite gneiss (diamonds) and HAOT and metapelite (squares), from 5 kbar (lowest A/MF ratio) to 15 kbar (highest A/MF ratio).

temperature for constant-enthalpy assimilation of upper amphibolite-facies rocks into an equal mass of basaltic melt at its liquidus temperature, and also because this is approximately the maximum temperature recorded in mafic granulites which are believed to represent the deep crustal environment where mantle-crust interactions are likely to take place. Samples were contained in welded Au capsules with no added H_2O, so that the only H_2O present (about 1 wt%) was that structurally bound in micas.

All experiments generated 35–40 wt% of silicic melt (SiO_2 > 70 wt%), but there were important compositional variations, as a function of both pressure and composition of the crustal end-member. The compositional spectrum of the melts and coexisting crystalline residues can be summarized as follows (see also Fig. 2):

- Reaction between HAOT and biotite gneiss at $P \leqslant 10$ kbar generated melts analogous to calc-alkaline rhyolitic and granitic rocks from continental margin settings. These melts were produced in equilibrium with gabbronoritic residues.

- Reaction between HAOT and metapelite at $P \leqslant 7$ kbar produced strongly peraluminous and 'mafic' (up to 4.5 wt% $FeO+MgO+TiO_2$) melts, that resemble S-type granites, in equilibrium with spinel norites (at 5 kbar) or garnet norites (at 7 kbar).- At $P > 10$ kbar both source compositions produced strongly peraluminous leucocratic melts (< 2 wt% $FeO+MgO+TiO_2$) that resemble the deep-seated granitoid rocks from the Idaho Batholith. These melts coexisted with assemblages rich in garnet (pelite source) or garnet + clinopyroxene (gneiss source).

The experiments show that granitic (and even leucogranitic) magmas with isotopic signatures reflecting inheritance from both crustal and mantle components can be primary products of reaction between anhydrous basaltic melts and amphibolite-facies metamorphic rocks, at P-T conditions appropriate for the deep crust of magmatically active environments. The experiments also demonstrate that pressure of magma generation and crustal source composition have equally important effects on melt composition, and that interplay of these variables can give rise to hybrid melts which match very closely the compositions of various types of silicic igneous rocks (with the notable exception of Himalayan-type leucogranites). Of course, the experiments do not prove that large volumes of felsic melts are generated in nature by reaction between mafic magmas and crustal rocks, nor that this is the only process that can lead to commonly observed silicic rock compositions. Determining whether other combinations of genetic and evolutionary processes can also give rise to common types of silicic magmas is, perhaps, one of the most important questions that must be resolved in order to advance our understanding of crustal magmatism.