



Dehydration melting and the relationship between granites and granulites



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ABSTRACT

For more than half a century, thought about granite genesis and crustal evolution has been guided by the concept of partial melting in the lower crust. In this model, granitic magmas produced at depth are lost to shallow levels, leaving behind a more mafic, volatile poor residue that is depleted in incompatible components (H₂O, alkalis, and heat-producing elements). Although granite extraction must be the dominant process by which crust is modified over time, the preferred model of granite genesis triggered by metamorphic dehydration reactions (dehydration melting) does not adequately explain important aspects of granite formation. The temperatures required for voluminous granite production by dehydration melting need heat and mass input to the crust from mantle-derived mafic magmas. In addition, prediction of the H₂O contents of granitic liquids by extrapolation from low-pressure experiments to deep-crustal pressures (*P*) and temperatures (*T*) implies that the H₂O resident in hydrous minerals is insufficient to account for large granite volumes, such as anorogenic granite batholiths in continental interiors. To test this, we conducted new experiments on the H₂O contents of simple granitic liquids at 10 kbar and 800–950 °C. We confirm previous extrapolations from lower *P* and *T* indicating that a minimum of 3–4 wt% H₂O is present at the studied *P* and *T* in a granitic liquid in equilibrium with quartz and feldspars. For large-scale melting, this is much more than could have been supplied by the H₂O resident in biotite and amphibole by dehydration melting at these conditions, unless lower-crustal temperatures were higher than generally inferred. Another problem with the dehydration-melting model is that the crystal chemistry of the large-ion lithophile elements (LILE) does not favor their partitioning into granitic liquids; rather, U, Th, Rb and the rare earth elements (REE) would more likely be concentrated in the postulated mafic residues. Finally, observations of migmatite complexes reveal many features that can not be satisfied by a simple dehydration-melting model.

We suggest that the volatile components CO₂ and Cl are important agents in deep-crustal metamorphism and anatexis. They induce crystallization and outgassing of basalt magmas at lower-crustal levels, where the combination of latent heat and liberated H₂O may contribute to granite production, leading to larger melt fractions than for simple dehydration-melting models. Since the Cl and CO₂ are very insoluble in granite liquids, granite generation leads naturally to production or separation of a coexisting metamorphic fluid with low H₂O activity. Such a fluid could coexist with granulite-facies assemblages and yet be capable of dehydration, alkali exchange and LILE extraction to explain many chemical processes of deep-crustal metamorphism not readily explainable by dehydration melting.

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1. Introduction

Tuttle and Bowen's (1958) memoir on experimental melting of a simple granite (alkali feldspars + quartz) at elevated H₂O pressures is one of the most influential works in petrology. They showed that melting temperatures of common quartzofeldspathic rocks are lowered by high H₂O pressure to the temperature range thought to prevail in high-grade metamorphism. This led to the concept of

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granite formation as the culmination of regional metamorphism (Brown and Fyfe, 1970). To many petrologists, the new experimental work provided a satisfying guide to the interpretation of granite in all of its manifestations. Some aspects of granite described in classical field studies, observations that could be plausibly attributed to the interaction of rocks with migrating pore fluids, or metasomatism (Anderson, 1937; Misch, 1949), were downplayed in the expectation that these features could be explainable in the larger context of magmatism.

In the years following publication of the “Granite Memoir” experimental and theoretical petrology has shown that the temperature scale of crustal metamorphism extends well beyond the melting temperatures of crustal rocks at high H₂O pressures (~650–700 °C; e.g., Bohlen, 1987; Bohlen and Mezger, 1989; Harley, 1989, 1998; Pattison et al., 2003). An explanation commonly advanced for a refractory lower crust is H₂O deficiency. Rocks that had experienced granulite-facies metamorphism – an important fraction of the deeper parts of the continental crust – are dominated by anhydrous minerals and possess porosity so low that significant long-term storage of free volatiles is implausible.

Granulites exposed in uplifted deep-crustal terranes commonly contain segregations of feldspars and quartz, the components of the rocks that melt at lowest temperature in the presence of H₂O; that is, they are migmatized. The H₂O must have been restricted in amount (or in its activity) to limit the extent of partial melting. The model of “dehydration melting” provides a plausible explanation: the H₂O available comes entirely from micas and amphiboles initially present in the granodioritic or tonalitic gneisses and, to a lesser extent, metasediments in the deeper parts of the crust.

The concept of partial hydrous melting in the deep crust and extraction of granitic magmas leads naturally to a simple crustal evolution model which could account not only for removal of H₂O and other hyperfusible components, leaving a refractory granulite-facies lower crust, but might also explain certain trace-element signatures of the exposed high-grade terranes, including depletion, relative to upper crustal rocks of the same general major element compositions, of the large-ion lithophile elements like Cs, Rb, Ba, and, to a lesser extent, K, and the radioactive elements U and Th (Heier, 1973). Such a process might be important in long-term survival of the continents in that it creates a refractory underpinning to continental masses (Collerson and Fryer, 1978).

The dehydration-melting hypothesis satisfies some of the major observational requirements. These include the experimental facts that partial melting of metatonalites and Al-rich metasediments yields, respectively, liquids of the compositions of metaluminous (Rutter and Wyllie, 1988) and peraluminous (Vielzeuf and Holloway, 1988) granites, that the residual minerals are the mafic-aluminous silicates pyroxene, garnet, cordierite, and sillimanite characteristic of the granulites, and that the temperature range of melting, 750–900 °C, is attained in high-grade metamorphism (Bohlen, 1987; Bohlen and Mezger, 1989; Harley, 1989; Pattison et al., 2003). Dehydration melting has been suggested to play a major role in softening of the middle crust, thus expediting detachment faulting and the extraction of granite batholiths (Vigneresse et al., 1996; Vanderhaeghe and Teyssier, 2001). Fluid-absent dehydration melting is commonly invoked to explain crustal differentiation by upward removal of the granitic partial melt, leaving a volatile- and LILE-depleted granulite-facies lower crust (e.g., Clemens, 1990; Clemens et al., 1996; Vielzeuf et al., 1990; Brown, 2001).

Although the dehydration-melting model has gained wide currency, there remain key aspects of granite genesis and its relation to granulite-facies metamorphism that it does not adequately explain. It is difficult to supply sufficient heat to generate observed granite masses solely by dehydration-melting of the lower crust. In addition, the H₂O available for dehydration melting of

relatively anhydrous lower crustal granulitic rocks yields relatively small melt volumes. The partitioning of LILE between granitic liquids and granulite residues does not adequately explain observations in exposed terranes. The feasibility of efficient extraction of low-degree viscous partial melts from their residua remains uncertain. Finally, segregations or leucosomes with compositions different than those predicted for dehydration melting are commonly observed in granulite grade migmatites.

The purpose of the present paper is to discuss in more detail some of the aspects of the supposed granite-granulite connection that have not been adequately addressed but which may bear on the concept of fluid-deficient dehydration melting. We present new experimental results that support the low liquid fractions produced by typical amphibolite facies rocks during dehydration melting at 10 kbar, as inferred by Johannes and Holtz (1991). We build on this result by discussing additional observations that are not well-explained by the dehydration-melting model. We conclude by proposing that alternative conceptual schemes involving the introduction of volatile components, particularly H₂O, into the sites of deep-crustal melting can resolve some of these problems.

2. The problem of heat and mass transfer during crustal melting

Granites are chiefly products of melting of continental crust, with some input of mantle-derived material (Wyllie et al., 1976; Leake, 1990). While some granites may reflect fractional crystallization of a mantle-derived magma (e.g., Fowler et al., 2001), it is difficult to produce granite in the large amounts seen in batholiths by fractional crystallization-differentiation of basalts, or by assimilation of crustal material (Bowen, 1928).

As Bowen (1928) pointed out, simultaneous consideration of the heat and the material budgets places an important constraint on granite genesis. If mantle-derived basalt is the heat source for crustal melting (Harley, 1989; Bohlen, 1987) as well as the source of the extra-crustal material component, the creation of a certain mass of granitic liquid must be attended by crystallization of a nearly equal mass of injected basalt to supply the heat for melting. This would in turn imply that generation of granite in the lower crust also involves large-scale crustal accretion in the form of basalt underplating (Ewart et al., 1980). These considerations have at least two consequences.

First, the postulated mantle-derived basalts would, in some measure, be expected to supply some material to granitic liquids, as well as heat. Yet most granites are demonstrably almost entirely partial melts of pre-existing crust in their major element chemistry; it is in the Sr and Nd isotopes that large amounts of primitive mantle input are implicated (Leake, 1990). It is difficult to see how this incongruent contamination could occur unless some transfer mechanism exists that is not anticipated by models of melting in a closed system such as simple dehydration melting.

Second, the source-rock fertility determines the amount of granitic liquid that can be produced by crustal melting. Variations in fertility arise chiefly from the bulk H₂O content, as controlled by the abundance and identity of hydrous minerals in the source rock. The larger the H₂O content, the larger the volume of granitic liquid produced at a given pressure and temperature, all else being equal. The best case for generating substantial quantities of granitic liquid by dehydration melting can be made for Al-rich metasedimentary sources (Vielzeuf and Holloway, 1988; Thompson, 1996; Nabelek and Bartlett, 1998). Fig. 1A shows the percentage melt yield of a metamorphic rock containing 30 modal percent of biotite and muscovite at deep-crustal pressures. As much as 50 vol% of melt

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