J. D. Clemens · J. M. Watkins

The fluid regime of high-temperature metamorphism during granitoid magma genesis

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Abstract The strong negative correlation between the temperatures and melt $\text{H}_2\text{O}$ contents of granitoid magmas implies that the crustal melting reactions that produced the magmas were strongly buffered, with $T$ and $\text{aH}_2\text{O}$ co-varying within a narrow band. This observation can only be explained if the partial melting reactions that created the magmas were either fluid-absent from the outset or evolved toward this condition as melting progressed. Since these melting reactions occur during upper amphibolite- to granulite-facies metamorphism, it is reasonable to conclude that metamorphic events responsible for the generation of granitoid magmas generally occur in the absence of excess pervasive fluid.

Introduction

One of the most active debates in petrogenesis surrounds the question of whether high-grade metamorphism (and associated partial melting of Earth’s crust) occurs mainly under fluid-absent or fluid-present conditions. The upper range of temperatures required to partially melt crustal rocks, and form granitoid magmas, equate with those of granulite-facies metamorphism. There is thus an inferred intimate connection between the formation of granulite-facies mineral assemblages and the production and withdrawal of partial melts (e.g. Fyfe 1973; Clemens 1990; Thompson 1990). It is generally agreed that many (probably most) granitoid magmas that are emplaced into the upper continental crust, or erupted from silicic volcanoes, were generated mainly during high-$T$ crustal melting. The inferred temperatures for these high-level granitoid magmas (>800 °C) therefore suggest a genetic link between the generation of granitoid magmas and upper amphibolite- to granulite-facies metamorphism. These connections have been discussed in detail by Brown and Fyfe (1970), Fyfe (1973), White and Chappell (1977), Clemens (1990) and Thompson (1990). The link between crustal melting and granitoid magma genesis has been firmly established, since the 1970s, on the basis of the stable and radiogenic isotope characteristics of granitoid rocks, field studies of high-grade terranes and high-$P$-$T$ experimental studies; a vast literature exists on this subject.

What is certainly not agreed is the nature of the fluid regime during such metamorphism and partial melting. The hydrous character of granitoid magmas implies that the magma-forming partial melting reactions involve the transfer of $\text{H}_2\text{O}$ from the rock ± fluid systems to the melts. The initially $\text{H}_2\text{O}$-undersaturated character of all high-level granitoid magmas (e.g. Clemens 1984), as well as a great body of phase equilibrium evidence from the metamorphic rocks, suggests that pure aqueous fluid is not usually present, in excess, at these metamorphic grades (e.g. Stevens and Clemens 1993, and references therein). That is, $\text{aH}_2\text{O}$ is mostly <1 during these processes.

Types of fluid regime

There are four ways in which rock systems might achieve a state in which $\text{aH}_2\text{O}$ is <1. These are:

- a. The system initially contains aqueous ($\text{H}_2\text{O}$) fluid, but in insufficient quantity to saturate any melt that is formed. This is a fluid-deficient, rock-dominated system, as described by Clemens and Droop (1998). Here, the initial fluid will be entirely consumed by melting reactions and the system will evolve toward a fluid-absent state.

- b. The system is fluid-dominated (excess fluid present) but that fluid is not pure $\text{H}_2\text{O}$. This will control the $\text{aH}_2\text{O}$ of the system at a value defined by the fluid
composition, which could be essentially anything geologically reasonable. Current suggestions for the diluting species include \(\text{CO}_2\) and alkali chlorides (e.g. Newton et al. 1980; Smulovich and Graham 1996).

c. The system is fluid-present and the fluid is not pure \(\text{H}_2\text{O}\) (as in b above). However, the quantity of fluid is insufficient to globally impose an \(a\text{H}_2\text{O}\) value. Here the system is strictly neither rock- nor fluid-dominated. Wide \(a\text{H}_2\text{O}\) variations could exist, and the final \(a\text{H}_2\text{O}\) could extend down to very low values, though never to zero in a hydrous protolith. The actual value of \(a\text{H}_2\text{O}\) attained would be determined by the imposed \(T\), the equilibria (solid–fluid or solid–fluid–melt) that operate, the solubilities (in the melt) of the non-aqueous fluid species, their ability to wet grain boundaries, the fluid–rock ratio and the modal amounts of hydrous minerals in the protolith. If melting occurred, \(a\text{H}_2\text{O}\) would always evolve toward the value at the solidus for the imposed metamorphic \(T\).

d. The system is fluid-absent, apart from possible minor quantities of fluid species that do not wet the grain boundaries and are therefore effectively ‘invisible’ to the mineral grains, and reactions between them (e.g. Clemens 1990). In this case, \(a\text{H}_2\text{O}\) would be tightly constrained, with the system completely rock-dominated.

Figure 1 illustrates the potential extents of the \(P–T–a\text{H}_2\text{O}\) relations that could exist in each of the above fluid regimes.

**Metamorphic fluid regimes and \(\text{H}_2\text{O}\) contents of granitoid magmas**

As noted above, the first three fluid regimes (cases a to c) could result in a broad range of \(a\text{H}_2\text{O}\). Granitoid magmas formed by these melting equilibria could therefore have essentially any initial \(\text{H}_2\text{O}\) content. For case a, the lower limit would be the \(\text{H}_2\text{O}\) content at the fluid-absent reaction. For b it would be the solidus at the particular \(T\) and imposed \(a\text{H}_2\text{O}\), and for c it would be some potentially very low \(a\text{H}_2\text{O}\) determined by the rock composition and fluid:rock ratio. The upper limit would be the \(\text{H}_2\text{O}\) saturation level for granite melt at the local pressure. In these cases, it would be most unlikely that there would be any systematic co-variation between magma temperature and melt \(\text{H}_2\text{O}\) content. The temperature reached in the protolith, at the moment of magma extraction, would govern the temperature of the magma. The melt \(\text{H}_2\text{O}\) content would be governed by the \(a\text{H}_2\text{O}\) in the fluid or the amount of \(\text{H}_2\text{O}\) initially present in the protolith.

Case c is one in which the \(a\text{H}_2\text{O}\) (and melt \(\text{H}_2\text{O}\) content) would be constrained to co-variation. However, unlike the fluid-absent case (d) the \(T–\text{H}_2\text{O}\) band for melts could be broad, as in case b. At any given \(P\), the metamorphic temperature would determine the range of \(a\text{H}_2\text{O}\) over which melt could be present.

Among fluid-present systems, an exception to this general rule (of unbuffered \(a\text{H}_2\text{O}\) values) would occur if graphite were stable in the presence of a \(\text{C–O–H}\) fluid. In this case, the graphite–fluid equilibria would buffer the fluid composition; temperature and \(a\text{H}_2\text{O}\) would systematically co-vary. Over the \(P–T\) range of interest (0.3 to 1 GPa and 650 to 1,000 °C), calculations using the program COHSgraph 3.3 (Holloway 1987) show that graphite would not generally be stable unless \(O_2\) is below that defined by the fayalite–magnetite–quartz (FMQ) buffer. At log\(O_2 = \text{FMQ-1}\), a typical value for granulite-facies paragneisses, the \(\text{C–O–H}\) fluid in equilibrium with graphite would mostly be rather \(\text{H}_2\text{O}\)-rich (\(X\text{H}_2\text{O} \approx 0.8\)), except at the lowest pressure (0.3 GPa) and \(T \geq 850 \, ^\circ\text{C}\), where \(X\text{H}_2\text{O}\) would fall to \(< 0.3\). Other fluid species (e.g. \(CH_4\)) would be very low in abundance under these conditions, so the fluid would be closely approximated as \(\text{H}_2\text{O}–\text{CO}_2\).

The implications of the graphite–fluid situation will be discussed later. However, note that this analysis assumes maintenance of equilibrium between the graphite and fluid. Disequilibrium melting might still occur, but the melt \(\text{H}_2\text{O}\) contents would not be buffered, and the situation would be most comparable to the fluid-present