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## 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 H<sub>2</sub>O contents of granitoid magmas implies that the crustal melting reactions that produced the magmas were strongly buffered, with *T* and *a*H<sub>2</sub>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 H<sub>2</sub>O from the rock ± fluid systems to the melts. The initially H<sub>2</sub>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, *a*H<sub>2</sub>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 *a*H<sub>2</sub>O is < 1. These are:

a. The system initially contains aqueous (H<sub>2</sub>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 H<sub>2</sub>O. This will control the *a*H<sub>2</sub>O of the system at a value defined by the fluid

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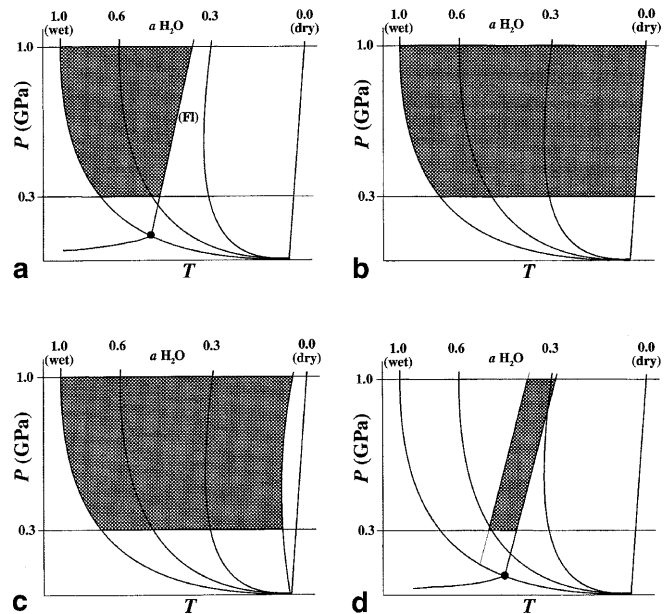
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composition, which could be essentially anything geologically reasonable. Current suggestions for the diluting species include  $\text{CO}_2$  and alkali chlorides (e.g. Newton et al. 1980; Shmulovich and Graham 1996).

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.



**Fig. 1** Hypothetical  $P$ – $T$  plots contoured in  $a\text{H}_2\text{O}$ . Each  $a\text{H}_2\text{O}$  contour is the location of the granite solidus at that value of  $a\text{H}_2\text{O}$ . The upper  $T$  limit of a hypothetical fluid-absent melting reaction is shown (where applicable) as a curve labelled (F). The shaded area on each plot illustrates the range of  $P$ – $T$ – $a\text{H}_2\text{O}$  values that could result from the particular fluid regime, assuming pressure limits of 0.3 and 1 GPa. The regimes are labelled as in the text: **a** rock-dominated with  $\text{H}_2\text{O}$  fluid, **b** fluid-dominated with complex fluid, **c** rock-dominated with complex fluid, **d** fluid-absent. It is assumed that, for partially melting systems that evolve toward fluid-absent conditions (cases **a** and **d**), metamorphic  $T$  recorded in any escaped granitoid magmas will not exceed the upper limit of the fluid-absent equilibrium. If it did exceed this value,  $a\text{H}_2\text{O}$  values would extend toward the lower values at the high- $T$  ends of the plots. See text for further explanations

### 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 granitoid 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-vary. 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 C–O–H fluid. In this case, the graphite–fluid equilibrium 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  $f\text{O}_2$  is below that defined by the fayalite–magnetite–quartz (FMQ) buffer. At  $\log f\text{O}_2 = \text{FMQ}-1$ , a typical value for granulite-facies paragneisses, the 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  $T \geq 850$  °C, where  $X\text{H}_2\text{O}$  would fall to  $< 0.3$ . Other fluid species (e.g.  $\text{CH}_4$ ) 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

case, with  $a\text{H}_2\text{O}$  controlled by whatever fluid composition was attained. Also note that this argument has no bearing on the behaviour of graphite in a fluid-absent system. It is perfectly possible to have fluid-absent partial melting in the presence of graphite. For a treatment of this situation see Holloway et al. (1992).

The above considerations suggest that, in most cases, granitoid magmas formed through fluid-present high- $T$  metamorphism could have a range of temperatures (say 650 to 1,000 °C), with  $\text{H}_2\text{O}$  contents that could vary randomly from almost zero to quite high values. There could be hot wet melts, hot dry melts, cool dryish ones, cool wet ones, and any combination in between.

The fluid-present cases contrast strongly with the effects of fluid-absent metamorphism (case d, above). In examining the theoretical variations in granitoid melt viscosity, Clemens and Petford (1999) pointed out that, in fluid-absent melting, temperature and melt  $\text{H}_2\text{O}$  content should systematically co-vary such that cooler magmas are wetter and hotter magmas are drier. This occurs because higher- $T$  fluid-absent reactions buffer  $a\text{H}_2\text{O}$  at lower values.

Equally importantly, this co-variation is constrained to occur within a narrow band of  $T$ - $\text{H}_2\text{O}$  values. It is certainly true that, in nature, fluid-absent melting reactions are at least divariant, and occur over  $P$ - $T$  bands, rather than along univariant lines. It might therefore be argued that fluid-absent melting would produce granitoid magmas with a wide range of  $a\text{H}_2\text{O}$ . However, because of the relatively steep  $dP/dT$  slopes of fluid-absent melting reactions,  $a\text{H}_2\text{O}$  does not vary greatly along them, at least at pressures relevant to regional metamorphism (Clemens and Petford 1999). Also, experiments (e.g. Vielzeuf and Holloway 1988) show that these bands are quite narrow in some crustal magma source rocks, allowing only limited independent variation in  $T$  and  $a\text{H}_2\text{O}$ . Even given a relatively broad  $T$  band for a given fluid-absent melting reaction, many experimental studies have shown that melt is produced in a major pulse over a much narrower  $T$  interval. The most important thing to realize here is that, at whatever  $T$  value the magma is extracted from the residue, it will inherit the  $a\text{H}_2\text{O}$  uniquely defined by that combination of  $P$ - $T$  conditions. This is an inherent property of fluid-absent behaviour (e.g. Clemens and Vielzeuf 1987) and sets fluid-absent melting apart from melting under any other fluid regime.

### Temperatures and $\text{H}_2\text{O}$ contents of real granitoid magmas

Scaillet et al. (1998) collated experimental data on the temperatures and initial  $\text{H}_2\text{O}$  contents of granitoid magmas, for the purpose of constraining granitoid melt viscosities. The data were taken from studies that compared experimentally determined phase relations with petrographic evidence of mineral paragenesis, to infer the  $T$  and initial melt  $\text{H}_2\text{O}$  contents of the magmas.

Scaillet et al. presented a table and a plot of the data, re-plotted here in Fig. 2.

The magmas plotted in Fig. 2 (39 volcanic and 5 plutonic) range in composition from rhyolitic (granitic) to dacitic (tonalitic). They include a good range of S-type, I-type and A-type magmas, as defined by Chappell and White (1974) and Collins et al. (1982), but with a preponderance of I-types, probably reflecting their relative abundance. They are from a variety of localities spread over five continents and several island arcs. They cover both plutonic and volcanic emplacement styles, including lava domes and pyroclastic deposits. The tectonic regimes range from inter-oceanic arcs to Andean margins, continental collision zones and within-plate settings, and the ages of the rocks vary from early Palaeozoic to late Cainozoic. The five data points for the plutonic rocks do not plot in any distinctive position, but are scattered through the middle part of the distribution. This is in accord with the inference made by some workers that there is nothing in the composition of a granitoid magma that predetermines its emplacement mechanism (e.g. Clemens and Mawer 1992). The data set seems to fairly represent the compositional and tectonic spectrum of granitoid magmas. We therefore suggest that any conclusions drawn from examination of these data will be widely applicable to granitoid magmatism and the genesis of granitoid magmas.

The temperatures and  $\text{H}_2\text{O}$  contents determined for these magmas all represent the earliest identified stages of crystallization, not conditions and compositions that prevailed during late magmatic evolution. Thus, these data enable us to discuss conditions as close as possible to the initial states of the magmas when they first separated from their source regions. A good deal of other data on temperatures and  $\text{H}_2\text{O}$  contents are available in the literature (e.g. from melt inclusion studies), but many of these seem to relate to highly fractionated magmas, and are not useful for the present purpose of discussing initial conditions of magma formation.

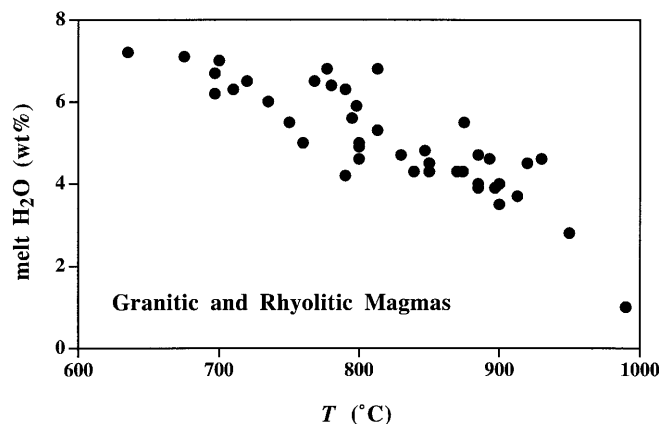


Fig. 2 Plot of experimentally constrained magma temperatures and melt  $\text{H}_2\text{O}$  contents for granitoid magmas. The data are from 31 independent studies, as compiled by Scaillet et al. (1998). See text for further discussion

The notable feature in Fig. 2 is the strong negative correlation displayed ( $r^2 = 0.760$  for a second-order polynomial fit). This remarkable feature was also noted by Scaillet et al. (1998). From the above discussion it is clear that this relationship implies that the melting reactions that created the granitoid magmas took place under conditions that buffered the melt  $H_2O$  contents. As suggested above, it would be pure coincidence if such a correlation emerged in a fluid-present regime – where no buffering should occur. However, see the comments below regarding the effects of the presence of graphite in a fluid-present system.

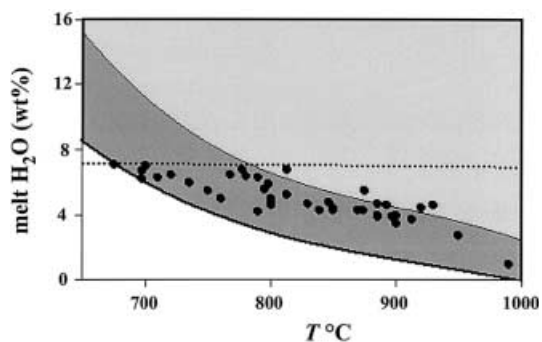
## Modelling

As discussed by Clemens and Vielzeuf (1987), the solidi for quartzofeldspathic and pelitic rocks are adequately modelled by the solidus in Qtz–Ab–Or– $H_2O$  (haplogranite), and the solidi of intermediate rocks (e.g. meta-andesites) are similar to the higher- $T$  solidus in Qtz–Ab– $H_2O$ . The data of Holtz and Johannes (1994), on the  $H_2O$  contents of haplogranite melts as a function of  $P$ ,  $T$  and  $aH_2O$ , can be used to calculate the ranges of melt  $H_2O$  contents expected for granitoid melts derived from pelitic and quartzofeldspathic sources. Similarly, using the calculated locus of the Qtz–Ab– $H_2O$  solidus at  $aH_2O < 1$  (Clemens 1981) and a model for the solubility of  $H_2O$  in silicate melts (e.g. Burnham 1981), it is possible to calculate the  $H_2O$  contents of granitoid melts derived from source rocks of intermediate composition. For such calculations it is assumed that most crustal melting takes place at pressures between 0.3 and 1.0 GPa (3 to 10 kbar).

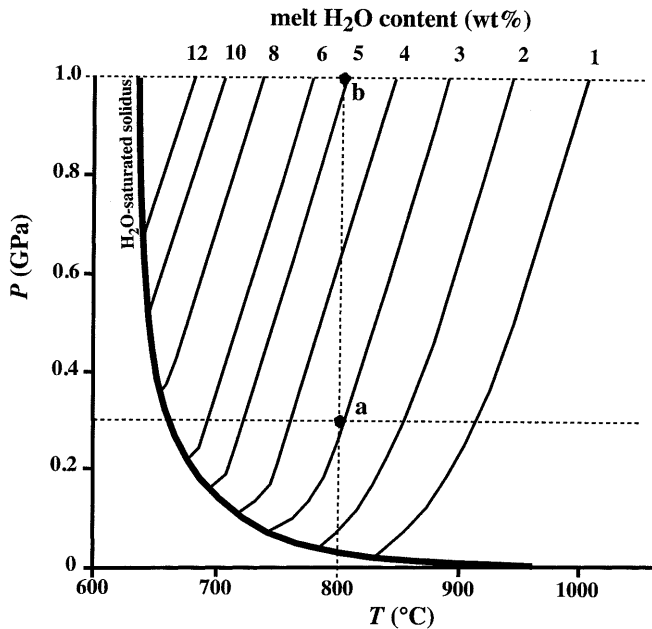
For wet melting, the range of melt  $H_2O$  contents is simply the range of solubility of  $H_2O$  in granitoid melts under the appropriate  $P$ – $T$  conditions. This is readily calculated using  $H_2O$  solubility models such as that of Burnham (1981). For melting in the presence of fluids with  $aH_2O < 1$ , the range is constrained by the region of  $P$ – $T$  space in which granitoid melt is stable for any specified  $aH_2O$ . This can most easily be obtained by examining a  $P$ – $T$  graph of the granite solidus as a function of  $H_2O$  activity or fluid composition, as in Fig. 2.12 or 2.13 of Johannes and Holtz (1996). The large shaded envelope outlined by the heavy line in Fig. 3 shows the results of this process. It confirms the inference that there should be a huge range of possible initial melt  $H_2O$  contents in granitoid melts formed by fluid-present reactions. Note that all the experimental data points fall on or below the dotted line representing the maximum  $H_2O$  solubility at  $P = 300$  MPa. This would represent the upper pressure limit for magma generation if we were to assume that the melts were  $H_2O$ -saturated when first formed. Abundant geological and geobarometric evidence shows that most high-grade metamorphic rocks (and granitoid magma sources) are not limited to such a low pressure. Therefore the only meaning of this feature is that most natural granitoid melts are initially  $H_2O$ -undersaturated.

For fluid-absent conditions, at any  $P$  and  $T$ , the  $H_2O$  content of the melt is defined by the  $H_2O$  content isopleth at that  $P$  and  $T$ . This is a consequence of the properties of fluid-absent melting reactions (see e.g. Clemens and Vielzeuf 1987), and means that the  $H_2O$  contents of melts formed by fluid-absent reactions can be read directly from a graph showing the  $P$ – $T$  position of the granite solidus as a function of  $H_2O$  content of the melt, such as Fig. 2 of Holtz and Johannes (1994). This is illustrated in Fig. 4. The horizontal dashed lines at 0.3 and 1 GPa show the range of pressures of interest. The vertical dashed line is at a notional  $T$  of 800 °C. Point ‘a’ represents the fluid-absent solidus at 0.3 GPa, and indicates a melt  $H_2O$  content just over 3 wt%. If the system had less  $H_2O$  than this, it would be below the solidus (no melt); if it had more, there would be a free fluid present (not fluid-absent). Thus, in this model, the minimum melt  $H_2O$  content, at any fixed temperature, is given by the melt  $H_2O$  content isopleth at 300 MPa and that  $T$  (e.g. point ‘a’ in Fig. 4). Since the isopleths have positive  $dP/dT$  slopes, the maximum is given by the  $H_2O$  isopleth at 1 GPa and that  $T$  (e.g. point ‘b’ in Fig. 4). The equivalent process for Qtz–Ab– $H_2O$  is not as simple because no graphs such as Fig. 4 have been constructed for this system. Instead the  $H_2O$  contents of the melts must be calculated directly. Collecting the maximum and minimum values for each temperature, in both of the systems, produces the darker grey-shaded area in Fig. 3. This is where the  $H_2O$  contents should fall for all granitoid melts formed by fluid-absent reactions in quartzofeldspathic, pelitic and intermediate protoliths.

The first point to note about the modelled  $H_2O$  contents of granitoid melts, formed by fluid-absent partial fusion, is that they form a rather narrow band in Fig. 3. This illustrates the strong buffering character of such reactions. Indeed, the band would be even nar-

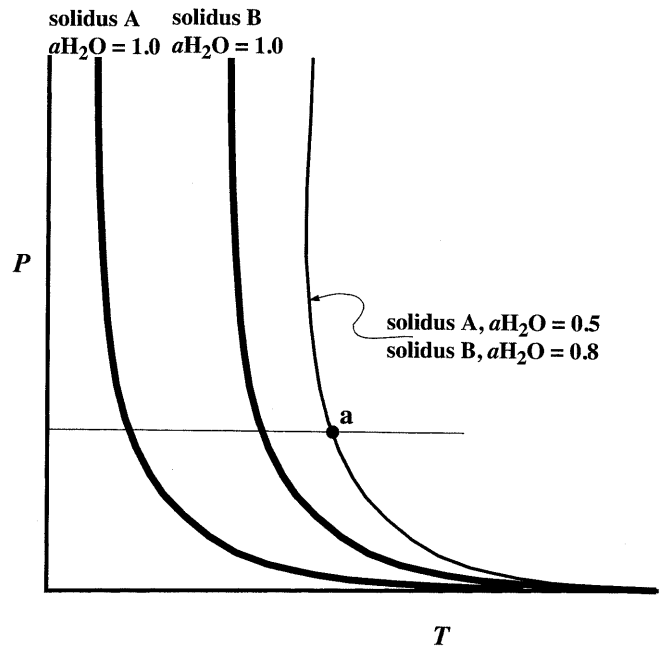


**Fig. 3** Plot similar to Fig. 2 but for model haplogranitic partial melts. The *heavy black outline* delineates the *shaded region* of possible  $H_2O$  contents of granitoid melts. Possible compositions of melts formed by fluid-present reactions occupy the entire *shaded portion* of the graph. The smaller, *darker grey-shaded region* shows the  $H_2O$  contents possible in melts formed by fluid-absent reactions. *Black dots* are the real-rock data transposed from Fig. 2, and the *dotted line* represents the solubility of  $H_2O$  in haplogranitic melts at a pressure of 300 MPa. See text for further details



**Fig. 4**  $P$ - $T$  plot showing the  $\text{H}_2\text{O}$ -saturated (wet) solidus for haplogranite and the solidus curves for a number of fixed melt  $\text{H}_2\text{O}$  contents (redrawn from Fig. 2 of Holtz and Johannes 1994). The pressure range of interest (0.3 to 1 GPa) is shown by two horizontal dashed lines. At an example temperature of 800 °C, point *a*, at 0.3 GPa, defines the minimum  $\text{H}_2\text{O}$  content of a fluid-absent melt formed at that temperature. Point *b*, at 1 GPa, represents the maximum  $\text{H}_2\text{O}$  content of a fluid-absent melt formed at that temperature, in the pressure range of interest. This is the basis of the model presented in Fig. 3

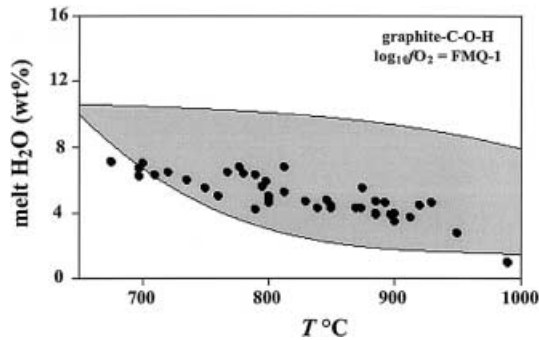
rower if we limited our consideration to melts formed from the pelitic and quartzofeldspathic protoliths. Also plotted in Fig. 3 are the experimentally constrained points for natural granitoid magmas. The correspondence between the predicted  $\text{H}_2\text{O}$  contents and these real-world data is quite good, but there are a few points, toward the higher- $T$  end that are more hydrous than predicted. Some of the higher- $T$  melts may have been derived through hornblende breakdown reactions in mafic (amphibolitic) protoliths. As pointed out by Clemens and Vielzeuf (1987), there is no sufficiently well-studied simple system that can be used to adequately model the solidus of a basaltic (amphibolitic) source rock at reduced  $a\text{H}_2\text{O}$ . Using a more appropriate solidus, at higher temperature for any given pressure, the calculated  $\text{H}_2\text{O}$  contents of the melts would increase, as required to fit the data. This is because, for any  $P$  and  $T$  above the solidus,  $a\text{H}_2\text{O}$  (and hence melt  $\text{H}_2\text{O}$  content) would be higher for the rock with the higher- $T$  solidus (see Fig. 5). Given the difficulty in modelling an amphibolite solidus, no attempt is made here to produce a more sophisticated model. The major point is that, unlike any other kind of melting reaction modelled above, fluid-absent melting results in a narrow band of melt  $\text{H}_2\text{O}$  contents on a graph such as Fig. 2. The data from real granitoid magmas form such a restricted band.



**Fig. 5** Schematic  $P$ - $T$  plot illustrating the effect of choosing an inappropriate solidus to model the  $\text{H}_2\text{O}$  contents of fluid-absent partial melts. The two thick curves show the wet solidi (A and B) for two different systems (e.g. Qtz-Ab- $\text{H}_2\text{O}$  at lower  $T$  and Pl-Hbl- $\text{H}_2\text{O}$  at higher  $T$ ). Point *a* lies on a solidus curve at some  $a\text{H}_2\text{O} < 1$ . If A is chosen as the model solidus then point *a* will represent a much lower  $a\text{H}_2\text{O}$  than if solidus B is chosen to represent the partial melting system. Thus, if B is the correct solidus but is modelled using A, the calculated  $a\text{H}_2\text{O}$  (and hence the melt  $\text{H}_2\text{O}$  content) value at point *a* would be too low. This explains the deviation of some of the higher- $T$  data points from the model band in Fig. 3. See text for further comment

At this point, it is appropriate to further discuss the only other fluid regime that could potentially limit melt  $\text{H}_2\text{O}$  contents to a narrow band – a C-O-H fluid in equilibrium with graphite. From the calculations outlined above, we can obtain  $X\text{H}_2\text{O}$  in such a fluid, at any chosen  $P$  and  $T$ . Assuming ideal mixing of  $\text{H}_2\text{O}$  and  $\text{CO}_2$  at these relatively high temperatures, we can equate  $X\text{H}_2\text{O}$  with  $a\text{H}_2\text{O}$ . With these data we can then use a model such as Burnham (1981) to calculate the corresponding melt  $\text{H}_2\text{O}$  contents. The results of such calculations are plotted in Fig. 6, along with the data points from Fig. 2.

The shaded field in Fig. 6 is far broader than the narrow band predicted for the fluid-absent case. If the partial melting reactions that gave rise to these granitoid melts had occurred in the presence of graphite and a C-O-H fluid, the real-rock data points would be expected to scatter throughout the predicted field. Instead they are confined to a very narrow band. Additionally, graphite is unlikely to be ubiquitous in crustal protoliths of granitoid magmas. At granulite-facies temperatures, it is only likely to be stable in certain metapelitic rocks. From a large number of studies of redox conditions in high-grade rocks, it appears that  $f\text{O}_2$  values in most protoliths will fall in the range of Ni-NiO to FMQ – too



**Fig. 6** Graph showing the field (grey shading) of H<sub>2</sub>O contents of melts produced by reactions taking place in the presence of graphite and a C–O–H fluid phase, with log<sub>10</sub>O<sub>2</sub> fixed at FMQ-1. The 31 experimentally constrained real-rock data points are transposed from Fig. 2. See text for discussion

high to allow graphite stability. In the light of these observations, it seems reasonable to conclude that the observed variations of melt H<sub>2</sub>O content with *T* are not consistent with any fluid-present scenario.

## Conclusions

As noted by Scaillet et al. (1998), the calculated melt viscosities for the studied granitoid magmas cluster at a value of 10<sup>5</sup> Pa s, irrespective of the magma emplacement mechanism (plutonic or volcanic). It is theoretically possible that there is some physical factor in granitoid melt segregation that permits melts to be extracted only when they have a viscosity of about this value. However, this seems rather improbable. Hot wet melts should have very low viscosities and should most readily segregate and be extracted from their protoliths. Despite this, the data in Fig. 2 suggest that such hot wet granitoid magmas do not exist. The most plausible explanation for the observed correlation between granitoid magma temperature and H<sub>2</sub>O content is that, at the time of magma extraction, the metamorphic conditions in the protoliths were fluid-absent.

A second important inference can be drawn from the relationship in Fig. 2 and its interpretation as the effect of fluid-absent partial melting during high-*T* metamorphism. On the basis of geochemistry, some types of granitoid rocks are interpreted to be the products of crustal assimilation by mantle-derived mafic magmas. This is an especially common interpretation of I-type calc-alkaline suites, which are often modelled using variants of the assimilation and fractional crystallization (AFC) process, originally proposed for basalt genesis by DePaolo (1981), and subsequently extended to granitoid rocks (DePaolo et al. 1992). Such modelling has been criticized (e.g. Roberts and Clemens 1995, 1997), principally because of the general lack of constraints on the mixing end members that might be involved, and the inconsistency between trace element or isotope based models and major element constraints. There are also potential problems with the physics of magma mixing to

form homogeneous hybrid granitoids (e.g. Sparks and Marshall 1986).

As noted above, the narrow spectrum of melt H<sub>2</sub>O contents in natural granitoid magmas is most unlikely to have arisen without strong buffering of the melting reactions (for *T*–H<sub>2</sub>O) – hence the interpretation as fluid-absent melting. It seems equally unlikely that such a systematic variation would arise if the parental magmas had been basaltic, given the wide ranges of mixing ratios and crustal compositions that would be required to produce granitoid hybrids of syenogranitic to tonalitic compositions. Thus, it seems probable that AFC processes play only a minor role in forming the majority of granitoid magmas. This is not to deny a role for magma mixing in the genesis of some granites, and especially the major role played by magma mingling in producing the spectacular mafic enclave swarms described from some batholiths. However, the great bulk of granitoid magmas seem to be mainly the products of crustal partial melting under fluid-absent conditions. An instructive example of the critical re-evaluation of mixing models for granitoid genesis is given in Villaseca et al. (1999).

The data in Fig. 2 seem to be representative of granitoid magmas in general. Given this, it is clear that Fig. 2 carries evidence of a near-universal relationship – that the kind of high-grade metamorphism that produces granitoid magmas generally takes place in the absence of a free, connected (pervasive) fluid phase, at the time of magma extraction. Furthermore, it seems likely that the chemistry of granitoid rocks does indeed mirror (in an indirect way) the chemical characteristics of deep crustal protoliths, which are commonly unrepresented among exposed rocks in an orogen. This has major importance for how we think about crustal evolution (see e.g. Vielzeuf et al. 1990).

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