Hot and cold granites? Implications of zircon saturation temperatures and preservation of inheritance

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ABSTRACT

Zircon saturation temperatures (T_{Zr}) calculated from bulk-rock compositions provide minimum estimates of temperature if the magma was undersaturated, but maxima if it was saturated. For plutons with abundant inherited zircon, T_{Zr} provides a useful estimate of initial magma temperature at the source, an important parameter that is otherwise inaccessible. Among 54 investigated plutons, there is a clear distinction between T_{Zr} for inheritance-rich (mean 766 °C) and inheritance-poor (mean 837 °C) granitoids. The latter were probably undersaturated in zircon at the source, and hence the calculated T_{Zr} is likely to be an underestimate of their initial temperature. These data suggest fundamentally different mechanisms of magma generation, transport, and emplacement. "Hot" felsic magmas with minimal inheritance probably require advective heat input into the crust, are crystal poor, and readily erupt, whereas "cold," inheritance-rich magmas require fluid influx, are richer in crystals, and are unlikely to erupt.

Keywords: granite, zircon saturation temperature, inheritance, petrogenesis, restite.

INTRODUCTION

Assessing temperatures of magmas that solidified to form plutonic rocks is notoriously difficult because of (1) scarcity of appropriate mineral pairs with temperature-sensitive exchange reactions and (2) reequilibration during cooling. Estimating temperatures of magma generation is even more problematic. Zircon saturation thermometry (Watson and Harrison, 1983) provides a simple and robust means of estimating magma temperatures. Solubility of zircon is extremely sensitive to temperature, but, in most cases, only weakly sensitive to other factors. Furthermore, zircon is ubiquitous in intermediate to felsic plutonic rocks, and all that is required to apply the geothermometer is an adequate estimate of the composition (major element and Zr concentration) of a melt saturated in zircon. Zircon is unique in that it commonly can be shown to have been transported in melt as preexisting grains. The combination of the robust and forgiving nature of the thermometer, the ubiquity of zircon, and the common presence of grains that suggest saturation at the source permits inferences to be drawn about temperatures at which felsic melts are generated in the crust.

RATIONALE

Inherited Zircon

Zircon in igneous rocks either precipitated from the melt or is premagmatic—i.e., entrained as a solid and never dissolved. Premagmatic zircon may be accidental, entrained from wall rock through late-stage contamination, or inherited, derived at a deeper level from a contributing source material. Inherited zircon cores, which are more intrinsic to the magma and form an important basis for our interpretations, are generally more abundant if present and, because they have a longer magmatic residence time, have thicker magmatic overgrowths than accidental grains.

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Zircon Saturation Thermometry

Watson and Harrison (1983) established the following relationship among zircon solubility, temperature, and major element composition of melt:

$$\ln D^{\mathrm{Zr,zircon/melt}} = \{-3.8 - [0.85(M - 1)]\} + 12{,}900/T, \quad (1)$$

where $D^{\mathrm{Zr,zircon/melt}}$ is the ratio of Zr concentration (ppm) in zircon (~476,000 ppm) to that in the saturated melt; M is a compositional factor that accounts for dependence of zircon solubility on SiO_2 and peraluminosity of the melt [(Na + K + 2·Ca)/(Al·Si), all in cation fraction]; and temperature, T, is in kelvins (however, all temperatures referred to in this paper have been converted to °C). Rearranging the equation to yield T yields a geothermometer for melt:

$$T_{Zr} = 12{,}900/[2.95 + 0.85M + \ln(496{,}000/\mathrm{Zr}_{melt})]. \quad (2)$$

The thermometer requires the following: (1) Proper calibration under the appropriate conditions. Watson and Harrison (1983) demonstrated that their empirical relationship applies over a wide range of conditions and melt compositions. Solubility is largely insensitive to pressure and appears to deviate from their equation only for dry (<~1.5 wt% H_2O) or peralkaline melts; thus, it should apply to most intermediate to felsic magmas in the crust. (2) Melt saturated in zircon. Textural evidence can be used to identify early saturation. Inherited zircon suggests saturation throughout the parent magma's history. (3) An adequate estimate of melt composition (major element and Zr concentrations). Igneous rocks, especially plutonic rocks, rarely represent quenched melts—they form from mixtures of crystals and liquid. The presence of zircon crystals implied by saturation indicates that some of the measured Zr in the rock was not in the melt. Nonetheless, the very strong temperature dependence of zircon solubility results in a highly robust geothermometer. Large errors in estimates of Zr and major element concentration (M) result in relatively small errors in calculated T_{Zr} (Fig. 1). Furthermore, the mass fraction of zircon present in cores is generally far less than 50%, and in any case, the errors introduced by crystal-rich composition tend to cancel: Cumulate zircon raises Zr concentration and T_{Zr}, but other cumulate crystals lead to more mafic composition than coexisting melt and hence higher M and lower T_{Zr}.

Constraining Emplacement and Generation Temperatures of Plutonic Rocks

We interpret T_{Zr} as follows: (1) Compositions of felsic fractionates (aplites and other late, highly fractionated rocks) approximate segregated melt, and these extracted melts were invariably saturated in zircon. Effective melt segregation removes most inherited and early-crystallized zircon, so most Zr is in solution. Therefore, $T_{Zr} \approx$ temperature of melt segregation and thus provides a minimum estimate of temperature of the initially emplaced magma. (2) Rocks lacking evidence for inherited or early-crystallizing zircon reflect zircon-undersaturated melt compositions. Therefore, T_{Zr} provides a minimum estimate for magma temperature at a time before extensive crystallization, probably effectively upon emplacement. Absence of inherited zircon is consistent with un-

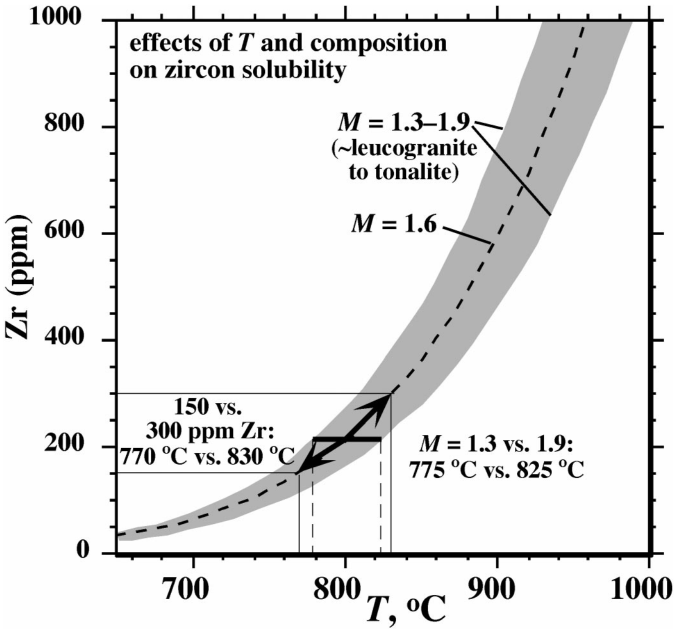

Figure 1. Solubility of zircon as function of temperature, *T*, and melt composition, *M*. Large variation in *M* results in relatively small change in solubility; thus, large uncertainty in melt-phase composition introduces small error in estimated temperature (tonalite vs. leucogranite, 50 °C). Likewise, because zircon solubility is so strongly temperature dependent, large errors in estimated Zr concentration in melt introduce small errors in temperature estimate.

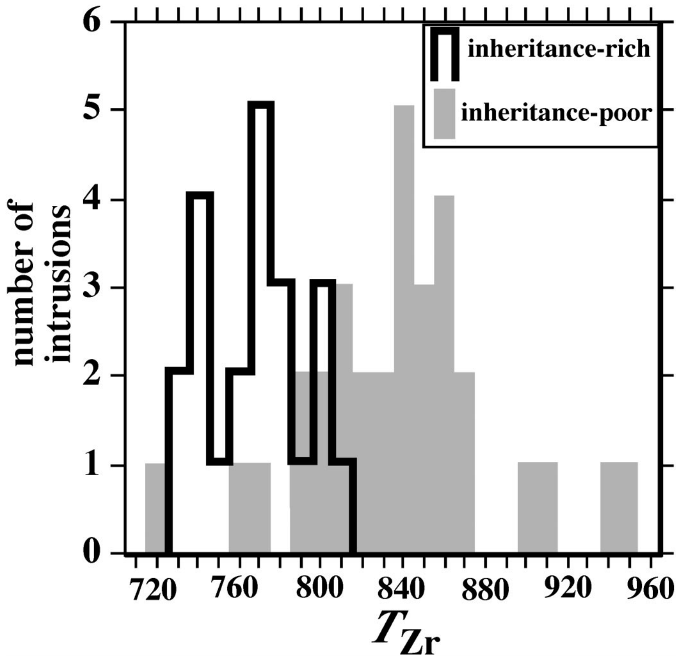

Figure 2. Comparison of calculated T_{Zr} (zircon saturation temperature, °C) values for investigated intrusions with abundant inheritance and minimal inheritance.

dersaturation at the source, and thus for rocks that lack inheritance, T_{Zr} suggests a minimum initial magma temperature at the source. (3) Inheritance-rich intrusions were zircon saturated at their source and, because part of their total Zr concentration is in crystals rather than melt, T_{Zr} should place an upper limit on magma temperature. Expectable modest errors in Zr concentrations and major element compositions have limited impact on calculated T_{Zr} values. Compositions of inheritance-rich granitoids, especially average or typical compositions for a pluton, are useful and probably acceptably accurate estimates of initial melt composition. The fact that abundant inherited zircon is still present indicates that thorough and extensive fractionation did not occur during ascent, and in any case, moderate extraction of zircon would partly offset the overestimate of Zr. Compositions of granitoid plutons that are derived largely from the crust—as inheritance-rich intrusions presumably are—generally suggest limited fractionation. Extensive fractionation (e.g., fraction of crystals removed over ~30%) leads to severe and obvious depletion of Sr, Eu, and Ba because of the dominance of crystallizing assemblages by feldspars. Such depletions are not common except in late segregated melts like aplites, and they are absent in the examples we present in the next section. T_{Zr} of inheritance-rich granitoids is thus a useful estimate of the temperature of melt generation; if anything, it is a slight overestimate.

DATA SET AND RESULTS

Intrusions Studied and Treatment of Data

The 54 intrusions for which we have elemental and zircon U-Pb data represent a wide array of environments, including convergent (subduction, collision, postorogenic), divergent, and anorogenic tectonic settings. They range from 15 Ma to 1700 Ma and include peraluminous and metaluminous granites, trondhjemites, tonalites, and granodiorites.

For most intrusions, we used an average rock composition based upon multiple analyses (excluding aplites) to calculate T_{Zr}. In some cases, a single analysis of a representative sample was used.

We subdivided the intrusions into inheritance rich and inheritance poor or inheritance free. For intrusions with high-resolution ion-microprobe data and many backscattered-electron or cathodoluminescence images of internal zoning in zircons, our cutoff is ~10% of grains with premagmatic cores. Zircons from a great majority of samples have either >50% or <5% premagmatic cores. For intrusions with only conventional U-Pb data, we consider samples from which analyzed zircon fractions are mostly concordant or are displaced <5% from the lower intercept of discordia to be inheritance poor. Where samples have very few premagmatic grains, it is likely that they are accidental or perhaps were metastably preserved (see subsequent discussion of metastable preservation) and therefore are not indicators of zircon saturation at the source.

Results

Of the investigated intrusions, 22 are inheritance rich and 32 are inheritance poor. Composition correlates with inheritance, but by no means perfectly. A total of 21 appear to totally lack inheritance, all metaluminous or marginally peraluminous; they are slightly less felsic (59–72 wt% SiO_2) than intrusions with inheritance. Nine metaluminous to weakly peraluminous and three strongly peraluminous (muscovite ± garnet bearing; Miller, 1985) intrusions with 62–75 wt% SiO_2 have very small amounts of premagmatic zircon. Of the inheritance-rich intrusions, 4 are metaluminous, 4 are weakly peraluminous, and 14 are strongly peraluminous; SiO_2 ranges from 61 to 73 wt%. Despite their highly peraluminous nature, the inheritance-rich granitoids are neither highly evolved nor S-type: most have relatively low $\delta^{18}O$ (<10‰), high Sr (>200–300 ppm), low K_2O/Na_2O (<1), and modest Eu anomalies (Eu/Eu* ≈ 0.6 to >1). According to the scheme of Patiño Douce (1999), most of the inheritance-rich granitoids are Cordilleran-type peraluminous granites (some grading into the peraluminous leucogranite category), with a lesser number of calc-alkaline granites; trondhjemites and high-silica granodiorites are common. The inheritance-poor granitoids are all calc-alkaline granites.

Zirconium concentrations in inheritance-rich granitoids are uniformly lower than those of inheritance-poor intrusions (~80–150 ppm vs. ~200–800 ppm). Consequently, calculated T_{Zr} values are also lower for inheritance-rich granitoids (Fig. 2). Of 22 values, 16 are between

730 and 780 °C, and only 1 exceeds 800 °C (811 °C); the average value is 766 ± 24 °C (1σ). In contrast, T_{Zr} values for most intrusions with little or no inheritance are >800 °C, and the mean is 837 ± 48 °C. The T_{Zr} populations differ with >99.5% confidence. Because T_{Zr} values should be minima for magmas undersaturated in zircon and maxima for magmas that carry zircon crystals, the difference between the two may be even greater than the calculated 70 °C.

POSSIBLE EXPLANATIONS FOR THE DISCREPANCY IN T_{Zr}

There are three apparent explanations for the discrepancy between T_{Zr} values of inheritance-rich and inheritance-poor intrusive rocks. (1) Inheritance-rich granitoids are highly fractionated relative to their parents or to the inheritance-poor granitoids and simply reflect lower temperatures at a later stage. (2) Inherited zircons were preserved metastably in strongly undersaturated magmas, so T_{Zr} in this case is meaningless. (3) The inheritance-rich granitoids were generated at temperatures that were considerably lower than those of the inheritance-poor granitoids, suggesting a fundamentally different mechanism of melt production.

We reject explanation 1 because the inheritance-rich intrusions are not notably more fractionated than the inheritance-poor intrusions, and as we stated in the previous section, they are probably not highly evolved in comparison to their parent magmas. Explanation 2 is plausible and intriguing, but calculations by Watson (1996) indicate that even large zircons (90 μm radius) are dissolved in undersaturated melt within a few thousand years at 800 °C and within tens of thousands of years during crustal-melting events that culminate at 800 °C. Encapsulation of zircons within larger grains that survive melting (restite) could shield them from dissolution, but the cored zircons that we observe have thick magmatic overgrowths indicating protracted immersion in melt, and in many cases essentially all separated grains have cores. We therefore doubt that the melts were undersaturated in zircon.

IMPLICATIONS—"HOT" AND "COLD" GRANITES

The preceding reasoning leads initially to two important implications: first, there may be two distinct classes of granitoid, generated at different temperatures; and second, the low-T ("cold") granitoids require a mechanism of melting that can account for sub-800 °C magmas.

The "hot," 800 °C+, inheritance-poor granitoids present no apparent difficulties in interpretation. These temperatures are consistent with currently popular modes of felsic magma generation (dehydration melting in the crust; fractionation of mantle melts, with or without crustal contamination) and with transport of the magma in crystal-poor state. The cold granites, however, require further consideration.

Generating Cold Granites

All current models for generating magmas within the crust require a source of water, because anhydrous melts require unrealistically high temperatures. Most emphasis is on dehydration reactions, in which the necessary water is supplied by breakdown of biotite, muscovite, or Ca-amphibole (e.g., Best and Christiansen, 2001; Patiño Douce and Beard, 1995; Gardien et al., 1995; Vielzeuf and Montel, 1994; Thompson, 1982). Among these, only muscovite may undergo substantial dehydration at $T < 800$ °C (except at unrealistically shallow depths) (Fig. 3). However, because its dehydration yields a melt fraction comparable to or less than its initial modal proportion (Gardien et al., 1995; Clemens and Vielzeuf, 1987; Clemens, 1984; Patiño Douce and Harris, 1998), muscovite must be extremely abundant to generate large, pluton-scale volumes of magma. None of the inheritance-rich intrusions we have studied is compositionally consistent with the pelitic source implied by abundant modal muscovite.

Infiltration of the source region by a water-rich fluid phase appears

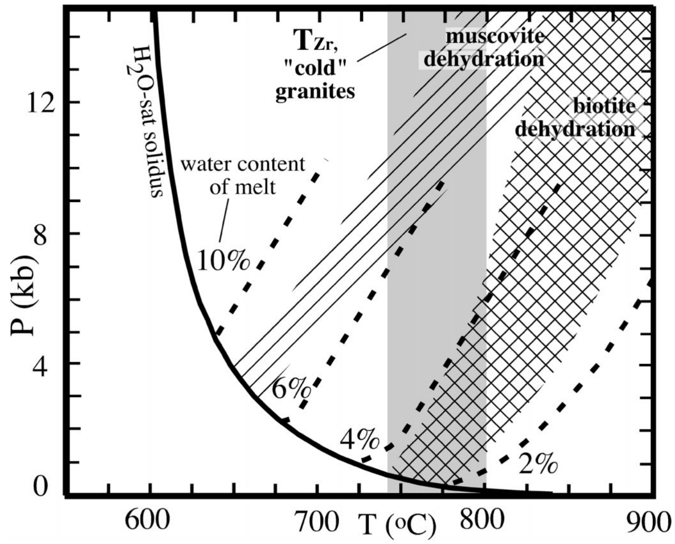

Figure 3. Wet granite solidus, approximate ranges of dehydration of micas in presence of quartz and plagioclase, and minimum water contents of felsic melts; modified from Patiño Douce and Harris (1998), Holtz and Johannes (1994), and Spear (1995). Zircon saturation temperature (T_{Zr}) range of inheritance-rich ("cold") granites is given for comparison. P—pressure.

to be the only mechanism for inducing large-scale melting at $T < 800$ °C. At moderate crustal depths, melts require ~6 wt% H_2O at ~750 °C (Holtz and Johannes, 1994; Fig. 3); for melt fractions of 10%–40%, attaining such a water content would require addition of ~1–2 wt% of water to the zone of melting. Melting under fluid-excess conditions (cf. Clemens and Watkins, 2001) is not required, and is highly unlikely, because it would require much larger volumes of water and produce large melt fractions at temperatures considerably lower than our T_{Zr}. The origin of the fluid remains problematic. Plausibly, fluids could ascend into the zone of melting as a consequence of dehydration of underthrust sedimentary rocks or of hydrous mafic silicates in ultramafic-mafic rocks (cf. Thompson, 2001; Patiño Douce, 1999; Spear, 1995).

If our model is correct, cold granites are generated in tectonic settings that do not reach especially high temperatures and where fluid influx is permitted by lithologic stratigraphy, tectonics, and history of the lithosphere. Heating by influx of mafic magma is permitted but may not be required. In contrast, generation of hot granites is likely to require an important influx of heat but not fluid; heating is most simply explained by intrusion of mafic magma. Although the timing relative to thrusting is not always certain, all of the cold granites were emplaced in environments of crustal thickening. A majority of the hot granites for which a tectonic setting can be determined intruded extensional or transtensional terranes.

Ascent and Eruption of Cold Granites

Even with sufficient water, most of the granitoids we examined would have significant crystal fractions at T of ~750 °C (e.g., Patiño Douce and Harris, 1998; Patiño Douce and Beard, 1995; Miller et al., 1986). At such low temperatures, mafic minerals and calcic plagioclase component are highly insoluble and melts are near Ab-Or-Qz minimum melt compositions. If the compositions of these plutons are indicative of magma compositions generated at ~750 °C, most must have carried ~5%–25% crystals from their sources. A sizable restitic fraction is consistent with the presence of abundant inherited zircon, but both the abundance of crystals and the low T would impede ascent and render the magmas almost uneruptible. The magma would approach or reach its solidus before it reached the surface (Fig. 3).

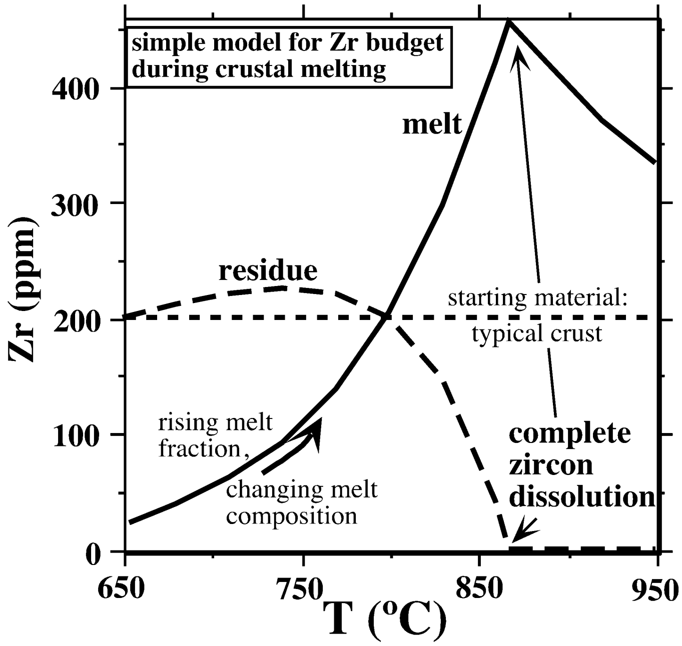

Figure 4. Schematic representation of Zr concentrations in evolving melts and residues during melting of typical crustal rock. Initial Zr concentration is taken as 200 ppm; melt composition is assumed to become less felsic (increasing *M*). Zr concentration in residue first rises (because initial concentration in melt at low *T* [temperature] is low), then falls as solubility and melt fraction rise; Zr in melt rises until all (accessible) zircon dissolves.

Model for Zr Concentrations in Crustal Melts

The Zr concentration in typical crustal rocks is ~100–200 ppm (e.g., Taylor and McLennan, 1985; Weaver and Tarney, 1984), most of it contained in zircon. During prograde melting of such rock, Zr concentration in the melt will increase until the last zircon (in contact with melt) dissolves; subsequent melting diminishes Zr through dilution. Figure 4 shows schematically the evolution of melts and residues during melting of typical crustal rock. Inheritance-rich granites are likely to be generated when the residue of melting is still relatively zircon rich, and at these temperatures they will have fairly low Zr concentrations, as we observe. In contrast, Zr concentrations can be much higher at higher *T* when most or all zircon has dissolved, leading to hot, Zr-rich, inheritance-poor or inheritance-free granitoids.

Generality of the Hot and Cold Granite Paradigm

Chappell et al. (1998) suggested a similar model, with inheritance limited to cold granitoids. Their cold granites are similar to ours, with $T_{Zr} \approx 750$ °C. However, in contrast to our inheritance-poor samples, their two suites of hot granites have low Zr contents (increasing with fractionation), reflecting initial strong undersaturation.

A literature search for intrusive rocks with zircon U-Pb and elemental chemistry data yielded results that matched those from our samples. Of 57 intrusions, 23 with abundant inheritance have an average T_{Zr} value of 772 °C, and 34 with little apparent inheritance have mean T_{Zr} values of 831 °C; the two T_{Zr} groups differ with >99.5% confidence. We are aware of very few volcanic rocks with abundant inherited zircon, and most felsic volcanic rocks have relatively high Zr (a brief literature search suggests T_{Zr} generally >800 °C). We infer that equivalents of the hot granites commonly erupt but that cold granites do not.

CONCLUSIONS

1. T_{Zr} provides good estimates of melt temperatures for rocks representing crystal-poor, zircon-saturated magmas; it also yields useful approximations of melt-generation *T* for inheritance-rich rocks.

2. T_{Zr} and zircon inheritance distinguish two distinct classes of intrusive rocks: cold inheritance-rich granitoids with T_{Zr} <800 °C and hot inheritance-poor granitoids with T_{Zr} >800 °C.

3. Cold granites appear to form at temperatures too low for dehydration melting involving biotite or hornblende and probably require fluid influx; hot granites may form through dehydration melting and, if they are produced in the crust, probably require a substantial transient heat flux.

4. Cold granites are relatively crystal rich and unlikely to erupt, whereas hot granites are drier, contain fewer crystals and are highly eruptible.

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REFERENCES CITED

Best, M.G., and Christiansen, E.H., 2001, Igneous petrology: Oxford, Blackwell Science, 480 p.

Chappell, B.W., Bryant, C.J., Wyborn, D., White, A.J.R., and Williams, I.S., 1998, High- and low-temperature I-type granites: Resource Geology, v. 48, p. 225–235.

Clemens, J.D., 1984, Water contents of silicic to intermediate magmas: Lithos, v. 17, p. 273–287.

Clemens, J.D., and Vielzeuf, D., 1987, Constraints on melting and magma production in the crust: Earth and Planetary Science Letters, v. 86, p. 287–306.

Clemens, J.D., and Watkins, J.M., 2001, The fluid regime of high-temperature metamorphism during granitoid magma genesis: Contributions to Mineralogy and Petrology, v. 140, p. 600–606.

Gardien, V., Thompson, A.B., Grujic, D., and Ulmer, P., 1995, Experimental melting of biotite + plagioclase + quartz ± muscovite assemblages and implications for crustal melting: Journal of Geophysical Research, v. 100, p. 15,581–15,591.

Holtz, F., and Johannes, W., 1994, Maximum and minimum water contents of granitic melts: Implications for chemical and physical properties of ascending magmas: Lithos, v. 32, p. 149–159.

Miller, C.F., 1985, Are strongly peraluminous magmas derived from mature sedimentary (pelitic) sources?: Journal of Geology, v. 93, p. 673–689.

Miller, C.F., Rapp, R.P., and Watson, E.B., 1986, AFM mineral-felsic liquid phase relations: Potential for elucidation of the origin and evolution of felsic magmas: Geological Society of America Abstracts with Programs, v. 18, no. 6, p. 695.

Patiño Douce, A.E., 1999, What do experiments tell us about the relative contributions of crust and mantle to the origin of granitic magmas?, *in* Castro, A., et al., eds., Understanding granities: Integrating new and classical techniques: Geological Society of London Special Publication 168, p. 55–75.

Patiño Douce, A.E., and Beard, J.S., 1995, Dehydration-melting of biotite gneiss and quartz amphibolite from 3 to 15 kbar: Journal of Petrology, v. 36, p. 707–738.

Patiño Douce, A.E., and Harris, N., 1998, Experimental constraints on Himalayan anatexis: Journal of Petrology, v. 39, p. 689–710.

Spear, F.S., 1995, Metamorphic phase equilibria and pressure-temperature-time paths: Washington, D.C., Mineralogical Society of America, 799 p.

Taylor, S.R., and McLennan, S.M., 1985, The continental crust: Its composition and evolution: Oxford, Blackwell Scientific Publications, 312 p.

Thompson, A.B., 1982, Dehydration melting of pelitic rocks and the generation of H_2O-undersaturated granitic liquids: American Journal of Science, v. 282, p. 1567–1595.

Thompson, A.B., 2001, Partial melting of metavolcanics in amphibolite facies regional metamorphism: Proceedings of the Indian Academy of Sciences (Earth and Planetary Sciences), v. 110, p. 287–291.

Vielzeuf, D., and Montel, J.M., 1994, Partial melting of metagreywackes: Part 1. Fluid-absent experiments and phase relationships: Contributions to Mineralogy and Petrology, v. 117, p. 375–393.

Watson, E.B., 1996, Dissolution, growth and survival of zircons during crustal fusion: Kinetic principles, geological models and implications for isotopic inheritance: Royal Society of Edinburgh Transactions, Earth Sciences, v. 87, p. 43–56.

Watson, E.B., and Harrison, T.M., 1983, Zircon saturation revisited: Temperature and composition effects in a variety of crustal magma types: Earth and Planetary Science Letters, v. 64, p. 295–304.

Weaver, B.L., and Tarney, J., 1984, Empirical approach to estimating the composition of the continental crust: Nature, v. 310, p. 575–577.

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