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The sources of energy for crustal melting and the geochemistry of heat-producing elements

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ABSTRACT

Crustal melting to produce granite magmas requires a tremendous amount of energy. In principle, there are three main mechanisms of heating that can extensively melt a fertile crust: radiogenic heat caused by the decay of ^{40}K, ^{230}Th, ^{235}U and ^{238}U; increased subcrustal heat flux caused by the upwelling of deeper, therefore hotter, mantle materials; advection of heat caused by the emplacement and crystallization of hot mantle magmas. Two-dimensional finite elements modeling reveals that a fertile crust thickened to 65–70 km would produce copious granite magmatism after 30–40 M.y. if its average heat-production is $A>1.2\ \mu W\ m^{-3}$, but it would scarcely melt if $A<0.65\ \mu W\ m^{-3}$. Increasing the subcrustal heat flow from the normal value of $Q_M \approx 0.025\ W\ m^{-2}$ to $Q_M \geq 0.04\ W\ m^{-2}$ may also lead to extensive crustal melting, especially if the crust does not thin to less than 30–35 km. Very high Q_M ($\geq 0.06\ W\ m^{-2}$) affecting the continental crust is unlikely, but the combination of moderately high Q_M ($\approx 0.04\ W\ m^{-2}$) and a thick fertile crust with $A<1.2\ \mu W\ m^{-3}$, such as often happens in the volcanic and back-arc areas of subduction zones, is ideal to produce copious granite magmatism. Lastly, the emplacement of hot mantle magmas in a fertile crust can produce crustal melts in just a few thousand years, but the volume of these is equal to or less than the volume of the intruding magma. A clue for understanding the relative importance of each of these three mechanisms comes from the radiogenic heat production of granite rocks calculated from the concentration of ^{40}K, ^{230}Th, ^{235}U and ^{238}U at the time of their formation. This parameter estimated on more than 3400 granites samples of different ages and provenance reveals a strongly asymmetric distribution peaking around $2.4\ \mu W\ m^{-3}$, a value much higher than the average continental crust (about $1–1.2\ \mu W\ m^{-3}$) and certainly much higher than the average lower continental crust (about $0.4–0.8\ \mu W\ m^{-3}$). Only those granite rock types that are clearly connected with mantle heat sources such as the Archean TTG, post-Archean subduction-related trondhjemites, and recent adakites have a heat production equal to or smaller than the lower continental crust. Since the bulk melt/solid partition coefficient of the heat-producing elements (HPE: K, Th and U) is $k \leq 1$, the elevated HPE contents of granites indicates that most of them have been derived from HPE-rich sources. We conclude that radiogenic heating is often essential, and always advantageous, for generating large volumes of granite magmas, and that granite magmatism is the main cause of the accumulation of HPE in the upper crust.

1. Introduction

The generation of crustal melts requires a tremendous amount of heat, which is consumed in bringing the temperature of the crustal source to the solidus, in the solid-to-melt phase transformation, and in overheating the resulting magmas above the solidus to provide some ascensional capability. The solid-to-melt transformation, despite often being ignored, is the most heat-demanding process because silicates latent heat of melting is very high, about $400{,}000\ J\ kg^{-1}$ (e.g., Bottinga et al., 1982; Schmucker, 1969, etc.), a magnitude that is ~350–400 times the specific heat (C_P) (Robinson and Haas, 1983). A simple calculation assuming an average C_P of ~$1000\ J\ K^{-1}\ kg^{-1}$ for the T interval 400 °C–750 °C (because C_P increases with T, see Robinson and Haas, 1983) indicates that melting 1 km^3 of haplogranitic (eutectic) material with an initial temperature of 400 °C needs about $8.1 * 10^{17}$ J to bring it to 700 °C (assumed to be the solidus), and another $1 * 10^{18}$ J for the solid-to-melt transformation at the solidus temperature. Considering that crustal sources most often are not haplogranitic, and the melt fraction of granite magmas is around 0.6–0.8, the heat required to produce them within the crust can be conservatively estimated at around $1.5 * 10^{18}\ J\ km^{-3}$.

This enormous amount of heat can be supplied, in principle, by three main mechanisms: (1) accumulation of radiogenic heat after crustal thickening; (2) increased heat flux from the mantle, mostly due to astenospheric upwelling or mantle wedge convection; and (3) advection by hot mantle magmas emplaced into the crust (e.g. England and Thompson, 1986; Fyfe, 1973; Huppert and Sparks, 1989, etc.). The relative importance of these three mechanisms is

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not yet clear. Granite geologists have historically paid little attention to radiogenic heating, despite geophysicists having acknowledged that this mechanism governs the thermal evolution of the earth and drives the lithosphere geodynamics (e.g., Dye, 2010, and references therein). Perusing the specialized literature published in the last 40 years reveals that Fyfe's (1973) clear-sighted assertion that radiogenic heating is essential for the generation of granite batholiths mostly fell on deaf ears. In the past few years, however, the recognition that differences in heat production of crustal materials may cause different metamorphic styles (Andreoli et al., 2006, 2011; Attoh, 2000; Goffé et al., 2003; Kramers et al., 2001), and even lead to the formation of granites (Bea et al., 1999, 2003; Gerdes et al., 2000), points to fluctuations in heat production as a first-order variable in orogenic processes and brings new interest on the crustal geochemistry of heat-producing elements (HPE: K, Th and U).

The aim of this paper is to ascertain the effectiveness of the different mechanisms of crustal heating to produce granite magmas and, especially, the role of radiogenic heating. To this end, we first examine the distribution of HPE in granite rocks using a database of more than 3400 granite samples from all over the world with ages from Archean to Recent and discuss their behavior during metamorphism and partial melting. This reveals that the heat production of most granites is considerably higher than the average continental crust because they were derived from HPE-rich sources. Then, we evaluate the effects of the elevated heat production of the magmatic sources using 2D numerical models of the thermal evolution of segments of continental crust undergoing either crustal thickening, increased heat flux from the mantle, or intrusion by hot mafic magmas. The results emphasize the role of radiogenic heating for granite generation at a batholithic scale.

2. Radiogenic heat production and the crustal distribution of the heat-producing elements

2.1. Average heat production of the continental crust

The main mechanism of heat production within the Earth's lithosphere is the decay of four naturally occurring isotopes (^{40}K, ^{232}Th, ^{235}U, ^{238}U) of the three heat-producing elements: K, Th and U (e.g., Schmucker, 1969). The radiogenic heat production (A) of the three elements is different; 1% K_2O produces about 0.074 μW m^{-3}, nearly the same as 1 ppm Th ($A = 0.072$ μW m^{-3}), but 1 ppm U yields about 0.264 μW m^{-3}, nearly four times more than 1 ppm Th or 1% K_2O. The larger heat production of U with the respect to Th is because U has two radioactive isotopes, ^{238}U and ^{235}U, and these decay faster than ^{232}Th, the only naturally abundant isotope of Th. Anyway, since the terrestrial Th/U ratio is roughly constant at about 3.7, the global contribution of Th and U to radioactive heating is similar.

The three HPE are highly incompatible in mantle minerals. Therefore, they have been accumulated into the continental crust, the average composition of which (Rudnick and Fountain, 1995; Shaw et al., 1986; Weaver and Tarney, 1984; Wedepohl, 1995) implies a current heat production of 0.9 to 1.2 μW m^{-3} for the whole crust and ~0.5 μW m^{-3} for the lower crust, estimations that satisfy global-scale heat flow measurements (see Chapman and Furlong, 1992). The heat production of the continental crust can vary over geological time because of two contrasting effects that affect the concentration of HPE: enrichment caused by progressive extraction from the mantle and impoverishment caused by radioactive decay. The two effects, however, seem to have canceled each other out because available data for the Archean continental crust (Rudnick and Fountain, 1995; Shaw et al., 1986) indicate that heat production 3000 M.y. ago was 1.14 μW m^{-3} for the average continental crust and 0.42 μW m^{-3} for the lower continental crust, roughly the same as present. A recent model of continental crust growth by relamination (Hacker et al., 2011) suggests that the lower crust might be more silicic and radiogenic than previously believed, with a median heat-production of 0.7 μW/m^3. Therefore, to be on the safe side, we can assume that 1–1.2 μW m^{-3} and 0.5–0.8 μW m^{-3} are representative ranges of the average crust and lower continental crust heat-productivity, respectively, at least since the Mesoarchean.

Nonetheless, it should be considered that these values are world averages compatible with the world average heat flow, but do not represent the mean of a Gaussian population. In fact, there are striking differences in the heat-flow estimated heat production among different segments of the continental crust, which may vary for one order of magnitude, from 0.25 μW m^{-3} (e.g., Kukkonen et al., 1997), to 3 μW m^{-3} (e.g., Fernandez et al., 1998; Palomeras et al., 2011). As discussed below, these differences are enough to influence the style of granite generation profoundly.

2.2. Vertical distribution of HPE in the continental crust and their mobility during metamorphism

The intensity of radiogenic heating in a given crustal section depends not only on the average concentration of the heat-producing elements, but also on the vertical position of the HPE-rich layers. The good correlation between superficial heat-flow and heat-production observed in basement areas of many parts of the word, known as the Birch–Lachenbruch Law (Oxburg, 1980), indicates that HPE concentrations decrease with depth. This law can be satisfied by different models of vertical distribution of HPE depending on whether convective heat transport is assumed (e.g., Bodri and Cermak, 1993; Singh and Manglik, 2000), but with all of them involving a regular exponential or quasi-exponential decrease of the HPE with increasing depth, which agrees with the popular belief that the concentration of HPE decreases progressively as the metamorphic grade increases.

Nonetheless, geochemical evidence from studies on lower crustal sections do not support these ideas. Fig. 1 reports the vertical distribution of K_2O, Th and U in the Ivrea–Verbano lower crustal section, which goes from 4 kb to 9 kb, roughly from 16 to 34 km. It is evident that the main control on the abundances of the HPE is lithological, depending on whether the rock is metasedimentary or metabasic. In metasediments, despite the vertical distribution of the three elements being irregular in detail, K and U decrease at the amphibolite–granulite transition (see Bea and Montero, 1999, for explanation), whereas Th increases so that the heat production remains constant or decreases slightly (Fig. 1). In metabasic rocks, which are much less heat-productive, there is no perceptible variation with depth. It seems, therefore, that whereas Th behaves as an immobile refractory element during deep crustal processes, U can be mobilized either at low to moderate temperatures in aqueous solutions if it is partially oxidized to the highly mobile uranyl ion (UO_2^{2+}), or at the amphibolite–granulite transition in monazite-bearing rocks, but these effects have little impact on heat production (see Harrison et al., 1986). Accordingly, Bea and Montero (1999) suggested that radiogenic heat production along a given crustal section mostly depends on the lithology, so that it is the large abundance of metabasic rocks (or HPE-poor felsic material relaminated during subduction, Hacker et al., 2011) in the lower crust being what causes the reduction of heat production with increasing depth. This being the case, the vertical distribution of HPE can be better approached by considering a discontinuous, multilayered structure than by considering a continuous exponential decrease such is often proposed in the geophysical literature (see also Lexa et al., 2011).

3. Radiogenic heat production in granite rocks

We determined the abundance of the HPE in granite rocks using a dataset of more than 3400 whole-rock analyses of world granitoids ($SiO_2 > 60\%$) of known age, in which Th and U were determined either