Dehydration melting and differential uplift of a partially molten crust in the Black Hills, South Dakota, USA

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Introduction

The genesis of granitic magmas is a fundamental process in the evolution of the Earth's crust. Among granites, peraluminous leucogranites (PLGs) are volumetrically important in continental regions worldwide, including the Hercynian granite suite of western Europe, the Cenozoic collisional granites of the Himalayas (e.g., Le Fort *et al.*, 1987). In many regions of the world, PLGs are associated with rare-element pegmatite fields as in many localities in the Canadian Shield and elsewhere (Černý, 1991; Černý and Meintzer, 1988). It is generally thought that PLG's are derived by partial melting of metasediments, in particular schists. Indeed, in many cases, the genetic relationship is indicated by the occurrence of peraluminous leucogranites and granitic pegmatites within schist terranes and by the highly evolved compositions of the granites and radiogenic isotope ratios which suggest evolved continental protoliths.

The Black Hills, South Dakota, provide a particularly good setting to study leucogranite generation and melt production in the crust, inasmuch as protoliths and resultant Harney Peak and related granites are found in the area. Moreover, one of the largest pegmatite fields in North America is found in the Black Hills. The Black Hills are a window on the southern extension of the Trans-Hudson Orogen which resulted from the collision of the Wyoming and Superior cratons at the time of emplacement of the granites. The current research is aimed at understanding the role of fluids during melt production, mineral–melt equilibria during partial fusion of metasediments and the mechanism of magma extraction and emplacement in a partially molten crust undergoing thickening.

Geologic and isotopic relationships

The Harney Peak leucogranite has an age of 1.7 Gy (Redden *et al.*, 1990). The granite was emplaced at 3–4 kbar into Proterozoic schists and graywackes, although Archean metasediments are found in its core and to the west of exposure of Precambrian rocks. The granite has a domal structure and consists of hundreds of sills and dikes. Folding and faulting associated with emplacement of the granite is evident in the metasediments. Toward the core, the dominant ferromagnesian mineral is biotite; along the perimeter of the main pluton and in satellite plutons and sills it is tourmaline. Most of the outer granites contain pegmatitic segregations. The isograds in the metamorphic rocks define a prograde sequence reaching second-sillimanite conditions to the west of the main pluton (Helms and Labotka, 1991). Extensive migmatization in this zone gives evidence for *in-situ* melting in the upper crust.

The biotite and tourmaline-containing granites have distinct isotopic compositions. The former have average $\delta^{18}O$ value of 11.5‰ and the latter 13.2‰, suggesting isotopically distinct metasedimentary sources (Nabelek *et al.*, 1992). The higher value is virtually identical to the $\delta^{18}O$ value of the Proterozoic metasediments. K-feldspars from the high and low-$\delta^{18}O$ suites define distinct $^{207}Pb/^{204}Pb$-$^{206}Pb/^{204}Pb$ arrays (Krogstad *et al.*, 1993). The high $\delta^{18}O$ granites have low values of $^{207}Pb/^{204}Pb$ for their $^{206}Pb/^{204}Pb$ ratios relative to the low-$\delta^{18}O$ granites. The array for the low-$\delta^{18}O$ biotite granites gives a secondary isochron intercept of ~2.6 Ga, suggesting an extended crustal residence of the source prior to melting, whereas the array for the high-$\delta^{18}O$ tourmaline granites suggests a shorter, 100 to 300 Ma crustal residence time for the Pb. Walker *et al.* (1986) obtained $\varepsilon_{Nd}(T)$ values between −9.90 and −2.05 for the Harney Peak Granite and −3.03 to −1.90 for the schists surrounding it, indicating a source component older that the Proterozoic schists.

Melting reactions leading to Harney Peak magmas

The isotopically distinct granite suites have similar major element and compatible trace element concentrations. However, aside from isotopic ratios, they also differ in the relative B and TiO_2

concentrations, where the high-$\delta^{18}O$ tourmaline granites have significantly higher B/TiO_2 ratios, 0.1–30.0 vs. 0.01–0.07 in the low-$\delta^{18}O$ biotite granites. Inasmuch as B in schists is concentrated primarily in muscovite and Ti in biotite, the high ratios in the tourmaline granites suggest that these granites formed by low-degree muscovite-dehydration melting whereas the biotite granites formed by higher degree, biotite-dehydration melting at more elevated temperatures deeper in the crust. Oxygen isotopic equilibration temperatures among minerals in the granites in excess of 750°C confirm the dry conditions of melting.

The sub-biotite-dehydration melting leading to the tourmaline granites lead to disequilibrium fractionation of *REE*'s. The tourmaline granites have relatively flat, although kinked *REE* patterns at approximately 10 × chondrites. They contrast to the 'normal' crustal light-*REE* enriched patterns of the biotite granites which are similar to those of the metasediments. Analysis of unmelted biotite in the migmatized zone within the metasediments shows abundant inclusions of monazite which have not participated in the melting process. It is the monazites which retained bulk of the light-*REE*'s in the residue. Thus, light-*REE* depletion in granites may be indicative of low degrees of melting of crustal protoliths instead of post-emplacement fractionation of accessory minerals.

Extraction and emplacement of the Harney Peak magmas

The melts within the second-sillimanite isograd zone of the aureole formed by small degrees of melting, with small batches of melt ultimately extracted through fractures which may have formed as a result of volume increase associated with melting. In contrast, migmatized metasediments in the core of the Harney Peak Granite have undergone higher extents of melting. The chemistry of the associated granites indicates restite unmixing. Concentrations of Al in hornblende in mafic schists suggest that the core metasediments were brought-up from depths of ~18 km (M. Terry, pers. comm.), indicating differential uplift of the core of the pluton relative to its periphery. The doming may in part explain the quasi-concentric isograds near the pluton. Calculations show that a diapiric rise of a partially molted 3 km thick layer with 10^{11} Pa s viscosity to 10–12 km through a slightly molten 10^{17} Pa s upper layer would have occurred rapidly on a scale of 10^5 y. Such short time-scales are consistent with lack of evidence of a difference between the age of the granite and metamorphism based on $^{40}Ar/^{39}Ar$ data (P. Dahl, pers. comm.).

Conclusions

The petrologic and geochemical data demonstrate a strong link between heating of metasediments during the Trans-Hudson orogeny and water-undersaturated production of granite melts. The data suggest melting of the crust over a depth from 9 to >18 km with relatively high extents of melting of Archean metasediments in the lower portion of the molten zone. The partially molten zone rose diapirically. The diapiric rise may have been promoted by small degrees of partial melting of Proterozoic metasediments higher in the crust, which may have been promoted by concomitant heat advection and exsolution of fluid from the ascending magmas, perhaps leading to production of pegmatitic melts.

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