



High silica granites: Terminal porosity and crystal settling in shallow magma chambers



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ABSTRACT

High silica (>70 wt.% SiO₂) granites (HSGs) are important carriers of highly incompatible elements, thus, understanding their origin is relevant to understanding how the composition of the continental crust evolves. We examined a large-scale geochemical study of plutons in the Peninsular Ranges Batholith in southern California (USA) to better understand the petrogenetic relationships between HSGs and the batholith. Using highly incompatible and compatible elements, we show that HSGs represent residual liquids within a felsic (69–72 wt.% SiO₂) magmatic crystal mush at crystal fractions of 50–60% and residual liquid fractions of 40–50%. Trace element systematics show that separation of the HSG liquid from the crystal mush is inefficient, such that no more than 70–80% of the HSG is fully extracted and the remaining greater than 20–30% remains trapped in cumulate mush. We find little evidence of more efficient liquid–crystal segregation, which suggests that compaction-induced segregation may be too slow to be important on a large scale. Instead, the terminal porosity of 20–30% coincides with theoretical maximum packing fraction of unimodal particles settled out of suspension (~0.74), which may indicate that crystal settling – perhaps in the form of hindered settling – drives segregation of viscous silicic melts and crystals. Unlike compaction, settling operates on timescales of 1–10 ky, fast enough to generate large volumes of HSG and complementary cumulates with trapped melt before magma chambers freeze. Many felsic plutons may thus be cumulates, but because of trapped melt, they are difficult to geochemically distinguish from plutons whose compositions fall along liquid lines of descent. The approach here, using a combination of highly incompatible and compatible elements, provides a way of identifying and quantifying trapped melt fractions. Finally, we show that HSGs appear to form only in the shallow crust (<10 km) and rarely in the middle to lower crust. Where HSGs are common, mafic magmas are common too, suggesting a genetic relationship between the two. If HSGs derive by crystal fractionation of basaltic parents, they represent at most 5% of the original mass of parental magma, but because they form almost exclusively at low pressures, they may be over-represented in shallowly exhumed batholiths. Why HSGs form primarily in the upper crust is unclear.

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1. Introduction

The tops of many felsic magma bodies contain large volumes of high silica (>70 wt.% SiO₂) granites (HSGs) (Bachl et al., 2001; Bachmann and Bergantz, 2004, 2008; Hildreth, 1979; Hildreth and Wilson, 2007). Understanding how HSGs form is important: many ore deposits associate with HSGs; highly incompatible elements, like K, are transported by HSGs; and large, catastrophic rhyolite eruptions may be related to HSGs (Bachmann and Bergantz, 2004, 2008). There is a general agreement that most HSGs form by crystal–liquid segregation from a cooling and crys-

tallizing magma, but how segregation occurs is unknown. Do HSGs represent the residual melt formed by crystal settling or by expulsion from a compacting magmatic mush (crystals+melt)? Forming large volumes of HSG must be accompanied by a complementary reservoir of cumulates (Gelman et al., 2014). Segregation must be complete before magmas freeze, but compaction timescales are poorly constrained and magma chamber lifespans are debated. One way to constrain the dominant segregation process is to study the hypothetical cumulates, but where are these lithologies? Felsic plutons have been suggested to be the “missing” cumulates (Gelman et al., 2014; Mills et al., 2012), but their compositions can also be modeled as frozen liquids. Here, we show that the complementary cumulates are indeed disguised among the felsic plutons, not as pure crystal cumulate, but as frozen mixtures of crystals and

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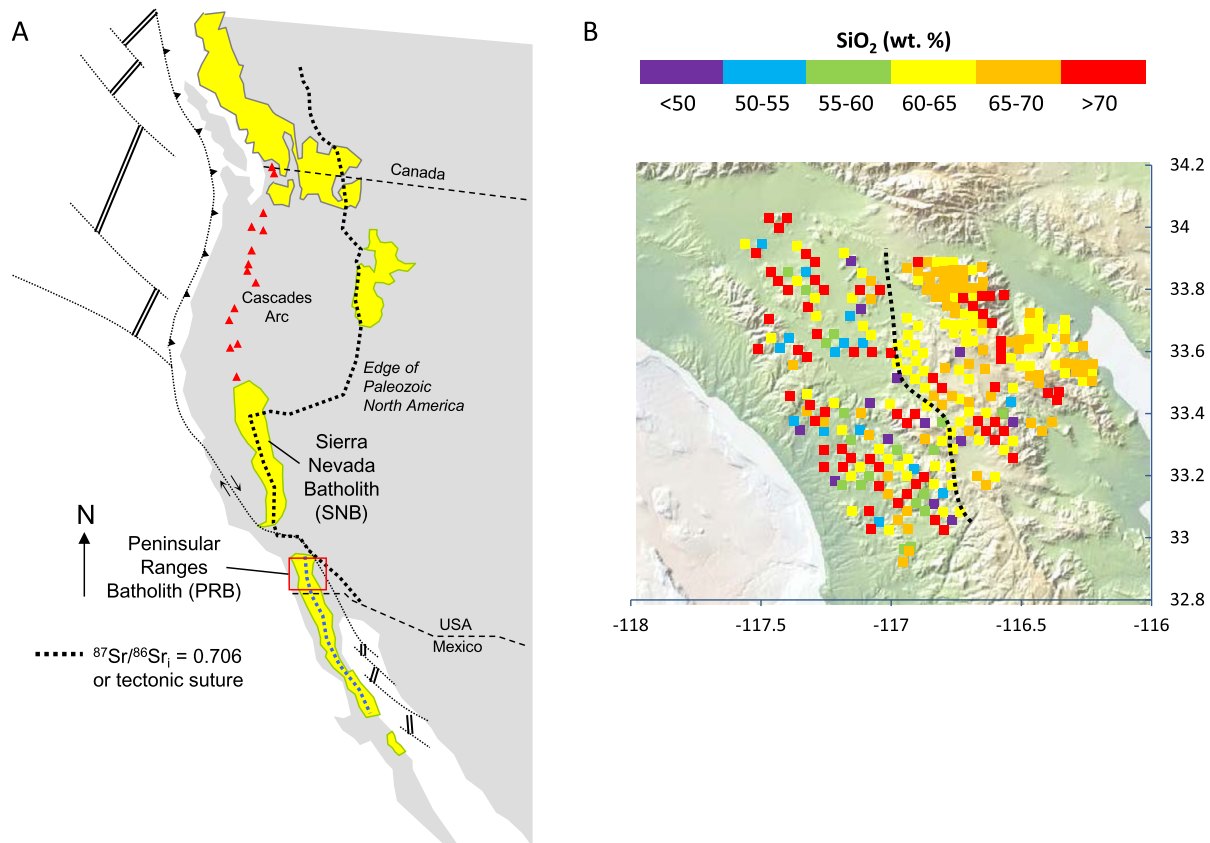


Fig. 1. A. Map of North America showing location of Cretaceous to early Paleocene continental arcs in yellow. Northern Peninsular Ranges Batholith (PRB) shown as inset. Dotted black line represents initial $^{87}\text{Sr}/^{86}\text{Sr}$ contour (Kistler and Peterman, 1973). Other lines denote plate boundaries. B. Elevation map of southern California with locations of PRB sampling, color-coded for SiO_2 content in weight% on a volatile-free basis. Data are from (Lee et al., 2007). Dashed line represents the boundary between western and eastern PRB, the former emplaced through thin Jurassic island arc-accreted crust and the latter through Paleozoic or older North American basement (Lee et al., 2007; Morton et al., 2014). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

trapped HSG melt, making them geochemically similar to liquids. What is new here is that we provide a means of quantifying the fraction of this trapped melt.

2. Regional database: the Peninsular Ranges Batholith

To explore crystal–liquid segregation scenarios on a batholith scale, we examined a regional database of plutonic rocks in the Peninsular Ranges Batholith (PRB) in southern California (Lee et al., 2007) (Fig. 1). The PRB consists of plutonic rocks (mostly tonalites and granodiorites) formed in a Cretaceous continental arc associated with the subduction of the Farallon plate beneath North America. The plutonic rocks have compositions typical of calc-alkaline (Fe-depleting) differentiation trends seen in many continental arcs. The database consists of rocks sampled along systematic grid points, and at each grid point, samples of equivalent weight from the corners of a 400×400 foot square grid were crushed and homogenized to generate a space-averaged sample (Baird et al., 1979). This approach was done to avoid sampling bias associated with small-scale heterogeneities. To minimize the effects of crustal assimilation or re-melting of pre-existing crust, we focus primarily on the western PRB (Fig. 1), which based on unradiogenic strontium isotopes, appears to have interacted less with the crustal basement than plutons in the east (Kistler et al., 2003; Lee et al., 2007; Morton et al., 2014). All data used in this paper have already been published in (Lee et al., 2007), but interpretations presented here are new.

3. Cumulate identification using highly compatible and highly incompatible elements

Because we are interested in identifying cumulates, we focus on highly compatible and incompatible elements, the former strongly partitioned into crystallizing phases and depleted in the liquid, and the latter strongly partitioned into liquids but depleted in crystals. Moderately compatible/incompatible elements do not fractionate enough between solids and liquids and are thus less ideal for distinguishing cumulates and melts. Fig. 2a–d shows variation diagrams of K, Rb, Sr and Eu versus SiO_2 . K and Rb (as well as other incompatible elements like Th and U) increase by 25–30 times as SiO_2 increases from gabbro ($\text{SiO}_2 \sim 50$ wt.%) to the HSGs ($\text{SiO}_2 > 70$ wt.%), indicating that these elements are almost perfectly incompatible, consistent with the dominant minerals in PRB plutons being quartz, plagioclase, and hornblende, none of which accommodate significant amounts of Rb and K. The extreme enrichments in Rb and K, even in the HSGs, is also consistent with the suggestion that K-feldspar is a late crystallizing phase in typical I-type granitoids and does not participate in crystal–melt segregation (Glazner and Johnson, 2013). In contrast, Sr decreases and Eu remains relatively constant with increasing SiO_2 , with both elements plummeting after SiO_2 increases beyond 71 wt.%. Such behavior reflects the strong compatibility of Sr and the moderate compatibility of Eu in plagioclase. We note that the inferred geochemical behaviors of K and Rb can be generalized for typical I-type granitoids, but not for alkalic granites in which biotite or alkali feldspar may be early crystallizing phases (Bucholz et al., 2014).

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