

Selective peritectic garnet entrainment as the origin of geochemical diversity in S-type granites

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ABSTRACT

Experimental melt (glass) compositions indicate that most of the S-type granites of the Cape Granite Suite in South Africa have ferromagnesian contents too high to represent melts. Consequently, the composition of the more mafic granites demands the addition of an Fe- and Mg-rich component to the magma. The compositions of the granites evolve along well-defined trends away from the likely melt composition for many components plotted against Mg + Fe. An increase in A/CNK, Mg#, Ca, and HREEs, as well as a decrease in K and Si, as a function of increasing Mg + Fe appears to limit the contaminant to garnet (up to 20 wt%). The rate of Ti increase, as a function of Mg + Fe increase in the granites, matches that defined by the stoichiometry of high-temperature biotite, but cannot be the product of accumulation of biotite (\pm other phases) in the magma because the chemical trends are inconsistent with this, particularly those portrayed by K and Ti as a function of Mg + Fe. This, in conjunction with the fact that no large, counterbalancing population of very leucocratic material exists in the Cape Granite Suite, suggests that the relatively mafic granites are not the products of garnet fractional crystallization. Rather, these appear to be the result of selective entrainment of peritectic garnet and ilmenite. Thus, this work indicates that much of the compositional variation in the granites is primary, reflecting the magma composition that ascended from the source, and is controlled by the proportion of peritectic products entrained into the melt. There is no indication of entrainment of a mineralogically diverse residuum (restite).

Keywords: S-type granite, granite geochemistry, granite petrogenesis, garnet.

INTRODUCTION

Partial melting (anatexis) of the crust can give rise to granite (s.l.) bodies that range in scale from centimeter-wide leucosomes in migmatites, to intrusive plutons and felsic volcanic sequences that crop out over thousands of km². Anatexis can occur in a number of different ways that largely depend on source mineralogy and the fluid regime during high-temperature metamorphism (see summaries by Stevens and Clemens, 1993, and Clemens and Droop, 1998). However, the important anatexis processes here are those that have generated voluminous and hot granitic magmas, capable of migration to high crustal levels, as this has produced the buoyant and chemically differentiated continental crust. A fundamental aspect of these high-level granites that remains temporally poorly understood is the origin of the major- and trace-element geochemical diversity that these rocks exhibit. Typically, large plutons or groups of temporarily and chemically related plutons (suites) show substantial major- and trace-element geochemical variability, without the clear and obvious field evidence for how this may have arisen that is typical for mafic intrusive bodies. Consequently, despite broad acceptance that source chemistry controls the genesis of fundamentally different chemical varieties of granitic magmas, little consensus exists on the dominant processes controlling the observed geochemical variations. In

many cases, several alternative processes appear to be viable, resulting in nonunique models. A possible reason for this is that the starting point from which compositional evolution must proceed is poorly constrained. This is despite the fact that experimental studies of partial melting have produced information that would seem to be useful in determining the major-element composition of the melts involved in granite genesis. This paper explores the use of experimental melt compositions in the specific case of the petrogenesis of granites derived through the partial melting of metasediments, using the example of the S-type granitic rocks of the Cape Granite Suite of South Africa.

S-TYPE GRANITE PETROGENESIS

Strongly peraluminous granites are believed to arise through the partial melting of aluminous clastic sediments (metapelites and metapsammities) (e.g., Chappell and White, 1974). The nature of the anatexis reactions involved in the genesis of such granites is well known, through theoretical considerations (e.g., Clemens and Watkins, 2001), experimental studies (e.g., Vielzeuf and Montel, 1994), and studies of migmatites (e.g., Johnson et al., 2001). The dominant melting reactions typically have the form $Bt + Qtz + Pl + Sil = Grt + melt + Ilm \pm Kfs$ and $Bt + Qtz + Pl = Grt + Opx + melt + Ilm \pm Kfs$, in metapelites and metapsammities, respec-

tively. Melting of biotite by these reactions typically begins at temperatures of 780 and 820 °C respectively (at 500 MPa), and progresses over a further 40–80 °C, within which biotite of changing composition coexists with granitic melt, a garnet-dominated solid peritectic mineral assemblage, and an assemblage of reactant restitic minerals.

S-type granites are characterized by significant major-element geochemical variation, from tonalitic to leucogranitic compositions, within suites of rocks that are temporally and genetically related. Typically, SiO₂ can vary from 65 to 79 wt%, Al₂O₃ from 11 to 17 wt%, FeO from near 0 to 8 wt%, MgO from near 0 to 3.5 wt%, CaO from near 0 to 3 wt%, Na₂O from 1 to 4 wt%, and K₂O from 2.2 to 6 wt%. In general, Mg + Fe values are strongly positively correlated and also correlate positively with the important ratios Mg# and Ca/Na. These variables usually correlate negatively with Si. Many different processes have been proposed to account for this geochemical variation. Among these, source-induced variation in initial melt composition (e.g., Brown and Pressley, 1999), fractional crystallization (e.g., Foden et al., 2002; Breaks and Moore, 1992), magma mixing (Gray, 1990; Collins, 1996), and restite unmixing (e.g., White and Chappell, 1977; Chappell, 1996) feature most prominently. Relatively few studies have considered the likely composition of the initial melt as a constraint. Notable exceptions are (1) Sawyer (1996), who proposed that the component of source residuum that combined with the melt to form peraluminous leucosomes was not simply a random sample of unmelted material, but rather the solid peritectic products of the melting reaction, and (2) the observation by Miller et al. (1985) and Montel and Vielzeuf (1997) that the increase in ferromagnesian component in the melts produced in high-temperature melting experiments was insufficient to account for the range of compositions observed in natural granites.

EXPERIMENTAL MELT COMPOSITIONS AND S-TYPE GRANITE PETROGENESIS

As the specific composition of the source of the Cape Granite Suite is unknown, this study has considered the melt produced from a wide range of metasedimentary protolith compositions and conditions of melting (Stevens et al.,

1997; Pickering and Johnston, 1998; Patiño Douce and Harris, 1998; Patiño Douce and Beard, 1996; Vielzeuf and Montel, 1994; Patiño Douce and Johnston, 1991; Spicer et al., 2004). As reactions identified through phase changes in the experimental charges are the biotite incongruent melting reactions discussed above, the experimental glass compositions should reflect the compositions of the melts that existed in the anatectic sources of a wide variety of S-type granites. All the experimental glasses are silicic (Fig. 1), even those from experiments at 1000 °C, where melt proportions were >60 vol% of the products. Total FeO + MgO values for the 100 wt% normalized glass compositions vary between 0.9 and 3.9 wt%, with a general increase in this parameter with temperature. A/CNK [0.5Al/(Ca + 0.5Na + 0.5K)] values for the glasses vary from 1.0 to 2.0. K is not correlated with Mg + Fe values; A/CNK, Ca, Mg#, and Ti are positively correlated with Mg + Fe; and Si is negatively correlated with Mg + Fe (Fig. 1).

The S-type granites of the Cape Granite Suite occur as part of an extensive belt of S- and I-type granites developed as a consequence of the Pan-African Saldanian orogeny along the southwestern margin of Africa (Scheepers and Pujol, 2002). These rocks form a suite of strongly peraluminous ($1 < A/CNK < 2$), K-rich granites with a substantial range in total FeO + MgO values (between 0.8 and 9 wt%) (Fig. 1). The suite contains both volcanic and plutonic rocks, and the presence of garnet, cordierite, and tourmaline confirms the inference of an aluminous metasedimentary source. As is typical for such granites, Si decreases as a function of Mg + Fe; A/CNK, Ti, Mg#, and Ca correlate positively with Mg + Fe; and K decreases as a function of Mg + Fe (Fig. 1; GSA Data Repository¹).

When compared to the experimental melt compositions, a significant proportion of the Cape Granite Suite rocks plots outside of the compositional range of the experimental glasses (Fig. 1). Typically, the glasses coincide only with the more leucocratic Cape Granite Suite compositions ($Mg + Fe < \sim 0.06$), and even the 1000 °C experimental melts contain less than half the Mg + Fe component of common S-type granites. This suggests that within the compositions defined by both the source rocks and the mafic granites, suitably mafic melts do not appear to be able to exist at reasonably attainable conditions. Thus, the mafic granites cannot represent mafic granitoid melts that evolved

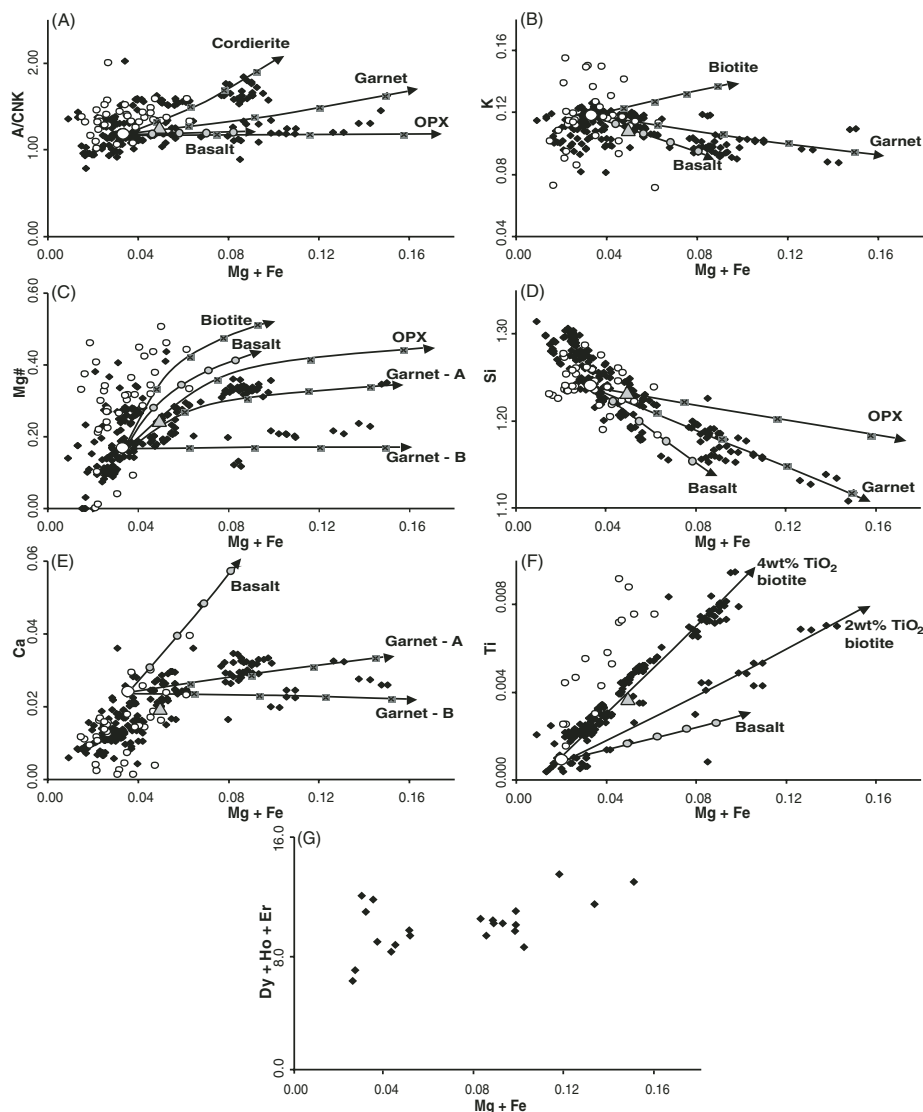


Figure 1. A comparison of the compositions of experimental glasses (small white circles) and the compositions of Cape Granite Suite S-type rocks (black diamonds) from Scheepers (1990), Scheepers and Pujol (2002), and Scheepers and Armstrong (2002). The suite of Cape Granite Suite rocks includes a small subset of rocks that have $A/CNK < 1.1$, considered to be genetically related to the more aluminous granites (Scheepers, 1990). The gray triangle represents the average of the Cape Granite Suite compositions. The large white dot represents a leucocratic S-type subvolcanic composition (sample B16) from the Cape Granite Suite, considered to be a nearly pure-liquid composition. The evolution of this composition, as a function of the addition of the labeled mineral and basalt components in 5 wt% increments, is shown by the evolution of the gray crossed squares away from this proposed melt composition. Garnet A (4 wt% CaO and $Mg\# = 38$) and garnet B (0.5 wt% CaO and $Mg\# = 17$) represent two different garnet compositions from granulite facies metasediments.

via fractionation toward the more silicic compositions. Rather, these compositions must be achieved by the inclusion of an Fe- and Mg-rich component in the silicic melt.

Two possible mechanisms proposed to account for the compositional range exhibited by the S-type granites of the well-studied Lachlan Fold Belt, i.e., magma mixing (e.g., Collins, 1996) and restite unmixing (Chappell, 1984; Chappell et al., 2000), have been evaluated for the Cape Granite Suite compositions. Addition of a basaltic magma to granitic melt in a pro-

portion sufficient to produce the observed Mg + Fe values results in both a decrease in A/CNK to below 1 and an increase in Ca values to 0.12 (0.05 is the maximum value in the Cape Granite Suite S-types). Furthermore, the addition of some 40 wt% basaltic melt is required to drive the granitoid magma to suitably mafic compositions. These factors appear to rule out the involvement of a mafic magma of this composition in Cape Granite Suite S-type petrogenesis. The effects of residuum (restite) entrainment are complicated by the fact that the nature of the

¹GSA Data Repository item 2007012, experimental melt and mineral compositions used in the geochemical modeling presented in this paper, is available online at www.geosociety.org/pubs/ft2007.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

residuum changes as a function of source composition, as well as the P - T conditions and fluid regime of melting. The restite unmixing model argues that variation in chemical composition within suites of granites results from varying degrees of entrainment and subsequent segregation of restite (unmelted source material) in the melt (White and Chappell, 1977; Chappell et al., 1987). It further proposes that the temperatures of melt generation are typically toward the low end of the magmatic range (750 °C or less) (Chappell et al., 2000) and that melt ascent occurred following the attainment of a critical melt fraction (Chappell et al., 2000). Collectively, these conditions imply fluid-present melting, that significant biotite incongruent melting is unlikely, and that the upper amphibolite facies xenoliths commonly contained within S-type plutons represent an entrained source component. This melting scenario differs from the high-temperature, fluid-absent process under discussion here. However, the effects of entrainment of a residual mineral assemblage appropriate to the granulite facies conditions of melting can most simply be evaluated by considering the effects of entrainment of a mineral in addition to garnet, which will generally always be present in metapelitic sources under these conditions. Other likely major residual phases include orthopyroxene, sillimanite, quartz, Ca-plagioclase, and cordierite. Addition of significant mixtures between garnet and any of these minerals to the melt produces magma evolution trends that differ from those defined by the Cape Granite Suite in Figure 1. For example, residua consisting primarily of garnet + sillimanite mixtures (as would be common for metapelitic sources) results in trends of A/CNK evolution with Mg + Fe values that plot above the garnet line on Figure 1A. Garnet + Ca-plagioclase mixtures (common for metapsammites) results in vectors on Figure 1E that are more Ca-rich than the natural rocks. Garnet + quartz (possible in some metapsammites and metapelites) addition produces compositions on Figure 1D that lie above the garnet trend. In short, the trends defined by the Cape Granite Suite compositions appear to be quite sensitive to the addition of other minerals with Mg + Fe ratios to Ca, Si, and Al that are different from those defined by the stoichiometry of high-temperature garnet from aluminous metasedimentary sources.

The combined requirements of increasing A/CNK, Mg#, and Ca as a function of Mg + Fe, with a corresponding decrease in Si and K, appear to be met by only garnet addition to the melt (Fig. 1). Indeed, the major-element trends defined by the granites cannot be modeled effectively as the result of any simple process, other than garnet addition, once the starting point of a silicic melt has been defined (Fig. 1). Thus, the crux of the matter becomes the source of

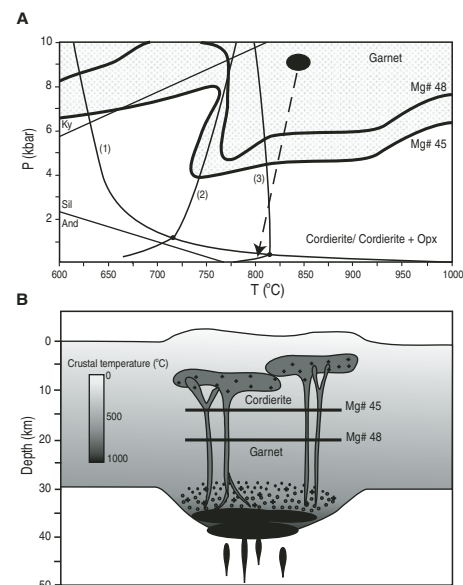
the garnet—does it represent an accumulation of a magmatic crystallization product, or does it represent a component preferentially entrained from the source? Three lines of evidence appear to argue against the former and for the latter. Firstly, the average Cape Granite Suite S-type granite is significantly more mafic than the average experimental melt, suggesting that the large volume of very silicic compositions that would be needed to counterbalance a large proportion of relatively mafic rocks produced by fractional crystallization from a relatively silicic melt is absent from the preserved rock record. Secondly, and perhaps most importantly, a strong positive correlation exists between Ti and Mg + Fe in the Cape Granite Suite S-type granites (Fig. 1F). This cannot represent biotite fractionation due to the negative correlations between K and Mg + Fe, and between K and Ti. Despite this, these correlations appear linked to the stoichiometric association of these elements within high-grade metasedimentary biotite. Thus, the trends on Figure 1F suggest that the silicic melt composition from which the Cape Granite Suite formed was characterized by low Ti (despite the relatively large range of Ti contents exhibited by the experimental glasses) and that the garnet and ilmenite produced by biotite incongruent melting were entrained into the melt with no fractionation of one phase over the other, but in variable proportions relative to the melt. Thirdly, there is a positive correlation between the heavy rare earth element (HREE) concentration in the granites and Mg + Fe (Fig. 1G), consistent with garnet as the source of Mg + Fe increase in the

magma, yet no strong HREE depletion in the most leucocratic granites, which show La/Yb values little different from those of the most mafic granites. However, the positive correlation that exists between Zr and Mg + Fe suggests that zircon, a common inclusion in biotite in high-grade metasediments, was a coentrained phase due to its proximity to the sites of melting and that the factors that controlled garnet entrainment also regulated the amount of zircon entrained. Monazite is probably also involved for similar reasons, complicating simple interpretations of the rare earth element (REE) patterns of the granites.

DISCUSSION AND SUMMARY

Rapid ascent of melts and magmas from the anatexic sources through fracturing and dike propagation processes is effectively geologically instantaneous (Clemens and Mawer, 1992; Petford et al., 1993). Thus, magmas initially emplaced into the shallow crust may be only slightly cooler, but at a much lower pressure than at the source (Fig. 2). Garnet breaks down to cordierite, or cordierite + orthopyroxene, at low pressures in a manner that is sensitive to bulk rock Mg# (Green, 1976). Importantly, higher Mg# equates with high-pressure (earlier) garnet destruction (Fig. 2). In S-type granites, higher Mg# equates with more Mg- and Fe-rich compositions and thus a higher entrained garnet fraction. Consequently, the system appears to be naturally ordered toward more effective garnet destruction in magmas that require the largest fractions of garnet addition. The magmatic

Figure 2. The model for the petrogenesis of S-type granite proposed in this study. A: Summary phase relations. Reaction 1 represents the wet granite solidus; reactions 2 and 3 represent the fluid-absent biotite incongruent melting equilibria in metapelites and metapsammites, respectively (Stevens et al., 1997). The dashed arrow represents a roughly adiabatic magma ascent path as appropriate for a high-temperature, water-undersaturated melt/magma generated by biotite fluid-absent melting at high pressures. The limits of garnet stability in two mafic granite compositions, CSS (Mg# = 0.45) and MBS (Mg# = 0.48), are superimposed on the melting reactions. The pseudosections constraining garnet stability were constructed via PERPLE_X (Connolly, 1990; Connolly and Petrini, 2002) following the method of Connolly and Petrini (2002) and using the thermodynamic data set of Holland and Powell (1998) (2.5 wt% H₂O and MnO-free). B: A simplified crustal section during granite genesis. Melting occurred within the garnet stability field, and the melting reactions progressed rapidly due to the high heat flux associated with intraplated or underplated mantle melts. The granitic magmas rapidly intruded to high levels in the crust via dike systems. The garnet-bearing magmas arrived at the low-pressure intrusive sites at a temperature only slightly cooler than at the melting sites. Garnet in both compositions is markedly out of equilibrium under these conditions, but garnet breakdown initiated earlier on the ascent path in the higher-Mg# magma. Ky—kyanite; Sil—Sillimanite; And—Andalusite.



nature of the products of garnet breakdown may create the textural impression of high Mg + Fe solubility in the melt, as well as garnet crystals equilibrated within the magmatic environment.

In summary, primary geochemical diversity in S-type granites is produced in the source. S-type granitic melt compositions will always be silicic, even at the highest temperatures possible for crustal anatexis, and melt compositions vary as a function of source chemistry, probably accounting for much of the compositional variability observed in leucocratic granite compositions. In contrast, mafic S-type granites cannot represent melts and must represent melt-crystal mixtures. The large-scale major-element geochemical trends defined by S-type granites appear to be the products of garnet addition to melts of different composition, with the most mafic compositions representing melt + ~20 wt% of the peritectic products of biotite breakdown. The peritectic garnet is likely to be preferentially entrained into the melt because it is abundant at the sites of melting, and because it may be texturally distinct (smaller in crystal size) from the earlier generations of regional metamorphic minerals.

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