

INTRODUCTION



Gary Stevens was born in Benoni, a small town 40 km east of Johannesburg, on 3 July 1965. He matriculated from Benoni High School in 1983, thanks in part to Dorothy Maree, a wonderfully kind-hearted (and pretty) young lady who used to hand in his very late essays to a particularly fierce English mistress. At the time, his interests were oceanography and athletics. UCT beckoned as a place to study the sea, but Rand Afrikaans University offered a very attractive athletics scholarship and the chance to stay with his long-standing coach, Owen van Niekerk. In the end, there was no way he could bring himself to leave Benoni, where Dorothy was still at school, so Athletics and RAU it was; the sea was for holidays. During his first years of study he was a mediocre student of Geology, concentrating more on representing RAU and Transvaal as a sprinter. However, in his 2nd year, a chance to train with Frank Fredericks, a young Namibian contemplating enrolling at RAU, demonstrated very clearly that he was not going to be the next Carl Lewis.

Stevens attacked his studies with renewed vigour and subsequently won the Rand Pioneers Yule Crosby Prize for 3rd year Geology in 1986. He went on to complete his BScHons (Geology) with distinction in 1987. He enrolled for an MSc degree under the supervision of Dirk van Reenen. This study took him into the Limpopo Belt and into the realm of rock evolution under the extreme pressure and temperature conditions of metamorphism, attainable only in the deep roots of mountain belts. Here, rocks undergo a transition from metamorphic (solid-state) to igneous (molten) processes and this interface has been his academic home ever since. His MSc thesis won the Rand Afrikaans University Vice-Chancellor's medal for the best MSc thesis produced at RAU in 1991. While at RAU he was offered a Research Assistantship in Experimental Petrology at the University of Manchester, under the guidance of John Clemens. This included the opportunity to enrol for a PhD (Geology) and presented fascinating new tools with which to directly replicate the conditions of the Metamorphic-Igneous interface. He jumped at the chance, departing for Manchester with Dorothy in 1992, shortly after getting married.

Manchester was a time of deep personal learning. He and Dorothy voted in the first democratic election in a cathedral in Manchester, feeling lonely and acutely aware of missing the monumental changes at home. He learnt to function in a less nurturing and more demanding environment; that he belonged in South Africa; and that some of the aspects of the country that he had perceived to be failings, were perhaps strengths. He also learnt to catch trout in Welsh streams, to play sport in any weather and to celebrate Burn's night like a Scotsman. Upon completing his PhD in 1995, he returned to South Africa and was offered the post of Research Officer at the Economic Geology Research Unit at the University of the Witwatersrand. A WITS Vice-Chancellor's research award and an NRF P-rating offered the space and funding to establish an Experimental Petrology laboratory and, for the first time, to do this type of research in Africa. In 2000 he was fortunate to be offered the position of Associate Professor at Stellenbosch University. The expanded laboratory is now located here, in part because WITS very generously agreed to donate his original equipment. In the end, he is as close to the sea as he always wanted to be and doing the science he always wanted to do.

Gary and Dorothy have a beautiful 5-year-old daughter, Lara, who is as fascinated by the world, its creatures and its functioning as her father is.

Acknowledgements

The author acknowledges Arnaud Villaros for construction of the pseudosections that Figure 6 is based on; Jeanne Taylor for compiling the LFB S-type compositions from the literature; Alex Kisters for advice on Figure 6; and John Clemens and JF Moyen for discussions, over several years, that have helped refine the concepts presented here.

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MAKING GRANITES: UNDERSTANDING THE MELTING OF EARTH'S CRUST.

INTRODUCTION

Incongruent partial melting (anatexis) of rocks is a process of major petrologic and geodynamic importance. In Earth's crust, either oceanic or continental, the process gives rise to granites (*sensu lato*) that range in scale from centimetre-wide leucocratic segregations within migmatites, to intrusive plutons and felsic volcanic rocks that outcrop over thousands of km² (Fig. 1). Crustal anatexis may occur in a number of different ways that are largely dependant on the mineralogy and fluid regime present during high temperature metamorphism (Fig. 2). However, the important anatectic processes, from the perspective of planetary geodynamic consequence, are those that have generated voluminous granitic magmas, capable of migration to high crustal levels. This is the process responsible for the formation of the buoyant continental crust and for producing the chemical differentiation of this crust. It is one of the important, large-scale chemical recycling processes on the planet, and has arisen due to the combination of the presence of water and plate tectonic activity on Earth.

Despite the importance of the process, some aspects of granite petrogenesis remain poorly understood. In part, because detailed information about the mechanisms of granite genesis cannot easily be derived from the resultant magmatic rocks. This is a result of the tendency of the minerals in granites to predominantly record information from close to the relatively low temperature solidus, as well as the commonly non-unique nature of interpretations based solely on granite geochemistry. Studies of granulite-grade anatectic migmatites (partially melted source rocks exhumed from near the base of the crust), where the field relations commonly indicate that the products of the melting reactions have been frozen in place (e.g. Stevens *et al.*, 1992; Srogi *et al.*, 1993), as well as some studies of magmatic systems (e.g. Clemens and Wall, 1984; Noyes

et al., 1983) have demonstrated that melting must occur through the incongruent breakdown of hydrous silicates, mostly with internally buffered $a\text{H}_2\text{O}$ (fluid-absent melting).^a However, it is difficult for these studies to accurately constrain the factors controlling the melting reactions at the sites of anatexis, or the composition of the melts produced by these reactions. This is due to common evidence for melt loss from the migmatitic leucosomes, leaving behind a cumulate composition, (e.g. Stevens *et al.*, 1992) and to the chemical re-equilibration of the leucosomes with the solid, unmelted portion of the rock during the protracted cooling that such high-grade metamorphic terrains must undergo (Fourcade *et al.*, 1992).



Figure 1: Coarse porphyritic S-type granite of the Peninsular pluton, Western Cape, South Africa. In this view the granite is well exposed in coastal outcrops at Bakoven Bay. The Peninsular pluton intruded lower greenschist facies grade metasediments (Belcher and Kisters, 2003) at relatively high levels in the crust, indicating that the magma was hot and markedly water under-saturated (Fig. 2). The prominent crystals in the outcrop forming the foreground are K-feldspar phenocrysts.

a. In this study the term “fluid-absent melting” implies the incongruent melting of a hydrous silicate to produce water-undersaturated granitic melt coexisting with an assemblage of anhydrous phases. It is synonymous with, but preferred to, the term “dehydration melting” used in some other works.

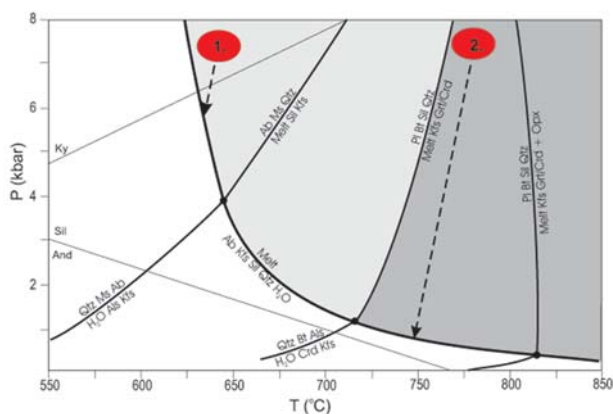


Figure 2: The typical biotite and muscovite fluid-absent incongruent melting reactions, as relevant to clastic sediments, superimposed on the wet granite solidus. The positions of the K_2O - Na_2O - Al_2O_3 - SiO_2 - H_2O sub-solidus and melting reactions are constrained by the theoretical calculations of Holland and Powell (2001); Al_2SiO_5 phase boundaries are from Holdaway (1971); Biotite melting reactions are constrained by the experiments of Stevens *et al.* (1997). In the unshaded area no melt is present. Above the wet solidus melt can exist if water is present (light shading). As discussed by Stevens and Clemens (1993), this is an unlikely situation in the high-grade crust, and for most rocks the fluid-absent solidi involving incongruent melting of muscovite and biotite, represent the effective solidi in natural rock systems. Mineral proportions in suitable high-grade granite source rocks dictate that biotite-melting reactions are the main producers of melt (area of dark shading). These melts are hot and markedly water-undersaturated (2.). The adiabatic magma ascent paths represented by the dashed arrows illustrate the fact that fluid-saturated, low temperature melts developed near the wet solidus (1.) would be trapped near their sites of generation by the negative slope on the wet granite solidus (Cann, 1970). Only high-temperature water-undersaturated melts (2.) have the ability to ascend to high crustal levels (> 2 MPa confining pressure). Modified from Spicer *et al.* (2004).

In contrast to the problems associated with studies of anatexis in natural rocks, properly designed experiments have the ability to provide information on the details of the anatexis process. Experimental petrology involves the laboratory synthesis of geological materials in special autoclaves under the high temperature and pressure conditions appropriate to relevant geodynamic scenarios. Through rapid cooling (50 to 400°C per minute), these techniques offer the possibility of freezing the equilibrated geological materials in the process of anatexis reaction. In this way, both the modified reactants and the products of the reaction are available for study. This information has the potential to provide very useful constraints on the petrogenesis of granitoid

rocks. To date, modelling of the petrogenesis of granites has remained largely unconstrained by the details of what occurs in the anatexis source, despite a relatively good knowledge of this based on experimental studies conducted over the past 20 years. This paper seeks to explore these constraints in the specific case of granites derived from the partial melting of metapelites. This has special relevance to the south western seaboard of the Western Cape, South Africa, large areas of which are underlain by granites of this type.

S-TYPE GRANITE PETROGENESIS

Strongly peraluminous granites (i.e. granites containing a mineral more aluminous than biotite (Miller, 1985)) are believed to arise through the partial melting of aluminous clastic sediments such as shales and greywackes (Chappell and White, 1974). These rocks are characterised by significant major element geochemical variation, from tonalitic to leucogranitic compositions, within suites of rocks that are temporally and genetically related. Typically, SiO_2 can vary from 65 to 79 wt%; Al_2O_3 between 11 and 17 wt%; FeO from 0 to 8 wt%; MgO from 0 to 3.5 wt%; CaO from 0 to 3 wt%; Na_2O from 1 to 4 wt%; and K_2O from 2.2 to 6 wt%. In general, Fe^b and Mg are strongly positively correlated and also correlate positively with the important ratios $Mg\#$ ($Mg/(Mg + Fe)$) and model anorthite content ($Ca/(Ca + Na)$). These variables usually correlate negatively with Si content.

A large variety of processes have been proposed to account for the geochemical variation in these rocks. Among these, source-induced variation in initial melt composition (e.g. Brown and Pressley, 1999), fractional crystallisation (e.g. Foden *et al.*, 2002; Breaks and Moore, 1992), magma mixing (Collins, 1996) and the entrainment of components from the magmatic source (White and Chappell, 1977; Chappell *et al.*, 1988) feature most prominently. Of these, fractional crystallisation and the entrainment of source material appear to be the most viable mechanisms to generate the large-scale geochemical variation noted above, as both these processes are free from the problems with heat budget that appear to limit the applicability of magma mixing and crustal assimilation models. Chappell (1966) first suggested that geochemical variation in granites could result from differing degrees of separation of granitic melt from its crystalline residue, resulting in a magma^c more- or less-rich in crystals, and consequently of variable composition. Subsequent works on examples from the Lachlan Fold Belt in South-Eastern Australia, have

- b. In this work, use of the molecular oxide formula of the element (e.g. SiO_2) implies the wt% of the oxide in the composition, use of the element symbol implies the atomic proportion of this element in the composition.
- c. The terms magma and melt are not synonymous; magma represents a mixture of melt and crystals; melt only the liquid produced by partial or complete fusion of the prior mineral assemblage.

suggested that such granites provide a strong geochemical image of their source rocks (e.g. Chappell, 1996) due to the entrainment of this restite component. It has been suggested that the more ferromagnesian-rich S-type granite compositions are unlikely to be cumulates because these compositions exist in both plutonic and volcanic rocks (Wyborn and Chappell, 1986). Consequently, it has been proposed such compositions must closely reflect those of the parental magmas, which were either mafic peraluminous granitoid melts (Gray, 1990; Collins, 1996), that may have arisen through the mixing of metasedimentary derived melts with more mafic magmas, or, alternatively, mixtures of a more felsic melt and entrained metasedimentary restite (White and Chappell, 1988; Chappell, 1996). Subsequent variable segregation of this solid material from the residual melt (Chappell, 1996; DePaolo, 1981) has been proposed as the dominant mechanism for generating geochemical variation. This is a process similar to fractional crystallisation, but differing in the origin of the mechanically segregated solids. Sillimanite and biotite bearing xenoliths in some of these plutons have been proposed to represent this restite component (White *et al.*, 1999). Many of these “restites” contain abundant biotite and a relative lack of high-grade minerals, illustrating that, in the view of these workers, some high-level granites must represent the products of relatively low-temperature melting, and that the concept of restite equates with “unmelted fraction of the source” not residua from the melting reaction, as their compositions are far from the anhydrous residua that would be expected to coexist with melt in the source – in this sense the term “restite” is a misnomer.

Following a comprehensive review of the petrogenesis of S-type granites, Clemens (2003) proposed, on the grounds of the above argument, that the metasedimentary xenoliths in the Lachlan Fold Belt S-type granites are mid-crustal in origin and represent metamorphic rocks from a level above the anatexitic source. Clemens (2003) noted that dyking is the only viable mechanism by which granite magmas may ascend through large thicknesses of crust and emplace at high levels (e.g. Clemens and Mawer, 1992; Petford *et al.*, 1993). This rapid ascent of hot, water-undersaturated magma results in a significant capacity of the melt to dissolve entrained crystals, both during and after ascent of the magma (Clemens *et al.*, 1997). Consequently, restitic rock fragments and/or crystals cannot represent more than a very small fraction of the solid material in freshly emplaced high level plutons, and as a result, crystal fractionation during cooling of the magma, as opposed to the unmixing of a solid restite fraction, must be the major cause of large scale major ele-

ment geochemical diversity in plutons and plutonic suites (Clemens, 2003).

The hypotheses highlighted above have been selected to illustrate the typical divergence that exists in views of S-type granite petrogenesis. A similar range of views can be put forward for almost all areas of significant S-type granite exposure. This study holds that the long-standing debate over the dominant cause of major element geochemical diversity in S-type granites is, in part, a function of insufficient heed paid to the constraints imposed by data from experimental investigations of anatexitic processes. The remainder of this work investigates the findings of these studies for interpretations of S-type granite petrogenesis, and focuses, in particular, on the role of the experimental melt compositions.

EXPERIMENTAL ANATEXIS OF METAPELITES

The nature of the anatexitic reactions involved in granite genesis from metapelitic and metapsammitic sources is well known, through theoretical considerations (e.g. Clemens and Vielzeuf, 1987), experimental studies (e.g. Vielzeuf and Holloway, 1988; Le Breton and Thompson, 1988; Vielzeuf and Montel, 1994; Stevens *et al.*, 1997; Spicer *et al.*, 2004) and studies of migmatites (e.g. Stevens *et al.*, 1992; Johnson *et al.*, 2001). The dominant reactions believed to result in the genesis of water-undersaturated granitic magmas typically have the forms $Bt^d + Qtz + Plag + Sil = Grt + Melt \pm Kfs$ and $Bt + Qtz + Plag = Grt + Opx + Melt \pm Kfs$ (Fig. 2) in metapelitic and metapsammitic sources respectively (e.g. Clemens and Vielzeuf, 1987; Stevens *et al.*, 1997). Melting of biotite via these reactions typically begins at temperatures of approximately 780 and 820°C respectively (at 5 kbar) (Fig. 2), and progresses over a further 40 to 60°C interval, within which biotite, of changing composition, coexists with melt and the solid peritectic products. At higher temperatures further melting occurs through the consumption of anhydrous minerals, and melt production, as a function of temperature increase, is typically much lower than during the incongruent melting interval of biotite (e.g. Stevens *et al.*, 1997; Spicer *et al.*, 2004). The exact temperature of melting and the width of the melting interval is controlled by the composition of biotite. Higher Mg# (Stevens *et al.*, 1997), Ti content (Stevens *et al.*, 1997; Patiño-Douce and Johnston, 1991) and F content (Patiño-Douce and Johnston, 1991) all increase the thermal stability of biotite, as does any deficiency of quartz or albite component in the starting composition (e.g. Patiño-Douce and Johnston, 1991).

d. In this work the following mineral name abbreviations apply: Bt = biotite; Qtz = quartz; Grt = garnet; Opx = orthopyroxene; Sil = sillimanite; Ms = muscovite; Ab = albite; Kfs = potassium feldspar; Plag = plagioclase; Crd = cordierite; Als = Al_2SiO_5 polymorphs.

This study has examined experimental melt compositions produced from a range of metapelitic and metapsammitic sources (Table 1) across a broad temperature range and at a variety of pressures. In all cases, the glasses produced were silicic, peraluminous and leucocratic (Fig. 3). The highest temperature melts reported were from experiments run at 1000°C, and, even in these cases, with typical melt volumes in excess of 60%, the melt compositions are strongly leucocratic. The reactions identified through phase changes in the experimental charges are the biotite incongruent melting reactions considered to be responsible for S-type granite genesis. Consequently, it is reasonable to propose that the experimental glass compositions accurately reflect those of the melts that existed in the anatexis sources of these granites. Importantly, the experimental glass compositions differ significantly from those of many S-type granites (Fig. 3). Principally, the glasses are more leucocratic than average granites. In general, experimental melt compositions have not been used as a systematic constraint on granite petrogenesis. Notable

exceptions are: 1. The application of such melt compositions to understanding migmatite formation (Sawyer, 1996), where it has been 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, as proposed by proponents of Lachlan restite model (e.g. Chappell and White, 1974), but rather the solid peritectic products of the melting reaction (i.e. garnet in the case of metapelitic sources and garnet and orthopyroxene in the case of metapsammitic sources); and 2. The observation by 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, and that some other process such as magma mixing or restite unmixing must be invoked to account for these compositions. The remainder of this paper will pursue this line of investigation by comparison between the experimental glass compositions and the compositional variation in granite suites.

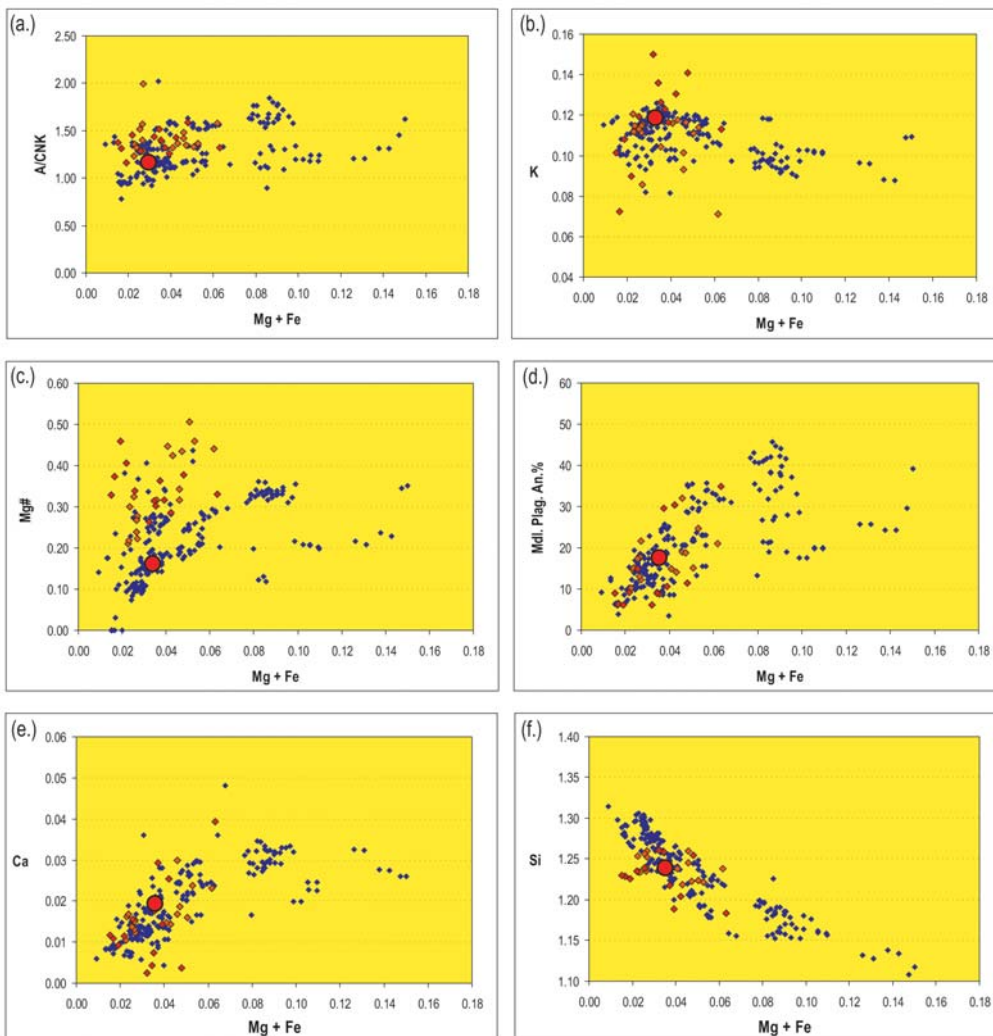


Figure 3: A comparison of the compositions of experimental glasses (orange, < 920°C, and red, > 920°C, diamonds) and the compositions of plutonic, subvolcanic and volcanic S-type rocks from the CGS (blue diamonds). The experimental glass compositions are listed in Table 1, those for the S-type rocks are from Scheepers (1990); Scheepers and Poujol (2002); and Scheepers and Armstrong (2002). Note that the suite of CGS rocks plotted includes a small subset of rocks that have $A/CNK < 1.1$ ($A/CNK = \frac{1}{2}Al/Ca + \frac{1}{2}K + \frac{1}{2}Na$). These rocks were considered to be genetically related to the more aluminous S-type rocks by Scheepers (1990). They generally also have high SiO_2 contents, and may therefore constitute fractionated liquids. They are included for this reason.

Wt% oxide composition									CIPW normative composition					
Comp	T (°C)	SiO ₂	Al ₂ O ₃	FeO	MgO	CaO	Na ₂ O	K ₂ O	Q	C	Or	Ab	An	Hy
NB	855	73.5	14.7	1.8	1.0	0.9	2.8	5.2	32	3	31	24	4	6
	875	74.8	14.5	1.8	0.5	1.0	2.6	4.9	37	3	29	22	5	4
	900	74.8	14.4	2.2	0.6	0.9	2.2	4.8	39	4	28	19	5	6
	950	75.7	13.4	2.3	0.6	1.7	2.0	4.4	41	2	26	17	8	6
	1000	74.4	14.6	2.5	1.1	1.3	2.7	3.4	39	4	20	23	6	7
NBS	830	75.3	14.1	1.3	0.2	0.6	2.9	5.7	34	2	34	25	3	3
	850	75.3	14.1	1.5	0.2	0.7	2.7	5.5	35	2	32	23	3	3
	875	73.2	15.2	1.8	0.7	0.8	2.7	5.5	32	3	33	23	4	5
	900	74.4	14.4	1.6	0.7	0.8	2.6	5.5	34	3	32	22	4	5
	950	73.5	14.8	1.9	0.8	1.0	2.5	5.5	33	3	32	21	5	6
	1000	73.4	14.6	2.1	1.0	1.3	2.2	5.4	34	3	32	19	7	6
HP	820	75.7	16.0	1.4	0.3	0.9	1.7	4.0	47	7	24	15	4	3
	850	74.2	15.3	1.4	0.3	0.7	2.7	5.4	35	4	32	23	4	3
	875	74.2	15.3	1.3	0.2	0.9	2.9	5.3	34	3	31	24	4	3
	900	74.5	15.6	1.4	0.3	0.8	2.1	5.3	38	5	31	18	4	3
	925	74.2	15.1	1.2	0.3	0.9	2.9	5.4	33	3	32	25	5	3
	950	75.5	14.8	1.2	0.3	0.8	2.0	5.3	40	4	31	17	4	3
	975	74.4	14.7	1.2	0.3	0.9	2.8	5.6	33	2	33	24	4	3
MU	835	73.8	16.2	0.8	0.3	0.6	4.9	3.4	30	3	20	42	3	2
	850	73.9	16.1	0.7	0.2	0.7	3.6	4.8	32	4	28	31	3	2
	900	73.6	15.3	0.7	0.4	0.5	4.4	5.1	26	2	30	37	3	2
SBG	910	72.4	15.6	2.2	0.5	1.4	1.8	6.1	33	3	36	15	7	5
	950	73.2	15.0	1.7	0.5	1.6	2.2	5.8	33	2	34	18	8	4
	1000	71.1	15.2	3.0	0.8	2.2	2.3	5.3	29	2	31	19	11	8
VM	858	74.2	16.0	0.9	0.4	0.6	3.6	4.2	35	4	25	30	3	3
	1000	71.4	16.1	1.9	0.5	0.8	3.7	5.5	25	3	32	32	4	5
HQ	850	74.2	14.9	1.8	0.4	0.4	2.3	6.0	35	4	35	20	2	4
	900	75.6	14.2	1.7	0.4	0.2	1.4	6.4	41	5	38	12	1	4
	950	75.8	13.8	1.7	0.3	0.1	1.1	7.1	40	4	42	10	1	4
	1000	75.4	14.0	2.1	0.7	0.2	0.9	6.6	42	5	39	7	1	6

Table I: The experimental glass (melt) compositions used in this study. All compositions have been normalised to 100%. NB and NBS (Stevens *et al.*, 1997); HP (Pickering and Johnston, 1998); MU (Patiño-Douce and Harris, 1998); SBG (Patiño-Douce and Beard, 1996); VM (Vielzeuf and Montel, 1994); HQ (Patiño-Douce and Johnston, 1991).

EXPERIMENTAL CONSTRAINTS APPLIED TO CAPE GRANITE SUITE PETROGENESIS

The S-type granites from the Cape Granite suite (CGS), an extensive belt of S- and I-type granites developed as a consequence of the Panafrican Saldanian orogeny along the south western margin of Africa (Scheepers, 1995), will be used for the purpose of comparison with the experimental glass compositions. The CGS S-type granites are 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%) (Scheepers, 1990; Scheepers and Poujol, 2002; Scheepers and Armstrong, 2002). The suite contains both extrusive and intrusive rocks, and the presence of cordierite and tourmaline in many of the plutons confirms an aluminous metasedimentary source. As is typical for such granites, SiO₂ decreases as a fairly tightly constrained linear function of MgO + FeO; A/CNK, TiO₂, Mg# and average model plagioclase anorthite content correlate positively with MgO + FeO; and, K₂O decreases as a function of FeO + MgO (Fig. 3).

When compared to the experimental melt compositions, a significant proportion of the CGS compositions plot outside of the compositional range of the experimental glasses (Fig. 3). Typically, the experimental glasses coincide only with the more leucocratic CGS compositions (Mg + Fe < ~ 0.05). The glasses are more aluminous than an average leucocratic granite composition and have higher Mg#s than an average leucocratic granite composition. The scatter in experimental melt compositions reflects the combined influences of differences in source rock composition and different temperatures of equilibration. Collectively, these factors account for a similar degree of geochemical variation to that observed in the aluminous (A/CNK > 1.1) leucocratic CGS compositions. The 1000°C experimental melts represent compositions produced during anatexis at a higher temperature than is likely to be common-

ly attained in the crust, yet their compositions contain less than half the Mg + Fe component of common S-type granite compositions. This suggests that the initial melt compositions from which granites develop must be strongly leucocratic (Fig. 3) and that the evolution of these leucocratic compositions towards the more mafic compositions displayed by some S-type granites is achieved by a mechanism resulting from the solid accumulation of ferromagnesian minerals – i.e. within these bulk compositions more mafic melts do not appear to be able to exist at reasonably attainable conditions. The only ferromagnesian silicate phases likely to be involved in the evolution of magmas of this type are garnet, cordierite, orthopyroxene and biotite. The increase in A/CNK and the decrease in K₂O, as a function of FeO + MgO enrichment in the CGS, would appear to argue for the involvement of some phase more aluminous and FeO + MgO rich, but less potassic, than the melt. This requirement would appear to rule out biotite and orthopyroxene as individual contaminants (Fig. 4). The major element compositions of most of the natural granites can, however, be successfully modelled as mixtures of the glass compositions and up to 20 wt% garnet, or garnet and subordinate orthopyroxene. This appears to be a more effective mechanism for accounting for the increase in A/CNK as a function of increasing FeO + MgO than cordierite addition, on account of the fact that cordierite would produce a substantially higher increase in A/CNK relative to FeO + MgO than is observed in the CGS (Fig. 4). Thus, garnet contamination of the melt appears to shape the major element composition of S-type granites. The strongly leucocratic nature of the melt compositions suggests that this garnet must represent entrained material, as opposed to crystals fractionated from the melt, as the large population of ultra-leucocratic granitic compositions, that would have to exist to balance the Fe + Mg rich crystal cumulates represented by typical CGS compositions in this hypothesis, are not observed.

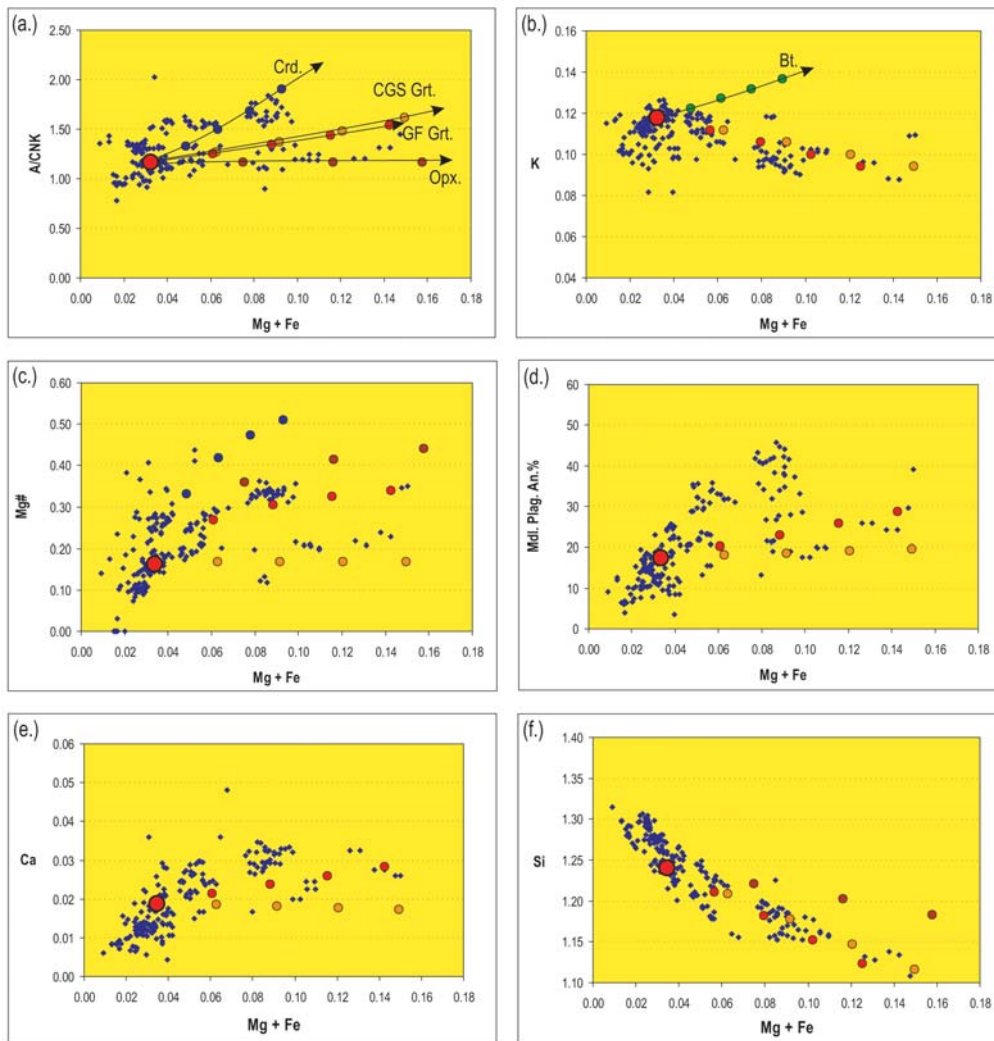


Figure 4: CGS S-type rocks compared to possible melt evolution trends as a function of the entrainment of individual minerals. The large red dot represents a leucocratic S-type sub-volcanic composition from the CGS considered, on the grounds of comparison with the experimental melt compositions, to be a near pure liquid composition. The evolution of this composition, as a function of the addition of various mineral components in 5 wt% increments, is shown by the evolution of the smaller dots away from the melt composition. The orange dots represent addition of a garnet with $Mg\# = 0.18$ and 1.8 wt% CaO (CGS Grt). The red dots represent the addition on a garnet with $Mg\# = 0.38$ and 3.5 wt% CaO (GF Grt). The blue and brown dots represent cordierite and orthopyroxene addition respectively. The arrows represent the trends followed. For simplicity these are only presented once for each additive.

THE VIABILITY OF RESTITE ENTRAINMENT

Restite entrainment, as invoked by proponents of this model in the Lachlan Fold Belt (e.g., Chappell and White, 1974; Chappell *et al.*, 1988; Chappell, 1996), implies incorporation of the entire unmelted fraction of the source rock into the granitic melt to form the magma. An attempt has been made to compare the effects of this process, relative to garnet addition, by evaluating the effects of entrainment of the entire residua from a variety of metapelites and metagreywackes after evolving a 30 to 60% melt fraction (Fig. 5). None of these “restite”^e compositions produce trends that mimic those defined by the CGS compositions for all the components modelled. Some represent close approximations because melt extraction will leave a composition that is similar to garnet – i.e. the residua

for such compositions will consist predominantly of garnet, making garnet entrainment and restite entrainment effectively the same process for these compositions. However, the trends modelled by the addition of garnet and another possible restite phase are particularly instructive. Garnet + sillimanite clearly produces a trajectory on Figure 5a that is mimicked by some of the natural rock restite models but not by the CGS compositions. Likewise, garnet + plagioclase addition produces a vector on Figure 5e that is not matched by the natural rocks, as do garnet + quartz addition and garnet + spinel and/or magnetite addition in Figure 5f. It appears that the major element trends defined by the CGS compositions on these diagrams are best replicated by garnet + melt mixtures and that these trends are relatively sensitive to the addition of other minerals with Mg + Fe ratios to Ca, Si and Al that are different to those defined by the stoichiometry of garnet.

e. Note that the addition of relatively low-grade metasediments, regarded as restite in some LFB studies, is not modeled here due to the requirement that the magmas be hot and water under-saturated in order to form high level intrusive and eruptive complexes (as they do in some LFB examples).

It is also interesting to note that two average Lachlan Fold belt mafic S-type compositions plot within the trends defined by the CGS compositions. In the case of CSS, LOT has been proposed as the restite component leading to the Fe + Mg component diversity. In the case of the MBS granite composition, CPE has been proposed as possible restite. In both cases, with the constraints imposed by the leucocratic melt starting point, the addition of garnet appears to model the granite compositions better than the proposed restite. Different garnet compositions and different starting melt Ca contents are required by the strongly different bulk rock Ca contents. Ca in MBS could be reasonably

well modelled by the entrainment of garnet with some 3.5 wt% Ca and an initial melt composition towards the Ca-rich end of the compositional spectrum displayed by the experimental melts. Similarly, the CSS composition can be modelled as entrainment of an approximately 1.5 wt% Ca garnet component and a relatively Ca-poor initial melt composition. Grossular (Ca-component) content of high temperature metamorphic garnets varies, in response to both bulk rock Ca abundance and pressure, via the net transfer reaction (grossular + kyanite/sillimanite + quartz = anorthite), but 1 to 4 wt% CaO is within the range of normal granulite grade metapelitic and psammitic garnets.

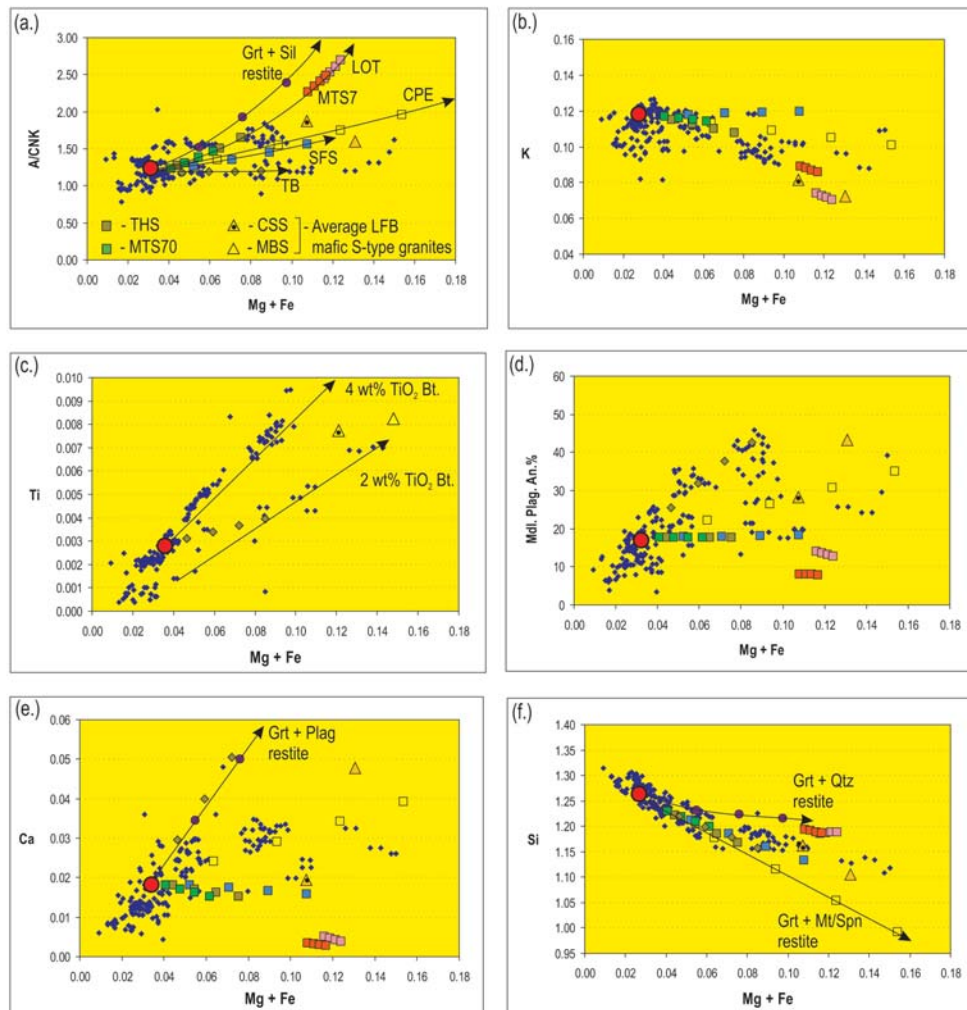


Figure 5: CGS S-type rocks compared to possible melt evolution trends as a function of the entrainment of different restite components (coloured squares), mineral mixtures (coloured dots) and a basaltic melt (grey diamonds). In modelling the restite addition, the melt component (using the CGS composition) was removed from the sediment at a fraction of between 30 and 50 wt%, dependent on the bulk rock H_2O , K_2O and Na_2O concentrations in the sediment. The resultant, melt depleted residua were added to the CGS melt composition in 5 wt% increments, resulting in the evolution trends away from this composition. Compositions MTS7 and MTS70 are natural meltapelites used in the study of Spicer *et al.* (2004). THS and SFS are natural metapelite compositions used in the study of Buick *et al.* (2004). CPE (Chappell, 1998) is an average composition from several metasedimentary enclaves associated with mafic S-type granites from the Bullenalong Suite, Lachlan Fold Belt (MBS), which is represented on the diagrams by the yellow triangle. LOT (Chappell, 1998) is an average Lachlan Ordovician turbidite composition that has been proposed as possible restite component to the S-type Cooma Supersuite. The average composition (Chappell, 1998) for this suite is represented by the yellow triangle with the black dot.

THE FATE OF GARNET

Rapid ascent of melts from the anatectic source via the fracture dyking models mentioned previously is effectively geologically instantaneous (Clemens, 2003). Thus, only adiabatic cooling has had a significant influence on the temperature of the magmas initially emplaced into the high crust. This leaves the melt hot but at much lower pressure than the source (Fig. 6). Garnet is a pressure sensitive, low molar volume phase that breaks down to cordierite or cordierite + orthopyroxene mixtures at low pressures. The pressure interval of garnet breakdown is sensitive to bulk rock Mg# (Hensen, 1971; Green, 1976), indicating that garnet in different magma compositions will decompose at different stages during magma ascent. Importantly, higher Mg# equates with earlier (high-pressure) garnet decomposition (Fig. 6). In the garnet entrainment model, higher Mg# equates with more Fe + Mg-rich compositions and thus a higher entrained garnet fraction. Consequently, the system appears to be naturally ordered towards more effective garnet destruction in the rocks that require the largest fractions of garnet addition (Fig. 6). Importantly, as these reactions would be occurring in a magmatic environment, the products of garnet breakdown are likely to crystallise with magmatic textures, creating the impression of high Fe + Mg solubility in the melt (Fig. 7).

Additionally, as the magma begins to cool aK_2O and aH_2O will begin to rise towards likely K-feldspar and H_2O saturation at some point in the magma evolution.

This favours reactions of the form: $Grt + Melt = Bt$, to consume persistent metastable entrained garnet as the magma cools. Similar reactions commonly consume excess cordierite and/or orthopyroxene. Thus, reaction to phases that are common constituents of S-type granites, i.e. biotite and cordierite, appears to be the likely fate of any entrained garnet (Fig. 7). Some Lachlan Fold Belt volcanic rocks are Fe + Mg component rich. In these rocks, such as the Violet Town Volcanic Complex, that may have undergone rapid ascent followed by eruption, garnet does occur (Clemens and Wall, 1981). These garnet crystals have been interpreted to be the products of magmatic crystallisation (Clemens and Wall, 1981), but the reported composition of these garnets does not rule out a high-grade anatectic origin. In the CGS, the volcanic rocks appear to have leucocratic compositions that require no garnet entrainment (Fig. 3). However, some plutonic rocks occasionally contain a minor garnet fraction (Fig. 7) that has survived replacement. These garnet crystals are interpreted to be derived from the anatectic source (Stevens *et al.*, 2004). The CGS rocks have unusually low Mg#s (Fig. 3), probably as a result of primary source characteristics. This allows for garnet stability to lower pressures than in rocks with more typical Mg#s, such as the two Australian average compositions depicted in Figure 6, for example. This has possibly allowed some CGS plutons to preserve a relatively unique record of the origin of cordierite and Fe + Mg enrichment in these rocks.

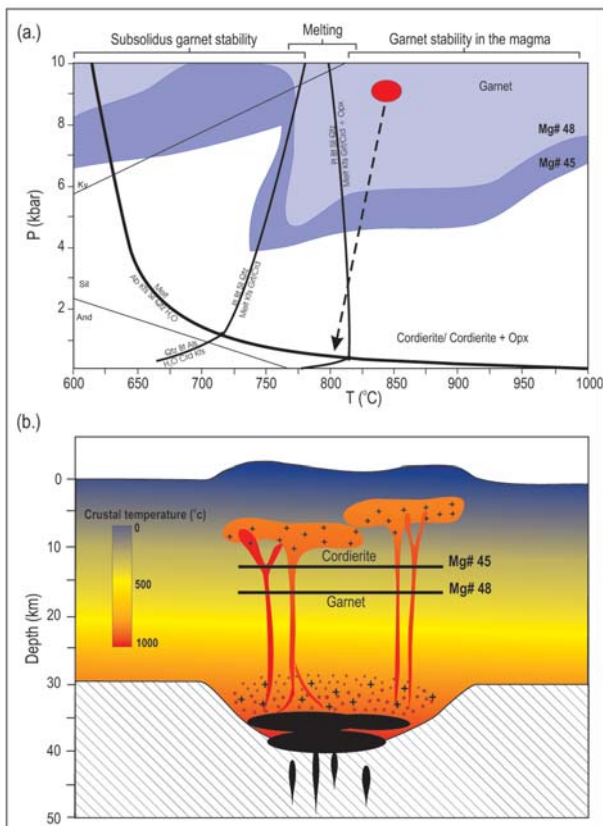


Figure 6: A cartoon representing the model for the petrogenesis of S-type granite proposed in this study. (a.) Selected melting reactions from Figure 2 superimposed on the limits of garnet stability in the two Australian average S-type mafic granite compositions discussed in this study (CSS = Mg# = 0.45; MBS, Mg# = 0.48). The pseudosections constraining garnet stability were constructed with the computer program PERPLE_X (Connolly, 1990; Connolly and Petrini, 2002) following Connolly and Petrini (2002) and using the thermodynamic dataset of Holland and Powell (1998) and the mixing models of Powell and Holland (1999). The water content of the rock was set at 2.5 wt% as this is very close to that which would result from biotite fluid-absent melting across much of the pressure range of the diagram. The magmas arose via the biotite incongruent melting reaction represented on the diagram, and consisted of melt and garnet as the principle entrained component. Garnet was stable in the anatectic domain, and the garnet volume in the source rock would have grown significantly during the melting reaction. (b.) Melting has occurred in thickened crust following delamination of the lithospheric mantle, producing basaltic melts that have under- and intraplated the thickened crust. The melting reactions have progressed rapidly due to the high heat flux and the magmas have rapidly intruded to high levels in the crust via dyke systems. The melt has arrived at the low-pressure intrusive sites at a temperature only slightly lower than the temperature of melting. Garnet in both compositions would have been markedly out of equilibrium under these conditions and would have been consumed by a variety of cordierite and biotite producing reactions. Note that temperature in the mantle is not indicated.

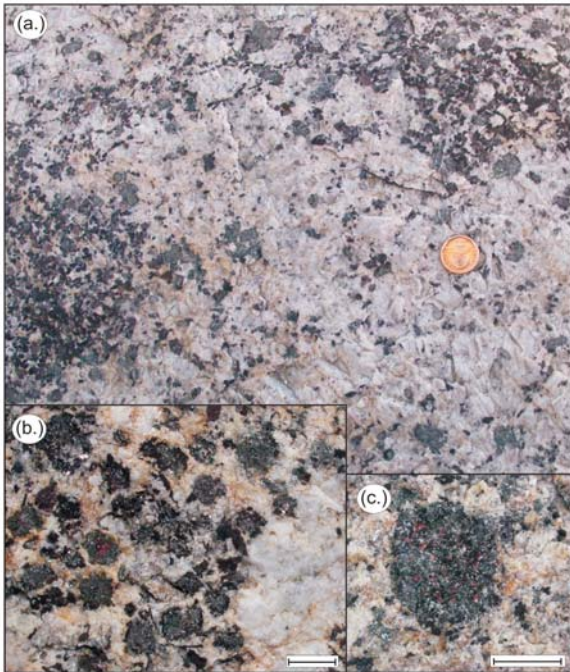


Figure 7: Cordierite mineral textures and associations in the Peninsular pluton. The more ferromagnesian-rich portions of the Peninsular pluton are typical of the mafic S-type granite compositions discussed in this study. In such rocks the Fe + Mg component is accommodated within cordierite and biotite (blue-green and black crystals respectively in (a.)) and, as depicted here, the euhedral textures that characterise cordierite commonly support interpretations of Fe + Mg-rich melts. In these coarsely crystalline rocks detailed examination of the mineral textural relationships is possible in clean outcrop sections, and this reveals evidence for cordierite formation from garnet and biotite formation from cordierite and garnet. Figure 7b. illustrates a wine-red garnet core to a cordierite crystal as well as biotite pseudomorphs of cordierite and biotite rims around cordierite, indicating the progression of reactions 1. $\text{Grt} + \text{Melt components} = \text{Crd}$; and, 2. $\text{Crd} + \text{Melt components} = \text{Bt}$. Figure 7c. depicts evidence for partial pseudomorphic replacement of a euhedral garnet crystal. The small wine-red flecks within the blue-green cordierite are remnants of the garnet crystal. The scale bar is 10mm in length; the coin used for scale in Figure 7a. is a South African 10c piece.

DISCUSSION AND CONCLUSIONS

The melt compositions developed from metapsamites and metapelites will always be leucocratic, even at the highest temperatures possible for crustal anatexis. Melt compositions vary significantly in terms A/CNK, as well as Na_2O , K_2O and CaO concentration. This is interpreted to reflect controls by source chemistry and mineralogy. Given the significant degree of layered chemical variation inherent to most fine-grained clastic sedimentary rocks, it seems reasonable to assume that the sources of most S-type granites would contain significant geochemical diversity. The data reviewed in this study suggest that this may account for most of the compositional variability observed in relatively leucocratic S-type granite compositions (Fig. 8). In contrast, mafic S-type granite compositions cannot represent melts and must represent melt crystal mixtures. Given that the melt compositions are always leucocratic and that 70% of the granite compositions in the suites examined in this study are more mafic than typical melt compositions produced at 900°C , it seems unlikely that the mafic compositions are the products of fractional crystallisation. This is because the required, very large volume of extremely leucocratic balancing compositions is not observed. The small population of CGS compositions that are more leucocratic than typical melts (Fig. 3, 4 and 5), are generally plutonic compositions from the upper portions of plutons, where nodules containing tourmaline + quartz intergrowths are common. These compositions are interpreted to represent Si-

enrichment during late stage crystallisation and fluid saturation. It may be possible that this “lost” population of very leucocratic compositions forms an, as yet, unidentified eruptive tuffaceous component that has been recycled into sedimentary depositories. In this case, the garnet addition that appears to have shaped S-type granite compositions could have been produced by a fractional crystallisation process, but consideration of the volumes involved makes this appear very unlikely^f.

The large-scale major element geochemical trends defined by S-type granites appear to be the product of melt and garnet mixtures, with typical leucocratic compositions representing pure melt and the most mafic compositions representing melt + approximately 15 wt% garnet (Fig. 8). Voluminous granite magmas generally arise in the deep crust (> 25 km), often as a result of mantle heat addition to the base of the crust. At these pressures, garnet is the dominant ferromagnesian phase produced by biotite incongruent melting. This peritectic generation of garnet is likely to be preferentially entrained into the melt because it is abundant at the sites of melting, and perhaps because it may be texturally distinct from the earlier generations of regional metamorphic minerals that constitute the matrix of the rock. Several important major element ratios appear to be sensitive to additional entrainment of quartz, plagioclase, biotite, sillimanite and cordierite. The fact that these trends are not commonly observed, yet these minerals must commonly make up part of the unmelted residuum from which the melts segregate, suggests that

f. The limit of SiO_2 concentration in a granite magma is not significantly above 78 wt%. This dictates that the proportion of leucocratic material formed from the melt (~ 75 wt% SiO_2) when fractionating garnet to form an approximately 68 wt% SiO_2 cumulate, is considerable.

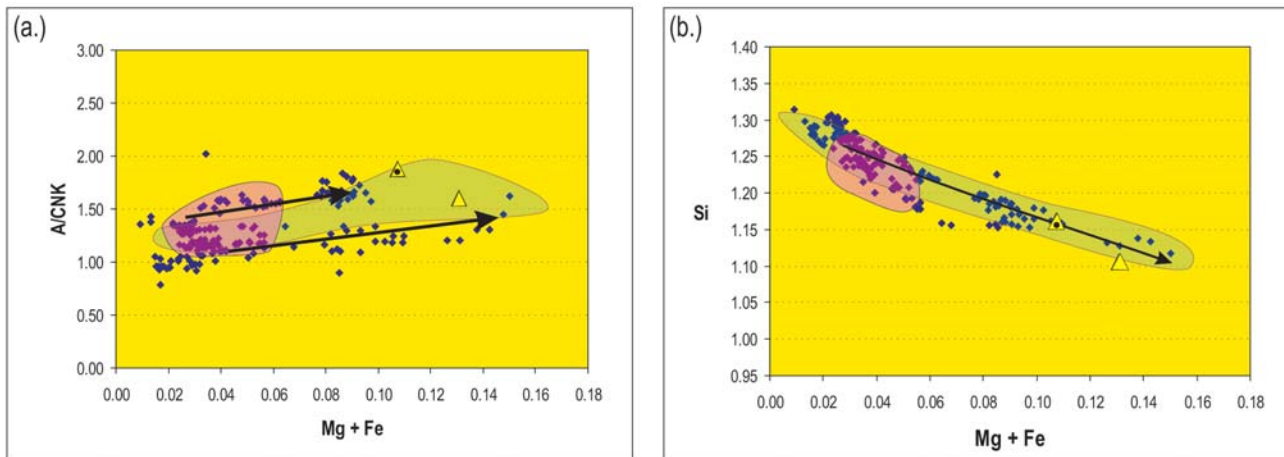


Figure 8: A summary diagram comparing the composition of the CGS S-types with several hundred Australian S-type granite compositions from the Lachlan Fold Belt (blue shaded domain). Melt compositional variation (pink shaded domain) accounts for much of the variation in the leucocratic rock compositions. Evolution away from these initial compositions occurs along vectors consistent with garnet entrainment. The similarity between the trends defined by these two granite suites, that can be connected only by means of process of formation with the magma evolutionary trends predicted by variable garnet entrainment, suggests that this process may be generally applicable.

the entire solid residuum is not commonly entrained into the melt. Modelling of the addition of residuum from a variety of metasedimentary rock compositions to the melt does not produce a more accurate fit with the trends defined by the natural granite population than does garnet addition. Similar arguments appear to rule out common mafic melt compositions as the additive driving the magma compositions to more ferromagnesian values.

Ti content of the granites also varies as a function of Mg + Fe (Fig. 5c). The common interpretation of this association would be co-fractionation of a ferromagnesian mineral (garnet would be appropriate in the CGS case) and a Ti-rich mineral, ilmenite in the case of peraluminous granites. Interestingly, each of the two well defined trends inherent to the CGS data (Fig. 5c) would require these segregated phases to always crystallise and concentrate in the same proportions. As the proportions defined by these trends coincide with the upper and lower limits in stoichiometric values of Ti: Fe + Mg found in high-grade metamorphic biotite (Fig. 5c), the key reactant involved in producing the granites, it seems much more logical to deduce that the Ti to Fe + Mg ratios in the granites are inherited from the stoichiometry of the reaction by which the magma arose,^g rather than some random fractionation process following their emplacement. This interpretation implies that

when the entrainment of solid products of the biotite breakdown reaction occurs, all the products are entrained into the melt, and always in the specific elemental ratios in which they occurred in the biotite.

In conclusion, granites do image the chemistry of their source regions in a relatively simple way, but via variable degrees of selective entrainment of the products of the incongruent melting reactions by which they arose, not the incorporation, in variable proportions, of the entire solid fraction of the source. Thus, the principal control on primary granite geochemistry is the stoichiometry of the melting reaction, with primary granite magma compositionally variability being controlled by the fairly narrow range within which this stoichiometry can vary as a function of source mineralogy and the compositional elasticity of the complex biotite solid-solution. This work suggests that this process must be limited by parameters that impose approximately 15 wt% solids as the maximum for the entrained component. Interestingly, this does not correspond with the entire solid fraction of typical biotite fluid-absent melting reactions, which produce upwards of 30 wt% solids. Thus, this study ends with a question: If the model for granite petrogenesis proposed here is correct, by what mechanisms do the physical properties of the melt, source and the melting episode control entrainment of the solid products of this reaction?

g. Note that the melting reactions presented earlier are simplified versions, in which the minor chemical constituents of biotite are not represented.

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