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S-type granitic magmas—petrogenetic issues, models and evidence

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Abstract

Despite a perception that it represents a perverse divergence, it is perfectly possible to believe in the existence of S- and I-type granites (and the implications for the nature of their protoliths), and to disbelieve in the applicability of the restite-unmixing model for chemical variation in granitic magmas. White and Chappell erected the S–I classification with impeccable validity. The isotopic evidence demands contrasting source reservoirs for S- and I-type granitic magmas. However, the major advance was not the classification, but the recognition that highly contrasting parental materials must be involved in the genesis of granitic magmas.

The restite-unmixing model is commonly seen as a companion to the S–I classification, but it is really a separate issue. This model implies that the compositions of granites 'image' those of their source rocks in a simple way. However, there are other equally valid models that can explain the data, and none of them represents a unique solution. The most cogent explanation for the high-grade metasedimentary enclaves in most S-type granites is that they represent mid-crustal xenoliths; restitic enclaves are either rare or absent. Inherited zircons in S-type rocks are certainly restitic. However, the occurrence of a substantial restitic zircon population does not imply an equally substantial restitic component in the rest of the rock. Zircon and zirconium behaviours are controlled by disequilibrium and kinetics, and Zr contents of granitic rocks can rarely be used to infer magma temperatures.

Since the dominant ages among inherited zircons in Lachlan Fold Belt (LFB) S-type granites are Ordovician and Proterozoic, it seems likely that crust of this age, but geochemically different from the exposed rocks, not only underlies much of the LFB but also forms a component in the granite magma sources. The evidence is overwhelming that the dark, microgranular enclaves that occur in both S- and I-type granites are igneous in origin. They represent globules of quenched, more mafic magma mingled and modified by exchange with the host granitic magma. However, magma mixing does not appear to be a significant process affecting the chemical evolution of the host magmas. Likewise, the multicomponent mixing models erected for some granitic rock suites are mathematically nonunique and, in some cases, violate constraints from isotopic studies. S- and I-type magmas commonly retain their distinct identities. This suggests limited source mixing, limited magma mixing and limited wall-rock assimilation. Though intermediate types certainly exist, they are probably relatively minor in volume.

Crystal fractionation probably plays the major role in the differentiation of very many granitic magmas, including most S-types, especially those emplaced at high crustal levels or in the volcanic environment. Minor mechanisms include magma mixing, wall-rock assimilation and restite unmixing. Isotopic variations within plutons and in granite suites could be caused by

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source heterogeneities, magma mixing, assimilation and even by isotopic disequilibrium. However, source heterogeneity, coupled with the inefficiency of magma mixing is probably the major cause of observed heterogeneity.

Normal geothermal gradients are seldom sufficient to provide the necessary heat for partial melting of the crust, and crustal thickening likewise fails to provide sufficient heat. Generally, the mantle must be the major heat source. This might be provided through mantle upwelling and crustal thinning, and possibly through the intra- and underplating of mafic magmas. Upper crustal extension seems to have been common in regions undergoing granitic magmatism. Migmatites probably provide poor analogues of granite source regions because they are mostly formed by fluid-present reactions. Granitic magmas are mostly formed by fluid-absent processes. Where we do see rare evidence for arrested fluid-absent partial melting, the melt fraction is invariably concentrated into small shear zones, veinlets and small dykes. Thus, it seems likely that dyking is important in transporting granitic magma on a variety of scales and at many crustal levels. However, one major missing link in the chain is the mechanism by which melt fractions, in small-scale segregations occurring over a wide area, can be gathered and focused to efficiently feed much wider-spaced major magma conduits. Answers may lie in the geometry of the melting zones and in the tendency of younger propagating fractures to curve toward and merge with older ones. Self-organization almost certainly plays a role.

Keywords: Granite; S-type; Petrogenesis; Lachlan Fold Belt

1. Introduction and philosophy

What follows is a personal view on the origins of S-type granitic magmas, some models for their generation/evolution and their meaning for the evolution of the continental crust, and the Lachlan Fold Belt (LFB) in particular. The focus on the LFB is appropriate, as this is the 'type locality' for S- and I-type granites. The debates centred on the rocks of this region closely mirror those current in most other granite-rich regions of the continental crust. The issue of the origins and evolutionary mechanisms of granitic magmas is a vast subject. Thus, it seems prudent to restrict my analysis to those granitic rocks that we designate S-type, in the sense of Chappell and White (1974, 2001), and that we infer to have been derived largely through partial melting of metasedimentary crust (Table 1). Throughout, the terms 'granitic rock' and 'granite' are both used sensu lato.

First, I would like to clarify the position of one who is said to hold divergent views. The supposed divergence here is my acceptance (on one hand) of the evidence for the existence of S- and I-type granites (and the implications for the nature of their protoliths),

Table 1
Original table of S- and I-type granite characteristics, as published by Chappell and White (1974)

I-types	S-types
Relatively high sodium, Na_2O normally >3.2% in felsic varieties, decreasing to >2.2% in more mafic types	Relatively low sodium, Na_2O normally < 3.2% in rocks with approximately 5% K_2O, decreasing to < 2.2% in rocks with approximately 2% K_2O
Mol. $Al_2O_3/(Na_2O+K_2O+CaO)<1.1$	Mol. $Al_2O_3/(Na_2O+K_2O+CaO)>1.1$
CIPW normative diopside or < 1% normative corundum	>1% CIPW normative corundum
Broad spectrum of compositions from felsic to mafic	Relatively restricted in composition to high SiO_2 types
Regular inter-element variations within plutons; linear or nonlinear variation diagrams	Variation diagrams more irregular

This list remains essentially valid, although nearly 30 years of progress in understanding and characterizing these rocks has considerably extended and refined it.

and (on the other hand) my doubt in the applicability of the restite-unmixing model for chemical variation in granitic magmas.

The view that this position is somehow contradictory seems to arise from a peculiar confusion between objective reality (the existence of mineralogical/chemical varieties of granites) and a human construct (a cherished but subjective model for the origin of observed chemical variations). The problem seems to be one of 'academic affection', a term coined by Thomas C. Chamberlain (1843–1928), in his work on the method of multiple working hypotheses (J. Geol., 1897, 5: 837–848). What he described is the situation in which a model has assumed the status of reality in the minds of its adherents; the whole system under discussion is viewed in the context of the model, and there is great resistance to any attempt to challenge it. Investigations predicated on this type of thinking can only lead to self-reinforcement of the initial ideas. Science, on the other hand, requires us to attempt to break out of such modes of thinking, by attempting to falsify models. In my view, the restite model has been well and truly falsified, but this has little bearing on the reality of S-type granites and what they may mean for the composition and geological/tectonic development of the crust in which they occur.

Borrowing from statements made in the introduction to the Allan White Symposium (LaTrobe University, Australia, January 11–12, 2001), published on the web (http://www.geology.latrobe.edu.au/ESWeb_Site/whitesymp/about_AJRW.htm), I will critically examine some of the major tenets of the restite model for S-type granites and see exactly how unconnected are the concept (and meaning) of S-type granite and the model of restite unmixing. I will also examine a number of other issues related to the geological and tectonic evolution of SE Australia, and more general questions surrounding granite petrogenesis.

2. The existence of S-type granites

Mapping and careful field observations in the Berridale region (White and Chappell, 1977), combined with petrographic and compositional data, led to the recognition of S-type granites. Pidgeon and Compston (1965) showed that the Sr isotopic compositions of the Cooma granite and its surrounding regional metamorphic rocks are very similar, consistent with derivation of that granite from a sedimentary source. Doubts about a sedimentary source for all granites followed from the study of Hurley et al. (1965), who showed that granites of the Sierra Nevada batholith are isotopically primitive. Chappell (1966) inferred that the source of the hornblende-bearing granites could not have been sedimentary, and proposed that the magmas resulted from partial melting of older igneous rocks, though there are other possible models.

When White and Chappell erected the S–I classification, they did so with impeccable validity. The isotopic evidence demands contrasting source reservoirs for S- and I-type granitic magmas. By accident of geology and tectonics, SE Australia is one of the places in the world where it is particularly easy to see that such differences exist. For some reason/s, granites of the LFB preserve these differences while, in some other regions, granite typology can be somewhat less distinct. A lack of contrast among granites might be due to the occurrence of mixed-character source regions, multiple sources with magma mingling, etc. The applicability of the S–I classification may be weakened by the existence of transitional types in some regions. However, the major leap forward was not the classification itself, but the recognition that highly contrasting parental materials can be involved in the genesis of granitic magmas.

Chappell's (1966) study also made the initial suggestion that the compositional variations within suites of granitic rocks could result from differing degrees of separation of partial melt from its crystalline residue. This idea developed into the restite-unmixing model, with the implication that the compositions of granites may 'image' those of their source rocks in a simple way.

The existence of S- and I-type granites shows convincingly that granites *do* image their sources. However, there is no prerequisite that such imaging be simple in character. Restite unmixing is one model, but it is not a unique solution to the problem of how the chemical variations might have arisen. As shown by Wall et al. (1987) and Clemens (1989), there are other equally mathematically valid models that can be applied, and none of them represents a unique solution. They are all just models, capable of being tested and potentially falsified.

3. The restite model

What about the restite model for S-type granites? The more mafic S-type granites commonly contain metasedimentary enclaves, including sillimanite-bearing gneisses or schists (Fig. 1). Sillimanite is usually absent from the exposed country rocks, so this implies a generally deeper, higher temperature origin for both the magmas and their enclaves. Using this evidence, such enclaves have been interpreted as fragments of restite (e.g., White et al., 1999).

Why are these enclaves considered restitic, as opposed to xenolithic? In most cases, such enclaves do not have the melt-depleted compositions expected of restites. Biotite remains a stable phase in these enclaves, its crystals defining prograde metamorphic fabrics (Figs. 2 and 3). Since biotite would be breaking down during most types of partial melting reactions that could lead to S-type magma formation (e.g., Clemens and Wall, 1981; Clemens and Vielzeuf, 1987; Clemens and Watkins, 2001), this strongly suggests that such metasedimentary enclaves are actually mid-crustal xenoliths rather than restites. Furthermore, petrographic, geochemical and experimental studies have shown that the S-type magmas cannot have been derived from pelite-dominated source rocks (e.g., Clemens and Wall, 1981, 1984; Miller, 1985). The persistence of fertile, quartz-saturated metapelitic restites in metasediment-derived magmas would be a rather curious phenomenon, since metapelites have been experimentally shown to be generally rather fertile rocks that begin to partially melt at about the same T as metagreywackes (e.g., Stevens et al., 1997; Clemens, 2002). Thus, any metapelites in a granite source region should contribute to the melt volume, and any metapelitic restites should have thoroughly refractory mineralogy (mica-poor, quartz- and/or feldspar-poor, and relatively rich in anhydrous mafic silicates and sillimanite or kyanite).

In one documented case (the Deddick granodiorite; Maas et al., 1997), the metasedimentary enclaves *are* garnet-bearing and migmatitic, with restite-like mineral assemblages. However, Maas et al. found these enclaves to be out of Sr and Nd isotopic equilibrium with the host granite, again suggesting a xenolithic origin. Maas et al. offered the possible alternative explanation that such enclaves might represent a minor lithological heterogeneity in the protolith. If this were the case, why does the Deddick granodiorite contain no recorded restitic enclaves derived from the dominant source rock? Maas et al. (2001) showed that these same metasedimentary enclaves are most probably exhumed fragments of the deeper equivalents of the locally exposed, low-grade Ordovician metaturbidites. They also showed that the metamorphism in the enclaves was coeval with the granitic magmatism. This suggests that the heat source for amphibolite-facies metamorphism, at this level, may also have been responsible for the development of granulite-facies conditions at greater depths, where the granitic magmas originated. Thus, the most cogent explanation for all the observations is that the high-grade metasedimentary enclaves in most S-type granites are mid-crustal xenoliths, and that restitic enclaves are either rare or absent.

If we assume that S-type magmas are not complex mixtures of melts formed from a number of different source materials (including basaltic magma), the geochemical and isotopic data suggest sources dominated by feldspathic, aluminous metagreywackes. Restites produced from such protoliths would be dominated by mineral assemblages involving Qtz, Pl, Grt and Opx, possibly with minor Bt. Metamorphic-textured enclaves with these compositions are rare to absent in S-type granites, so this suggests that crystalline restites, of any kind, cannot have been major volumetric components of most S-type magmas. In any case, Clemens et al. (1997) showed that granitic magmas have considerable potential to dissolve entrained restitic crystals during and after magma ascent (Fig. 4). This is a consequence of the constitutional superheating that H_2O-undersaturated granitic magmas attain as they ascend approximately adiabatically (without much cooling). Additionally, petrographic evidence shows that even quite mafic (granodioritic) S-type magmas have been emplaced with initial crystallinities of less than 5 vol.% (Clemens and Wall, 1984). This work demonstrated that shallow, hypabyssal equivalents of rhyodacitic S-type volcanic rocks had only a few percent of

Fig. 1. Typical, rounded, high-grade, gneissose, metapelitic enclave in an S-type, porphyritic monzogranite from Mt Wombat in the Strathbogie batholith, Victoria, Australia. The coin is an Australian $1 piece.

magmatic phenocrysts in a very fine-grained groundmass that was probably formerly glassy. Thus, it seems certain that restite unmixing can generally play only a subordinate role to other differentiation processes.

4. Inherited zircons and their significance

In discussing accessory mineral saturation in granitic magmas, Hoskin et al. (2000, p. 1365) correctly pointed out that the geochemistry of trace elements

Fig. 2. Photomicrograph (plane polarized light) of the texture of the enclave in Fig. 1. Note the fibrolitic sillimanite in schistosity-parallel pods, surrounded by unaltered, anhedral cordierite crystals. Biotite platelets and generally flattened grain shapes define the foliation. Quartzofeldspathic domains (relatively poor in biotite, e.g., lower left of the figure) alternate with domains rich in cordierite, sillimanite and biotite, to define a layering. Textures are metamorphic (granoblastic to granuloblastic) in all layers. The field of view is 5 mm wide.

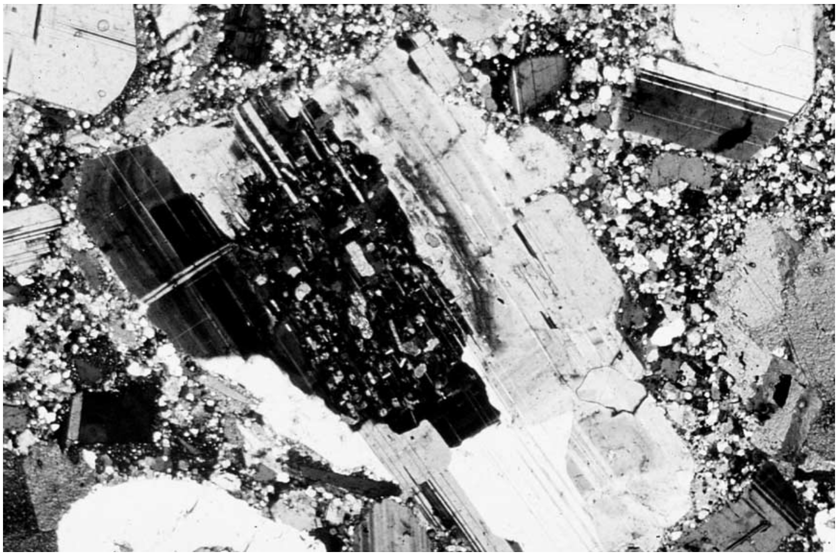

Fig. 3. Photomicrograph (crossed polarized light) of a plagioclase phenocryst in a rhyodacitic member of the Late Devonian, S-type, Violet Town Volcanics, Victoria, Australia. The core of the crystal is clearly not of igneous origin, although the oscillatory-zoned igneous rim is obvious. Note that the core contains small, well-orientated biotite and altered cordierite inclusions. Clemens and Wall (1984) showed that the magma from which these rocks crystallized was formed at temperatures exceeding the stability fields of biotite and cordierite. Thus, this core cannot be restitic. It more probably represents heterogeneous nucleation of magmatic plagioclase on a corroded seed of xenolithic origin. Of around 1000 crystals examined in these rocks, this is the only one with such a structure. The field of view is 5 mm wide.

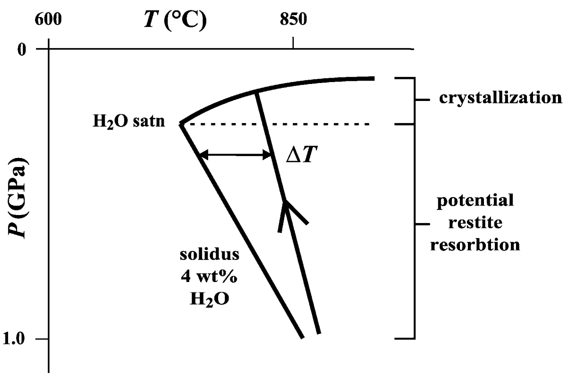

Fig. 4. Schematic pressure–temperature diagram showing the shape of the solidus curve for an H_2O-undersaturated granitic magma, with about 4 wt% H_2O in the melt. The line with the large arrow depicts an approximately adiabatic ascent path. After some initial cooling, the magma begins its ascent. Although it is continually cooling, the difference between its temperature and that of the solidus (ΔT) is steadily widening. Thus, this part of the ascent path will be characterized by potential resorbtion of minerals (magmatic, restitic or xenocrystal) that have appropriately shaped saturation curves in this magma. Clemens et al. (1997) used existing experimental data to suggest that S-type magmas, such as this, could dissolve substantial quantities of restitic garnet cordierite and quartz.

"may be controlled by accessory mineral saturation and fractionation". However, as will be seen below, disequilibrium processes can play major roles in controlling zirconium and zircon abundances in granitic magmas, and the interpretation of such features is far from straightforward.

An important feature of S-type granites (and most granites everywhere) is the occurrence of old, inherited zircon cores. Williams (1995) showed that inherited zircon cores increase in modal proportion as the rocks become more mafic. This is consistent with the derivation of these rocks from older sedimentary materials, and with the old zircons being a restitic component. Caution would be advisable here, with the assumption that the zircons can only be derived from sediments, though there is no doubt that the inherited zircon cores are a restitic component of the granites. Wall et al. (1987) showed that, if the inferred restite content of any granite in a suite is calculated from variations in any given chemical component, it commonly disagrees with estimates derived through similar calculations based on variations in other components. This must mean that the degree of control exerted by restites on magma compositions is rather variable, and depends on the particular magma component being considered. For example, a large proportion of the zirconium in a given granitic rock may have a restitic origin, but this does not necessarily mean that a similarly large proportion of the CaO, MgO or FeO, for example, is also hosted in restite. We cannot take the occurrence of a substantial restitic population among the zircons to imply an equally substantial restitic component in the rest of the rock. The reasons for the special behaviour of zircon (and some other accessory minerals) are explored below.

Using the Zr content of a granite, it is possible to calculate the temperature at which this assumed melt composition would be in equilibrium with zircon—the zircon saturation temperature. Such calculations are based on the experimental zircon/zirconium solubility measurements of Watson and Harrison (1983). Chappell et al. (2000) argue that the zircon saturation temperatures for the most mafic granites of the Bullenbalong Suite (Kosciusko batholith, SE Australia) are too low for such bulk rock compositions to have been melts, thus implying a significant restitic component in the magmas. This reasoning is erroneous because it assumes that we are dealing with equilibrium processes, with respect to trace-element concentrations in partial melts. Field and experimental evidence (e.g., Bea, 1996) shows that, during partial melting processes, equilibrium is most unlikely to be attained with respect to accessory minerals such as zircon and monazite, even though the major minerals probably do reach equilibrium with melt. Melting and melt segregation/extraction simply outpace the attainment of equilibrium for refractory phases like zircon (e.g., Harris et al., 2000).

Zircon dissolution into a silicate melt seems to be governed by kinetics rather than equilibrium phase relations. Multiple inherited cores commonly persist in zircons from migmatitic (i.e., partially melted) granulite-facies rocks that formed at temperatures exceeding 900 °C, in some cases. This indicates that equilibrium experiments (e.g., Watson and Harrison, 1983) may have little bearing on actuality in petrogenesis. The Ostwald ripening mechanism of zircon growth, as postulated by Nemchin et al. (2001), would presumably also operate during disequilibrium partial melting and could explain the presence of magmatic-looking overgrowths in some restitic zircons. Thus, the disequilibrium zircons should not be used to infer low melting T for the origin of the magmas, or high restite contents. Indeed, a low-T interpretation is inconsistent with the results of the application of well-calibrated geothermometers in S-type rocks, which indicate $T > 800$ and most probably > 850 °C (e.g., Clemens, 1981; Clemens and Wall, 1984). Clemens and Watkins (2001) showed that the experimentally constrained relationships between T and melt H_2O content, of most granitic magmas, can only be reconciled if the melting reactions responsible for magma genesis were fluid-absent in character. This finding is also at odds with the relatively low magma temperatures (< 811 °C) inferred by Chappell et al. (2000), since a large body of experimental work has shown that volumetrically significant fluid-absent partial melting of common crustal protoliths can only take place at much higher temperatures (mainly 850 to 950 °C).

A potential riposte to the above disequilibrium argument is that these restitic zircons must spend a long time bathed in hot, corrosive, granitic melt during magma ascent, emplacement and crystallization. Surely this would result in their equilibrium dissolution if temperatures were > 800 °C? As shown by Clemens and Mawer (1992) and Petford et al. (1993), the rate of buoyant ascent of granitic magmas in dykes and pipes (the most viable transport mechanism) is far too rapid to have significance in this time equation. Any given batch of magma might spend as little as a few days or weeks during ascent. However, it is certain that granitic plutons take 10^3 to 10^5 years to solidify and cool. Surely this would be enough to erase zircon inheritance at high T? Indeed this might be true if it were not the case that restitic and magmatic zircons commonly act as heterogeneous nuclei for the precipitation of early magmatic crystals of mafic silicates such as pyroxenes, amphiboles and biotite. This is why so many zircons in granitic rocks are found included in biotite crystals, for example. Once armoured by their magmatic overgrowths, the zircons would no longer be vulnerable to attack by the melt. The inescapable conclusion is that restitic zircons can and do survive in granitic magmas, at quite high temperatures.

Why would restitic zircons be preferentially incorporated into granitic magmas if other restitic components are minor? There are two reasons for this. The first is that zircon is highly refractory during partial melting. The second is that very many zircons in metamorphic rocks are enclosed within crystals of mafic silicates (mainly biotite in metasediments). This is also true of the locations of zircons in magmatic rocks; they seem to form ideal substrates for heterogeneous nucleation of certain mafic minerals. During partial melting, the biotite in the protolith decomposes, liberating many zircons that, because of their small size, can be carried away as the melt rapidly segregates and ascends, leaving behind the coarser-grained restitic phases.

It is certainly true that production of most granites (and especially S-types) has involved the partial melting of crustal rocks. Thus, granites are dominantly the products of crustal recycling, rather than juvenile crustal additions. This is a fair statement regardless of the validity of the restite model. The isotopic evidence, worldwide, points to a substantial crustal component in most voluminous granites.

5. Protolith petrology, zircons and mixing models

Some S-type granites in the LFB have chemical and isotopic characteristics that are generally consistent with derivation from local Ordovician metasediments, though this precise origin is uncertain (Ellis and Obata, 1992). In any case, by far the greatest volume of granitic rocks in the region has Na and Ca contents too high for such a derivation (Wyborn and Chappell, 1979). The experimental work of Clemens and Wall (1981) also showed that sillimanite-bearing metapelites could not have been the dominant source materials. The magmas were not in equilibrium with sillimanite crystals at any investigated combination of *P*, *T*, and melt H_2O contents (100–500 MPa, 700–900 °C and ~ 1–13 wt% H_2O in the melt). The main protoliths must have been rather more feldspathic than most of the exposed Ordovician metasediments.

S-type rocks range in composition from quite mafic tonalites to leucogranites. In the restite unmixing model, the more mafic S-type granites are interpreted to be close to their source rocks in composition because they are supposed to have evolved by the separation of the felsic melt from the mafic restitic component. One difficulty here is that no objective evidence has ever been presented to show that the mafic minerals concentrated in such rocks are restitic instead of magmatic cumulates. This was pointed out and argued in detail by Wall et al. (1987) and Clemens (1989). In short, there is no need to invoke the restite model in order to make useful inferences about the compositions and ages of the protoliths of S-type (or indeed I-type) granitic rocks.

Strongly peraluminous granitic liquids can be generated by partial melting of amphibolitic source rocks (Patiño Douce and Beard, 1995). Thus, granites with at least one geochemical characteristic similar to S-types (strongly peraluminous chemistry) can be derived through partial melting of nonsedimentary metaluminous protoliths. Indeed, there are examples of cordierite-bearing "S-type" granites that have rather low $^{87}Sr/^{86}Sr$ initial ratios (e.g., 0.706; Flood and Shaw, 1977).

There is a further complication in interpreting the character of protoliths for granitic magmas—isotopic shifts that can occur during partial melting (e.g., Ayres and Harris, 1997; Knesel and Davidson, 1999). These isotopic shifts commonly appear to give the magmas more isotopically evolved signatures than their source rocks. This possibility mitates against the interpretation of protolith characteristics, solely from isotopic parameters of a particular granite. Peraluminous granitic rocks may not always have evolved metasedimentary protoliths. Conversely, relatively unevolved initial isotope ratios need not indicate direct mantle input into a magma system.

Multicomponent mixing models have been proposed for the LFB granites (e.g., Collins, 1996). The components usually identified are: the early Palæozoic metasedimentary rocks, the Cambrian greenstones and juvenile mantle-derived magmas. Such models are superficially attractive because all the components can be demonstrated to exist in the local geology, and because such models offer integrated, all-encompassing solutions to granite petrogenesis. However, the solutions that they offer are mathematically nonunique. The results cannot be taken to indicate reality—only possibilities. Indeed, Maas et al. (2001, p. 1445) remarked that, although the Cambrian mafic rocks of the region are commonly required as one of the end members in these mixing models, "it is curious that no enclaves have been found [in the granitic rocks] that can be linked to the Cambrian greenstones".

When the Pb isotopes of zircons are studied in detail, the present mixing models are actually revealed as deficient. Keay et al. (1999) found that the age spectra of LFB granite zircons do not adequately match those of the detrital zircons in the region's Palæozoic metasediments. Since the dominant ages among inherited zircons are Ordovician and Proterozoic, it seems likely that crust of this age, but geochemically different from the exposed rocks, not only underlies much of the LFB but also forms a component in the granite magma sources.

On the basis of zircon dating, the dominant protolith is inferred to be Cambrian or younger in age (assuming that the inherited zircons are indeed from the magma source and that they have not undergone Pb-loss). One difficulty with the paper of Keay et al. (1999) is that it does not explicitly state whether the early Palæozoic inherited cores of the zircons in the S-type granites are metamorphic or igneous in origin. If these cores are igneous then it is clear that the sources of the granites were Palæozoic in depositional age. If they are metamorphic, there is no constraint on the maximum depositional age of the protolith. It could well be Precambrian. Keay et al. uncovered a great degree of heterogeneity in the ages of the zircons in the granites and in the detrital zircons of the Ordovician host metasediments. This heterogeneity means that we cannot, with confidence, identify the granite sources.

Keay et al. (1999) ruled out the possibility of involvement of Precambrian crust in the granite protoliths. Does this mean that such crust is not present? The presence of Proterozoic cores in some S-type granite or sedimentary zircons does not prove the presence of a Proterozoic basement to the region. Such cores only mean that Proterozoic source rocks were probably a component of the sediment sources. However, the fact is that we do not know what underlies the exposed Palæozoic rocks of the LFB. It could be earliest Palæozoic or it could be Proterozoic rocks. It seems that the Silurian S-type granites in the east (two of which were studied by Keay et al.) were derived from rocks that do not form the basement of the Fold Belt and are lithologically dissimilar to any exposed materials. However, the Devonian to Carboniferous granites in the Central Victorian Magmatic Province (further west) have somewhat different chemistry and petrographic character. They could have different protoliths.

None of this is meant to deny a possible role for mixing processes in the genesis of granitic magmas. The point is that none of the evidence presented so far demands multisource mixing models. Applying Ockham's razor, we are bound to accept the simplest model that explains all of the evidence. Based on a combination of the geochemical, isotopic and experimental evidence, the main source of the southeastern Australian S-type magmas seems most likely to be a layer of feldspathic metagreywackes structurally underlying the quartz-rich, less fertile, exposed, Palæozoic metasediments.

The Gibson et al. (1981) model for the crustal structure of Victoria shows a seismic discontinuity at 17 km depth. This is interpreted as the base of the Palæozoic sequences. Whatever this discontinuity represents, below it lies 19 km of crust with an average P-wave velocity of 6.3 km/s, consistent with high-grade rocks of felsic to intermediate composition. It is interesting to note that geobarometry on S-type rocks from Victoria (e.g., Phillips et al., 1981; Clemens and Wall, 1981, 1984) indicates early magmatic crystallization starting at a pressure of around 0.4 to 0.5 GPa (equivalent to a depth of about 17 km). It seems possible that the terrane below the 17-km discontinuity contains the actual source region for the granitic magmas. Perhaps, the magmas stalled here for a while, cooled and crystallized a little, and then continued on their ascent to higher levels and final emplacement.

Further east, the crust of SE Australia is slightly thicker, with a Moho at about 43 km. Here, the seismic data of Finlayson et al. (1998) suggest a 22-km-thick upper crust with P-wave velocities increasing to 6.0 km/s at the base. A discontinuity separates these rocks from the 21-km-thick lower crust, which has P-wave velocities of 6.5 km/s at the top and 6.8–7.0 km/s at the Moho. The highest pressure, exposed Ordovician metasediments in the LFB are from original depths of 10 to 15 km. This leaves another 7 km of upper crust, the petrology of which we have no real knowledge. This might be feldspathic Ordovician rocks that could form the granite protoliths, but can we rule out parts of the deeper crust as the magma source?

Collins and Hobbs (2001) used the Finlayson et al. (1998) model for crustal structure, and some heat-flow modelling, to suggest that the lower crust could not contain suitable source materials for the region's granitic rocks. They state that their modelling renders the presence of K-rich granulites in the lower crust unlikely and that the most probable composition of this crust would be mafic. However, if the vast volumes of granitic magma in the region were extracted from the lower crust, one would hardly expect these rocks to have remained potassic (fertile); they should now be highly depleted in LILE, U and Th. Thus, the heat-flow model may mean very little for the nature of the pre-granite rock types in the lower crust. Indeed, the seismic velocities quoted above suggest that felsic granulites and charnockites might well be abundant there, while amphibolites and mafic granulites are probably scarce components (e.g., Rudnick and Jackson, 1995; Fountain and Salisbury, 1996). The implication is that the lower crust of the LFB may well contain rocks that once had suitable compositions to act as the protoliths of the granites, but are now restitic (LILE-depleted and mafitized) granulites. The single-source model for the generation of SE Australian S-type magmas is possibly threatened but has yet to be overthrown by more complex models involving mixing processes.

6. Microgranular enclaves

As is the case in I-type granites, the S-types commonly contain fine-grained, igneous-textured enclaves that are more mafic than their host rocks. These are usually interpreted as globules of a separate magma, mingled with the volumetrically dominant host magma. In higher-level and higher-temperature S-type rocks (e.g., the Strathbogie granite in central Victoria; Phillips et al., 1981), such enclaves tend to be more abundant than the metasedimentary xenoliths mentioned above (Fig. 5).

A number of explanations have been put forward for the origins of these microgranular enclaves (restites—Chen et al., 1989; quench cumulates—Phillips et al., 1981; Clemens and Wall, 1984; or contaminated, mantle-derived mafic magma globules—Elburg and Nicholls, 1995).

Waight et al. (2001) studied the Sr and Nd isotope systematics of microgranular enclaves in the S-type Cowra granite. They showed that these enclaves represent globules of mingled non-mafic magma that had undergone hybridization (with the host granite

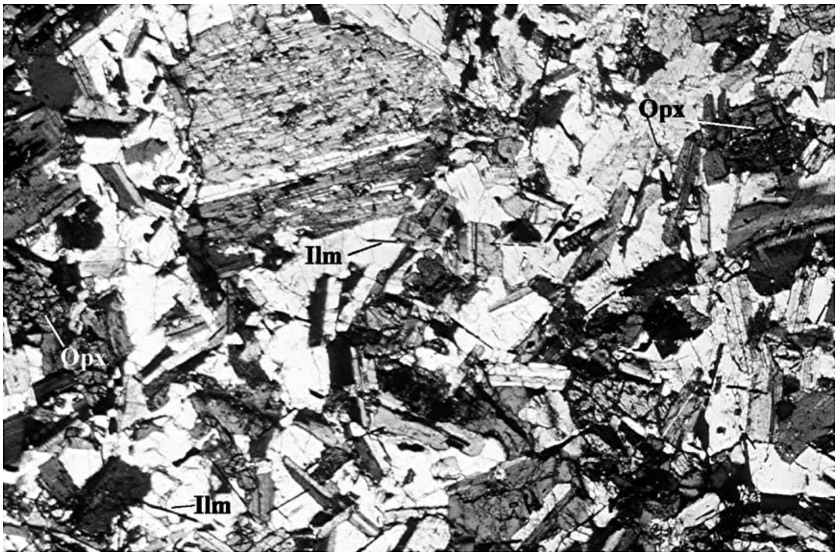

Fig. 5. Photomicrograph (crossed polarized light) of an igneous-textured, Opx-bearing microtonalite enclave from a rhyodacitic member the Violet Town Volcanics (S-type ignimbrites), Victoria, Australia. Note the lath-like plagioclase crystals, subhedral orthopyroxene (Opx) and platy ilmenite (Ilm) crystals poikilitically enclosed by quartz and trace alkali feldspar. There are needle-like apatite crystals in this rock also, plus rare euhedral biotite crystals, anhedral (xenocrystal?) cordierite and very rare garnet, pseudomorphed by Opx and sericite (after Crd). The larger plagioclase xenocryst (An_{74}) is more calcic than the smaller plagioclase laths (~ An_{60}). The large plagioclases, the cordierites and garnets suggest that both mafic magma (or rock) and metasedimentary rock have contributed material to the enclave magma. The field of view is 5 mm wide.

magma) through diffusive and mechanical exchange. Such an origin seems to hold true for enclaves in at least some I-type rocks as well (e.g., Waight et al., 2000a).

Waight et al. (2000b) used microdrilling of centimetre-sized feldspar phenocrysts in microgranular enclaves in the S-type Wilsons Promontory granite, from the southernmost tip of the Australian mainland, to study their isotopic characteristics. This work revealed complex internal zoning in Sr and Nd isotopic ratios, indicating isotopic heterogeneity on a single crystal and intergranular scale. Waight et al. (2000b) interpreted this structure as resulting from feldspar crystallization within a mixing (stirred) magma system, changing with time, due to the influx of mantle-like magmas. The host magma here has an initial $^{87}Sr/^{86}Sr$ of 0.70908 and ε_{Nd} of -3.59. Interestingly, although the enclaves have a slightly lower initial $^{87}Sr/^{86}Sr$ of 0.70884, they have a very much more crustal-looking Nd signature, with ε_{Nd} at -6.15. These values seem very crustal in character, though it can be argued that highly enriched mantle could be involved. It would be just as valid to interpret these results as mingling between batches of magma derived from a variety of crustal protoliths over a range of temperatures. This again illustrates the non-uniqueness of isotope-based petrogenetic models.

As is typical in many enclave-bearing granitic rocks, the Waight et al. studies show that it was the enclaves that were hybridised, and not their hosts. This is a simple consequence of the volumetric relations. The huge volume of host magma is buffered against significant overall change in composition, while the volumetrically minor enclave magma undergoes major shifts in its chemistry and isotopic ratios. Such enclaves almost certainly represent mingled magmas. However, these may play little role in determining the characteristics of their host rocks, at least at the level of magma emplacement. Without direct knowledge of the nature of the crustal protoliths of S-type magmas, we cannot comment sensibly on the role of magma mixing at near-source depths.

7. Other areas of debate

The following sections deal with further areas of on-going debate about the origin/s of granitic magmas, and particularly S-types. In the first section, I list a number of questions that are generally perceived to be problems. It is true that science only proceeds by questioning and testing of hypotheses. However, I believe that we currently have satisfactory, tested or testable explanations for a good number of these 'problems'. I will not explore these in detail, other than to state, and give references for, what I believe to be the best current explanations. The second group is more interesting, consisting of questions that I think we have neither consensus views on, nor satisfactory models for.

8. Questions satisfactorily answered

8.1. What was nature of the source rocks?

The combined evidence from geochemical and isotopic constraints, and experimental petrology quite clearly favours the development of most large-volume S-type magmas through partial melting of protoliths dominated by metasedimentary rocks. The most appropriate source materials would be metagreywackes, including labile volcaniclastic types and some metatonalites (biotite–plagioclase–quartz rocks). Metapelite-dominated terranes are much less common sources for S-type magmas, though they could potentially produce large volumes of magma (e.g., Clemens and Wall, 1981; Miller, 1985; Clemens and Vielzeuf, 1987). The apparent paucity of pelite-derived S-type granites in SE Australia is probably due to two factors. First, the Ordovician metapelites are generally very quartz-rich, and relatively infertile as magma sources during fluid-absent partial melting. Second, and more importantly, it seems that more fertile metasediments (quartz-poor and quartz-intermediate, feldspathic metagreywackes) dominate the deeper parts of the region's crust, as discussed above. It is this deeper, lithologically distinct terrane that seems likely to have been the main S-type granite protolith.

8.2. Are 'mafic' igneous enclaves magma globules, restites or xenoliths?

For S-type granites, the answer here seems to be yes, no, and yes—depending upon the individual case under discussion. The section above, on microgranular enclaves, summarises most of the data. Small volumes of enclaves that were evidently magma globules certainly exist in some S-type granites and volcanic rocks. These enclaves are not usually mafic, but granitic to tonalitic (e.g., Phillips et al., 1981; Clemens and Wall, 1984; Elburg and Nicholls, 1995). See Fig. 5 for an example of the microscopic texture of such a rock. Some appear to be reacted mafic magma globules; others are perhaps better explained as autoliths or chill cumulates. Chen et al. (1989, 1990) and White et al. (1999) have argued for a restitic origin for most enclave types. However, for the reasons given above, restitic enclaves appear to be rare, and should not show magmatic textures anyway. Fig. 6 shows a diatexitic granite that is packed with what is reasonably interpreted as restitic material. Such enclaves are texturally and morphologically dissimilar to the igneous-textured variety. Xenoliths, of various sorts and from various crustal depths, are certainly present in S-type granites (e.g., the enclave shown in Figs. 1 and 2). However, Vernon's (1984) paper shows conclusively the magmatic character of the vast majority of non-xenolithic enclaves. The textures of microgranular enclaves are dominated by euhedral plagioclase laths, biotite plates and hornblende prisms (in I-types), with varying amounts of interstitial or poikilitic quartz and K-feldspar crystals. In some cases, the plagioclase laths are aligned, in what appears to be a flow lineation. Such textures are most unlike those of any partially melted (migmatitic) rocks, and certainly not what one would expect in restitic enclaves with only a trace of partial melt (cf., White et al., 1999). These features, together with the occurrence of acicular apatite, and the fine to medium grainsize, provide overwhelming evidence of the magmatic origin of the microgranular enclaves.

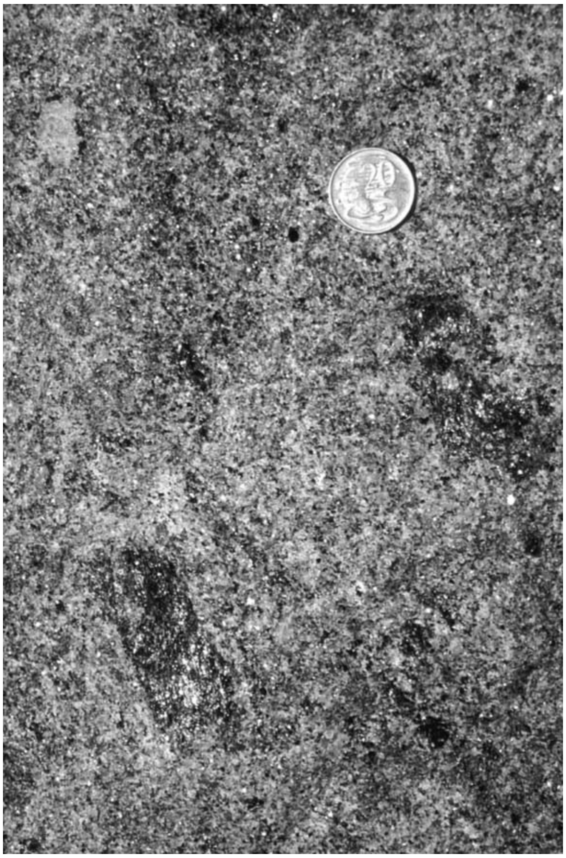

Fig. 6. Photograph of the surface of a broken slab of diatexitic S-type granite from the Falls Creek area, in the Omeo Metamorphic Complex of NE Victoria, Australia. The surface shows may shreds and lumps of highly foliated, mica-rich, restitic schlieren that have metapelitic mineralogy. The dominant mica is biotite, but muscovite (some, apparently magmatic) is also present. This magma was evidently formed, near to its source, by a high degree of relatively low-temperature, probably fluid-present partial melting. The coin is an Australian 20¢ piece.

8.3. What do enclaves tell us about source materials?

The answer to this is also dealt with above. Enclaves most commonly tell us about magma mingling (whatever the origin of the minor magma fraction), about the crust through which the magma has travelled, or about the local crust near emplacement level. For quite sound reasons (presented earlier), enclaves seem relatively silent on the subject of magma sources. Chen et al. (1989, 1990) and White et al. (1999) argue that the enclaves represent slightly melted, more refractory rocks from the source region. Even if we accept this idea, we are bound to conclude that such enclaves only tell us about the uncharacteristic rock types. Except for the migmatite-related, low-temperature, diatexitic granites, there is still no whisper from the enclaves regarding the dominant source material.

8.4. How were the magmas emplaced?

A good deal of research has shown that dyking is the only viable mechanism by which granitic magmas can be transported vertically through large thicknesses of crust, to allow high-level emplacement of magma, in a largely liquid state (Clemens and Mawer, 1992; Clemens, 1998; Petford et al., 1993; McNulty et al., 1996; Baker, 1998; de Saint-Blanquat et al., 2001). Even those urging caution about dyke ascent of granitic magmas in the deepest parts of the crust (e.g., Rubin, 1995) accept that dyking could control magma migration even here. What is still a matter of major uncertainty is what triggers the transition from dominantly vertical transport, to dominantly horizontal magma flow during emplacement in shallow intrusions.

A survey of the vast literature on emplacement of granitic magmas will yield examples of a large number of mechanisms, all of which (except diapirism) appear to have operated in particular cases (e.g., Hutton et al., 1990; Fowler, 1994; Scaillet et al., 1995; Cruden, 1998; Wilson and Grocott, 1999; Vigneresse and Clemens, 2000). Certain plutons seem to have been emplaced by several of these mechanisms operating either together or sequentially. Thus, there does not seem to be any general statement that can be made about granite emplacement. However, it appears that high-level granites are usually emplaced in association with major brittle or semi-brittle deformation of the underlying or overlying rocks (thrusting, roof lifting, floor depression and cauldron subsidence), sometimes with volcanic venting. S-type volcanism is almost always explosive, commonly giving rise to the emplacement of large volumes of ignimbrites. The only exceptions to this general rule of explosive eruption appear to be in unusually fluorine- and boron-rich magmas, that sometimes form small lava flows and domes. Even with such relatively fluid magmas, emplacement is commonly explosive (e.g., the Macusani ignimbrites; Pichavant et al., 1988).

8.5. The relationship between S- and I-type magmas; are there mixtures of the two types?

If it is accepted that I-type granites are mostly derived through partial melting of mafic to intermediate meta-igneous crustal rocks, this question reduces to one about the lithological characteristics of typical source terranes. When we look at rock successions, in a range of tectonic environments, do we see terranes:

- dominated by sediments with a few igneous rocks,
- dominated by andesitic to basaltic igneous successions with minor intercalated sediments, or
- terranes containing large amounts of andesitic to basaltic igneous and sedimentary material complexly interlayered?

From field observations and reading of the literature, I suggest that the first two situations are probably the most common. Thus, we would naturally expect to find an essentially binary subdivision of crustally derived granites, into those dominantly produced by partial melting of metasediments and those dominantly produced by partial melting of meta-igneous rocks (S- and I-types, respectively). It is the inferred rapid ascent rates of granitic magmas that would preserve these primary, fundamental, geochemical differences from large degrees of modification by wall-rock assimilation (Clemens and Mawer, 1992; Clemens, 1998).

In certain regions of the crust, dominantly igneous and dominantly sedimentary terranes may coexist, perhaps at different structural levels. If magmas derived from these separate areas are ponded together, deep in the crust, there is clear potential for mixing and mingling. Again, if rare source terranes *do* contain intimately interleaved sedimentary and igneous components, interactions during partial melting (e.g., Skjerlie and Patiño Douce, 1995) could certainly produce intermediate types. Despite these possibilities, it does seem that S- and I-type magmas commonly retain their distinct identities. This suggests limited source mixing, limited magma mixing and limited wall-rock assimilation (see also, Brown and Pressley, 1999). In other words, intermediate types certainly exist, but are probably relatively minor in volume. Geochemical studies of granites that use isotopic ratios to infer mixing origins of granitic magmas (in the absence of any mixing lines or evidence for the presence of true end members) are not to be trusted in the least.

8.6. What are the relative roles of fractional crystallisation and restite unmixing?

This question is most easily answered with reference to my conclusion (above) that, although most granitic rocks contain some restitic components, the volume of surviving restite is usually quite small (a few percent at most). If this is accepted, then most of the geochemical and mineralogical variation within comagmatic associations of granitic rocks must be due to processes other than restite unmixing. Such variations have been successfully modelled as crystal fractionation with crystal accumulation in the more mafic rocks, or as partial equilibrium crystallization followed by crystal unmixing. Models do not represent reality, but it seems safe to say that crystal fractionation probably plays a major role in the differentiation of very many granitic magmas, especially those emplaced at high crustal levels or in the volcanic environment. Minor mechanisms include magma mixing, wall-rock assimilation and restite unmixing.

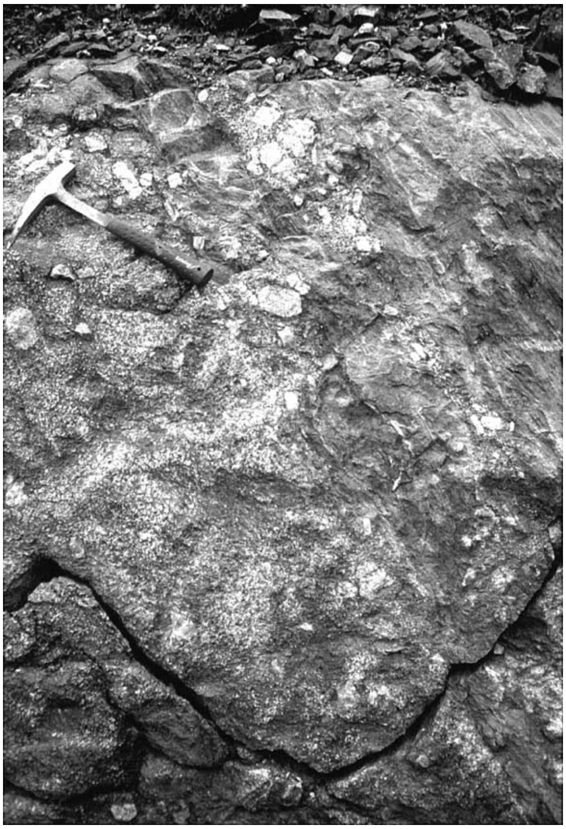

Fig. 7. Contact between the S-type cordierite–biotite Margeride monzogranite (French Massif Central) and its pelitic wall rocks. Note the dark colour of the granitic rocks (on the left), due to the high concentration of plagioclase, biotite and cordierite. Large, euhedral K-feldspar phenocrysts ('megacrysts') are also involved, and many seem to be concentrated into zones. This feature suggests that they may have collected there as a result of filtering effects, during the draining of narrow magma conduits.

There are many mechanisms by which crystals can be removed from granitic magmas. Flow and gravity clearly play important roles. In some cases, magma has evidently been filter pressed, usually by flowing past or through a constriction, leaving behind crystal log-jams. Many high-level S-type granites show mineralogical layering near pluton or unit margins. In some such occurrences, the fabrics appear to mimic sedimentary structures such as current bedding and scour-and-fill. The crystals most commonly involved are the early-crystallizing minerals (such as plagioclase, biotite, garnet and accessory phases) plus large, later-crystallizing K-feldspars. Xenoliths and other enclaves are commonly concentrated in such zones. Fig. 7 shows the contact between an S-type monzogranite and its schistose metapelitic wall rocks, the concentration of large and dense minerals in the granite is evident.

9. Questions largely unresolved

9.1. What were the ages of the sources?

This question may have almost as many answers as there are plutons. Model ages derived from Sm–Nd isotopic studies can reveal the possible ages of extraction of the protolith from the mantle, but this is not particularly helpful for S-type granites. Unless we know the Rb and Sr content of an S-type protolith, we cannot constrain its age using the Rb–Sr isotopic system either. The best hope seems to come from combined petrographic and U–Pb isotopic studies of restitic accessory minerals, to constrain the ages of thermal (melting and crystallization) events in the protolith history. All sorts of complications arise where mixed sources or magma mixing processes are postulated, potentially rendering the whole problem rather intractable.

9.2. What caused the isotopic variations within plutons or suites?

The obvious answer to this question is that such variation could be caused by source heterogeneities, magma mixing, assimilation and even by isotopic disequilibrium (e.g., Ayres and Harris, 1997). Sorting out this jumble of possible processes will be a major challenge. Since there are many plutons that contain both S- and I-type zones, I suspect that source heterogeneity, coupled with the inefficiency of magma mixing is a major cause of observed heterogeneity. However, it would be well to remember that the relevant lithological unit to study will be the pluton or magma batch (Wall et al., 1987). Any attempt to use groups of plutons or suites will predetermine the answer because the criteria used to identify 'simple' suites (White et al., 2001) presupposes a particular style of chemical variation among the rocks involved.

9.3. What was the heat source for partial melting?

One thing that we do know is that normal geothermal gradients are seldom sufficient to provide the necessary heat for partial melting of the crust, except in some unusual cases of highly radioactive crust (e.g., Sandiford et al., 1998; McLaren et al., 1999). Crustal doubling, by thrusting or homogeneous thickening, likewise fails to provide sufficient heat (e.g., England and Thompson, 1984). Generally, we must look to the mantle as a source for the extra heat required. This might be provided through mantle upwelling and crustal thinning, and possibly through the intra- and underplating of mafic magmas. Worldwide, there does seem to be a common temporal and spatial association between major granitic plutonism and crustal extension (post- or anorogenic). Extension and granitic plutonism are linked in some collisional tectonic settings such as Andean margins (e.g., Atherton, 1990), and certainly in eastern Australia (e.g., Allen et al., 1998). Thermal modelling has shown that certain styles of mafic intraplating could be highly efficient in transferring heat into the surrounding crust, to cause partial melting (e.g., periodic multiple sheet injection; Petford and Gallagher, 2001).

9.4. What was the tectonic regime of magma generation?

The second-last sentence in the previous paragraph reveals my predisposition on this question. However, the honest answer is that large-volume, calcalkaline, granitic plutonism is possible wherever there are sufficiently voluminous fertile crustal rocks that reach conditions where they will partially melt. This rules out a few tectonic settings (oceanic spreading centres, ocean islands, juvenile inter-oceanic arcs and possibly passive margins) but the rest all seem possible. It is the geology of a region that should tell us the particular setting of the magmatism, not the types of granites we find or the geochemistry of some basalts.

9.5. How did the magmas leave their source regions?

It seems certain that melt segregation cannot occur on scales greater than centimetres without accompanying deformation (Brown et al., 1995; Clemens and Droop, 1998). However, this is perhaps the least well-understood part of the process of magma generation. It can be argued that we do not commonly see granitic sources in the 'act' of partial melting and melt segregation. As a starting point, it should be borne in mind that granitic magmas are nearly all produced by high-temperature, fluid-absent partial melting reactions (Clemens and Watkins, 2001). What we *can* study here is migmatites, and it is debatable whether these really tell us much about the mechanisms of melt segregation that lead to the formation of highly mobile granitic magmas. The argument goes along the lines that, if the rocks were really going to produce granitic magmas they would have done so, and all we could expect to see are restitic (melt-depleted) remnants. We do see such rocks. Migmatites, on the other hand, seem mostly to result from fluid-present melting in the middle crust, rather than from higher-T, fluid-absent melting in the deeper crust. It is true that some relatively low-T granites do seem to be related to migmatites, through diatexite formation (e.g., Ellis and Obata, 1992; Finger and Clemens, 1995). However, these granites do not seem to have moved far from where the magmas were formed.

Where we do see rare evidence for arrested fluid-absent partial melting, the melt fraction is invariably concentrated into small shear zones, veinlets and small dykes. Some migmatites show such a pattern of melt distribution, but more commonly the leucosome (melt fraction) lies in layering-parallel segregations and in boudin necks (e.g., Brown et al., 1995). My own bias is that fractures (and shears) are critical in initial melt segregation, as they are in larger-scale, vertical magma transport (e.g., Clemens and Mawer, 1992; Watt et al., 2000). One major missing link in the chain is the mechanism by which melt fractions, in small-scale segregations, occurring over a wide area, can be gathered and focused to efficiently feed much wider-spaced major magma conduits (Petford et al., 2000). Answers may lie in the geometry of the melting zones and in the tendency of younger propagating fractures to curve toward and merge with older ones (Ito et al., 1997). Self-organization almost certainly plays a part in the formation and growth of such networks (e.g., Petford and Koenders, 1998; Miller, 2000). Whatever is going on here, it is certainly a fertile field for future research. Of course, the same can still be said for the entire granite problem.

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