

# Low- and high-temperature granites

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**ABSTRACT:** I-type granites can be assigned to low- and high-temperature groups. The distinction between those groups is formally based on the presence or absence of inherited zircon in relatively mafic rocks of a suite containing less than about 68% SiO<sub>2</sub>, and shown in many cases by distinctive patterns of compositional variation. Granites of the low-temperature group formed at relatively low magmatic temperatures by the partial melting dominantly of the haplogranite components *Qz*, *Ab* and *Or* in H<sub>2</sub>O-bearing crustal source rocks. More mafic granites of this type have that character because they contain restite minerals, often including inherited zircon, which were entrained in a more felsic melt. In common with other elements, Zr contents correlate linearly with SiO<sub>2</sub>, except sometimes in very felsic rocks, and Zr generally decreases as the rocks become more felsic. All S-type granites are apparently low-temperature in origin. After most or all of the restite has been removed from the magma, these granites may evolve further by fractional crystallisation. High-temperature granites formed from a magma that was completely or largely molten, in which zircon crystals were not initially present because the melt was not saturated in that mineral. High-temperature suites commonly evolved compositionally through fractional crystallisation and they may extend to much more mafic compositions through the production of cumulate rocks. However, it is probable that, in some cases, the compositional differences within high-temperature suites arose from varying degrees of partial melting of similar source rocks. Volcanic equivalents of both groups exist and show analogous differences. There are petrographic differences between the two groups and significant mineralisation is much more likely to be associated with the high-temperature granites. The different features of the two groups relate to distinctive source rock compositions. Low-temperature granites were derived from source rocks in which the haplogranite components were present throughout partial melting, whereas the source materials of the high-temperature granites were deficient in one of those components, which therefore, became depleted during the melting, causing the temperatures of melting to rise.



**KEY WORDS:** Cumulate, fractional crystallisation, mineralisation, restite, zircon cores, zircon saturation temperature, zirconium.

Granites outcrop over an area of 63 000 km<sup>2</sup> in the Lachlan Fold Belt (LFB) of southeastern Australia, and their distribution is shown on the map of Chappell *et al.* (1991). Those rocks cover about 20% of the area of exposed Palaeozoic rocks in the LFB. Related volcanic rocks are also an important component of the LFB and many of the statements that the present authors make in this paper also apply to those extrusive rocks, when the volcanic rocks are not specifically mentioned. These igneous rocks have been subdivided into I- and S-types (Chappell & White 1974, 1992, 2001) and the S-types comprise a little more than half of the total area of these rocks. Most of the other granites are I-type, with A-type granites (King *et al.* 2001) comprising only 0.6% of the total area of granite in this region.

It has been recognised for some time (e.g. Wyborn *et al.* 1987; Chappell *et al.* 1987) that there are two fundamentally distinct varieties of I-type granite in the LFB. These two groups differ, for example, in some petrographic features, in the patterns of chemical variation within comagmatic or cogenetic suites, in the relative proportions of felsic, intermediate and mafic rocks, and in the presence or absence of older inherited zircons. These differences reflect differences in the temperatures of formation of the granite magmas with consequent differences in the physical properties of the magmas and the way in which they evolved compositionally. In an earlier paper (Chappell *et al.* 1998), the authors distinguished these two groups, and referred to them as low- and high-temperature I-type granites. It is the purpose of the present

contribution to further examine this subdivision, which is fundamental in terms of the origins of the granites and their prospectivity for related mineralisation. The present authors will also examine some criticisms of this subdivision that have been made since the 1998 paper. The terms low- and high-temperature will be used throughout this paper, although, in a sense, their validity will not be confirmed until the arguments for the existence of two such groups have been presented.

S-type granites, at least from all observations made to this time, are apparently always of low-temperature origin, and close analogues in that sense to the low-temperature I-type granites. Although there is no known group of high-temperature S-type granites with which those low-temperature S-type granites can be compared, the authors will examine the evidence for those rocks having formed at the lower magmatic temperatures.

In this paper, reference is made to the ‘linear’ compositional variations that are a distinctive feature of the low-temperature granite suites of the LFB. Such variations could, in principle, have resulted from processes of magma mixing or mingling. However, there are other compositional features of the granites of the LFB that preclude such processes having played any role in generating the larger scale variations within these suites of granites (Chappell 1996a; see section 3 of Chappell 2004). Those observations are probably more generally applicable.

The distinctive compositional differences between the two groups of I-type granite of the LFB are summarised in Table 1.

**Table 1** Contrasting compositional characteristics of low- and high-temperature I-type granites of the Lachlan Fold Belt

Low-temperature	High-temperature
Rocks with less than 60% SiO <sub>2</sub> uncommon, with lowest SiO <sub>2</sub> contents near 55%	Mafic rocks common, with compositions ranging down to around 50% SiO <sub>2</sub>
Compositions have a single SiO <sub>2</sub> mode near 68%, with a weak one near 76%	Compositions are strongly bimodal, with modes at about 60% and 75% SiO <sub>2</sub>
Linear or 'simple' element variations	Curved or 'intricate' element variations
Compositional inflexions sometimes seen when fractional crystallisation occurred at felsic compositions	Compositional inflexions at compositions near 68% SiO <sub>2</sub> for elements such as Zr and Ba are characteristic
Volcanic rocks match the plutonic rocks closely in compositions	Volcanic rocks may be fractionated melt compositions and more felsic than the cumulate plutonic rocks

Of all of those features, it is the behaviour of Zr that provides the key to confirming the origins of those groups and that will now be discussed.

### 1. Contrasting patterns of Zr variation

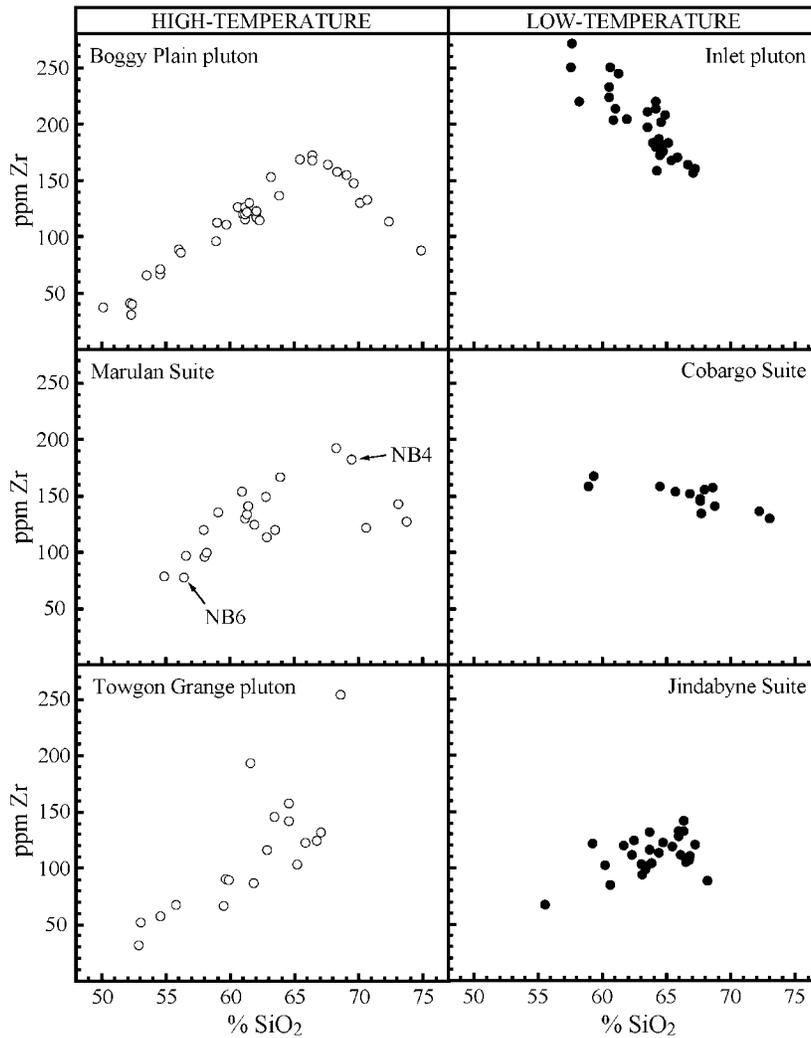
There are two distinct patterns of Zr variation within the I-type granite suites of southeastern Australia. In one case, the most mafic rocks of a suite generally have SiO<sub>2</sub> contents below 55%, and from a low level of Zr at those compositions, the values rise with increasing SiO<sub>2</sub>, with an inflexion in abundances if the SiO<sub>2</sub> contents pass above about 68% SiO<sub>2</sub>. Such variations are illustrated by two of the diagrams for high-temperature granites on the left-hand side of Figure 1. For the low-temperature granites on the right-hand side of that figure, mafic rocks are less abundant, and for only one analysed sample is the SiO<sub>2</sub> content of such a rock less than 55% (54.4%). Linear variations against SiO<sub>2</sub> are characteristic of all elements, and the Zr contents generally decrease with increasing SiO<sub>2</sub>. In a few cases, the Zr abundances remain fairly constant, and in rare instances, they increase with increasing SiO<sub>2</sub>. Our understanding of this contrasting behaviour of Zr abundances has been greatly facilitated by zircon solubility experiments (Watson & Harrison 1983) and by small-scale U-Pb dating of zircon crystals using the Sensitive High Resolution Ion Microprobe at the Australian National University (SHRIMP) ion microprobe (Williams 1995), both discussed below.

The uppermost two suites in Figure 1, Boggy Plain (36 km<sup>2</sup>) and Inlet (13 km<sup>2</sup>) are both potassic and comprise single concentrically zoned plutons that range from gabbro through quartz monzodiorite to monzogranite in the case of Boggy Plain (Wyborn *et al.* 2001), and from mafic monzodiorite through monzonite to quartz monzonite for Inlet (Chappell 1966). The other four suites shown in Figure 1 are less potassic and more calcic in composition, and vary from quartz diorite or tonalite to granodiorite or monzogranite. Marulan (151 km<sup>2</sup>; Carr *et al.* 1992), Cobargo (208 km<sup>2</sup>) and Jindabyne (120 km<sup>2</sup>; Hine *et al.* 1978) all contain several plutons (eight, four and nine respectively). Towgon Grange is a body of relatively mafic Cordilleran-like tonalite to granodiorite compositions with an area ~65 km<sup>2</sup> (Bryant *et al.* 1997). Together with the Inlet pluton, Towgon Grange is located in the younger New England Fold Belt to the northeast of the LFB, which is where all of the other suites referred to here are located.

The Boggy Plain pluton (Fig. 1) exemplifies one of the patterns of Zr variation. After Zr in that pluton has increased in amount by about a factor of five from the most mafic rocks, the compositions show an inflexion at close to 66% SiO<sub>2</sub>. Because of their high Cr and low Zr contents, and the small

positive Eu anomaly of one sample, at least the more mafic rocks of this body must represent cumulate rather than melt compositions (see also section 3.2), and this is thought to be the case for almost all of the rocks of the Boggy Plain pluton. The fact that the pluton is progressively zoned (with one major break) from 50.1% to 74.8% SiO<sub>2</sub>, implies that all except perhaps the most felsic rocks formed as cumulates. The increase in Zr abundances with increasing SiO<sub>2</sub> in the early cumulates shows that zircon was not saturated in the melts from which those rocks formed, although some zircon eventually crystallised from trapped intercumulus melt. As the Zr concentrations in the main body of melt increased, the amounts of Zr in the more evolved trapped melts and, hence, in the cumulate rocks, also rose. Separated zircon grains from these more mafic rocks have irregular shapes that were apparently imposed by the earlier-formed minerals between which they crystallised, confirming their late crystallisation from trapped melt. Zircon became saturated in the melt at a composition corresponding to the inflexion in Zr abundances in the cumulate rocks. That happened both because of falling temperature and the changing composition of the melt, i.e. its bulk composition, but particularly, the increasing Zr content. Beyond that point, the melts remained saturated in zircon, and Zr decreased in abundance as that mineral separated from the melts and became incorporated in the cumulus minerals. There are several other zoned plutons in the BPS, but Boggy Plain is the one that has been studied in detail (Wyborn 1983). The other zoned plutons of the BPS may vary in the details of their compositional evolution, but all have in common an origin as cumulate rocks formed by sidewall crystallisation (Wyborn *et al.* 2001).

The pattern of Zr variation for the Marulan Suite is very similar to that of Boggy Plain, but with fewer felsic rocks. In contrast to Boggy Plain, the plutons of the Marulan Suite are relatively homogeneous and most of the variation within the suite results from the differences between the eight plutons. The present authors ascribe most of the variation in these rocks either to fractional crystallisation at depth, or to different degrees of partial melting of similar source rocks. Similar patterns of variation in Zr contents have been generated in a magma chamber at shallow levels in the crust (Boggy Plain) and at deeper levels (Marulan), and the mechanisms that generated those variations may have been different. The precise mechanism for the Marulan Suite is not immediately relevant to this discussion and will not be examined further here. The significant observation here is that the trend of increasing Zr with increasing SiO<sub>2</sub> for Marulan again corresponds to zircon undersaturation, and that of decreasing Zr with increasing SiO<sub>2</sub> to zircon saturation. These interpretations have been confirmed using SHRIMP. For sample NB6, 1550 grains were imaged by cathodoluminescence, no possible



**Figure 1** Variation diagrams for Zr in six granite suites of southeastern Australia. The suites on the left-hand side were derived from high-temperature magmas which that initially completely or largely molten. Variation of the other suites resulted from the separation of restite from a more felsic melt at lower temperatures. Age inheritance has been checked for the samples of Marulan labelled NB6 and NB4 using the SHRIMP ion probe (see text).

cores were identified and the 12 grains that were dated all gave Early Devonian crystallisation ages. For NB4, 2040 grains were imaged and 22 possible cores were identified and analysed, of which six proved to be older than Early Devonian (535, 1040, 1080, 1140, 2540 and 2770 Ma).

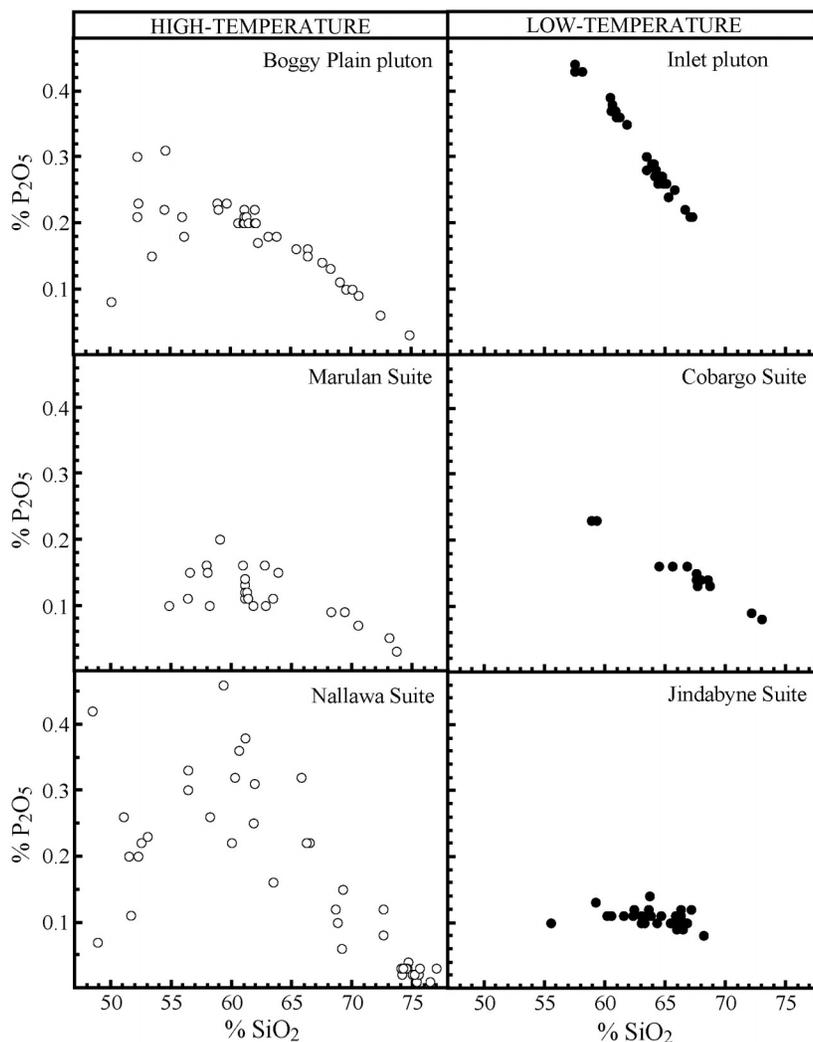
The critical observation for Marulan at this time is that there is a sequence of compositions that were formed from melts that were in part undersaturated in zircon, and in part saturated. The low-K Towgon Grange pluton shows similar variation, but no rocks are sufficiently felsic for the Zr contents to show an inflexion. The variation in this body has the same possible origins as that in the Marulan Suite.

Like Boggy Plain, the Inlet pluton is also near-concentrically zoned, from 57.5% to 67.2% SiO<sub>2</sub>, but in this case the variation is considered to have been dominated by the accretion of restite crystals from the magma (Chappell *et al.* 1987) to the margins of the pluton, so that the rocks become more restite-free and, hence, more felsic towards the centre of the body.

Variation within the Cobargo Suite, like the Inlet pluton, was caused by varying degrees of separation of restite crystals from melt, as was generally the case for suites of the large I-type Bega Batholith (8940 km<sup>2</sup>). The small Murrabrine pluton (1.4 km<sup>2</sup>) of the Cobargo Suite is the most mafic (~59% SiO<sub>2</sub>) intrusion in that batholith. Zr variations in the

Inlet and Cobargo suites are distinctly different in character from those of the suites discussed earlier, with Zr having its maximum abundance in the most mafic rocks, decreasing progressively towards more felsic compositions. Such variation is consistent with zircon crystals having been present in the melts involved in the production of those granites which formed under conditions in which the melt was always saturated in zircon. This is confirmed by the presence of rare inherited Precambrian cores in the zircons from the Cobargo Suite. Whether or not the granites of the Inlet Suite contain inherited zircon has yet to be tested.

The Jindabyne Suite illustrates the much less common case in which, based on the presence of inherited zircon, the magma was apparently saturated in zircon (see section 4), but Zr abundances increase slightly with higher SiO<sub>2</sub> contents. The present authors interpret this as resulting from the partial melt being less felsic (~68% SiO<sub>2</sub>), so that there was a higher concentration of Zr in such a melt at higher temperatures than in the bulk restite. Hence, the mass fraction of Zr retained in the restite was reduced to a level such that the content of Zr in the bulk restite was less than in the melt. Variation is again ascribed to varying degrees of separation of restite, but from a less felsic melt. It is difficult to see how the variation could have resulted from fractional crystallisation, given that the melt was saturated in zircon and Zr contents rise with increasing SiO<sub>2</sub>.



**Figure 2** Variation diagrams for  $P_2O_5$  in six granite suites of southeastern Australia. The three suites on the left-hand side are high-temperature in origin and those on the right are low-temperature. However, the pattern of variation for  $P_2O_5$  in the Jindabyne Suite is consistent with a slightly higher temperature of formation than for the other two low-temperature suites.

While the Towgon Grange and Jindabyne suites do show similar Zr-SiO<sub>2</sub> systematics (Fig. 2), these two suites are regarded as high- and low-temperature in origin, respectively. This shows that, while Zr variations may be distinctive for the two groups, as shown by the other four plots in Figure 1, that is not necessarily the case when the Zr abundances increase with increasing SiO<sub>2</sub> contents in more mafic rocks and felsic rocks are not seen. Apart from Zr, there are significant compositional differences between these two suites. Towgon Grange has compositions that are more evenly distributed throughout their total range, and Jindabyne does not include any analysed rocks with SiO<sub>2</sub> contents of less than 55%. However, while those differences might possibly reflect the nature of the exposures of Jindabyne that are available for sampling, there are other elements for which that is very unlikely. Towgon Grange has a significantly higher ratio of Na/K, and substantially lower abundances, i.e. about half, of the elements Rb, Nb, Pb, Th, U and the light rare-earth elements (REE). In cases where discrimination using Zr abundances is ambiguous, the distinction of high- and low-temperature granites can generally be made using other criteria, as will now be discussed below.

Plagioclase crystals probably provide the clearest petrographic distinction between the two groups (see section 7; White & Chappell 2004). Except for the most felsic rocks, the

plagioclase crystals in low-temperature granites commonly have corroded cores, with fairly uniform calcic compositions, surrounded by complexly zoned plagioclase. Such crystals are a feature of the Jindabyne Suite. Plagioclase crystals in the high-temperature granites are generally better-shaped and are uniform in composition. The corroded cores that are a feature of the low-temperature granites are not present, but in some cases, including the sample examined by White & Chappell (2004) from Towgon Grange, the plagioclase crystals have large uniform cores surrounded by relatively narrow more sodic rims. Such crystals are distinct in appearance from those with broader rims that surround corroded cores in the low-temperature granites, and are thought to indicate rapid cooling of the granites before they had fully crystallised. The presence or absence of inherited zircon is taken to be diagnostic of the low- and high-temperature granite suites (see 5.1). Such older zircons occur in the Jindabyne Suite, which is therefore certainly low-temperature. Their possible occurrence has not been checked in Towgon Grange, a member of the Cordilleran tonalite-like Clarence River Supersuite of Bryant *et al.* (1997); inherited zircon crystals are typically absent from such rocks.

Variations in Zr contents and conclusions that can be drawn about zircon saturation or undersaturation have the potential to provide information about the temperatures at which at least some of these rocks formed, using zircon saturation

temperatures calculated from the information of Watson & Harrison (1983). However, before doing that, objections that have been made to the use of such temperatures for these rocks must be examined (see sections 3 and 4).

## 2. Contrasting patterns of variation for other elements

Elements other than Zr also show characteristic differences in their patterns of variation between the low- and high-temperature granite groups. Of these, the most instructive are P and Ba.

### 2.1. Phosphorus variations

Variations in  $P_2O_5$  for six granite suites of southeastern Australia are shown in Figure 2. Cobargo and Inlet have patterns that are very characteristic of low-temperature I-type suites, with P falling sharply and in a very regular fashion from the most mafic to the most felsic compositions. Such variation results from the low solubility of P in metaluminous to weakly peraluminous felsic low-temperature granite melts (Harrison & Watson 1984; Mysen *et al.* 1999). This is consistent with the present authors' view that the magmas which produced all the rocks of those two suites comprised felsic melt and more mafic restite, so that the higher P contents of the less felsic rocks result from greater proportions of restite. Variation for the Jindabyne Suite is similar, but with a much lower gradient. That case probably corresponds to higher temperature felsic melt that had a higher P content that was closer to that of the associated restite.

$P_2O_5$  abundances in the most mafic rocks of the Boggy Plain and Marulan suites are scattered, but at more felsic compositions the contents fall very systematically with increasing  $SiO_2$ . For those more felsic compositions, the variation is analogous to that in the low-temperature granites. P for the Nallawa Suite is similar to the other two high-temperature suites, but with much more scatter. The Nallawa Suite is potassic, and grouped with Boggy Plain within the Boggy Plain Supersuite (BPS) (Wyborn *et al.* 2001). Rocks of this suite cover an area of about 130 km<sup>2</sup> in the Yeoval Batholith in the northern part of the LFB, ranging from diorite through to very felsic one-feldspar hypersolvus granites. The more felsic rocks are separated from the diorites by an approximately horizontal contact, which Wyborn *et al.* (2001) interpreted as the boundary between cumulate rocks in a zoned pluton and overlying felsic granites formed from the fractionating melt that escaped to the top of the magma chamber.

### 2.2. Barium variations

Ba variations in low- and high-temperature granites has been discussed in some detail by Chappell *et al.* (1998), and are illustrated for selected granite suites in Figure 3. This element behaves in a similar way to Zr in the high-temperature suites, but the variation is not related simply to saturation or under-saturation in a single mineral. During the initial stages of development of progressive cumulate compositions in the Boggy Plain pluton, plagioclase was the only precipitating mineral that contained Ba, and the bulk partition coefficient of the cumulus minerals was much less than one, so that the Ba contents of the remaining melt progressively increased (Fig. 3). The later appearance of biotite as a significant liquidus mineral led to both the melt and the rocks that formed from it being subsequently depleted in Ba, at rock compositions near 67%  $SiO_2$ . Variation in Ba in the Nallawa Suite is similar (Fig. 3), except that the inflexion in Ba contents occurs at the significantly higher  $SiO_2$  content of about 74%. For Nallawa, the

decrease in Ba abundances could have resulted from the appearance of K-feldspar as a liquidus mineral, rather than biotite, when the fractionating melt reached a haplogranite composition. The three Ba data that lie well above the main trend for the Nallawa Suite perhaps represent cumulative rocks formed by fractionation from that haplogranite melt, although that suggestion is not supported by higher Sr abundances. These observations for Boggy Plain and Nallawa are consistent with the formation of cumulate rocks by fractional crystallisation. That could also be so for the Marulan Suite, but in that case it could also have resulted from different degrees of partial melting, with biotite and K-feldspar, and therefore Ba, being largely removed from the source rocks during the earlier stages of that anatexis.

Ba variation in the low-temperature granite suites is always linear with increasing  $SiO_2$  contents, sometimes increasing (e.g. Cobargo and Jindabyne) and sometimes decreasing (e.g. Inlet). When the Ba contents increase, some Ba was present in restite plagioclase, but that element was more abundant in the melt. When Ba abundances decrease with increasing  $SiO_2$ , a phase or phases that contain significant amounts of Ba, i.e. K-feldspar and/or biotite, was present in the restite.

The effects of later fractional crystallisation are sometimes observed in the most felsic rocks of those suites as rapidly decreasing Ba contents, but an example of such variation is not shown in Figure 3. The consistent linear variations at less-evolved compositions are distinct from the variations in the high-temperature suites and are difficult to reconcile with fractional crystallisation, as discussed in some detail for accumulative rocks by Chappell (1996b).

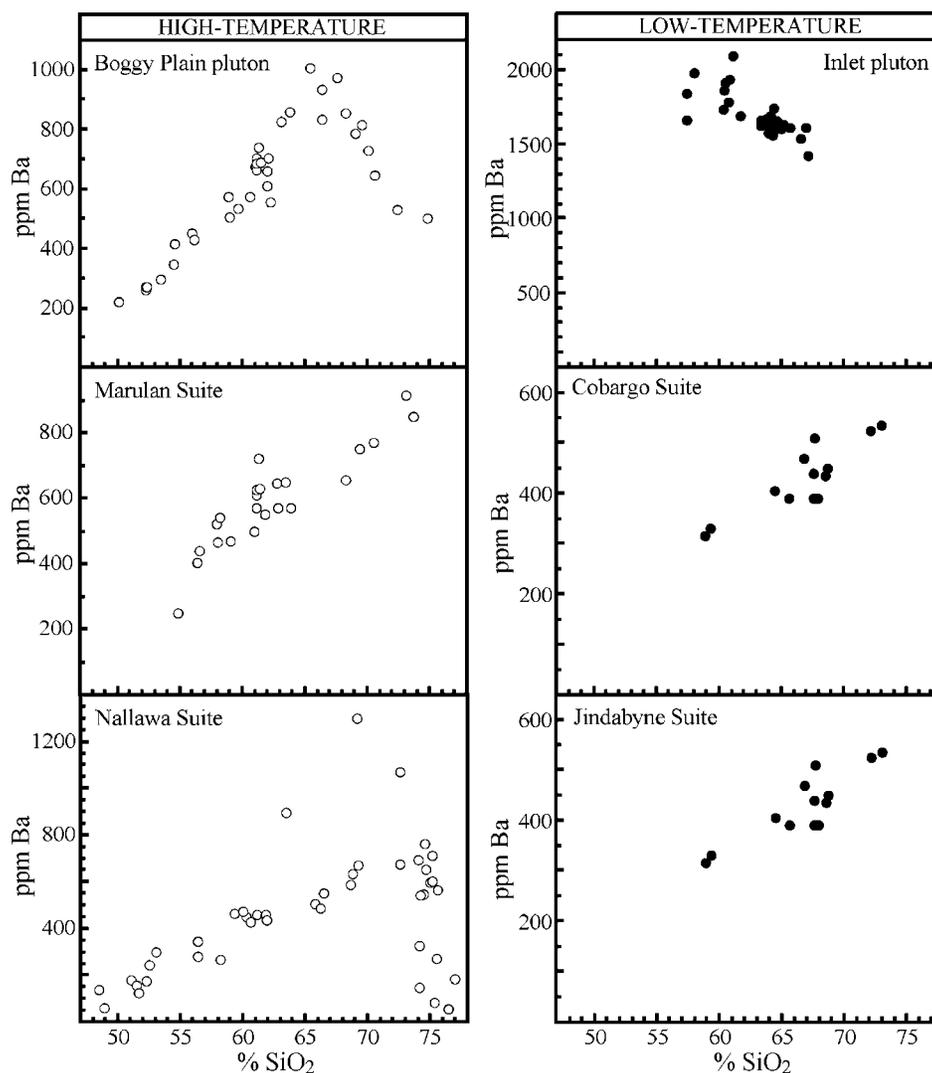
## 3. Accumulative granites in the Lachlan Fold Belt

Clemens (2001), in discussing S-type granites, stated that 'it is likely that the more mafic granites are cumulates, rather than former liquids'. He then correctly pointed out that zircon saturation temperatures calculated for such compositions would be meaningless. This is a legitimate concern which must be addressed. The present authors were aware of this possible problem when they proposed the low- and high-temperature groups in 1998. However, they also knew of strong arguments against any of the low-temperature granites of the LFB, both S- and I-type, being cumulates, which they did not enumerate at that time. The authors will examine these after here considering the terminology for such rocks and summarising the evidence that many of the high-temperature granites of the LFB did indeed have such a cumulate origin.

### 3.1. Cumulate, cumulative and accumulative rocks

The terminology for what are referred to here as cumulate, accumulate and accumulative rocks has recently been discussed by Chappell & Wyborn (2004). The use here of the term cumulate follows that of Irvine (1982) who stated that, 'A cumulate is defined as an igneous rock characterised by a cumulus framework of touching mineral crystals or grains that were evidently formed and concentrated primarily through fractional crystallisation.' The space between the cumulus minerals is occupied by material that crystallised from inter-cumulus liquid. Since some granites formed in precisely that way, it is desirable to use the term cumulate in exactly the way proposed by Irvine (1982).

Chappell & Wyborn (2004) have proposed that the term 'cumulative' be used for granites with compositions that resulted in part from the concentration of crystals within a melt, where those crystals did not form a cumulus framework. In general, such rocks result from any process that fractionates



**Figure 3** Variation diagrams for Ba in six granite suites of southeastern Australia. The three suites on the left-hand side are high-temperature in origin and those on the right are low-temperature.

melt from a mixture of melt and crystals, such as filter differentiation (Propach 1976) and sorting during flow. In some rocks, there is compositional evidence for the concentration of crystals by their movement relative to the supernatant melt in which they crystallised, but the cause of that movement is not known in that instance. Examples are positive Eu anomalies, or high abundances of Th and other elements resulting from the concentrating of monazite. Following Chappell & Wyborn (2004), the term 'accumulative' will be used here for such rocks.

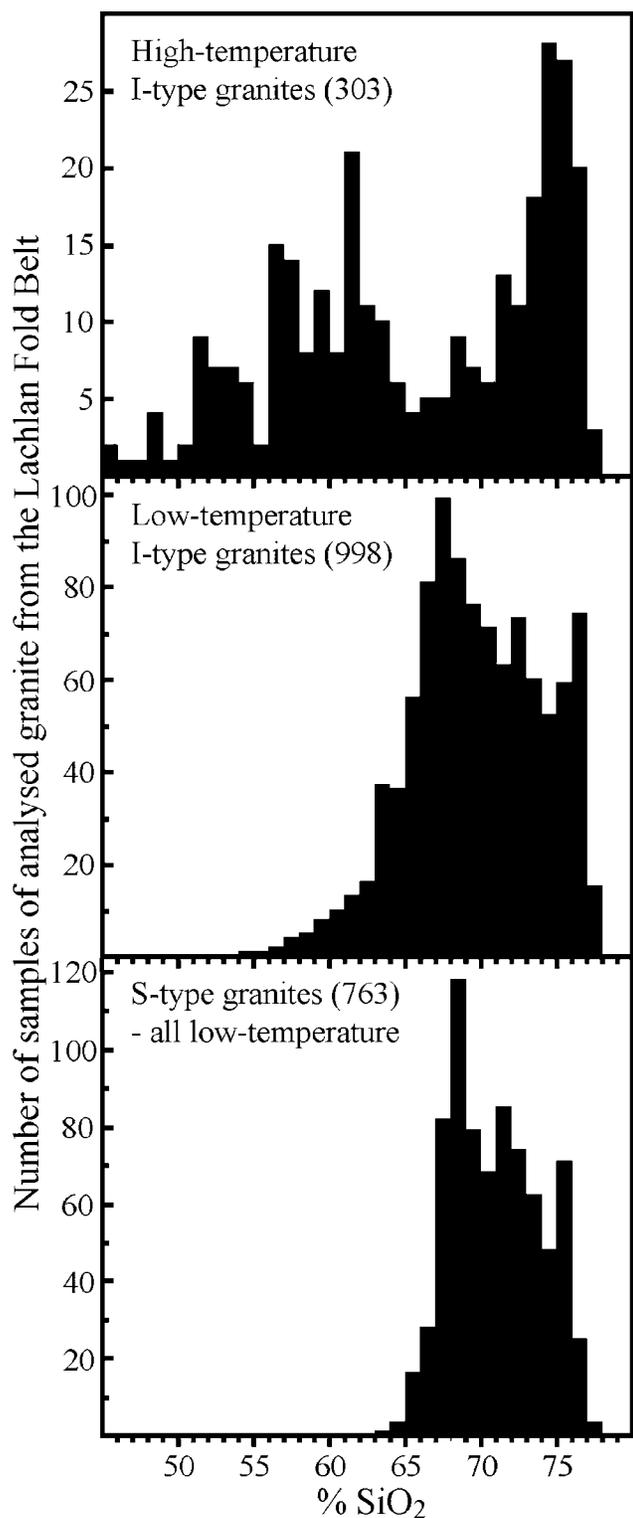
Clemens (2001) regarded the mafic granites of the LFB as cumulates (accumulative in the present usage). McCarthy & Groves (1979) had previously proposed that the granites of the Blue Tier Batholith of Tasmania are cumulate rocks, and pointed out that the alternative scenario in which the granites represent melt compositions, would imply that 'each pluton was formed by a vast number of small separate intrusions, analogous to separate lava flows, each one different from the others'. Furthermore, they noted that this 'demands a second magma chamber at depth where fractional crystallisation occurred', an argument that could be applied more broadly to the other batholiths of the LFB. McCarthy & Groves (1979) were of the view that variations within the granites of the Blue Tier Batholith resulted from fractional crystallisation, so that the granites had to be either accumulative or represent crystallised melts. They did not recognise the other possibility that

those granites formed from restite-bearing magmas that underwent crystal fractionation of restite from melt. There are some extremely evolved felsic granites in the Blue Tier Batholith that clearly represent melts formed by fractional crystallisation. But the less felsic granites are low-temperature in origin, and as the present paper shows, must therefore have evolved compositionally by the fractionation of restite. Apart from the minor occurrences of garnet-bearing cumulative rocks in the Blue Tier Batholith (see section 3.3), those granites have no compositional features which would suggest that they are accumulative.

### 3.2. Cumulate rocks of the Boggy Plain Supersuite

The rocks of the BPS show compositional variations that, in the present authors' view, unquestionably resulted from the production of cumulate rocks by fractional crystallisation. The observations, mainly compositional, which lead to that conclusion will now be summarised, so that the BPS can then be compared to and contrasted with other granite suites of the LFB.

The BPS comprises more than 25 plutonic complexes with a total area of approximately 2300 km<sup>2</sup>, together with related volcanic rocks. These rocks are the most compositionally diverse among the granites and associated rocks of the LFB, ranging from 45.3% to 77.4% SiO<sub>2</sub> (Fig. 4). Two-pyroxene geothermometry on the cumulate rocks of the Boggy Plain



**Figure 4** Histograms showing SiO<sub>2</sub> abundances in analysed high- and low-temperature I-type and S-type granites of the Lachlan Fold Belt.

pluton and magnetite-ilmenite geothermometry on volcanic rocks of the BPS indicate high temperatures for both, commonly in excess of 1000°C (Wyborn & Chappell 1986). That the more mafic rocks of the BPS represent cumulate rather than melt compositions is confirmed by extreme values for several elements, with a highest Cr content of 850 ppm, and lowest values for K<sub>2</sub>O (0.06%), P<sub>2</sub>O<sub>5</sub> (0.01%), Rb (0.8 ppm), Ba (11 ppm) and Zr (8 ppm) in the gabbros of the supersuite. None of these values could be those of mafic melts, and they suggest that the rocks are cumulates in the sense of Irvine (1982), with small amounts of intercumulus melt. That is

confirmed by the continuous cryptic zoning in plutons such as Boggy Plain where, despite the extreme compositional range, there is only one discontinuity in the zoning at an internal contact (Wyborn *et al.* 2001). More generally, compositional trends within the BPS clearly indicate that the rocks formed progressively either as cumulates from an originally liquid or largely liquid magma, or else by direct crystallisation of the fractionated and more felsic melt. Many elements show trends that have inflexions, or are curved. W-Nb-Ta-Bi mineralisation is present in the most felsic rocks, which have melt compositions, as a result of those elements becoming concentrated in the melt during prolonged removal of crystals during fractional crystallisation. The volcanic rocks of the BPS are crystal-poor and more felsic, and they correspond to fractionated liquid lost during formation of the plutonic rocks (Wyborn & Chappell 1986).

The Boggy Plain pluton and the BPS in general show that fractional crystallisation can produce a wide range of compositions for several elements. Because granites of the BPS are so distinctly different in their mode of variation from others in the LFB, apart from the Marulan Suite, any suggestion that the variation within granite suites of the LFB arose generally by fractional crystallisation, and that those other suites contain cumulate rocks, or more generally accumulative rocks, must be examined very critically, as will now be done.

### 3.3. Arguments for the low-temperature granites not being accumulative

We have seen that mafic rocks of high-temperature granite suites, which are always I-type, may be cumulates, and that is always the case for the BPS. But that does not seem to be the case for the much more abundant low-temperature I-type suites in the LFB, and for the S-type granites, for four main reasons.

#### 3.3.1. Rarity of low-silica rocks in low-temperature suites.

Low-silica rocks that are cogenetic with granites, apart from those of the BPS and the Marulan Batholith, are very rare in the LFB (Fig. 4). About 26% of the analysed rocks of the BPS contain less than 59% SiO<sub>2</sub>. Excluding the high-temperature granites of the Marulan Batholith, no other I-type rocks in the LFB contain less than 54.4% SiO<sub>2</sub> and only 0.8% of the total samples have less than 58% SiO<sub>2</sub>. There is only one analysed S-type granite that contains less than 63% SiO<sub>2</sub>. That sample with 57.6% SiO<sub>2</sub> has a concentration of garnet (Chappell & Wyborn 2004) and is quite distinct from other more mafic S-type granites of the LFB. In none of the other analysed granites did mafic minerals such as biotite (SiO<sub>2</sub> ~35%), hornblende (SiO<sub>2</sub> ~47%), pyroxenes (SiO<sub>2</sub> ~50%) or cordierite (SiO<sub>2</sub> ~50%) concentrate to the exclusion of minerals such as plagioclase (SiO<sub>2</sub>=66.3% at An<sub>50</sub>) and quartz. Rocks of the BPS are bimodal in SiO<sub>2</sub> content (Fig. 4), with mafic cumulate rocks and the complementary fractionated melt compositions being the most abundant, and only 10.4% of analysed rocks have compositions between 65% and 70% SiO<sub>2</sub>. In contrast, for the other I-type and the S-type granites, 39.8% and 42.3% of the analyses, respectively, have SiO<sub>2</sub> contents in that interval.

#### 3.3.2. Compositional equivalence of plutonic and volcanic rocks.

Comagmatic plutonic and volcanic rocks of the LFB exhibit two distinct relationships (Wyborn & Chappell 1986). In the first case, the more mafic plutonic rocks represent crystal cumulates, and the volcanic rocks and the exclusively felsic plutons are the complementary fractionated melt. This situation is illustrated by the BPS, which includes rhyolitic lavas, the Mountain Creek Volcanics, which are much more felsic than the comagmatic or cogenetic cumulate plutonic rocks. In the second case, the plutonic and volcanic rocks can be

matched fairly closely, and the compositional differences that distinguish between plutonic suites are also found among the volcanic suites. These comprise the low-temperature suites, and Wyborn & Chappell (1986) argued that those rocks must represent true magma (i.e. melt  $\pm$  restite) compositions and cannot be cumulative rocks produced during fractional crystallisation. The volcanic rocks are not more felsic with a greater proportion of melts from which early-formed crystals had been removed, as would be expected if the more mafic granites are accumulative, and which is seen for the BPS. The equivalence in chemical compositions between plutonic and volcanic rocks of the low-temperature granite suites of the LFB strongly suggests that none of the former is accumulative.

**3.3.3. Compositional variations within granite suites.** Apart from the granites of the BPS and the Marulan Batholith, the variations for many elements within granite suites of the LFB are not consistent with those suites having formed progressively as a sequence of accumulative rocks. In no I-type suites that are regarded as low-temperature do elements such as P, Zr and Ba, that may appear as an important component of new liquidus phases during continuing fractional crystallisation, show inflexions on Harker diagrams. The low-temperature granite suites are characterised by linear trends on such diagrams. This implies that during fractionation, within a suite, the same minerals are generally being removed and in fixed relative proportions, as would generally be expected for restite minerals. If the separating minerals were being removed after progressive crystallisation, then the bulk compositional trends of the cumulative rocks that formed would reflect changes in mineral proportions and compositions. Chappell (1996a) modelled the variations of some trace elements in I-type suites of the Bega Batholith and the S-type Bullenbalong Suite, and showed that those variations cannot have resulted from the rocks forming as cumulates by fractional crystallisation.

**3.3.4. Granites with trace element compositions that complement those of granites lying on a liquid line of descent are rare or absent.** In the present authors' view, the less-felsic, low-temperature granites of the LFB evolved in composition through the progressive separation of entrained restite. However, there are some cases in which the more felsic magmas evolved further by fractional crystallisation after most or all of the restite had separated (e.g. Chappell & White 1998). In the latter cases, most of the compositional variation is seen among the trace elements since the major element compositions at that stage are generally close to those of minimum-temperature melts. Such trace element variations were discussed by Chappell (1999), and that paper basically assumed that these represented a sequence of melt compositions. That these changes in trace element abundances are those of melts rather than of a sequence of accumulative rocks is seen more easily for the fractionated S-type granites, in which the P abundances increase as the rock compositions become more evolved. These rocks have strongly peraluminous bulk compositions, with up to about 4% normative corundum. The data of Wolf & London (1994) show that P would be soluble in melts of such compositions, and therefore, behave incompatibly, which is what is observed in these rocks. Other distinctive features of these rocks are the low CaO contents, which decrease to about 0.4%, and the decreasing abundances of Th and the light REE apparently caused by monazite fractionation from the evolving melt (Chappell 1999). If these distinctive compositions are the result of fractional crystallisation, as they seem to be, then accumulative rocks with lower P, and higher Ca, Th and light REE must have also been produced. None of the approximately 770 S-type granites which the present authors have analysed from the LFB show those features, so it must again

be concluded that accumulative S-type granites are not present in that area at the level to which the granites are exposed. But they are present in other regions; for example in the Variscan-age Sameiro granite near Braga in northern Portugal, where La abundances can be as much as 500 times chondrites (Dias *et al.* 2000).

Chappell & White (1998) reported on a sequence of fractionated melt compositions in the S-type Koetong Suite of the LFB. In the same area, there are granites of similar bulk composition, but with distinctly higher Sr contents, which the above authors regarded as cumulate rocks of the same suite. Sr isotopic data obtained subsequently show that cannot be the case since the 'cumulate' granites have less radiogenic initial Sr isotopic compositions than the Koetong Suite. They are a separate suite, apparently derived from sedimentary source rocks with higher Sr contents.

Strongly fractionated I-type melt compositions of the LFB are best characterised by their high abundances of Y and the heavy REE, combined, of course, with other broader features, such as high Rb/Sr ratios and low Ca contents. Once again, the complementary accumulate compositions to these are not seen among our approximately 1120 analyses of the dominant Devonian-age I-type granites of the LFB, but may be present in the Carboniferous granites in the northeastern part of the belt, which comprise about 5% of the total area of granite exposures of that region (Chappell & Wyborn 2004).

#### 3.4. Implications of the lack of accumulative rocks among the low-temperature granites

We have seen that there is abundant evidence confirming that the more mafic rocks of what are here termed the low-temperature granite suites of the LFB are not accumulative. Hence, if these rocks are the products of fractional crystallisation, they are melt compositions to which it should be possible to apply zircon saturation thermometry. Before doing that, it is necessary to address the question of equilibrium between zircon crystals and melt, because Clemens (2001, 2003), for example, has argued that equilibrium is unlikely to be attained with respect to zircon and other minerals that are hosts to the trace elements in the rock.

#### 4. The question of equilibrium between zircon crystals and melt

Watson & Harrison (1983) developed an equation relating temperature and the solubility of zircon in silicate melts of known bulk composition. **Therefore, the temperature below which zircon would be saturated in a melt, a 'zircon saturation temperature', can be calculated.** Such temperatures have previously been used to discuss the origins of granites in the LFB (Chappell *et al.* 1998, 2000).

**The role of kinetics.** The use of calculated zircon saturation temperatures in this way has been questioned by Clemens (2003). He stated that zircon dissolution into a silicate melt seems to be governed by kinetics rather than equilibrium phase relations and that equilibrium experiments, such as those of Watson & Harrison (1983), may have little bearing on actuality in petrogenesis. It is necessary to consider this further before using data derived from those experiments in the arguments being developed in this paper.

Watson (1996) has considered zircon dissolution and growth quantitatively on the basis of experiments on zircon solubility and Zr diffusivity in granitic melts. He stated unequivocally that dissolution and growth of zircon in nature is not limited by interface kinetics, but by Zr diffusion in the contacting melt. He concluded that only the largest protolith zircons (>120  $\mu\text{m}$ )

are likely to survive magmatic events which exceed a temperature of 850°C. The old zircon cores in the LFB granites are more typically <50 µm in diameter. Also, if these suites evolved by fractional crystallisation, temperatures much higher than 850°C would have been involved in production of the more mafic rocks, and associated, more felsic granites would have been derived from melts that had passed through that high temperature stage. All of this implies that isolated crystals of zircon would not survive immersion in a melt at temperatures above the zircon saturation temperature during the period involved in partial melting above that temperature, transport of magma, fractionation and cooling.

For the I-type granites, it could be argued that the crystals were once much larger and attained their present size through incomplete dissolution. For the S-type granites, that was apparently not the case. Williams (2001) noted that abrasion textures are preserved on the surfaces of zircon cores in the S-type Cooma Granodiorite and that no cores have the deep embayments normally indicative of partial dissolution. This implies that Zr in the melt phase was derived from fine-grained zircon or from other minerals, and that the larger zircon grains were preserved because that mineral was always present in excess of the amount required for dissolution in the melt, i.e. zircon was saturated in the melt. The Cooma Granodiorite is an uncommon kind of S-type granite in the LFB in that it is situated within a wide, high-temperature metamorphic aureole and it also is compositionally distinct from most of the other S-type granites (White & Chappell 1988). But the comments and conclusions of Williams (2001) about the surfaces of zircon cores also hold for the Jilamatong Granodiorite, part of the voluminous mafic S-type granites of the Bullenbalong Suite, clearly showing again that the melt phase involved in the production of those granites was saturated in zircon. At Cooma, Williams (2001) showed that the new zircon growth on detrital grains in the progressively metamorphosed metasediments starts when the metamorphic grade becomes high enough to generate a partial melt. This apparently involves a transfer of Zr, via the melt, from fine zircon grains and any decomposing Zr-bearing minerals, to the larger zircon grains. That is clearly a scenario in which zircon is saturated in the melt throughout the partial melting and later evolution of that granite. **The observations of Jilamatong indicate that this can be applied more widely to other S-type granites.**

Recently, Hanchar & Watson (2003), in discussing the experimental results of Watson & Harrison (1983), have stated that 'An implication of these results is that zircon dissolution in an undersaturated (in zircon) water-bearing granitic melt occurs instantaneously on geologic timescales with little possibility that such pre-existing zircon would survive a crustal melting event.'

**No positive zirconium anomalies.** Clemens (2003) accepted that many zircon crystals in granites are restitic and argued that zircons are located within mafic minerals, mainly biotite, in the source rocks. He stated that '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 restite phases'. Older zircon cores may be rare in the more felsic S-type granites of the LFB (e.g. Elburg 1996). However, for the more mafic S-type granites of that region, almost every crystal of zircon has an older core and those cores together comprise a large fraction (about 45%) of the total zircon content of the rock. But none of these rocks show anomalously high Zr contents, or a 'positive zirconium anomaly', that might be expected in some cases if they formed from a melt in which zircon crystals had been preferentially incorporated as they left the source rocks.

**Granites on a liquid line of descent.** Clemens (2003) also pointed out that many zircons in granitic rocks are found included in crystals of biotite, and once armoured by magmatic overgrowths, would no longer be vulnerable to attack by the melt. Certainly, biotite is the principal zircon host in many S-type granites, but in I-type granites this is commonly not the case (Williams *et al.* 1983). To examine this argument of Clemens (2003), it is probably best to look at some compositional evidence from the rocks themselves. If the low-temperature granite suites of the LFB evolved by fractional crystallisation, then they represent a sequence of melt compositions and not a sequence of accumulative rocks (see section 3), i.e. the rocks would lie on a liquid line of descent in the sense of Bowen (1928). This means that the more evolved or more felsic rocks would have formed by the equilibrium crystallisation of melt with the same composition as the granite itself, apart from volatile components. That melt would have been derived by the removal of precipitated crystals from less-evolved melts that had compositions corresponding to earlier positions on the line of descent. Individual zircon crystals might not have been removed because of their small size, but larger crystals of biotite that were armoured old zircons crystals that could, therefore, not react with the melt, would have separated. But all of these granites contain older zircons! The implication is that they were not armoured and were in a melt that was at a temperature less than that of zircon saturation.

#### 4.1. Implications of zirconium variations within suites

Four patterns of Zr variation can be recognised within granite suites of the LFB, each with specific implications for zircon saturation or undersaturation, and for the use of zircon saturation temperatures. The first of these is the case of the high-temperature granites; the other three relate to the low-temperature granites. For the latter three cases, the compositional variations are ascribed, except in the most felsic rocks, to the fractionation of restite crystals. The implications of the different patterns of variations for the alternative fractional crystallisation model, will now be considered.

**Zr variations with an inflexion.** This is characteristic of the high-temperature granites (see section 1) and is illustrated by the diagrams on the left-hand side of Figure 1. Of course, the inflexion is only seen if the rocks as sampled reached sufficiently felsic compositions, which Towgon Grange in Figure 1 did not. In these cases, increasing Zr with increasing SiO<sub>2</sub> corresponds to undersaturation of Zr in the melt, conversely for decreasing Zr. This was confirmed by SHRIMP analysis of possible zircon cores in samples NB6 and NB4 from the Marulan Suite (see section 1). These relationships hold irrespective of whether the compositional variation resulted from fractional crystallisation (Boggy Plain), or from different degrees of partial melting of the source rocks (possibly Marulan and Towgon Grange). For Boggy Plain, all of the rocks are cumulates, except perhaps at the most felsic compositions. This implies the loss of Zr-rich melts from the system, probably as volcanic rocks (see Wyborn *et al.* 2001, fig. 4).

**Decreasing Zr contents with increasing SiO<sub>2</sub>.** This is the most common pattern of variation in the low-temperature suites, both I- and S-type, illustrated by the I-type Inlet and Cobargo suites in Figure 1. If, hypothetically, the compositional changes in these suites were the result of fractional crystallisation, then this pattern of variation would confirm that the melt from which zircon crystals were precipitating was saturated in zircon. This is consistent with the observation that all such suites so far examined with SHRIMP contain inherited zircon. It would likewise show that the concerns raised by Clemens (2003) regarding the use of zircon saturation are not valid. It

**Table 2** Average compositions of some low- and high-temperature mafic granites

	Low-temperature		High-temperature
	Mafic Inlet Suite G428 G42 G440*	Mafic Cobargo Suite AB126 AB127†	Mean of 17 PRB analyses (58–60% SiO <sub>2</sub> )‡
SiO <sub>2</sub>	57.74	59.10	59.03
TiO <sub>2</sub>	0.84	0.86	0.86
Al <sub>2</sub> O <sub>3</sub>	15.87	17.19	16.68
FeO <sub>total</sub>	5.72	5.40	6.38
MnO	0.12	0.11	0.11
MgO	4.42	3.43	3.56
CaO	6.08	6.44	6.67
Na <sub>2</sub> O	3.19	3.78	3.33
K <sub>2</sub> O	3.55	1.42	1.56
P <sub>2</sub> O <sub>5</sub>	0.43	0.23	0.16

\*G428, G432 and G440 are the three most mafic analysed rocks (quartz monzodiorites) from the Inlet Suite of the New England Batholith.

†AB126 and AB127 are the two most mafic analysed rocks (quartz diorites) from the Cobargo Suite of the Bega Batholith in the Lachlan Fold Belt.

‡The PRB composition is the mean composition of all analysed granites between 58% and 60% SiO<sub>2</sub> from the Peninsular Ranges Batholith among the data of L. T. Silver and B. W. Chappell.

also means that zircon saturation temperatures calculated for such suites can be used to assess whether or not the rock compositions are those of melts (see section 5).

**No significant changes in Zr contents with increasing SiO<sub>2</sub>.** In a few I-type low-temperature granite suites of the LFB (e.g. Glenbog; see figure in Chen *et al.* 1990), there is no significant change in Zr contents from mafic to felsic compositions. These are here interpreted as cases in which, fortuitously, the temperature of partial melting was such that the Zr content of the melt was close to that of the bulk restite. The compositional variations within the suite resulted from different degrees of separation of those two end-members, and the Zr contents remained unchanged. Any scenario that seeks to produce this type of constancy in Zr by fractional crystallisation would be quite complex, since it would imply not only a balance between the removal of Zr in precipitating minerals and the melt from which they were formed, but also the maintenance of that balance as both the temperature and bulk composition of the melt changed, both factors that affect the solubility of Zr.

**Increasing Zr contents with increasing SiO<sub>2</sub>.** This is illustrated by the Jindabyne Suite in Figure 1. Braidwood is the only other suite in the LFB to show this pattern of variation so distinctly. In the absence of other information, increasing Zr contents could be interpreted to support an origin for the development of variation in these suites by fractional crystallisation, from a melt undersaturated in zircon. But it could also result from fractionation of restite that contains less Zr than the melt, and that is confirmed by the presence of inherited cores in some zircon crystals, implying saturation in zircon. One interesting point that can be made from this pattern of variation is that, if zircon crystals are armoured by crystals of biotite (Clemens 2003) or other mafic minerals, then those other minerals could not have been involved in a fractional crystallisation process to any extent, because the Zr contents would then have decreased. Therefore, if we accept the conclusions of Watson (1996) regarding the instability of crystals of zircon in melts in which they are undersaturated, fractional crystallisation can be ruled out as a mechanism for generating the variation in these suites. That conforms to the present authors' views that were based on other criteria.

## 5. Zircon saturation temperatures

As noted above, despite their distinctive 'linear' nature, the compositional variations within the low-temperature granite suites of the LFB cannot be the result of magma mixing or mingling (Chappell 1996a). Neither can they be a series of cumulative compositions produced by fractional crystallisation (see section 3). The possibility that these rocks represent sequences of melts resulting from that process, will now be addressed. As shown in the previous section, it is valid to do that using the data on zircon saturation furnished by Watson & Harrison (1983).

### 5.1. Zircon saturation temperatures of I-type granites

Calculated zircon saturation temperatures (Watson & Harrison 1983) for the two most mafic granites of the Cobargo Suite and the three most mafic rocks of the Inlet pluton are all in the interval from 740 to 762°C. Those temperatures represent the maximum values at which crystals of zircon could have been present in melts having the compositions of those rocks, under equilibrium conditions. However, rocks with bulk compositions close to the most mafic rocks of the Cobargo and Inlet suites (analyses in Table 2) could only have been complete melts at temperatures much higher than ~750°C. This shows that, given that the rocks cannot be accumulative (section 3), the more mafic rocks of the Cobargo and Inlet suites cannot represent melt compositions, and therefore, that variations within those suites certainly cannot have resulted from fractional crystallisation. The present authors' view is that melts were involved in the formation of the Cobargo and Inlet suites, but they were much more felsic than the mafic bulk rock compositions. This confirms that the differences in the chemical trends between the two groups of granites in Figure 1 relate to differences in temperature. Thus Boggy Plain and the other suites on the left-hand side of Figure 1 formed from high-temperature molten or largely molten magmas, in which zircon was soluble, except at the more felsic compositions of Boggy Plain and Marulan. In contrast, the other suites in Figure 1 were derived from partially molten magmas, existing at substantially lower temperatures, which consisted of a felsic melt containing both zircon and other restite crystals. All of the compositional features of the six suites are consistent with

those observations. This subdivision into two groups of rocks which formed at relatively high or low temperatures is more generally applicable to the I-type granite suites of south-eastern Australia, and leads to their assignment as high- or low-temperature (see section 5.3).

It must be emphasised that the zircon saturation temperatures that are calculated do not tell us the temperatures at which these granites formed. That can only be done if the rock compositions are those of complete melts in which zircon is just saturated, and the first of those requirements does not apply here. These temperatures represent the maximum values at which those rock compositions could have formed as complete melts and still preserved inherited zircon, and through obtaining unrealistically low temperatures, it is argued that the rocks could not have been melts.

### 5.2. Zircon saturation temperatures of S-type granites

The more felsic S-type granites of the LFB may be free of older zircon (Elburg 1996), and in such cases, any older zircons would have been removed from melts by crystal fractionation. As far as is known, the more mafic S-type granites in the LFB invariably contain large amounts of inherited zircon, and virtually every zircon crystal in these rocks has an older core. The zircon saturation temperatures calculated for the most mafic rocks of the Bullenbalong Suite in the LFB are  $810 \pm 20^\circ\text{C}$ . An estimate that 45% of the zircon in those rocks is inherited has been used earlier (see section 4), and on the basis of correspondingly lower Zr contents, the calculated zircon saturation temperatures would be less than  $750^\circ\text{C}$ . All of these temperature estimates are far too low for these mafic but quartz-rich rocks to have been completely molten. Once again, these data show that the melt component of the Bullenbalong Suite was quite felsic and the mafic rocks have that character because of the presence of abundant entrained restite. Also again, these calculated temperatures are limiting values and do not tell us the actual temperature of any melt.

### 5.3. The low- and high-temperature granite subdivision

Following Chappell *et al.* (1998), the present authors recognise a fundamental subdivision of granites into those of low- and high-temperature origin, based on the presence or absence of inherited zircon in relatively mafic rocks of a suite, and shown in many cases by distinctive patterns of compositional variation (see sections 1 and 2) and some petrographic features (see section 7). While this subdivision is based on studies in eastern Australia, it is much more widely applicable. I-type granites may belong to either group, but in the authors' experience, all S-type granites are low-temperature, based on the ubiquitous presence of older zircon, even in the less felsic rocks. A-type granites, as recognised in the LFB, and peralkaline rocks are regarded as high-temperature, but they are distinguished as such using different criteria (see section 5.4). Zircon saturation is a function of both the bulk composition of the melt and temperature, so that the distinction between all low- and high-temperature granites would not be at a specific temperature. However, temperature rather than composition is the dominant parameter in determining whether or not zircon would be saturated in melts of various metaluminous granitic compositions.

Overall, low-temperature granites appear to dominate over high-temperature granites, but the relative proportions of the two in various regions does vary widely. About 95% of the plutonic rocks of the LFB are low-temperature, and the figure for the extensive areas of granite in all of eastern Australia would be similar. Likewise, they dominate among the Caledonian granites of Scotland and Ireland, and the largest

granite complex of that region, the Leinster granite, is S-type. That is also the case in regions in which S-type granites are common, such as the European Hercynian and Southeast Asia. On the other hand, high-temperature granites dominate throughout the Cordillera, and among the plutonic rocks of island arcs of varying maturity, such as New Britain and Japan.

The more felsic rocks of high-temperature suites may crystallise from melts that developed at high temperatures. An example is provided by the felsic rhyolites of the Mountain Creek Volcanics of the BPS, which have  $\text{SiO}_2$  contents up to 73.5% and were erupted at temperatures above  $1000^\circ\text{C}$  (see section 6). Many of the felsic granites of the BPS would have formed from melts that were initially produced by fractional crystallisation at similar temperatures. But felsic granites that formed from melts produced by the fractionation of high-temperature melts to progressively lower temperatures are regarded as part of a high-temperature suite. Such felsic rocks are petrogenetically distinct, and should, in detail, be compositionally different from those that crystallised from melts produced by partial melting of older source rocks at low magmatic temperatures or by the fractional crystallisation of such partial melts.

Granites and related volcanic rocks form from magmas which can exist over a wide range of temperatures. Whitney (1988), for example, has estimated the temperature of partial melting involving the breakdown of different hydrous minerals. Tuttle & Bowen (1958) showed that, if free water is available,  $\text{H}_2\text{O}$ -saturated granitic melts may form by partial melting of quartzofeldspathic rocks in the middle and lower crust at temperatures as low as  $630^\circ\text{C}$  (Johannes & Holtz 1996). Rather felsic peraluminous melts may form, often in relatively small quantities, as a result of partial melting involving the breakdown of muscovite at temperatures below about  $750^\circ\text{C}$ . Production of more voluminous granites, such as the batholithic S-type granites of the LFB (White & Chappell 1988), corresponds to the breakdown of biotite, and melts would have had temperatures from about  $750$  to  $850^\circ\text{C}$ . The production of some I-type granites at lower temperatures could likewise be dominated by the destruction of biotite, and in this context, it should be noted that the most felsic I-type granites are almost universally weakly peraluminous (Chappell & White 1974). More mafic I-type granite magmas that have formed at these lower temperatures are metaluminous because of the presence of entrained restite. The production of I-type granite melts could continue to higher temperatures through the dehydration melting of hornblende. At some point, zircon would be soluble in the more mafic melt compositions and high-temperature granite melts are then being produced. Geothermometry on both the plutonic and volcanic rocks of the high-temperature BPS in the LFB indicates that at least some of those rocks formed at temperatures higher than  $1000^\circ\text{C}$  (see section 3.2). Hence, a range of temperatures of close to  $400^\circ\text{C}$  is indicated for the formation of those rocks broadly regarded as granitic.

Given that granite forms from magmas that exist over such a wide range of temperatures, it is reasonable to ask why they should be subdivided on the basis of temperature, given that all gradations of temperature within that range must have existed. The present authors propose this subdivision because the differences in temperatures of formation of the two groups correspond to significant diversity in other physical features of the magmas, in the compositions of the melt phase and in the mechanisms by which the granites evolve compositionally. At least in the early stages of their evolution, the high-temperature magmas are completely or largely molten, whereas the low-temperature magmas not only contain crystals of inherited

zircon, but also of other restite minerals, immersed in a relatively felsic melt. In the latter case, the magmas change in composition, at least initially, by the fractionation of restite, in complete contrast to the high-temperature magmas that may evolve by fractional crystallisation. Consequently, the high-temperature granites are more prospective for associated mineralisation. Also, as Wyborn & Chappell (1986) pointed out, the granites that we now assign to these two groups have distinctly different compositional relationships with any associated volcanic rocks (see section 6). For these reasons, the low- and high-temperature division has a much broader significance than simply differences in temperature, and therefore, it is worthwhile making this distinction.

The temperature at which the transition from low- to high-temperature granites, defined on the basis of zircon saturation, occurs is not precisely known, for many reasons. The slow cooling of plutonic rocks means that possible geothermometers are reset to lower temperatures. The understanding of the relationship between volcanic and plutonic rocks has not yet reached the stage where the temperatures of volcanic rocks can be widely used. The primary compositions of high-temperature magmas are not known if that magma fractionated into cumulate rocks and more felsic melts. In cases where the mafic high-temperature magmas did not fractionate, they are not saturated in zircon, so the zircon saturation temperature cannot be used. Neither is their precise H<sub>2</sub>O content known, which is needed for the liquidus temperature to be estimated.

Low-temperature granite magmas containing a minimum-temperature melt that is generally not saturated in H<sub>2</sub>O are produced up to temperatures of 800–850°C, and correspond to the breakdown of muscovite, if present, and biotite. The non-minimum-temperature magmas are formed at higher temperatures (see section 9.1) as the incongruent melting of hornblende progressively supplies H<sub>2</sub>O to the melt, in which zircon is still saturated. In the LFB, temperatures in excess of 1000°C have been measured for both plutonic and volcanic rocks of the BPS (see section 3.2) would certainly apply to many other high-temperature granites, but the lowest temperature at which such rocks could form is not known at present.

#### 5.4. A-type granites

The least-fractionated A-type granites of the LFB have very high Zr contents (~500 ppm) with calculated zircon saturation temperatures ~900°C. Therefore, they are regarded as high-temperature, although it is possible that those granites have high Zr contents because they crystallised from relatively dry melts and zircon saturation is dependent on water content (P. L. King, pers. comm.). Because these rocks do not generally extend to compositions much less felsic than 70% SiO<sub>2</sub>, they are not distinguished as high-temperature using the criteria given in the previous section. The metaluminous to weakly peraluminous A-type granites have been referred to as the 'high-temperature felsic granites' by King *et al.* (2001). The A-type granites can be distinguished, when unfractionated, as evidenced by high Ba contents, by greater abundances of high-field-strength elements, such as Zr. In the LFB, the most Zr-rich unfractionated A-type granites are those of the Gabo Island Suite (Collins *et al.* 1982) and the least felsic rocks of the Danswell Creek Suite (King *et al.* 2001). The Gabo Island rocks are relatively uniform in composition, with an average Zr content of 490 ppm at 73% SiO<sub>2</sub>, and calculated zircon saturation temperatures in the range 893 ± 10°C. The least felsic sample of the Danswell Creek Suite contains 535 ppm Zr at 70.5% SiO<sub>2</sub>, corresponding to a calculated zircon saturation temperature of 897°C. It is likely that most A-type granites

crystallised from melts that were only just saturated in zircon. As with more mafic high-temperature I-type granites, older zircon is probably not present in these rocks.

Peralkaline rocks are classified as A-type in some literature, as indeed they were when the term A-type was originally used by Loiselle & Wones (1979). Such a grouping is not favoured here (King *et al.* 1997) because peralkaline rocks themselves have distinctive and unique compositional features that are fundamentally different from those of the peraluminous to metaluminous granites that are regarded here as A-type. Peralkaline rocks typically have very high abundances of Zr, and are known to form at high temperatures, based on the geothermometry of volcanic rocks. However, it is not possible to examine Zr content relative to zircon-saturation in these rocks because the details of that relationship are unknown.

#### 5.5. Origins of the low- and high-temperature granites

The origins of the low- and high-temperature granite groups, and the reasons for their existence, are examined in some detail by Chappell (2004) and will only be considered briefly here. The high-temperature granites, other than the A-types, are the more compositionally primitive group. They result from partial melting in the deep crust, or perhaps in modified mantle, of mafic rocks that are, in general terms, basaltic or dioritic to monzonitic in composition. They represent a relatively juvenile addition to the upper parts of the crust. Partial melting of lower-K source rocks produces the dominantly tonalitic to low-K granodioritic Cordilleran-like rocks that Pitcher (1982) referred to as Cordilleran I-types and Chappell & Stephens (1988) termed tonalitic I-types. The Clarence River Supersuite of Bryant *et al.* (1997), including the Towgon Grange pluton, is an example. While such rocks are characteristic of Cordilleran-like igneous activity, they are also found less commonly in more mature continental regions; for example, the Marulan Suite of the LFB. In that environment, they could be associated with granites with higher K contents derived from more K-rich source rocks, such as those of the Boggy Plain Supersuite (Wyborn *et al.* 2001). Chappell (2004) ascribed the origin of the high-temperature granites to depletion during partial melting of a haplogranite component, i.e. *Qz* (tonalites and quartz diorites), *Or* (monzonites and monzodiorites) or H<sub>2</sub>O (A-type granites).

Low-temperature I-type granites are the products of partial melting of quartzofeldspathic source rocks in which all haplogranite components are available throughout melting. These sources may themselves have been of high-temperature origin. They are the Caledonian I-types of Pitcher (1982) or the granodioritic I-types of Chappell & Stephens (1988). Production of these granites represents a recycling of older components of the crust, and they may be spatially closely associated with S-type granites as they are in parts of the LFB (Chappell *et al.* 2000).

#### 5.6. 'Hot' and 'cold' granites

Miller *et al.* (2003) have proposed 'hot' and 'cold' groups of granites, but these are not equivalent to the two groups that are being discussed here. Those two groups are probably both within this paper's low-temperature variety, and the data set of Miller *et al.* (2003) does not seem to include representatives of the high-temperature granites. In cases where Miller *et al.* (2003) had ion-microprobe data and images of internal zoning, the boundary between their two groups was set at ~10% of grains with cores, whereas here, except for the Zr-saturated members of fractionated high-temperature suites, a single older core would be taken as evidence for zircon saturation and the rock would be assigned to the low-temperature group.

**Table 3** Petrographic characteristics of low- and high-temperature granites containing ~60% SiO<sub>2</sub>

Low-temperature	High-temperature
Heterogeneous–mafic aggregates or clots	Even distribution of mafic minerals
Some rocks have large crystals of quartz	Quartz is commonly interstitial
Plagioclase crystals have corroded calcic cores (up to An <sub>80</sub> ) with rather uniform compositions	Calcic cores in plagioclase absent or rare. Zoning normally throughout crystals
Most rocks have randomly oriented crystals of plagioclase	Rare and weak parallel orientation of tabular plagioclase crystals
Mostly poorly shaped mafic minerals with rare and small relict clinopyroxene crystals in hornblende	Large tabular hornblende crystals dominated by relicts of partly reacted clinopyroxene

In addition to data on zircons, the present authors also make use of patterns of Zr variations in rock suites as indicators of zircon saturation. The detailed relationship between the present subdivision and that of Miller *et al.* (2003) remains to be elucidated.

## 6. Volcanic rocks

The granites of the LFB are closely associated in time and space with volcanic rocks. Two types of volcanic rocks can be recognised: those associated with granites that evolved dominantly by restite fractionation; and those related to granites which evolved by fractional crystallisation. These are the low- and high-temperature volcanic rocks, and most of the comments that have been made earlier about the two groups of granites also apply to these rocks.

The chemical compositions of some I- and S-type granites and relatively fresh volcanic rocks of the LFB can be matched very closely. This is seen for low-temperature suites, for which the associated volcanic and plutonic rocks have essentially the same range of compositions (Wyborn & Chappell 1986). For example, S-type volcanic rocks of low-temperature origin are widespread around Canberra. The range of aluminum saturation seen in the S-type granites is mirrored in the volcanic rocks. Strongly peraluminous volcanic rocks with ubiquitous phenocrysts of cordierite can be matched chemically with granites of the Bullenbalong Supersuite. Other weakly peraluminous volcanic rocks do not contain cordierite, and can be matched in composition with adjacent weakly peraluminous S-type granites of the Shannons Flat and Dalgety suites (Wyborn *et al.* 1981). To the east of Canberra, I-type volcanic rocks which are porphyritic in both ortho- and clinopyroxene can be matched closely in composition with I-type granites of the Bega Batholith (Wyborn & Owen 1986). The volcanic rocks of these suites, both I- and S-type, are invariably porphyritic, with the bulk of the phenocrysts (30–60%) being interpreted by the present authors as crystals of restite (Wyborn & Chappell 1986). Phenocrysts of plagioclase have compositions that match those of the relatively uniform plagioclase cores in granites of the same suite, with few outer zones seen in the volcanic phenocrysts.

The high-temperature volcanic rocks of the BPS are sparsely phytic (<10% phenocrysts) rhyolites with minor associated andesites and basaltic andesites. These compositions are exclusively I-type, and the rhyolites complement the more mafic cumulate granites of that supersuite. The rhyolites were derived from the felsic tops of magma chambers that evolved through convective fractionation (Wyborn *et al.* 2001). They erupted at very high temperatures, with temperatures determined by magnetite-ilmenite thermometry, for example, commonly in excess of 1000°C for the rhyolites of the Mountain Creek Volcanics of the BPS (Wyborn & Chappell 1986).

## 7. Petrographic differences between low- and high-temperature granites

There are distinctive petrographic differences between the low- and high-temperature granites. These have been discussed by White & Chappell (2004) and are summarised for rocks with SiO<sub>2</sub> contents close to 60% in Table 3. High-temperature granites have a more uniform distribution of mafic minerals, which is apparent in both hand sample and thin-section. This feature extends to granites of higher SiO<sub>2</sub> contents. The mafic minerals in low-temperature granites occur in aggregates and clots, which represent recrystallised crystals of primary restite (Chappell *et al.* 1987). At compositions around 60% SiO<sub>2</sub>, quartz occurs as larger crystals in the low-temperature granites, whereas it is interstitial in the high-temperature rocks.

When new plagioclase is produced by melt-forming reactions in the source rocks, this is likely to be in equilibrium with the melt because of increased reaction rates with rising temperatures. In low-temperature granites, plagioclase crystals are likely to be retained in the magma and will appear in a granite as uniform cores within strongly zoned outer parts, or as uniform phenocrysts in volcanic rocks. These cores may be quite calcic, near An<sub>80</sub>, because of the flattening of the plagioclase loop in the presence of quartz (White & Chappell 2004). The first plagioclase to crystallise from the melt will have a similar composition. With slow cooling, early-formed plagioclase will be progressively made over to more sodic plagioclase. However, local disequilibrium is more likely with falling temperatures, leading to the preservation of corroded early plagioclase and complex zoning. This explanation is consistent with experimental findings showing that plagioclase is a particularly difficult mineral to re-equilibrate with a melt at temperatures near the lower end of the range for granite magmas (Baschek & Johannes 1995). Disequilibrium relationships in plagioclase are always seen in low-temperature granites, but are much less common in the high-temperature granites where continuous zoning from the crystal centre to rim is typical.

## 8. Implications for mineralisation

In general, high-temperature granites are much more likely to be related to mineralisation, for the following reasons:

- (1) During the partial melting process at higher temperatures, the solubility of trace metals in the melt will be greater than at lower temperatures.
- (2) Granite suites that evolve by fractional crystallisation concentrate incompatible trace metals at that magmatic stage, enhancing the probability of the later significant mineralisation (Blevin & Chappell 1992). High-temperature suites, particularly those that are monzonitic rather than tonalitic, are more likely to undergo

fractional crystallisation, which may increase the abundances of some rare elements in the evolving melt, but will also cause the abundances of others to decrease.

- (3) H<sub>2</sub>O contents of the melts will also increase with such fractionation, so that mineralising fluids are more likely to be released (cf. the low-temperature suites as discussed by White 2001).
- (4) High-temperature magmas are also largely molten magmas, and because of both the higher temperatures and that larger fraction of melt, will have a higher heat capacity and would introduce more heat into the country rocks during cooling.

This situation is illustrated by the granites of the LFB in which the Silurian to Carboniferous granites, which are dominantly low-temperature, are generally not associated with significant mineralisation, except for Sn-W in Tasmania and less important Sn associated with the Wagga Batholith (Blevin & Chappell 1992). In contrast, Ordovician-age high-temperature intrusive rocks in the northern LFB, typically high-K in character, are associated with major Cu-Au porphyry type mineralisation. For S-type granites, this is illustrated by Sn mineralisation associated with the Bullenbalong and Koetong suites of the LFB (Chappell 1996b). The Koetong Suite formed at slightly higher temperatures, and probably for that reason, the primary melt underwent fractional crystallisation after restite had been removed (Chappell & White 1998), so that Sn contents rose to a maximum measured level of 47 ppm. The more mafic granites of the Bullenbalong Suite are similar to Koetong in composition, but only one analysed sample shows slight effects of fractional crystallisation at felsic compositions with a Sn content of 10 ppm. These differences correlate with the reported amounts of Sn obtained from the areas in which those two groups of rocks are found, <10 t for Bullenbalong and ~5 kt for Koetong.

The better understanding of the low- and high-temperature granite groups that we are now developing, along with more criteria to recognise them, should have important implications for mineral exploration.

## 9. The future: Possible subdivisions of the low- and high-temperature granites?

The present authors have been aware for some time that it will probably be desirable at some stage to make a distinction between two groups within what are here termed low-temperature granites. In assembling and assessing information for this paper, it has likewise become apparent that two distinct groups of high-temperature granites are likely to emerge from further consideration of the data. Such subdivisions and their significance will be a fruitful area for future research and they will now be considered briefly.

### 9.1. Possible subdivision of the low-temperature granites

The present authors have long known of two distinct groups of granites that are both low-temperature in origin. No attempt has been made to formally subdivide these granites in this paper because, at this stage, the best criteria for distinguishing them are uncertain and have yet to be determined. These are what have previously been called minimum-temperature melt and non-minimum-temperature melt granites (Hine *et al.* 1978). All of these are low-temperature, they contain older crystals of zircon, and they are characterised by 'linear' compositional variations and evolve chiefly through the fractionation of restite. I- and S-type granites occur in both of these groups. The composition of the primary melt for the non-minimum temperature granites is less felsic and may

evolve through fractional crystallisation after restite has been removed as, for example, in the S-type Koetong Suite (Chappell & White 1998). Among I-type granites, the Jindabyne Suite, and probably the Inlet Suite, in Figures 1, 2 and 3 are of this type. When satisfactory criteria to distinguish these two groups are developed, those formed at higher temperatures could be termed 'intermediate-temperature', or perhaps, 'transitional' granites.

### 9.2. Possible subdivision of the high-temperature granites

It is becoming apparent that there are also two distinct groups within the high-temperature granites, in this case resulting from compositional differences rather than temperatures of origin. It is likely that these compositional differences, which reflect corresponding features of the source rocks, cause these two groups of granites to evolve in quite different ways. The present work has been very much influenced by the presence of the BPS in the LFB, and features of that supersuite have been discussed at some length in this paper. Fractional crystallisation was the dominant process that produced a wide range of compositions, with distinct differences between the compositions of plutonic and volcanic rocks. In contrast, Silver (2003) reported that the volcanic rocks of the western Peninsular Ranges batholith, which are most commonly basaltic andesite, low-K andesite and sodic rhyolites, have relative abundances that are comparable to the most common plutonic rocks of that area. L. T. Silver (pers. comm.) also points out that the plutons of that batholith are compositionally uniform (in contrast again to the BPS), and has proposed that the compositional differences within the rocks of that batholith are a consequence of different degrees of partial melting, rather than fractional crystallisation. Observations such as these may eventually form a basis for subdividing the high-temperature granites into high-K and low-K or tonalitic groups, which evolve compositionally in different ways.

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