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Two contrasting granite types: 25 years later

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The concept of I- and S-type granites was introduced in 1974 to account for the observation that, apart from the most felsic rocks, the granites in the Lachlan Fold Belt have properties that generally fall into two distinct groups. This has been interpreted to result from derivation by partial melting of two kinds of source rocks, namely sedimentary and older igneous rocks. The original publication on these two granite types is reprinted and reviewed in the light of 25 years of continuing study into these granites.

KEY WORDS: Berridale Batholith, I-type granite, Kosciuszko Batholith, Lachlan Fold Belt, S-type granite.

INTRODUCTION

Chappell and White (1974) first proposed the subdivision into I- and S-type granites principally on the basis of studies in the relatively restricted Berridale–Kosciuszko region of the Lachlan Fold Belt. However, we had seen sufficient other granites in the Lachlan Fold Belt to say that the two contrasting types 'are of widespread occurrence' in the belt. The general contrast between the more mafic representatives of the two types of granites in the Berridale and Kosciuszko Batholiths is dramatic. There are some felsic granites of both types, which comprise subequal amounts of quartz, K-feldspar and plagioclase, as the work of Tuttle and Bowen (1958) would lead one to expect, and hence do not provide a strong signal from their source rocks. The more mafic rocks are generally very distinct, comprising the traditional hornblende-bearing I-types on the one hand and the cordierite-rich S-types on the other. The presence of two groups of granites in the Snowy Mountains had long been recognised (see discussion in Chappell & White 1992), but the parameters used to distinguish them were uncertain and their significance was not understood. Browne (1929) and then Joplin (1962) demonstrated that there are compositional differences, with the gneissic Cooma type having the lowest, and the 'massive' types the highest, CaO and Na_2O contents. The key that unlocked this mystery was the restite model (White & Chappell 1977), because it provided a good explanation of why these two types of granites occur and implies that the distinctive compositional features of those granites were inherited from their source rocks. While publication of the I- and S-type subdivision preceded our initial publication about, and naming, the restite model (White & Chappell 1977), the idea that granites may have compositions that closely reflect those of their source rocks, had been part of our thinking for some time (Chappell 1966).

Our understanding of the relationship between granite and source rock compositions led to the recognition of the I- and S-type groups early in 1973. We were urged by Paul Bateman, who saw these rocks in the field later that year, to summarise these ideas for the meeting of IGCP Project 30 (Circum-Pacific Plutonism) held in Santiago, Chile, in September 1973. The extended abstract for that presentation was published in the 1974 volume of papers from that meeting (Chappell & White 1974).

The 1974 extended abstract has been extensively referenced in the granite literature, with approximately 750 citations over 25 years. However, it is likely that many, if not most persons, who have referred to the publication have in fact not seen it because the journal ceased publication shortly afterwards. Those persons were recognising the general concept of granites of contrasting properties being derived from sedimentary or older igneous rock sources. Both for the benefit of those who have not seen the original publication on I- and S-type granites, and as a basis for assessing it 25 years later in this contribution, the text is repeated here.

THE 1974 EXTENDED ABSTRACT

Granites of the major batholiths of the Tasman Orogenic Zone of eastern Australia are of two contrasting types which are of widespread occurrence and which may be distinguished by chemical, mineralogical, field and other criteria. We interpret these granites as being derived by partial melting of two different types of source material—igneous and sedimentary. Differences in the derived granites are inherited from the source rocks so that we recognise an I-type and S-type respectively.

Some of the distinctive chemical properties of the two types are shown in the following table:

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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 approx. 5% K_2O, decreasing to <2.2% in rocks with approx. 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 near-linear variation diagrams	Variation diagrams more irregular

These chemical properties result from the removal of sodium into sea water (or evaporites) during sedimentary fractionation, and calcium into carbonates, with subsequent relative enrichment of the main sedimentary pile in aluminium. S-type granites come from a source that has been subjected to this prior chemical fractionation.

Petrographic features reflect the differences in chemical composition. Hornblende is common in the more mafic I-types and generally present in felsic varieties, whereas hornblende is absent, but muscovite is common, in the more felsic S-types; biotite may be very abundant, up to 35%, in more mafic S-types. Sphene is a common accessory in the I-type granites whereas monazite may be found in S-types. Aluminosilicates, garnet and cordierite may occur in S-type xenoliths or in the granites themselves. All of these features result from the high aluminium content relative to alkalis and calcium in S-type granites and the converse in I-types. Apatite inclusions are common in biotite and hornblende of I-type granites whereas it occurs in larger discrete crystals in S-types.

Detailed studies in the Berridale Batholith (Compston, Shirahase, Chappell & White *in preparation*) have shown that strontium is more radiogenic in S-type granites (initial Sr^{87}/Sr^{86} >0.708) because their source rocks had been through an earlier sedimentary cycle. I-types have initial Sr^{87}/Sr^{86} ratios in the range 0.704–0.706. Isochrons of I-types show a regular linear set of points whereas those of S-types show a scatter of points within a broad envelope, reflecting variations in the initial Sr^{87}/Sr^{86} within a single pluton as a consequence of more heterogeneous source material.

Field relationships of the two types may be distinctive. More mafic I-types contain mafic hornblende-bearing xenoliths of igneous appearance whereas hornblende-bearing xenoliths are rare in the S-types but metasedimentary xenoliths may be common. When both types occur together in composite batholiths the S-types are usually early in the intrusive sequence and they often have a strong secondary foliation truncated by later I-type intrusions which are either massive or have a dominant primary foliation.

Economic minerals are also different in their association with the two types. Tin mineralisation appears to be confined to highly silicic S-type granites whereas tungsten and porphyry-type copper and molybdenum deposits are associated with I-types.

DISCUSSION OF THE 1974 ABSTRACT

The 1974 publication was written approximately 6 months after we recognised the significance of the two granite types in a small area of the Lachlan Fold Belt, and the ideas that it incorporates were brought together rather quickly. As we have been progressively examining the granites over the whole of the Lachlan Fold Belt for another 25 years, and as our understanding of the genesis of those rocks has developed substantially during that time, we reflect here on those initial concepts and trace their later development. We have published two general papers on the I- and S-type granite subdivision since the 1974 extended abstract (Chappell & White 1984, 1992).

Is the Berridale–Jindabyne area typical of the Lachlan Fold Belt?

It was both fortuitous and fortunate that our studies on the Lachlan Fold Belt granites commenced in the Berridale Batholith. That batholith had been known to contain a variety of granites, some of which had been shown to us by Tom Vallance, and its composite nature was confirmed by the mapping of Lambert (1963). He recognised the major components of the batholith that we subsequently termed S-type, the Cootralantra and Dalgety Granodiorites, and also part of the felsic I-type Buckleys Lake pluton, which is one of the largest plutons in the Lachlan Fold Belt, and the very felsic Wullwye pluton. Black (1965) was the first to map a hornblende-bearing granite in the batholith, the Tara Granodiorite. Mapping of the Berridale Batholith (1670 km^2) was completed within a few years and it was seen to be comprised of approximately equal amounts of what we later termed I- and S-type granites. The sedimentary screen that extends down much of the axis of the batholith separates exclusively I-type granites to the east from dominantly S-type granites to the west; this was later termed the I–S line by White *et al.* (1976a). Detailed mapping in the Kosciuszko Batholith near Jindabyne commenced in 1968. Granites of that area include the 'foliated' and 'massive' types of earlier workers, and the compositional distinction between those two types was confirmed by Hine *et al.* (1978).

In many ways, the Berridale Batholith and the Jindabyne region were ideal places to start our studies of granites of the Lachlan Fold Belt. The Berridale granites comprise a variety of both I- and S-types, while those of the Kosciuszko Batholith are sharply divided into rocks of very distinct I- or S-type character. There is no other place in the Lachlan Fold Belt where such features are so well developed in such a relatively small area, and in that sense it is not typical. However, these I- and S-type characteristics have subsequently been found in many other parts of the Lachlan Fold Belt. Fortunately, the initial area straddles the I–S line, which is the most prominent boundary between granites of generally I- or S-type character in the Lachlan Fold Belt. Inevitably, features are seen elsewhere in the Lachlan Fold Belt that are not present in such a small part of it. Most notably, these include the high-temperature granites of the Boggy Plain Supersuite, which Owen and Wyborn (1979) recognised initially further north in the

Kosciuszko Batholith, and the fractionated granites, such as those of the Koetong Suite (Chappell & White 1998) and Tasmania (Chappell 1999). All of the granites that were initially studied in the Berridale and Jindabyne areas are low-temperature, unfractionated types in the current idiom, which dominate in the Lachlan Fold Belt. White *et al.* (1976b, 1977, 1989) and White and Chappell (1989) have published detailed maps and explanatory notes on all of the granites of the Berridale and eastern part of the Kosciuszko Batholiths.

Sodium and calcium contents of I- and S-type granites

The sodium contents of the I- and S-type granites are relatively high and low, respectively, as noted by Chappell and White (1974). However, the limits that were then set for the groups are not applicable over the complete Lachlan Fold Belt, so that as a whole there is overlap, as shown in Figure 1. Among the S-type granites of the Berridale and Kosciuszko Batholiths, components of the S-type Bullenbalong Supersuite tend to be relatively mafic and low in Na_2O. However, granites of the Dalgety Granodiorite of the Berridale Batholith, which are on the whole relatively felsic, also contain more Na_2O than Bullenbalong at comparable Fe contents. We have grouped those rocks with the Wyangala and Shannons Flat Granodiorites in a Wyangala Supersuite, whose origin we ascribe to derivation from less mature sedimentary source rocks that contained more feldspar. There are also S-type granites, assigned to the Cooma Supersuite, that were derived from source rocks that were more mature than those that produced the Bullenbalong Supersuite (White & Chappell 1988). Hence, one important outcome of continuing studies of the Lachlan Fold Belt is that the S-type granites were apparently obtained from source materials with a range of feldspar contents, of which the granites studied prior to 1974 were not completely representative. Of the 751 S-type granites of the Lachlan Fold Belt plotted on the K_2O *vs* Na_2O diagram in Figure 1, 91 (12.1%) have Na_2O contents lying above the limit set in the 1974 publication, shown on the figure.

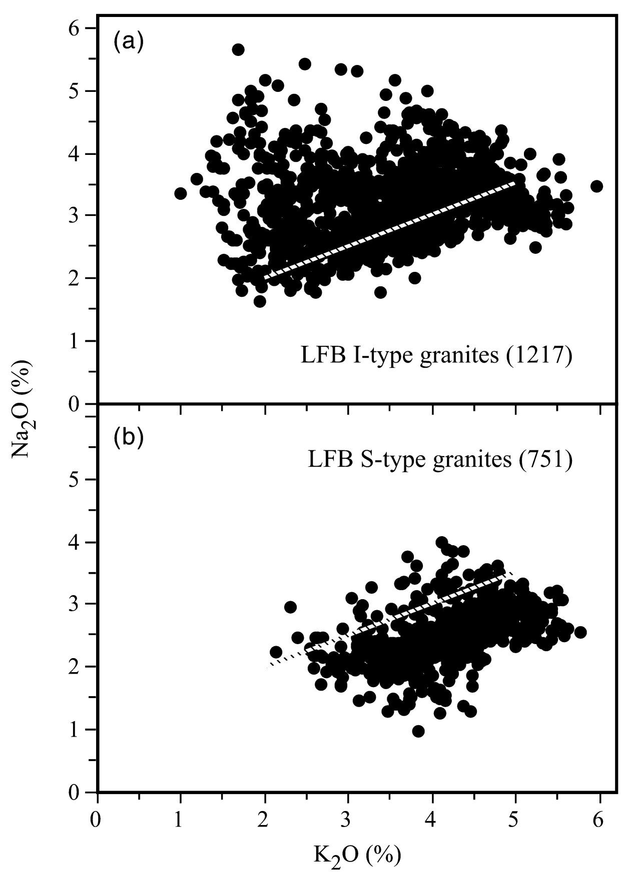

Figure 1 Na_2O *vs* K_2O for (a) 1217 I-type and (b) 751 S-type granites of the Lachlan Fold Belt (LFB). Only rocks containing >57% SiO_2 are plotted, thus excluding I-type gabbros and gabbroic diorites. The line shown on both plots joins the points 2% K_2O, 2% Na_2O and 5% K_2O, 3.5% Na_2O, which was given by Chappell and White (1974) as a boundary between the two types.

Likewise, there are granites in the Lachlan Fold Belt that we regard as I-type, which have Na_2O contents lower than the limits originally recognised by Chappell and White (1974). The suites at the western edge of the Bega Batholith, such as Glenbog and Tonghi, are the most prominent examples of these. In Figure 1, 20.4% of the I-type granites have Na_2O contents less than the 1974 limit.

The compositions of felsic granites, of any origin, including their Na_2O contents, converge towards the low-temperature melt composition of Tuttle and Bowen (1958). This convergence accounts for some of the overlap between the I- and S-type Na_2O contents, but there is still a degree of overlap among the less felsic rocks, which must to some extent reflect similarities in the Na_2O contents of the source rocks. Another factor could be that these compositions are those of rocks and not necessarily precisely those of magmas (allowing for the loss of volatiles). In particular, any movement of Na during alteration of a rock could obscure primary magmatic features.

Chappell and White (1974) probably overstressed the role of Na in distinguishing the I- and S-type granites. For the initial study area of the Berridale and Kosciuszko Batholiths, Ca is a much better discriminant, as is seen in Figure 2. That figure plots all currently available CaO and total FeO data for those two batholiths and shows that the complete separation between the two granite types, for these two components, has been maintained with the additional data. Such a separation is, however, not found over the whole of the Lachlan Fold Belt; Figure 3 shows that while the I-type granites tend to have higher CaO contents at a given total FeO content, there is some overlap particularly among the more felsic rocks. At high total FeO contents, the CaO contents of the two types diverge, as the compositions of the granites approach those of their distinctive source rocks. The very low and characteristic Ca contents of the S-type granites of the Cooma Supersuite are clearly shown on that diagram as a series of compositions at approximately 1% CaO with varying total FeO contents that diverge from the main trend.

As a group, the S-type granites are depleted in Na, Ca and Sr relative to the I-types, because those three elements are lost in solution when feldspars are weathered to clay minerals. They also contain somewhat higher amounts of K, Rb and Pb, three elements that are incorporated into clay minerals, either during weathering or by subsequent

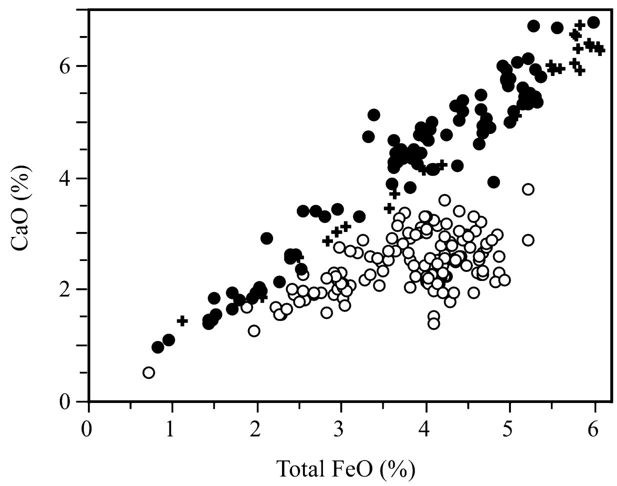

Figure 2 CaO *vs* total FeO for all 251 analysed granites and related rocks of the Berridale and Kosciuszko Batholiths that contain <6.1% total FeO. When the Boggy Plain Supersuite is excluded, these represent the current data for the granite suites from which Chappell and White (1974) proposed the I- and S-type subdivision. Seventeen of 43 Boggy Plain rocks containing >6.2% total FeO, and one other I-type granite having 6.81% total FeO and 8.10% CaO, are not shown: +, Boggy Plain Supersuite (26 analyses); ●, other I-type granites (88 analyses); ○, S-type granites (137 analyses).

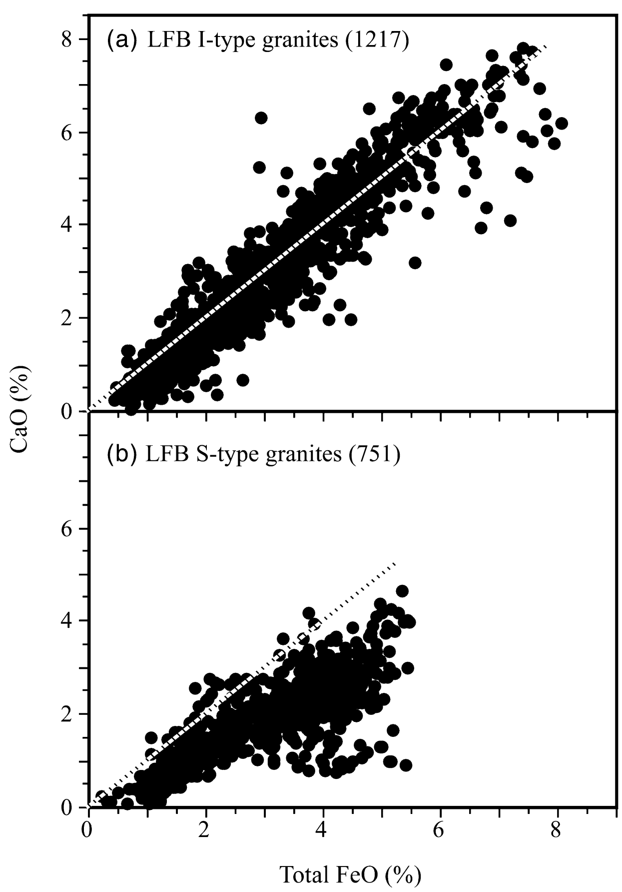

Figure 3 CaO *vs* total FeO for all available analyses of (a) I- and (b) S-type granites of the Lachlan Fold Belt (LFB). The line on both figures represents compositions with equal wt% CaO and total FeO.

reactions of clays with seawater. One important compositional difference between the two types, not noted in 1974, is that as a group, the S-type granites are more reduced with respect to oxygen fugacity. Flood and Shaw (1975) suggested that the more reduced nature of an S-type granite suite from the New England Batholith was the result of graphite in the source rocks, a view that is generally accepted. However, subsequent work has shown that in some regions, such as around Melbourne, the I-types are also strongly reduced. Chappell and White (1992) have discussed in detail the chemical compositions of the two granite types.

Relative saturation in aluminium

As a consequence of the lower Na and Ca contents, the S-type granites are always oversaturated in Al, or peraluminous, and that is the case also for the more felsic I-type granites. Chappell and White (1974) recognised this in drawing their boundary between the I- and S-types, with a limiting value for the Aluminium Saturation Index (ASI: Zen 1986) of 1.1, or 1% normative corundum. Chappell and White (1992) pointed out that at the most mafic compositions, those that are closest to the source rocks in composition, there is no overlap in ASI between the I- and S-types (Figure 4). As granites become more felsic, the ASI values converge so that the most felsic unfractionated I-type granites have values of 1.0–1.1, which overlap with S-type values ranging from 1.01 to 1.25 (Chappell 1999 figure 3). The fact that the Al-saturation values converge, and eventually overlap in felsic rocks, is of no consequence as far as the I–S division is concerned, because a small degree of Al-oversaturation is intrinsic to all of the most felsic granitic melts. Chappell and White (1974) found a complete break in ASI values for the two types in samples that they had studied to that time, but we now know that such a clear separation is not seen throughout the Lachlan Fold Belt.

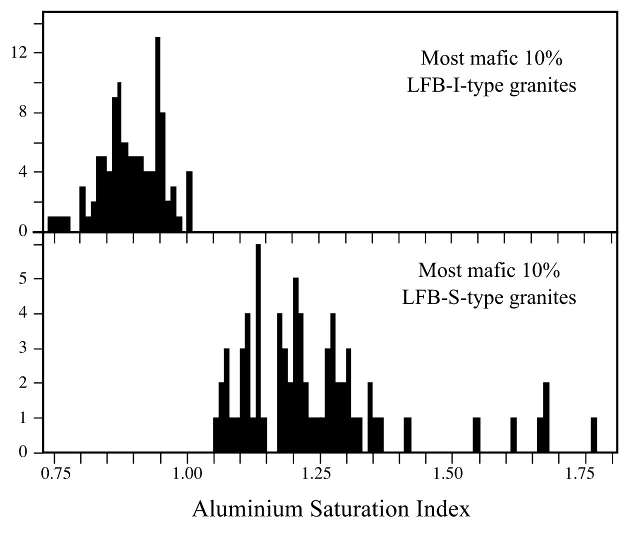

Figure 4 Aluminium Saturation Index (ASI) values for low-temperature granites of the Lachlan Fold Belt (LFB) (from Chappell 1999). Data are for the most Fe-rich 10% of I-type (103) and S-type (76) granites. Data for the high-temperature I-type granites of the Boggy Plain Supersuite are not included because the more mafic rocks of that supersuite are mainly cumulate rocks and the most mafic 10% of the total samples all have ASI values less than 0.71.

Chappell (1999) pointed out that almost half (46.5%) of all samples of I-type granites from the Lachlan Fold Belt, exclusive of the Boggy Plain Supersuite, are peraluminous. The extent of the Al-oversaturation of what we now classify as low-temperature I-type granites (Chappell *et al.* 1998) is emphasised here. Chappell and White (1974) were well aware that felsic granites derived from older metaluminous igneous source rocks are commonly peraluminous. This was one reason for suggesting the terminology I- and S-type, using terms not directly related to Al-saturation, rather than more cumbersome terms, such as the 'peraluminous metasediment-derived types' of Wall *et al.* (1987).

Barbarin (1999) has recently reviewed the nomenclature of different granite types. He placed the I-type granites in the metaluminous field of Shand (1927) and also extended the S-type granites into the metaluminous field. Those placements are incorrect. Barbarin (1999) also stated that most I-type granites of the Lachlan Fold Belt belong to his type ACG, which also comprises the main components of the Cordillera, which again is incorrect. Barbarin (1996) had earlier proposed two groups of peraluminous granites, the MPG (muscovite-bearing) and CPG (cordierite-bearing), and ascribed different origins to the two groups. Chappell *et al.* (1998) discussed those subdivisions as they apply to the Lachlan Fold Belt, and pointed out that they can have a close genetic relationship in that region. Those MPG granites that are S-type represent a more advanced stage of evolution where fractional crystallisation of largely anhydrous minerals has enriched the melt in H_2O.

Range of compositions

Chappell and White (1974) noted that I-type granites have a broad spectrum of compositions from felsic to mafic, while the S-type granites are restricted to higher SiO_2 contents. In our present dataset of 751 S-type granites only one sample has a SiO_2 content less than 63% and that is a very unusual garnet-rich cumulate rock containing 57.6% SiO_2. Furthermore, only four of our S-type granite analyses contain less than 65% SiO_2. Among the I-type granites, the cumulate rocks of the high-temperature Boggy Plain Supersuite (Wyborn *et al.* 2001) extend the SiO_2 contents below 50%, and 27% of the rocks in that supersuite that have been analysed have SiO_2 contents of less than 59%. Among the low-temperature I-type granites, no sample has a SiO_2 content of less than 54% and 2% of the rocks have SiO_2 contents below 59%, with 13% of samples below 65%. Even these low-temperature I-type granites contain significantly less SiO_2 than the S-types. Hence, the observation of Chappell and White (1974) that the S-type granites are restricted to higher SiO_2 contents has been borne out by much more extensive data. At SiO_2 contents of less than approximately 72%, S-type granites contain more Mg and Fe than I-type granites of similar SiO_2 content. They could not be described as 'felsic' rocks, despite their rather high Si-contents and the very high abundance of quartz. They are dark-coloured rocks in which biotite and cordierite may make up more than 25% of the mode. These more mafic S-type granites are distinct modally as well. The rocks have low feldspar contents, of plagioclase because of the low Na- and Ca-contents inherited from previously weathered source rocks, but particularly of K-feldspar because a substantial Or-component is tied up in the abundant biotite. The relatively high quartz content of these S-type granites has two causes. First, they were derived from quartz-rich fertile sedimentary rocks. Second, high amounts of biotite, a SiO_2-poor mineral, leads to high quartz contents. In contrast, I-type granite magmas, produced by the partial melting of less-siliceous source rocks, reflect that feature in their more mafic compositions. In addition, the high-temperature varieties include many rocks that are low in SiO_2 by virtue of the accumulation of mafic minerals.

Regularity of interelement variations

Chappell and White (1974) noted that samples of granites in I-type plutons display more regular interelement variations than is the case for the S-types, with data for suites showing linear or near-linear trends on variation diagrams. That contention has been strongly supported by more recent data, but only if applied to what we now call simple suites (White *et al.* 2001), which are exclusively low-temperature granites and which dominate the exposed Lachlan Fold Belt I-type granites. The high-temperature suites of the Lachlan Fold Belt, not known to us in 1974, do not normally show linear variations (Wyborn *et al.* 2001; White *et al.* 2001).

For low-temperature granites, the chemical compositions of all but the most felsic rocks reflect, at least to a degree, the compositions of their source materials. A corollary is that a greater scatter in compositions about the general variation for a suite reflects a corresponding degree of heterogeneity in the source rocks. We realised this at the time the 1974 publication was written, but it was not explicitly pointed out for the chemical compositions (cf. the isotopic compositions). Later, Chappell and White (1984), having pointed out that the poorer correlations for S-type granites can be ascribed to the imperfect mixing of heterogeneous source rocks, made the statement repeated in the following paragraph (Chappell & White 1984 p. 99):

> 'This implies that I-type source rocks are relatively homogeneous, through volumes large enough to produce plutons up to 1000 km^2 in the Lachlan Fold Belt. This implies a large volume of relatively homogeneous source material. For this reason, it is thought that I-type granites are derived from deeper levels than S-types, from material produced by earlier underplating of the crust (White 1979). We therefore suggest that the two types of granite come from source rocks of fundamentally different origin, one formed by deposition on the crust, the other by accretion beneath the crust, so that we have:
>
> S-type = Sedimentary or Supracrustal
>
> I-type = Igneous or Infracrustal'

Chappell and White (1984) referred to these terms as representing 'a more fundamental difference' between the I- and S-type granites, so that the two groups do not just correspond to differences in source compositions, but also to fundamental differences in the character of those source rocks. It has been our view since our initial studies of eastern Australian granites in the New England Batholith (Chappell 1966) that the I-type granites must come from rather homogeneous sources that cannot, therefore, have been supracrustal or volcanic. Such a conclusion seems to be required by the extremely strong correlations between elements for the low-temperature I-type suites. Another argument for regarding the source rocks of the I-type granites as infracrustal, is the lack of enclaves of supracrustal origin in those granites, apart from xenoliths of local country rock origin. This is in strong contrast to the S-type granites for which the more mafic rocks invariably contain a rich assemblage of supracrustal enclaves carried from depth (White *et al.* 1999). These and other reasons for regarding the I-type source rocks as infracrustal were discussed more fully by Chappell and Stephens (1988).

Petrographic features of I- and S-type granites

As Chappell and White (1974) stated, many of the petrographic (mineralogical) differences between the I- and S-type granites reflect the differences in chemical composition between the two groups. The occurrences of different minerals listed in the 1974 publication remain correct with our present knowledge, except that monazite can also occur as an accessory mineral in felsic peraluminous I-type granites. In that case, the monazite is probably a product of very late crystallisation, in contrast to the monazite in S-type granites, which is either an early crystallised mineral, or restite.

In the Berridale–Kosciuszko region muscovite is common in the S-type granites, as we pointed out in 1974, but much of this is secondary muscovite resulting from subsolidus alteration of cordierite. Alteration was probably more prevalent in that region as a result of more pronounced deformation (see below). Because of this, we had not recognised that cordierite is important in virtually all S-type granites except those which formed from magmas that underwent fractional crystallisation, so that increased H_2O in the melt caused late magmatic reaction of cordierite to muscovite.

One prominent difference between the I- and S-type granites not noted in 1974, is that biotite in the S-type granites is typically pleochroic to a red-brown colour, whereas that in the I-type granites shows much stronger absorption and is pleochroic from chocolate to straw-coloured. Biotite in I-type granites that are reduced is also red-brown in colour. Biotite in the S-type granites typically shows very intense pleochroic haloes, probably related to the composition of the biotite and not to a greater presence of radioactive minerals. Fe^{3+} and probably Ti are generally less abundant in the biotites of S-type granites (Tetley 1978).

These differences in mineral chemistry are related to the lower Fe^{3+}/Fe^{2+} of the S-type granites, which also means that the opaque mineral in the S-type granites is generally ilmenite rather than the magnetite that is typical of the I-type granites (Whalen & Chappell 1988). The I-and S-type subdivision is analogous to that of the magnetite and ilmenite series of Ishihara (1977), but the correspondence is not exact (Takahashi *et al.* 1980): in Japan the magnetite and ilmenite series subdivision is almost exclusively within I-type granites. A further indication of the difference in oxidation state between the two types is the presence of sulphur as S^{2-}, principally in pyrrhotite (Whalen & Chappell 1988), in more reduced granites of the Lachlan Fold Belt, which are typically S-type. In contrast, S^{6+} is present in apatite at the 200–600 ppm level in all but the most felsic I-type granites (Sha & Chappell 1999).

The general difference in oxidation of the two types gives rise to some useful field criteria for distinguishing I- and S-type granites, which were not noted in the 1974 publication. The K-feldspar in S-type granites is always white in colour, never pink, provided the rock is not weathered or hydrothermally altered. However, in I-type granites the K-feldspar crystals are frequently pale pink in colour, but sometimes white. The presence of magnetite can easily be confirmed by testing crushed mineral grains with a hand magnet.

Chappell and White (1974) stated that apatite inclusions are common in biotite and hornblende of I-type granites whereas apatite occurs in larger discrete crystals in S-types. That observation was partly a result of the restricted area of granites in the Lachlan Fold Belt that we had studied to that time. It is generally the case for low-temperature I-type granites, but is not the case for high-temperature I-type granites such as the Boggy Plain Supersuite in which apatite is seen as larger discrete crystals. The occurrence of larger crystals of apatite in S-type granites is not completely understood. It is an indirect result of the higher solubility of apatite in more peraluminous melts (London 1992), so that apatite crystals were precipitated from a cooling melt. The solubility of P in the felsic melt component of low-temperature I-type granite magmas is very low, and in contrast to the S-type magmas, apatite occurs as a fine-grained restite component. Apart from these differences in the texture of apatite, we note that there are many similarities in texture between the low-temperature I-type and the S-type granites, as both types formed from restite-bearing magmas. Features shared by both types are calcic plagioclase cores, old zircon cores, and the relatively poor shapes of the mafic minerals. It is the high-temperature I-type granites that are texturally distinct.

Isotopic properties of I- and S-type granites

Early Sr isotope measurements on the granites of the Berridale Batholith were available to Chappell and White (1974) and showed that Sr is more radiogenic in the S-type than in the I-type granites. There was no overlap in the initial isotopic compositions for the data available in 1974. Chappell and White (1992 p. 16) discussed later isotopic measurements for granites of the Lachlan Fold Belt, which they summarised as follows: 'For I-type granites the range in initial $^{87}Sr/^{86}Sr$ is from 0.704 to 0.712 and for ϵ_{Nd} from +3.5 to –8.9. For the batholithic S-type granites the corresponding values are from 0.708 to 0.717 and from –5.8 to –8.8. For the granites of the Cooma Supersuite the values are from 0.718 to 0.720, with one ϵ_{Nd} measurement of –9.2. There is a large overlap between the I- and S-type initial isotopic compositions, with a continuity in $^{87}Sr/^{86}Sr$ from 0.704 to 0.720, and a strong negative correlation between initial Sr and Nd isotopic values'.

The large range in Sr isotopic compositions of the I-type granites was recognised by Compston and Chappell (1979) who ascribed it to the prior ageing of the isotopes in various source rocks for different lengths of time. McCulloch and Chappell (1982) considered an alternative possibility that the relatively evolved isotopic composition of the I-type Jindabyne Tonalite (initial $^{87}Sr/^{86}Sr$ ~0.707) was due to the incorporation of sedimentary material. They showed that the chemical composition of that granite was not consistent with the large amounts of sediment that would be required to produce such an evolved isotopic composition. The Glenbog Suite of the Bega Batholith provides a clear example of evolved isotopic compositions of I-type granites that did not result from the incorporation of sediment. That suite is more isotopically evolved, but contains more Ca than other suites of the batholith, despite the fact that the country-rock sediments, and detrital sedimentary rocks in general, are depleted in Ca (Chappell *et al.* 2000 figure 4).

Criticisms of the I- and S-type granite subdivision have mainly derived from a particular interpretation of the isotope data for these granites. Gray (1984 p. 47) stated that 'All of the granitic rocks, from hornblende tonalites to cordierite granodiorites, are a single broad family, products of variable mixing between distinct batches of basaltic material and a uniform partial melt of the regional basement'. Keay *et al.* (1997) have shown that all of the isotopic compositions of the granites of the Lachlan Fold Belt can be accounted for if those rocks were derived from source materials that were mixtures of three components, two igneous and one sedimentary. Those authors stated (Keay *et al.* 1997 p. 307) that 'S- and I-type granites appear to be mixtures, rather than unique products from, contrasting sources . . .'. That interpretation is not consistent with the data presented here. For instance, the smooth progressions in isotope compositions are consistent with mixing processes, but the discontinuous nature of some chemical compositions, such as the ASI values plotted in Figure 4, suggest discrete sources. We have recently discussed in some detail the inability of mixing models, based on isotopic data alone, to account for all aspects of the compositions of the granites of the Lachlan Fold Belt (Chappell *et al.* 2000). We note here that there are difficulties in applying radiogenic isotopes as a simple discriminant of granite source rocks because the effects of ageing in the crust of the isotopic systems of the I-type source rocks prior to partial melting cannot be readily quantified.

Williams (1995) showed that the patterns of age inheritance in S-type and I-type granites, and detrital zircon in the Ordovician sediments, are very similar. Collins (1998) used this fact to argue that there is no distinct difference between the two granite types. However, the amount of zircon showing such inheritance is vastly different between the I- and S-types. Williams *et al.* (1992 p. 503) noted that 'Zircons with inherited cores are rare in I-type granites, but virtually every zircon in the S-types contains an older core'. Chappell *et al.* (1999 p. 829) pointed out that this implies that 'the sediment component in the I-type granites, at least as indicated by the amount of inherited zircon, is trivial, a conclusion sustained by the observation that zircon was saturated in all of the low-temperature I-type magmas'. We have no argument with the proposition that there is a small amount of sedimentary material in the I-type granites. In fact, Chappell and White (1992 p. 18) stated that 'the combined chemical, isotopic and age data for the Jindabyne Suite lead to a similar conclusion to that reached for the western suites of the Bega Batholith, namely that there is a component of sediment in the source rocks of these isotopically evolved suites, but that the amount is not sufficient alone to account for the evolved isotopic compositions'.

Data on oxygen isotopic compositions of the two granite types were not available in 1974. O'Neil and Chappell (1977) found differences in such composition between the I- and S-type granites of the Berridale Batholith, with the two types having $\delta^{18}O$ values less than and greater than 10‰, respectively, relative to SMOW. This division is supported by our additional unpublished data on granites from other parts of the Lachlan Fold Belt, but needs to be tested further.

Chappell and White (1974) noted that the initial $^{87}Sr/^{86}Sr$ values for a single S-type pluton are more variable than for I-type plutons, interpreted to reflect the more heterogeneous nature of the source material. That observation has been confirmed by later observations. The heterogeneity of isotopic compositions of S-type plutons is illustrated by the Jillamatong Granodiorite of the Kosciuszko Batholith. For that single unit, the range in $^{87}Sr/^{86}Sr$ calculated at 430 Ma is from 0.71115 to 0.71541 (Chappell *et al.* 1999 figure 2).

Field observations of I- and S-type granites

Although the origin of the enclaves is controversial, the basic dichotomy observed by Chappell and White (1974) that hornblende-bearing enclaves occur in the I-type granites, whereas metasedimentary enclaves are seen in the S-type granites, has been supported by all subsequent studies (White *et al.* 1999).

The statement by Chappell and White (1974) that S-type granites are generally older than I-type granites occurring in the same batholith, is substantiated by later investigations. It is also the case that the earlier S-type granites may have a strong secondary foliation, truncated by I-type granites that are either unfoliated or have a primary foliation. We were strongly influenced by our early studies in the Kosciuszko Batholith, and while it is also the case in parts of the Wyangala Batholith and elsewhere, S-type granites of the Lachlan Fold Belt are more typically massive than foliated. This led to a misassignment of some granites in an early attempt to distinguish compositionally between the foliated and massive granites of the Snowy Mountains region by Kolbe and Taylor (1966). Those authors concluded that the two groups of granites could not be distinguished geochemically, and that all were derived, without significant differentiation, from varying proportions of geosynclinal sediments.

The observation that the S-type granites of the Lachlan Fold Belt may be more foliated than the I-type granites carries a connotation of older age. However, White *et al.* (1977) pointed out that the quartz-rich nature of that former group could contribute to the development of foliation, as rocks comprising a quartz framework are more easily deformed than the more feldspar-rich I-type granites.

Economic implications of the I- and S-type subdivision

Chappell and White (1974) recognised that various kinds of mineralisation are related to specific types of granites, but their observations in that area were limited and not completely correct. They stated that 'tin mineralisation appears to be confined to highly silicic S-type granites'. In the Lachlan Fold Belt, there is major Sn mineralisation associated with an extremely evolved S-type granite at Ardlethan, but the significant Sn deposits of Tasmania are related to felsic I-type granites. That is also the case for most of the younger Sn mineralisation in the New England Orogen and north Queensland. The important feature of significant Sn mineralisation is a relationship to strongly fractionated felsic granites, which may be of any type as long as they are reduced. The statement of Chappell and White (1974) that porphyry-type Cu and Mo deposits are associated with I-type granites is correct; however, W mineralisation can occur in association with any granite type.

Blevin has carried out a comprehensive study of the relationship between different granite types and ore–element associations in eastern Australia (Blevin & Chappell 1992, 1995; Blevin *et al.* 1996). He has shown that the principal parameters that controlled the concentration of the ore elements are the oxygen fugacity, expressed in the degree of oxidation of Fe in the granite, and the extent of fractional crystallisation. When the association with specific kinds of mineralisation is being considered, the subdivision of granites into magnetite and ilmenite series (Ishihara 1977) is in a sense more significant than that of the I- and S-types. However, at least in eastern Australia, there is generally a strong correlation between S-type and ilmenite series on the one hand, and I-type and magnetite series on the other. Hence, there is a strong correlation between the granite classification based on source rocks and specific types of mineralisation. Blevin and Chappell (1992) emphasised the importance of concentration of elements at the magmatic stage through fractional crystallisation as a precondition for the formation of many mineral deposits. They (Blevin & Chappell 1992 p. 314) stressed that there is 'an extreme lack of significant magmatic hydrothermal mineralisation associated with restite fractionated granite suites within the Lachlan Fold Belt'. Such a dearth of mineralisation, related to what we now term low-temperature granites, is discussed elsewhere in this issue (White 2001). In the Lachlan Fold Belt, the principal high-temperature granites, those of the I-type Boggy Plain Supersuite, are, as far as is known, only associated with subeconomic Cu mineralisation. The large W deposit at King Island is related to unfractionated I-type granites.

From the observations of Blevin and Chappell (1995), the relationship between mineralisation and the I- and S-type granites in the Lachlan Fold Belt is summarised here. Highly evolved S-type magmas were all relatively reduced and are related to Sn $\pm$ W mineralisation. Tin is also associated with reduced I-type granites. There is a progression within a sequence from Cu–Au to W to Mo mineralisation related to oxidised I-type magmas as they became progressively more fractionated. Blevin *et al.* (1996) have shown that these relationships also apply more generally to the granite – ore element associations in other areas of Palaeozoic granites in eastern Australia.

DEVELOPMENTS SINCE 1974

The concept of infracrustal and supracrustal source rocks (Chappell & White 1984) has been discussed. The other main developments in our understanding of two granite types in the Lachlan Fold Belt since the original publication have resulted from the occurrence elsewhere in the Lachlan Fold Belt of rock types not seen in the initial study area. These have led, first to a recognition that when felsic granite melts undergo fractional crystallisation they can be readily characterised as I- or S-type, and second to the concept of high- and low-temperature granites. Finally, the I- and S-type subdivision has been extended to include associated volcanic rocks.

Characterisation of fractionated felsic granites

We have noted that both I- and S-type granite compositions converge towards simple Tuttle and Bowen (1958) haplogranite compositions, that is, rocks comprising subequal amounts of quartz and two feldspars. If such felsic melts undergo fractional crystallisation to produce 'fractionated' granite compositions, then the major element compositions change very little, whereas trace-element abundances do change, and in different ways between the I- and S-type groups. This was noted initially by Chappell and White (1992) and discussed in much more detail by Chappell (1999).

With progressive fractional crystallisation, evidenced by parameters such as increasing Rb/Sr ratios, the felsic S-type melts in the Lachlan Fold Belt became progressively more peraluminous with up to 4% normative corundum, whereas the I-type melts did not. Apatite is soluble in such strongly peraluminous and felsic melts (London 1992) and hence the abundances of P_2O_5 increased progressively with fractional crystallisation in these S-type granites. In contrast, that component rapidly falls to very low levels in strongly fractionated I-types. The contrasting behaviour of P_2O_5 is a simple indicator of I- or S-type character among the fractionated felsic granites of the Lachlan Fold Belt. Other elements that occur in phosphate accessory minerals, such as Th, La and Y, decreased in abundance with continuing fractional crystallisation of S-type melts (Chappell 1999), because of the low solubility of monazite.

High- and low-temperature granites

The recent subdivision of granites in the Lachlan Fold Belt into high- and low-temperature groups (Chappell *et al.* 1998) is independent of the criteria used to separate the I- and S-type granites. However, there is some correspondence between the two subdivisions, with the high-temperature suites that include more mafic rocks being I-type, and those that are felsic being the A-type granites (King *et al.* 2001). The low-temperature granites include other I-type granites and most (~90%) of such granites in the Lachlan Fold Belt, and all of the S-type granites.

The high- and low-temperature granite groups do not show strong differences in mineralogy. However, recognition of those two groups is perhaps a more fundamental subdivision than that into I- and S-types. This is because it distinguishes between those granites that represent a relatively new addition of material to the crust, that is, the high-temperature I-type granites, and those that involve magmatic recycling of older crust, the low-temperature I-type and the S-type granites. It is those three types of granite together that dominate all plutonic igneous rocks. The I-type granites of the Lachlan Fold Belt are mainly low-temperature, whereas those of the Cordilleran batholiths generally formed at high temperatures. In the younger New England Fold Belt of eastern Australia, both low- and high-temperature I-types are important, with the latter group having distinct Cordilleran compositional affinities (Allen *et al.* 1997; Bryant *et al.* 1997).

Collins and Vernon (1994) pointed out that the average I- and S-type granite compositions for the Lachlan Fold Belt are more similar to each other than are those I-type compositions to the high-temperature granites of the Frieda River area, Papua New Guinea. As Chappell *et al.* (2000) discussed in detail, such a conclusion is expected. Interestingly, it confirms that unlike those high-temperature granites, the origin of the low-temperature I-type granites of the Lachlan Fold Belt formed in a tectonic setting other than simple subduction (cf. Collins 1998).

I- and S-type volcanic rocks

Work by D. Wyborn has shown that the mid-Palaeozoic volcanic rocks of the Lachlan Fold Belt can also be subdivided into I- and S-types (Owen & Wyborn 1979). The chemical compositions of relatively unaltered volcanic rocks can be matched very precisely with those of granites, and are either I- or S-type. As with the granites, the mineralogical features of the volcanic rocks reflect their chemical compositions, with the minerals being either less hydrous than those in the plutonic rocks, or anhydrous. The volcanic rocks of low-temperature origin are generally porphyritic and we interpret the phenocrysts as generally being primary restite minerals (Wyborn & Chappell 1986; Chappell *et al.* 1987). I-type volcanic rocks typically contain quartz, plagioclase, orthopyroxene and clinopyroxene. In the S-type volcanic rocks, cordierite occurs in place of clinopyroxene. The high-temperature volcanic rocks are I-type. They are generally non-porphyritic and similar in composition, and probably in origin, to the very felsic plutons resulting from convective fractionation discussed by Wyborn *et al.* (2001). As Wyborn and Chappell (1986) pointed out, whereas the volcanic rocks of low-temperature suites match those of their cogenetic granites suites very closely, those formed at high temperatures do not; they are more felsic.

CONCLUSIONS

Although the original separation into the I- and S-type groups was largely based on studies over a short period of time in a small part of the Lachlan Fold Belt, its validity has been confirmed by extended studies in that whole region. The separation between the two types based on chemical and mineralogical compositions is very clear in the more mafic rocks that are closest in composition to the source materials. These properties converge as both types become more felsic and all of the compositions approach those of low-temperature melts. The cause of overlap in the initial radiogenic isotopic compositions is not known. The proposal that the overlap is the result of derivation from a range of source rocks comprising various proportions of igneous and sedimentary material is not consistent with the chemical compositions of the granites.

In addition to confirming the subdivision recognised in 1974, more recent data and interpretation have extended the I- and S-type concept in various ways. First, it has been shown that while unfractionated felsic granite compositions of both types are difficult to distinguish, fractionated compositions are not, as the abundance of several trace elements in the two types diverge with progressive fractional crystallisation. Second, a significant subdivision of the I-type granites is now recognised, into high- and low-temperature groups, with important implications for how those rocks are involved in continental growth and evolution. The S-type granites are apparently always of low-temperature origin. Third, it is now known that the volcanic rocks of the Lachlan Fold Belt belong to three similar groups, high- and low-temperature I-type and S-type. Finally, we emphasise that the I- and S-type subdivision is not simply one that refers to source rocks of different compositions, but also to source rocks of fundamentally different origins, involving prior infracrustal and supracrustal origins.

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