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Aluminium saturation in I- and S-type granites and the characterization of fractionated haplogranites

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Abstract

Granites of the Lachlan Fold Belt resulted from partial melting of the crust. In most cases, fusion involved mainly quartz and feldspar, producing felsic melts. Varying degrees of separation of those melts from the unmelted source rock (restite) were responsible for much of the compositional variation seen in the granites of the belt. Less commonly, melting occurred at higher temperatures forming more mafic melts, such as for the I-type Boggy Plain Supersuite and the S-type Koetong Suite. Hence, the felsic haplogranites of the Lachlan belt dominantly formed initially as primary melts that separated from restite and less often by the fractionation of more mafic melts. Source rocks of the I- and S-type granites were undersaturated or oversaturated in Al, respectively, and the more mafic granites share that characteristic with their source. As the magmas of the Boggy Plain Supersuite evolved progressively by fractional crystallization, the rocks trended towards saturation in Al, to eventually form a mode close to Al saturation. Other felsic I-type magmas, formed directly by partial melting, were generally more oversaturated in Al, as were the corresponding S-type melts derived from peraluminous source rocks. In an unfractionated state, there are some overlaps in the degree of Al saturation in these magmas produced by partial melting. However, when extended fractional crystallization of these felsic partial melts took place, an almost complete separation in Al-saturation developed between I-type and more peraluminous S-type melts. Because apatite is soluble in peraluminous melts, P became progressively more abundant in the S-type melts as they fractionated. This led to contrasts in the abundances of P and of elements such as Y, the rare earth elements, and Th, between the strongly fractionated I- and S-type granites. Hence, such granites can easily be distinguished from each other.

Keywords: Granite; Lachlan; S-type granite; I-type granite; Fractional crystallization

1. Introduction

It was at an earlier granite symposium in South America (Santiago, Chile) that Chappell and White (1974) first proposed the I- and S-type granite[1] subdivision. Later contributions (Chappell and White,

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[1] The term ‘granite’ is used here in a general sense to include all coarse-grained igneous rocks comprising quartz and feldspars, the ‘granitoid’ of some authors.

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1984, 1992) provided further details of the I- and S-type subdivision of granites in the Lachlan Fold Belt (LFB) of southeastern Australia. The two groups are based on features of granites that can be observed or measured, and which were inferred to relate to features of the source rocks. Recognition of the two types focused attention on the role of source rock compositions in determining many of the chemical compositional features of granites, which in turn either determine, or are related to, the mineralogy of granites additional to the essential quartz and feldspars.

The I- and S-type subdivision has been widely, but not universally, accepted as a useful concept. It might be expected to be an oversimplification, since in natural systems, one could expect a continuous gradation in the compositional properties of source rocks. However, the view can be taken that source rocks should be unweathered or not sufficiently weathered to affect their chemical composition (igneous), or else weathered, or derived from material weathered, to a sufficient extent for that to be expressed in the composition (sedimentary), with probably only a small region of overlap. At least for the LFB, such a relatively sharp subdivision is supported by the strongly bimodal character of the derived granites for many elements in those granites that are closest to the source rocks in composition. Also, the two types of sources are probably fundamentally different in the sense that the igneous sources were generally *infracrustal*, and the sedimentary ones *supracrustal* (Chappell and White, 1984).

This paper is concerned principally with examining the degree of Al-saturation in the granites of the LFB, both in rocks that have and have not undergone fractional crystallization. The degree of Al-saturation, in both I- and S-type granites is traced through from the most mafic to the most felsic and strongly fractionated compositions. The clear separation between the I- and S-type granites that is evident at the most mafic compositions, also manifests itself in the most fractionated rocks. The often profound mineralogical differences between the two granite types, often related to Al-saturation, will not be examined here. Chappell and White (1992) have provided information on those mineralogical and other more general aspects of the I- and S-type groups.

2. Aluminium saturation and the aluminium saturation index (ASI)

Na and Ca are removed in solution during weathering. Those elements therefore have lower abundances in those sedimentary rocks that can be partially melted to produce a granite than they have in unweathered igneous rocks. More mafic granites, being closer to source rock compositions than felsic granites, therefore have lower abundances of Na and Ca in S-type relative to I-type granites. Hence, one of the most useful ways of discriminating the two granite types is by use of the molar ratio $Al_2O_3/(Na_2O + K_2O + CaO)$. This ratio has been referred to as A/CNK by Clarke (1981) and the aluminium saturation index (ASI) by Zen (1986). A/CNK has been widely used but use of ASI is preferred because the name stresses the importance of the concept of Al saturation. The terms metaluminous and peraluminous of Shand (1927), corresponding to CIPW normative diopside (di) or corundum (C), are likewise valuable. The boundaries between those pairs of terms correspond to ASI = 1 if the CaO value is corrected for apatite. In this paper, the ASI values are not corrected for apatite.

Miller (1985) proposed that peraluminous granites be referred to as strongly peraluminous (Ps) when they contain a mineral more aluminous than biotite and weakly peraluminous (Pw) when they do not. This is a useful mineralogical distinction and will be broadly followed here, although the differences in Al-saturation recognized in this paper are based on chemical compositions alone. Miller (1985) argued for the use of mineralogical criteria partly on the basis of avoiding chemical analytical problems, which is mostly valid. He noted that more than 3–4% C may be reported in norms when the primary mineralogy would not be consistent with so much excess Al_2O_3. Here, we consider granites with up to about 4% C, including WG57 and VB140 in Table 1 and with the average Cornubian granite (CNG) in that table containing 3.3% C. All of the strongly peraluminous rocks considered here have modes consistent with that feature, with common muscovite, and perhaps also andalusite or cordierite. Stoichiometric muscovite contains 25.6% C, so that mineral is generally a major contributor to very high C contents. However, the use of Al-saturation based

Table 1
Compositional data for some felsic granites

	G223	BB21	TB5	TB130	ZB107	DCC34	KB102	WG61	WG57	VB140	CNG	VB98	AB141
SiO_2	75.30	76.56	73.79	76.31	76.48	75.58	73.81	70.54	73.72	72.48	72.35	73.49	77.12
TiO_2	0.15	0.19	0.20	0.06	0.14	0.03	0.30	0.51	0.05	0.25	0.26	0.12	0.12
Al_2O_3	13.08	12.60	12.88	12.40	11.81	12.50	13.22	14.44	14.79	14.50	14.52	14.54	11.79
Fe_2O_3	0.28	0.43	0.38	0.32	1.05	0.46	0.62	0.39	0.17	0.29	0.30	0.32	0.40
FeO	1.06	0.43	1.41	0.84	0.73	0.47	1.65	2.63	0.52	1.33	1.56	0.75	0.64
MnO	0.06	0.02	0.03	0.02	0.04	0.02	0.04	0.05	0.05	0.03	0.06	0.04	0.02
MgO	0.25	0.21	0.21	0.05	0.03	0.05	0.60	0.79	0.07	0.47	0.41	0.21	0.04
CaO	1.10	0.97	1.18	0.60	0.32	0.55	1.68	1.54	0.40	0.66	0.79	0.64	0.34
Na_2O	3.45	3.52	3.00	3.50	4.21	3.95	2.97	2.91	4.00	2.80	2.96	3.28	3.07
K_2O	4.75	4.16	5.17	4.91	4.84	4.50	4.05	4.78	4.11	5.20	5.12	4.72	5.12
P_2O_5	0.05	0.03	0.06	< 0.01	0.01	< 0.01	0.09	0.20	0.42	0.33	0.25	0.29	0.02
Trace elements (ppm)													
Rb	288	214	349	805	230	745	187	275	945	419	483	496	248
Cs	13	4	15	27	5	35	10	18	44	33	49	79	9
Sr	160	99	82	6	7	3	89	89	15	65	74	37	38
Ba	420	545	330	4	56	4	495	360	2	220	176	86	520
Zr	126	115	181	140	470	142	139	206	27	99	113	46	171
Nb	14	17	13	30	24	39	8	19	47	20	17	20	19
Y	26	26	56	158	64	165	40	36	12	14	18	12	94
La	18	40	51	46	58	17	28	43	5	21	29	8	62
Lu	0.49	0.50	0.89	2.6	1.00	3.1	0.57	0.53	0.14	0.14	0.19	0.10	1.30
Cr	2	< 1	2	< 1	< 1	< 1	8	9	< 1	9	8	3	< 1
Ga	16	12	19	30	20	19	15	19	26	20	24	20	20
Sn	6	3	5	44	7	19	6	6	39	25	16	47	12
Th	37	20	50	79	28	44	19	25	3	14	15	6	28
U	13	4	3	30	7	6	4	5	21	11	13	5	6
ASI	1.021	1.045	1.016	1.019	0.927[a]	1.011	1.073	1.132	1.258	1.268	1.226	1.246	1.052
C	0.38	0.61	0.35	0.24	0[a]	0.13	1.11	2.16	4.04	3.86	3.27	3.57	0.63
Q[b]	37.1	41.0	37.1	37.5	34.7	36.1	42.2	36.0	37.3	38.6	37.3	38.6	40.7
ab[b]	32.1	32.3	28.5	31.6	35.4	35.6	29.6	29.8	36.5	26.7	28.4	30.6	27.4
or[b]	30.8	26.7	34.4	30.9	29.9	28.3	28.2	34.2	26.2	34.7	34.3	30.8	31.9

	Sample	Unit	Batholith	Latitude	Longitude
‘Unfractionated’ I-type granites	G223	Bendemeer	New England[c]	30°52.80′S	151°13.25′E
	BB21	Maffra	Berridale	36°32.10′S	148°58.55′E
‘Fractionated’ I-type granites	TB5	Coles Bay	Bassian	42°04.90′S	148°17.95′E
	TB130	The Hazards	Bassian	42°09.50′S	148°18.90′E
	ZB107	Nallawa	Yeoval	32°36.70′S	148°30.85′E
	DCC34	O’Briens Ck	Herberton[c]	17°59.85′S	144°02.55′E
‘Unfractionated’ S-type granite	KB102	Happy Jacks	Kosciuszko	36°03.50′S	148°29.60′E
‘Fractionated’ S-type granites	WG61	Interview	Taswegia	41°37.70′S	144°54.55′E
	WG57	Sandy Cape	Taswegia	41°25.35′S	144°44.75′E
	VB140	Granya	Wagga	36°07.50′S	147°19.20′E
	CNG	Mean value	Cornubian[c]		
	VB98	Mt Flakney	Wagga	35°13.50′S	147°20.05′E
‘Unfractionated’ A-type granite	AB141	Mumbulla	Bega	36°35.50′S	149°55.15′E

C is the percent of CIPW normative corundum.
[a] Sample ZB107 contains 1.52% normative acmite.
[b] Normative Q, ab, and or are recalculated to a total of 100%.
[c] Not part of the LFB.

on chemical analyses should not be made without a knowledge of the petrography of the rocks, so that one is not simply measuring a mass of clay minerals produced by hydrothermal alteration. Of course, a major element analysis alone can be used to confirm that the proportions of normative Q, ab, and or are close to those of a minimum temperature melt (Table 1 and Fig. 7), and it is important that it be done.

Zen (1986) considered in some detail the production of peraluminous melts by the fractional crystallization of originally metaluminous melts. The development of peraluminous compositions by the fractional crystallization of hornblende (ASI < 0.5) had previously been proposed by Cawthorn and Brown (1976). Zen (1986) pointed out that such a process would be inhibited by the precipitation of feldspar (ASI = 1) while the melt remains metaluminous, but for the same reason the melt would become progressively more peraluminous with the removal of feldspar, once it became saturated in Al. Zen (1986) noted that the generation of peraluminous compositions by fractional crystallization in that way is inefficient and that larger bodies of peraluminous magma require a more efficient mechanism for their derivation. Such large bodies of magma can be produced by partial melting of peraluminous source rocks (S-type). However, peraluminous felsic I-type granites are common in many regions, and they comprise 41% of all I-type granites of the LFB. Clearly, another mechanism for producing peraluminous I-type compositions is required, and it is proposed here that these weakly peraluminous compositions result largely from partial melting rather than fractional crystallization (Section 5.3). Those compositions may in turn be modified by the precipitation of feldspar so that the final rocks may be more peraluminous (Figs. 3 and 4).

3. Overlap between I- and S-type granite compositions

A major difficulty in applying the I- and S-type subdivision is that more felsic granites converge towards the minimum temperature composition (Tuttle and Bowen, 1958). Such haplogranites are characterised by approximately equal amounts of normative quartz (Q), albite (ab) and orthoclase (or), and mineralogically by similar abundances of quartz, K-feldspar and Na-plagioclase, with minor amounts of other minerals. To a first approximation, such granites have compositions that are independent of their precursor materials and separation into I- or S-type, at least using major element and mineral abundances, is often not possible, unless the granite is part of a suite that extends to more mafic (or, as this paper shows, more fractionated) compositions where compositional distinctions emerge. Because haplogranites are dominated by quartz and feldspars (ASI = 1), the ASI also converges to values close to one for all of those rocks, and the values for I- and S-type granites overlap; this is shown for the granites of the LFB in Fig. 1. This figure shows that the S-type granites are always oversaturated in Al (ASI > 1). The I-type granites may be either metaluminous or peraluminous, and they overlap the S-type granites. Rocks of the I-type Boggy Plain Supersuite (Wyborn et al., 1987), which are either cumulates or derived liquid compositions (Section 4.4), are not included in Fig. 1. The I-type granites represented in Fig. 1, generally correspond to magma compositions that were either

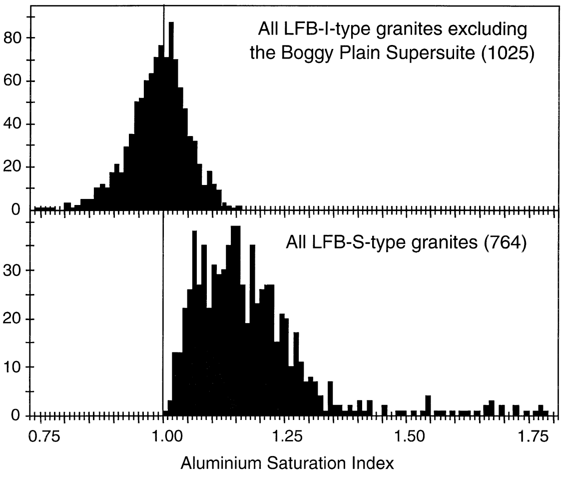

Fig. 1. Histograms of ASI values for 1025 I-type granites exclusive of the Boggy Plain Supersuite, and 764 S-type granites, from the LFB. ASI values of the I-type granites range from 0.774 to 1.154, and the S-type granites from 1.001 to 1.997. Three S-type granites with ASI values of 1.872, 1.882, and 1.997 are not shown. The I-type data include seven samples for which $SiO_2 <$ 57% (gabbroic diorites) but there are none for which $SiO_2 < 53\%$ (gabbros).

melts, or melts containing entrained restite crystals (Chappell et al., 1987). Almost half (46.5%) of those 1025 I-type compositions, exclusive of the Boggy Plain Supersuite, have ASI values greater than 1.0, and therefore overlap with some S-type granites. The importance of peraluminous I-type granites in the LFB, or elsewhere, is perhaps not generally realized, and it shows that it is inadvisable to refer to those granites in a group as metaluminous, in contrast to the 'metasediment-derived' or even the 'peraluminous metasediment-derived types', as Wall et al. (1987) have done. In proposing the I- and S-type classification, Chappell and White (1974) were aware that I-type granites may be peraluminous, which is partly why they suggested terms not intrinsically related to Al-saturation.

4. Petrogenetic framework

4.1. The importance of the haplogranites

The I- and S-type subdivision must be examined in terms of other compositional properties of granites that reflect on their origin. The most important of those features is that the most felsic granites, or haplogranites, almost universally have the compositions of low-temperature hydrous silicate melts in equilibrium with quartz and feldspar (Tuttle and Bowen, 1958). That study established the magmatic character of granites and while Bowen himself did not regard granite magmas as likely to be primary, he noted that studies showing that granite is a late-crystallizing residuum of fractional crystallization imply that it would likewise be an early product of selective fusion of appropriate material (Bowen, 1947). Thus, the simple haplogranites can form in two ways, both of which are seen among the granites of the LFB.

Some felsic granites of the LFB were produced by the removal by fractional crystallization of mafic components from less felsic silicate melts, so that the more mafic rocks represent cumulates, and the more felsic ones liquids. This is illustrated by the I-type Boggy Plain Supersuite and the S-type Koetong Suite. More commonly in the LFB, haplogranites formed under conditions where only the felsic components of the source rocks were fused, leaving the mafic components as a solid residue, which may have disengaged from the melt at or near the source, or later. In both of these cases, the felsic melts have the distinctive major element compositions that reflect the equilibrium between quartz, feldspars, and a hydrous melt during their formation as observed by Tuttle and Bowen (1958).

4.2. Major element compositions of haplogranites

Analyses of 13 haplogranites, mostly from the LFB, are listed in Table 1. These analyses show the limited range in major element compositions for such rocks, regarding P as a trace element. Such rocks are very siliceous (73–77% SiO_2). Except for the strongly fractionated S-type granites, they contain low Al_2O_3 ($< 13\%$), and they have very low to low contents of Mg, Ca, and the transition elements. Na and K have high and relatively constant abundances. These rocks are dominated by four elements, Si, Al, Na and K, which do not vary greatly in amount, and the variation in abundances of the normative minerals Q, ab, and or, that incorporate those four elements are likewise restricted (Table 1).

The analyses in Table 1 include four unfractionated rocks, two I-type (G233 and BB21), one S-type (KB102), and one A-type (AB141). All the other rocks show compositional effects of fractional crystallization. The pairs TB5 and TB130 (I-type), and WG61 and WG57 (S-type), represent the least and most evolved granites available from two suites that underwent extreme fractional crystallization. ZB107 is a rock that apparently fractionated from an originally rather mafic metaluminous composition, that is itself slightly peralkaline. DCC34 is a strongly fractionated representative of what is certainly one of the best and most extensive examples worldwide of highly evolved granites, the Carboniferous I-type granites of northern Queensland (Champion and Chappell, 1992). VB140 is a fairly strongly fractionated S-type granite from the Wagga Batholith of the LFB, which is strikingly close in major element and many trace element abundances, to the average Cornubian granite CNG of Chappell and Hine (unpublished data). VB98 is a more strongly fractionated S-type granite from the Wagga Batholith.

4.3. Trace element compositions of haplogranites

In contrast to the major element compositions, many trace elements can vary widely in concentration in felsic rocks, with some of those variations illustrated in Table 1. Those trace elements that occur in feldspars (e.g., Rb, Sr, Ba) and those that are major components of accessory minerals (e.g., P, Zr, Nb, Y, Ce, Sn, Th, U) may vary widely in abundance both within and between rock suites. Those that are found in mafic minerals (e.g., Cr) are invariably low in amount. Those trace elements that occur in feldspars and accessory minerals, and which may as a result have abundances that vary with, and reflect, the degree of fractional crystallization of such minerals from a felsic melt, are a major focus of this discussion. In a sense, all granites are fractionated rocks, in that they have compositions that differ from other igneous rocks or average crust. However, in this paper, the term *fractionated* is used to refer to those felsic granites that (a priori) show the compositional effects of fractional crystallization of feldspars and accessory minerals; those that do not are said to be *unfractionated*. Examples of both groups are provided in Table 1 and the different behaviour of some trace elements in fractionated I- and S-type granites will be considered in detail in later sections.

4.4. Production of haplogranites by fractional crystallization

The I-type Boggy Plain Supersuite (Wyborn et al., 1987), which comprises approximately 5% of all exposed granites of the LFB, has compositional features which show that the range of rocks was produced by fractional crystallization from relatively mafic liquids, so that the more mafic rocks represent cumulates and the more felsic granites and related volcanic rocks generally represent liquid compositions. Evidence for this includes the wide range in composition (45.34 to 77.32% SiO_2), inflexions of elements on variation diagrams, and the occurrence of rocks with cumulate chemical features, such as high Ca and Al, or Ca and Mg, or Cr, or extremely low abundances of K, P, Rb, Zr, etc., which were components of a trapped interstitial melt. Direct evidence for the production of S-type haplogranites in the LFB by fractional crystallization is seen only in rocks of the Koetong Suite (Chappell, 1996b), although some other felsic S-type granites that are not associated in the field with more mafic rocks might also have formed in such a way. For Koetong, at SiO_2 contents greater than about 69%, the abundance of elements such as Rb, Nb and Sn begin to increase rapidly in abundance with increasing SiO_2 content, while others including Sr, Y and Th start to decrease, consistent with fractional crystallization. The haplogranites of the Boggy Plain Supersuite and the Koetong Suite were therefore initially produced by fractional crystallization of more mafic melts. In that respect, they are unusual among the felsic granites of the LFB.

4.5. Production of haplogranites by partial melting

More commonly, it was partial melting of the crust, of earlier igneous or sedimentary components, that produced the LFB haplogranites, at or close to minimum temperature melt compositions (not H_2O-saturated). Evidence for these rocks representing primary magmatic compositions, includes the absence (or at least rarity) of cumulate rocks and the absence of mafic rocks analogous to those of the Boggy Plain Supersuite. For these I-type granites, the minimum SiO_2 content is 54.4% and for only 2.7% of all analyzed 1025 samples is the SiO_2 below 60%. For the S-type granites, the minimum SiO_2 content is 63.4%. The relative absence of mafic rocks not only implies that cumulate rocks were not formed, but also that the more mafic compositions corresponding to molten magmas that might have been the source of these granites through fractional crystallization, are uncommon. Further evidence against a process of fractional crystallization in producing these rocks, comes from the lack of inflexions in concentrations of elements in variation diagrams, and the characteristic linear variations of many elements. Also, Chappell (1996b) has shown, by modelling variations of some trace elements in the I-type Glenbog and Moruya suites, and the S-type Bullenbalong Suite, that variation in those suites cannot have resulted from the development of cumulate rocks by fractional crystallization; similar calculations show that likewise, those suites cannot represent liquid lines of descent resulting from fractional crystallization. Furthermore, processes of magma mixing and hybridization are localized and insignificant on a pluton scale and the popular model that some granite suites result from the interaction of mantle melts and crust cannot be sustained by the data for the LFB (Chappell, 1996a).

4.6. Production of more mafic granites

The bulk of the haplogranites of the LFB acquired that property as a primary feature by the partial melting of quartz and two feldspars. Some more mafic magmas, such as those that produced the Jindabyne Suite (Hine et al., 1978) or the Koetong Suite, formed as a result of melting to higher temperatures, such that there was an absence of quartz, K-feldspar or H_2O in the residue. Sometimes, but not generally, those magmas underwent fractional crystallization. In the extreme case of the Boggy Plain Supersuite, melting at high temperatures produced a hot completely molten magma that yielded a wide range of rocks by fractional crystallization. However, in most cases, the more mafic granites of the LFB acquired that character by the entrainment of crystals of unmelted source material (restite) in a low temperature melt (Chappell et al., 1987; Chappell, 1996b).

5. Aluminium saturation in granites of the LFB

5.1. Aluminium saturation in I- and S-type granites

Chappell and White (1974) noted that the distinctive mineralogical features of I- and S-type granites correlate with differences in the abundance of Al relative to Na, K and Ca in the two types, which can now be expressed as the ASI. Chappell and White (1974) proposed that the boundary between the two types be drawn at an ASI of 1.1. At that time, the distinction between the two types was largely based on observations of the Berridale Batholith, although analogous differences had been observed elsewhere in the LFB. From the current LFB database, the range in ASI for the I-type granites of the Berridale Batholith is from 0.902 to 1.092 with only one sample greater than 1.065, and for the S-type granites from 1.044 to 1.248.

Chappell and White (1974) nominated a value for the ASI significantly greater than 1.0 as the boundary between the I- and S-types, despite the fact that a value of 1.0 might be arbitrarily taken as a boundary between unweathered and weathered source rocks. In part, they did that because of the observed values for the Berridale Batholith. However, they also recognized more generally that very felsic granites of I-type suites may be weakly peraluminous, while more mafic compositions within that suite are metaluminous. The defining sample in that regard is G223 of Table 1, a very felsic granite from the New England Batholith (Chappell, 1978). This sample is associated in the Bendemeer pluton with rocks having SiO_2 contents down to 65.7% SiO_2 and containing up to 7% hornblende. G223 contains 3% biotite and small amounts of hornblende, less than one small crystal per thin-section. Despite the presence of hornblende, G223 is peraluminous; it contains 0.38% C and has an ASI of 1.021. This rock is, or is very close to, a minimum temperature melt produced from metaluminous source rocks. It shows empirically that minimum temperature granite melts, formed in equilibrium with such source rocks, are slightly Al-oversaturated. This is in accord with experimental studies showing that peraluminous melts can be produced by partial melting of mafic rocks (e.g., Helz, 1976; Ellis and Thompson, 1986). The composition of another I-type granite representing a partial melt composition, rock BB21 from the Berridale Batholith, is also shown in Table 1. This is slightly more peraluminous than G223, with a C content of 0.61% and an ASI of 1.045. This rock contains a small amount of muscovite (0.3%) that is possibly subsolidus, rather than hornblende but its I-type character is confirmed by an initial $^{87}Sr/^{86}Sr$ ratio ~ 0.705.

The composition of an S-type granite close to a minimum temperature melt is also given in Table 1. This rock KB102 is significantly more saturated in Al than the two I-type granites discussed earlier, with 1.11% C and an ASI value of 1.073. This is to be expected in a composition resulting from partial melting in equilibrium with peraluminous minerals, which show an appreciable solubility in felsic melts. However, it must be noted that there are felsic S-type granites in the LFB which are less peraluminous than KB102, just as there are felsic I-type granites than are more peraluminous than BB21.

5.2. Aluminium saturation in the Boggy Plain Supersuite

As noted earlier, the data represented in Fig. 1 show the degree of overlap in ASI between the I- and S-type granites of the LFB. A similar diagram was provided by Chappell and White (1992), but that figure included data for the Boggy Plain Supersuite, which are here plotted separately in Fig. 2. The cumulate character of at least some of the mafic rocks of that supersuite is confirmed by some very low vales of ASI, down to 0.178 for a clinopyroxene-rich cumulate, and 61 of the Boggy Plain rocks have ASI values less than the lower limit of that parameter of 0.774 for the other I-type granites of the LFB shown in Fig. 1. The data represented in Fig. 2 are a composite of values for rocks formed as cumulates and from the derived liquids. For the zoned and intensively analyzed Boggy Plain pluton (34 km^2; Wyborn, 1983), almost all granites are cumulate rocks and their ASI values extend up to 0.943; two rocks from that pluton that probably correspond to fractionated liquid compositions have ASI values of 0.990 and 1.024. Elsewhere in the supersuite, the ASI values extend from low values in mafic cumulate rocks continuously up to a maximum ASI of 0.95, overlapping slightly with melt compositions a few of which extend down to 0.90. Some fractionated melts were later enriched in crystals of K-feldspar for example, and are therefore cumulate rocks of a different kind. This supersuite provides an excellent example of the development, by fractional crystallization, of peraluminous melts from a metaluminous starting composition (Zen, 1986), but the degree of Al-saturation that developed was restricted (ASI < 1.07) relative to those other peraluminous I-type granites of the LFB (ASI < 1.16) that formed directly by partial melting, followed in some cases by fractional crystallization. Fig. 2 shows that fractional crystallization from initial mafic melts in the Boggy Plain Supersuite resulted in a distinct peak at an ASI close to one for the derived liquids. For one component of this supersuite, the most strongly fractionated rocks include some peralkaline compositions, including sample ZB107 in Table 1; that ZB107 has true peralkaline character is confirmed by the high Zr content of 470 ppm for a fractionated rock.

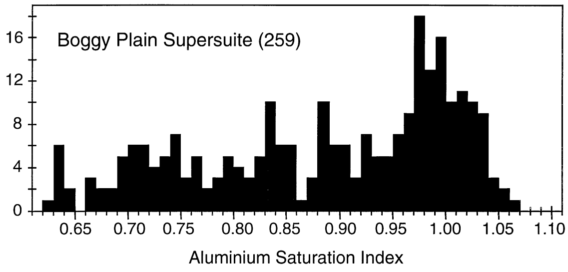

Fig. 2. Histogram of ASI values for 259 rocks of the I-type Boggy Plain Supersuite from the LFB. The rocks include 26 gabbros ($< 53\%$ SiO_2) and 27 gabbroic diorites ($SiO_2 = 53–57\%$). Three ASI values at 0.178, 0.383, and 0.587 are not shown.

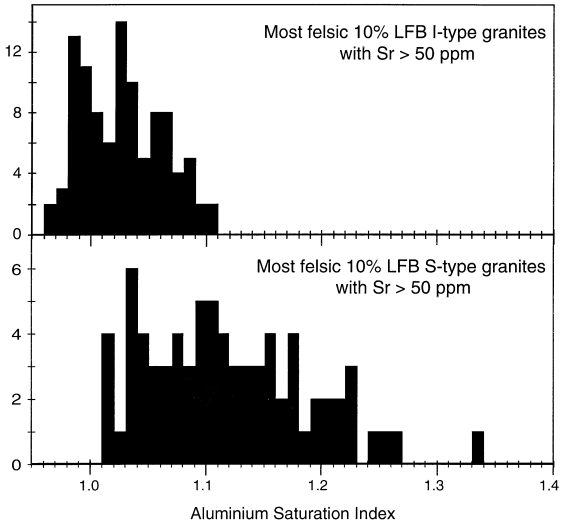

Fig. 3. Histograms of the most felsic (Fe-poor) 10% of I- and S-type granites of the LFB having Sr contents greater than 50 ppm. The I-type granites are exclusive of the Boggy Plain Supersuite.

5.3. Aluminium saturation in felsic granites

Histograms of ASI values for felsic I- and S-type granites from the LFB, exclusive of the Boggy Plain Supersuite, are shown in Figs. 3 and 4. In Fig. 3, the most felsic 10% of both types with Sr > 50 ppm are represented, and in Fig. 4, all granites with Sr < 50 ppm are shown. The separation based on Sr content has been made to assess the effects of fractional crystallization of haplogranite compositions, during which Sr would be removed by the separation of feldspars. No single Sr content can perfectly separate

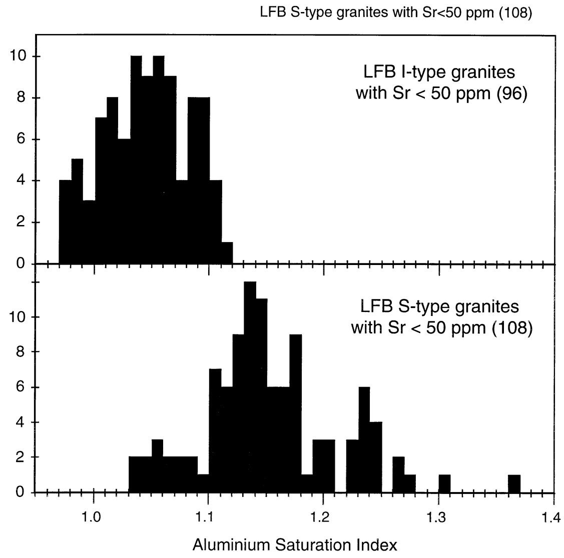

Fig. 4. Histograms of I- and S-type granites of the LFB with Sr contents less than 50 ppm. The I-type granites are exclusive of the Boggy Plain Supersuite.

fractionated from unfractionated granites, since the value must depend on the initial Sr content of the melt, which can vary significantly, and the conditions under which the fractionation occurred. However, the value of 50 ppm should achieve a separation into compositions that have undergone fractionation, and those which have been mildly fractionated, or not fractionated at all.

These compositions that are represented in Fig. 3 are taken to represent partial melts from metaluminous and peraluminous sources, with those melts at most being only weakly fractionated. While there is overlap between the two granite types, the data represented in Fig. 3 broadly reflect the contrasting Al-saturation of the sources. The S-type compositions are all peraluminous, and for the I-type granites that is dominantly the case (82% of total). The felsic I-type granites are mainly between ASI = 0.98 and 1.08, with a suggestion of bimodal maxima at ASI ~ 1.00 and ASI ~ 1.04. The S-type granites comprise a broad range of ASI values with no suggestion of a single preferred composition.

The range of Al-saturation in the fractionated I-type granites, shown in Fig. 4, is almost identical to that of the unfractionated equivalents in Fig. 3. However, the most abundant compositions are slightly but distinctly more peraluminous, centred at close to ASI = 1.06. These data show that the less peraluminous I-type haplogranites may become slightly more peraluminous with fractionation, whereas those initially more Al-saturated do not change. There is no tendency for the Al-saturation of the I-type granites to be driven to high values by the fractional crystallization of feldspar. These data point to the moderating effect of biotite precipitation in this regard.

The fractionated S-type granites (Fig. 4) have a very similar range in Al-saturation to the most felsic unfractionated rocks (Fig. 3), but in contrast, the fractionated granites show a distinct concentration of values in the interval from ASI = 1.11 to 1.19. For these rocks, their slightly more peraluminous composition when unfractionated (Fig. 3) is apparently sufficient for the precipitation of feldspars, with ASI = 1, to drive them further into the peraluminous field. A comparison of Figs. 3 and 4 suggests that at the same time, the most strongly peraluminous unfractionated melts (ASI = 1.2 to 1.3 in Fig. 3) remain largely unaffected by the fractional crystallization, and may be driven to slightly less peraluminous compositions. This effect could result from the precipitation of a strongly Al-saturated mineral, such as andalusite from the most peraluminous melt compositions.

There is very little overlap between the abundances of fractionated I- and S-type granites in Fig. 4. Only 13% of the fractionated S-type compositions have an ASI less than 1.11, and 5% of the I-type granites are above that value. This almost complete separation between the degree of Al-saturation of fractionated representatives of the two granite types, becomes very significant in considering the evolution of many trace elements during fractional crystallization of the those two groups (Sections 6 and 7). The separation also supports the division of the LFB granites into the I- and S-types.

5.4. Aluminium saturation in mafic granites

Chappell and White (1992) have previously shown that at the most mafic compositions, there is no overlap in ASI between the I- and S-type granites of the LFB. This is confirmed by the histograms in Fig. 5, which use a slightly larger database and exclude

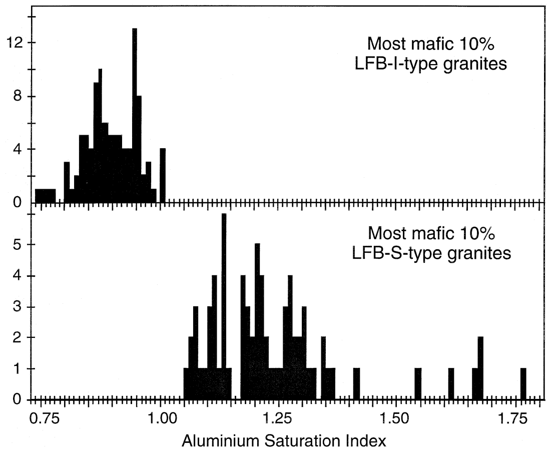

Fig. 5. Histograms of the most mafic (Fe-rich) 10% of I- and S-type granites of the LFB. The I-type granites are exclusive of the Boggy Plain Supersuite. Three S-type granites with ASI values of 1.873, 1.882, and 1.997 are not shown.

I-type rocks of the Boggy Plain Supersuite, which since the mafic rocks of that supersuite are cumulates, means that they include a disproportionately large number of the most mafic granites. By excluding most of the cumulate rocks, these mafic rocks generally represent magma compositions. If that magma includes retained restite crystals, the view of this author, then the correlation between those compositions and source compositions is clear. If the magmas represent liquid compositions, they will again relate to source rock compositions, but less precisely. In either case, the Al-saturation in a mafic granite, less or greater than one, will correlate with that property in the source rocks. Hence, the I- and S-type subdivision is clear. The fact that the ASI values of I- and S-type granites converge, and eventually overlap in felsic rocks, is of no consequence as far as the I-S division is concerned, since a degree of Al-oversaturation is an intrinsic property of the most felsic granitic melts. The overlap in the ASI parameter for felsic I- and S-type granites is to be expected and therefore in no way invalidates the subdivision.

These general conclusions have been reported previously (Chappell and White, 1992). It is therefore surprising that Keay et al. (1997) concluded that ‘‘S- and I-type granites appear to be mixtures of, rather than unique products from, contrasting sources’’, implying that the I- and S-type separation is invalid. Collins (1996) has made the interesting argument that with a mixture of contrasting sources, the granites derived from source rocks where either component is dominant will be more common than those derived from subequal proportions of the two end-members. If that were the case, it would account for the bimodality of the I- and S-type granites, as Collins (1996) pointed out. However, the argument that those granites were formed from mixtures of contrasting sources does not stand scrutiny when the isotopic and chemical data are looked at in conjunction. It can be shown that the changes in chemical composition that would be required by the isotope mixtures proposed by Keay et al. (1997) are not those that are observed. A critical element is Ca, which has an exceptionally low abundance in the Ordovician sedimentary rocks of the LFB, averaging 0.31% in 38 analyzed samples. For the I-type granites of the Bega Batholith, Ca has the highest abundances in those suites which on simple isotopic arguments would have contained the largest amounts of that low-Ca sediment in their source materials. Again, for the S-type granites of the Bullenbalong Suite, the Ca content is too high, relative to that sediment, to be accounted for by the presence of mafic material in the source rocks in the amount required by the isotope data alone. The presence of a more Ca-rich sedimentary source rocks at depth is inferred.

6. Compositional contrasts between fractionated I- and S-type granites

6.1. Contrasting behaviour of major and trace elements during fractionation

Major element compositions show only slight variation when melts of haplogranite composition undergo continuing fractional crystallization. This can be seen by reference to Table 1, which includes both unfractionated haplogranites (G223, BB21, KB102) and others that have undergone strong to extreme fractionation. This situation arises because the concentrations of Si, Al, Na and K are set by the largely static equilibrium between quartz, feldspars and the minimum temperature melt. However, Al decreases slightly with progressive I-type melt fractionation, but increases for S-type fractionation because of increasing saturation in Al (increasing C), in the melt. The elements Ti, Fe, Mn, Mg and Ca, are already at low levels before fractional crystallization of the haplogranite melt occurs, and in absolute amounts decrease only slightly. The trace transition elements have low abundances in these rocks. Most other trace elements undergo significant changes in abundance with increasing fractionation, and in fact provide the main evidence for the degree of fractionation that has occurred. Those elements that are incorporated in feldspars always behave consistently, so that Rb, Cs, and Ga increase in abundance with fractionation, while Sr and Ba decrease. Some other elements are fairly constant in behaviour, so that Nb, Sn, and U, for example, increase with fractionation, while Zr decreases in abundance except in peralkaline liquids. Other elements, notably P, Y, the rare earth elements, and Th, show varying patterns of behaviour, governed by the accessory minerals that precipitate, which are in turn largely determined by the composition of the melt, and specifically by its degree of saturation in Al.

6.2. Contrasting behaviour of P in I- and S-type granites

The contrasting patterns of behaviour of P in I- and S-type granites of the LFB are shown in Fig. 6. The I-type granites show a band of compositions that decrease with increasing SiO_2, converging on values less than 0.01% P_2O_5 between 75 and 77.5% SiO_2, showing that the concentration of P in the I-type haplogranite melts is always very low. It is the strongly fractionated I-type haplogranites that have the very low P contents (compare TB130 with the preceding three analyses in Table 1). The decrease in P_2O_5 contents with increasing SiO_2 for the I-type granites in Fig. 6 is consistent with the decreasing solubility of P in more siliceous melts (Harrison and Watson, 1984), but for these rocks it is thought to be due to the presence of different proportions of low-P felsic melt and restite that includes apatite crystals. The analogous plot for S-type granites shows a strikingly different distribution, with the data lying in a triangular area extending from about 0.15% P_2O_5 in the most mafic rocks, to both higher and lower values in the felsic granites, ranging from 0.02 to 0.42%. There is a concentration of points in the low-P_2O_5 part of the triangle, extending from the more mafic to intermediate compositions. These are dominantly the granites of the Bullenbalong Supersuite in which the compositional variation resulted from separation of a lower-P_2O_5 melt such as KB102 in Table 1, from a magma containing higher-P_2O_5 mafic restite components. Rocks with higher P contents reflect the role of fractional crystallization, as in the more felsic parts of the Koetong Suite (VB140 and VB98 in Table 1). The granites with highest P_2O_5 contents are the most strongly fractionated of the S-type granites, but are not at the highest SiO_2 values. This is because of the increasing abundance of C in the most felsic rocks, so that in the extreme case about 4% C dilutes the other components, and consequently, the rock fractionated to a lower SiO_2 content.

The higher P_2O_5 abundances in the S-type granites are consistent with their more peraluminous compositions. Montel et al. (1988) demonstrated that apatite is soluble in peraluminous melts. Wolf and London (1994) have shown experimentally that the solubilities of apatite in a haplogranite melt, and equivalent P_2O_5 abundances, increase linearly with ASI, up to ~0.63% of P_2O_5 in a melt of ASI = 1.3. The highest P_2O_5 content measured in a fractionated S-type granite of the LFB is 0.42% in two samples, one of which is WG57 in Table 1, which has an ASI value of 1.26 and a C content of 4.04%. Using the data of Wolf and London (1994), this would suggest that the fractionated S-type granites were never saturated in P, so that the element behaved incompatibly and increased in abundance. The average CNG in Table 1, which contains 3.27% C, is correspondingly high in P_2O_5 (0.25%). The contrasting behaviour of P_2O_5 during the fractional crystallization of I- and S-type granites will be considered further in Section 7.2.

6.3. Contrasting behaviour of rare earth elements in I- and S-type granites

The concentrations of La and Y in I- and S-type granites of the LFB are also plotted in Fig. 6. As a broad body of data, there is more scatter in the I-type

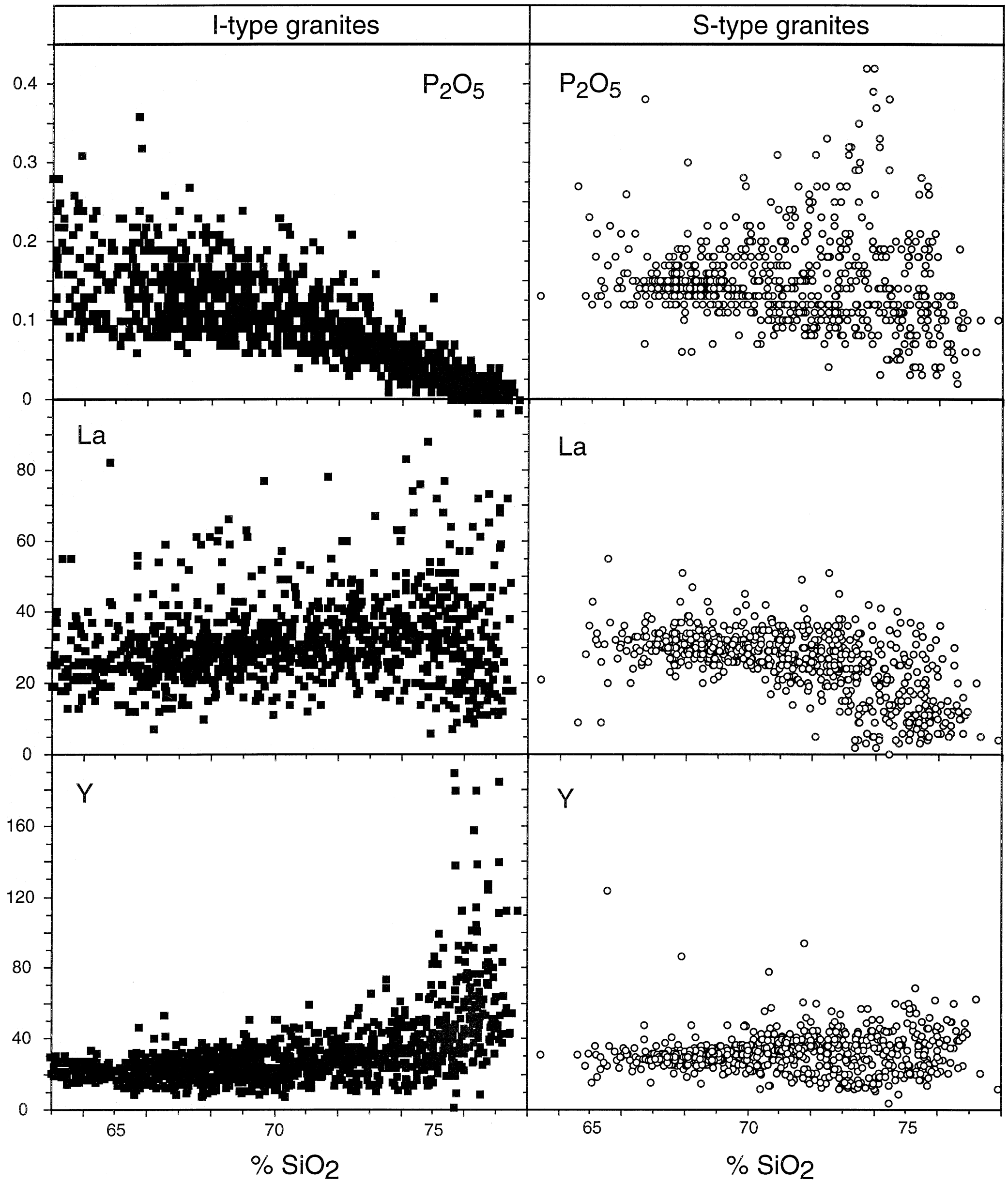

Fig. 6. Harker diagrams for P_2O_5, La and Y for I-type (filled squares) and S-type (open circles) granites of the LFB. Because there are no S-type granites with less than 63% SiO_2, I-type granites below that SiO_2 level are not plotted. Data from the Boggy Plain Supersuite are not included.

granites, particularly for La, as might be expected since the I-type rocks were derived from a wider range of source materials. However, for Y in the S-type granites, there are individually four analyses which lie above an otherwise well-defined band of compositions. These are perhaps cumulate compositions, or may represent magmas from a source enriched in Y by sedimentary processes.

For La in the I-type granites, the general gradient is broadly slightly positive with increasing SiO_2, whereas for the S-type rocks it is very slightly negative. Above 73% SiO_2, corresponding to fractional crystallization of haplogranite liquids, La decreases markedly in the S-type granites, but to a lesser degree in the I-type compositions, where some rocks retain high La levels. This change in behaviour of La in the S-type granites was determined by the fractional crystallization of monazite from the felsic liquids, in contrast to its earlier separation as a restite phase in the more mafic rocks. Monazite occurs in some felsic I-type granites of the LFB, and it has been used successfully for U–Pb dating of those rocks (Williams et al., 1983). The lower La contents of some I-type haplogranites show that it was possibly, sometimes, a fractionating phase despite the very low P contents of those liquids, or else allanite was a fractionating phase.

The different behaviour of Y in felsic I- and S-type granites is, like P_2O_5, one of the most distinctive features of those two types of haplogranites (Fig. 6). For the LFB, Y has remarkably similar abundances in both groups up to 75% SiO_2, and it continues at the same level for the S-type rocks. For the I-type granites it increases dramatically, by a factor of around 5 times for some samples. Since these are liquid compositions, it means that Y is behaving as a strongly incompatible element, implying that no Y-bearing accessory minerals were being fractionated. For the fractionating S-type haplogranites, the bulk partition coefficient for Y was very close to one, implying the consistent presence of an Y-bearing accessory mineral.

Concentrations of Y, readily determined by X-ray spectrometry, can be used as indicators of middle to heavy rare earth element abundances. Values for Lu are given for the 13 haplogranites in Table 1. For the three unfractionated granites, concentrations for that heaviest rare earth element are close to 0.5 ppm (~ 13 times chondrites). For the fractionated I-type granites, the Lu abundances are significantly higher, up to 2.6 and 3.1 ppm for the strongly fractionated rocks TB130 and DCC34. In contrast, Lu in the three fractionated S-type granites from the LFB is substantially lower than the unfractionated values, in the range 0.10 to 0.14 ppm. This marked contrast between the abundance of Lu is a general feature of fractionated I- and S-type granites from the LFB.

6.4. *Comparison of very felsic I-type and A-type granites*

A comparatively high abundance of the heavy rare earths is a characteristic of the A-type granites of the LFB (King et al., 1997). The analysis of a very felsic A-type granite, AB141 in Table 1, illustrates the similarities between those rocks and the strongly fractionated I-type granites for major elements and traces such as Y, Lu and Ga. However, unlike those I-type granites, these are primary or close to primary features of AB141, as that rock is at most only slightly fractionated. Rb and Cs are much lower than in rocks such as TB130 and DCC34, while Sr and particularly Ba, are higher. King et al. (1997) noted that many felsic, highly fractionated I-type granites have compositions that overlap those of the intrinsically felsic A-type granites for some elements. For unfractionated to mildly fractionated I-type rocks, such as samples BB21 and TB5 in Table 1, the distinction from the A-type granites, including ones less felsic than AB141, is very clear. At the other extreme, A-type granites that underwent strong feldspar fractionation would be difficult to separate from similarly fractionated I-type granites.

7. Contrasting patterns of evolution of trace elements in the Freycinet and Interview River suites

The I-type Freycinet Suite and the S-type Interview River Suite of the LFB provide examples of extreme evolution of felsic granites, dominated by fractional crystallization. These suites are exposed on the eastern and western coasts of Tasmania, respectively. The Freycinet Suite comprises four plutons, Coles Bay (~ 30 km^2), The Hazards (11 km^2), Freycinet (50 km^2) and Schouten Island (28 km^2), in which all rocks that have been examined are fractionated, shown by Rb contents in the range from 343 to 825 ppm for 21 analyzed rocks. The Interview River Suite includes the Interview River (66 km^2), Sandy Cape (1.7 km^2) and Three Hummock (18.4 km^2) units, with Rb varying between 275 and 950 ppm. For both suites, individual plutons show a restricted range of Rb contents, hence, degree of

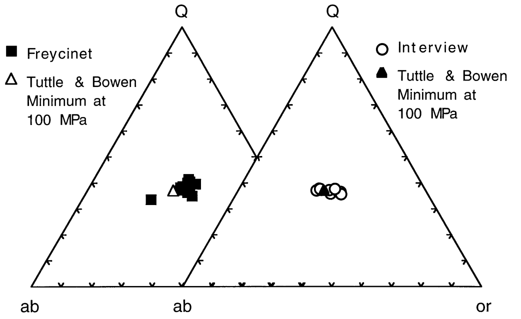

Fig. 7. Q–ab–or diagrams for the I-type Freycinet Suite and the S-type Interview River Suite. The totals of those three components range from 88.9 to 95.9% for Freycinet, and from 82.6 to 92.7% for Interview River, for which the lower totals are partly due to some rocks being less felsic, but also to normative C contents between 2.16 and 4.14%, compared with a maximum of 1.27% for Freycinet. The position of the minimum temperature at 100 MPa is shown (Tuttle and Bowen, 1958).

fractionation, relative to the whole suite. With one exception (TB121 from Schouten Island), all of the rocks that have been analyzed fall very close to the minimum temperature melt composition (Tuttle and Bowen, 1958) (Fig. 7), which shows that they represent liquid compositions and confirms the dominant role of fractional crystallization. Water is one component that would be concentrated by such extreme fractionation, but it is clear that the amount of low temperature alteration of feldspars was very restricted, although it is noteworthy that all granites of the Freycinet Suite are reddened. Examination of later figures will show that the samples from the Freycinet Suite are compositionally less cohesive than those from the Interview River Suite, which may represent a degree of alteration, and perhaps, a wider range of source compositions.

Sawka et al. (1990) have compared the fractionated S- and I-type granites of western Tasmania, and some of the features discussed here can also be seen in their data. However, the Freycinet Suite has been chosen here to compare with the those S-type granites because it is more strongly fractionated, and in that regard, very similar to the Interview Suite.

Analyses TB5 and TB130 in Table 1 are representative of the least and most fractionated rocks from the Freycinet Suite, and a comparison of those two compositions shows the most significant compositional changes associated with extreme fractional crystallization of an I-type melt. Likewise, for samples WG61 and WG57 from the S-type Interview Suite.

7.1. Aluminium saturation in the Freycinet and Interview River suites

Normative C contents are plotted against Rb for the I-type Freycinet Suite and S-type Interview River Suite in Fig. 8. Both suites had undergone a degree of fractional crystallization before even the least evolved compositions represented in that figure were produced. For Freycinet, the degree of Al-saturation does not change significantly with further fractionation, while for Interview River it commences at a high value (~ 2% C) and increases dramatically to an even higher level (~ 4% C). The data for Freycinet are consistent with the continuing separation of a slightly peraluminous assemblage of crystals, comprising quartz + feldspars (ASI = 1) and a small amount of biotite, from a melt with about the same degree of Al-saturation as the bulk crystals, so that the ASI of the melt does not change systematically with fractionation. For Interview River, separation of a similar group of crystals to the above, from an initially more peraluminous melt, leads to the melt evolving to even more peraluminous compositions. The latter parts of that evolution can be seen in Fig. 8. Both of the distinct trends in Fig. 8 resulted from the continuing separation of dominantly quartz and feldspars from haplogranite melts, with the S-type melt being initially slightly more peraluminous.

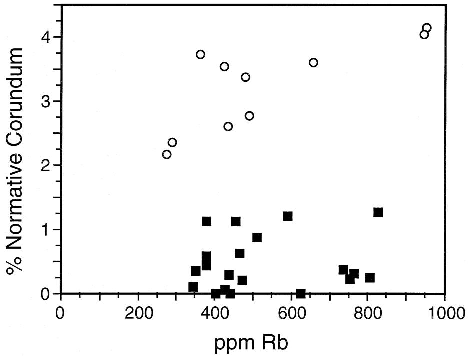

Fig. 8. Plot of normative C against Rb for the I-type Freycinet Suite (filled squares) and S-type Interview River Suite (open circles). Four samples from Freycinet plotted at zero C, contain up to 0.38% normative di.

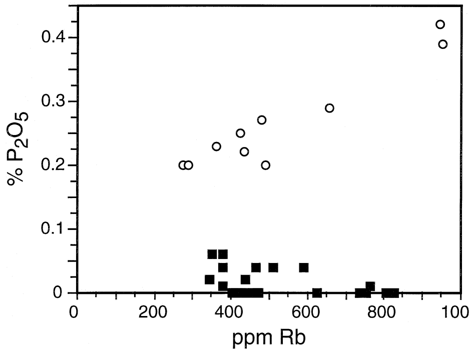

Fig. 9. Plot of P_2O_5 against Rb for the I-type Freycinet Suite (filled squares) and S-type Interview River Suite (open circles).

7.2. Evolution of phosphorus abundances in the Freycinet and Interview River suites

The general behaviour of P in the granites of the LFB has been considered in Section 6.2, with P_2O_5 increasing in abundance in the fractionated S-type granites and decreasing in the I-type rocks. This is shown for the specific example of the Freycinet and Interview River suites in Fig. 9. The two suites show a remarkably clear divergence in P abundances. For the Freycinet Suite, P abundances start at a low level (maximum of 0.06% P_2O_5 down to less than 0.01% P in some of the least fractionated rocks) and decrease further, so that the five rocks containing more than 500 ppm Rb all contain 0.01% P_2O_5 or less. This is in accord with the data of Harrison and Watson (1984), showing the low solubility of P in very felsic (and not strongly peraluminous) melts. For Interview River, P increases in a close to linear relationship with Rb, from 0.20% to 0.42% P_2O_5. As noted in Section 6.2, P_2O_5 concentrations in the Interview River Suite do not exceed the maximum solubility of P determined by Wolf and London (1994), so the trend for that element does not correspond to a line of saturation in P_2O_5. Rather it represents the increasing concentration of an element not being removed in precipitating minerals.

7.3. Trace elements varying in a similar way in both the Freycinet and Interview River suites

In contrast to P, and other elements to be discussed in Section 7.4, there are many elements whose abundances evolve in a similar fashion in strongly fractionated granites of both I- and S-type (Table 1). Those major and trace elements that occur in mafic minerals, already low in any felsic melts, are quickly purged from the evolving system. While the major element components of alkali feldspars change very little in abundance during prolonged fractionation, trace elements that occur in feldspars either increase or decrease rapidly in amount, depending on whether their bulk rock partition coefficients are less (Ga, Rb, Cs) or greater (Sr, Ba, Eu) than one (e.g., McCarthy and Hasty, 1976). Excluding peralkaline rocks, other elements that always increase in abundance in evolving felsic granites are F, Nb, Sn and U, while Zr decreases.

7.4. Trace elements varying in a contrasting way in the Freycinet and Interview River suites

The contrasting behaviour of P in the progressively fractionated haplogranites of the Freycinet and

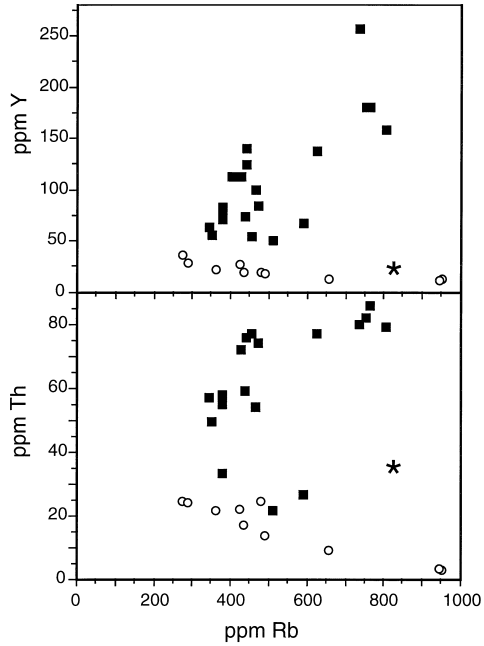

Fig. 10. Plots of Y and Th against Rb for the I-type Freycinet Suite (filled squares) and S-type Interview River Suite (open circles). The sample plotted as a star is TB121, the sample from the Freycinet Suite which plots away from the main group of compositions on the Q–ab–or diagram in Fig. 6. One sample from Freycinet, containing 403 ppm Rb and 122 ppm Th, is not plotted for Th.

Interview River suites has already been discussed. Two other elements with distinct patterns of behaviour, Y and Th, are shown in Fig. 10. For the Interview River Suite, both elements show a very regular trend and decrease with fractionation. This can probably be ascribed to their removal by incorporation in precipitating phosphate phases, since these melts contain abundant P (Fig. 9). Excluding sample TB121 (star in Fig. 10), which is not a minimum temperature melt composition and is therefore altered, there is a broad but regular increase in Y with fractionation for the Freycinet Suite. A similar but less consistent variation exists for Th. The variation in Y is consistent with the that of the fractionated I-type granites of the LFB as a whole, shown in Fig. 6. Clearly, no significant Y- or Th-bearing mineral was present in the mineral assemblage that fractionated to produce these compositions.

8. Conclusions

(1) Source rocks of I-type granites are undersaturated in Al, while those of S-type granites are oversaturated because of the loss of Na and Ca during weathering. The more mafic I- and S-type granites have degrees of Al-saturation that directly reflect that feature in their source rocks.

(2) Felsic granites of all types (haplogranites) are close to saturated in Al, and generally slightly oversaturated. This is due to the convergence of granites to the minimum temperature melt composition, with the normative minerals Q, ab, and or present in approximately equal amounts and together dominating the mineral assemblage.

(3) Hence, while the more mafic granites have ASI values and associated mineralogical features that are distinctly I- or S-type, the more felsic ones, when unfractionated, do not.

(4) Among the I-type granites of the Lachlan belt, the subordinate Boggy Plain Supersuite provides an example of the development of felsic granites through fractional crystallization. This process produced a mode in the ASI values close to 1.0. Among the S-type granites, the rocks of the Koetong Suite also evolved through fractional crystallization from a melt containing ~69% SiO_2, leading to strongly peraluminous compositions in that case.

(5) Most haplogranites of the LFB attained that character not by fractional crystallization, but rather by partial melting of quartz and feldspar in the crust. In the unfractionated state, there are some overlaps in ASI values between these I- and S-type compositions.

(6) There is close to a complete separation of ASI values between fractionated I- and S-type granites, with a boundary between most of the two sets of data at ASI = 1.1. With increasing fractionation, I-type melts stay close to just saturated, while the S-type melts become progressively more peraluminous, up to ~4% C in the LFB.

(7) As a consequence, there is a significant concentration of P in the S-type haplogranite melts, which increases with fractionation, whereas it falls to low levels in the I-type melts.

(8) Many elements vary in a similar way during the strong fractional crystallization of both I- and S-type haplogranites. However, some do not. The contrast in Al-saturation, and the dramatic difference in P abundances between the two types critically determine the accessory minerals that precipitate and are removed during fractional crystallization. Elements that occur in phosphate minerals, such as Y, the rare earth elements, and Th, therefore show strongly contrasting patterns of evolution between the highly fractionated I- and S-type granites.

(9) Highly fractionated granites comprise only a very small fraction of the components of the original source rocks, yet they have distinct properties according to whether those sources were igneous or sedimentary. The degree of Al-saturation of the melt was established during the initial equilibrium between melt and residual source rocks. This acted as a 'genetic code' during prolonged fractionation of those melts, resulting in distinctive end products.

(10) Highly evolved I-type granites are the extreme product of progressive stages of high temperature fractionation of the Earth, at least on the scale of tens of cubic kilometers.

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