Source Rocks of I- and S-Type Granites in the Lachlan Fold Belt, Southeastern Australia [and Discussion]

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Source rocks of I- and S-type granites in the Lachlan Fold Belt, southeastern Australia

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Granites and related volcanic rocks derived from both igneous and sedimentary source materials (I- and S-types) are widely distributed in the Palaeozoic Lachlan Fold Belt of southeastern Australia. Many of the granites contain material residual from partial melting of the source rocks, or restite, which enables attempts to be made to calculate source rock compositions. A few of the S-type granites are closely related to regional metamorphic rocks and are of relatively local derivation. Most, however, are intrusive into low-grade rocks and came from deeper levels in the crust; and volcanic equivalents are extensively developed. These dominant S-type rocks have chemical and isotopic properties unlike any known locally exposed sediments. For most of the S-types, and perhaps all of them, no mantle-derived component was present in the source. Chemical and isotopic data on the I-type granites suggest a variety of deep crust sources consisting of mantle-derived material showing differing amounts of isotopic evolution, according to the time since extraction from the mantle. These data do not favour a significant sedimentary component in the sources of even the most isotopically evolved I-type rocks. An origin of the I-type source rocks by crustal underplating is favoured, so that these sources were generally infra-crustal, whereas the S-type sources were of supra-crustal origin.

Introduction

The Lachlan Fold Belt of southeastern Australia was the site of very extensive igneous activity during late Silurian and Devonian times (Caledonian), when abundant granites and related volcanic rocks were produced (figure 1). These igneous rocks are considered to be at least dominantly and perhaps exclusively of crustal origin. They provide a clear example of a continental crust contribution to magma genesis. In this sense they are an end-member in assessing the relative contributions of mantle, oceanic crust and continental crust to magma genesis, the subject of this symposium.

The geological setting of the Lachlan belt granites has recently been discussed by White & Chappell (1983). The dominant country rocks to the granites are an Ordovician turbidite sequence of quartz-rich greywackes and shales (Wyborn & Chappell 1983). No rocks older than Cambrian are known to occur in the belt. Some altered basaltic rocks, partly of Cambrian age, are found in strips a few kilometres wide. Based on these occurrences, it has been suggested (see, for example, Crook 1980) that the Ordovician turbidites were deposited on a substrate of oceanic crust. This seems unlikely since the presence of such large quantities of granite would require the presence of a thick crust.

Seismic investigations in the eastern part of the Lachlan Fold Belt give a depth to the Moho of between 40 and 52 km (Finlayson *et al.* 1979). The present day heat flow is relatively high, between 70 and 90 mW m^{-2} (Sass & Lachenbruch 1979). White & Chappell (1983) have suggested that heat flow might have been high in the Lachlan belt since the mid-Palaeozoic, since the abundance of granites of that age shows that thermal gradients were high at that time, and evidence from inclusions in breccia pipes intruding the belt shows that thermal gradients were high during the Mesozoic.

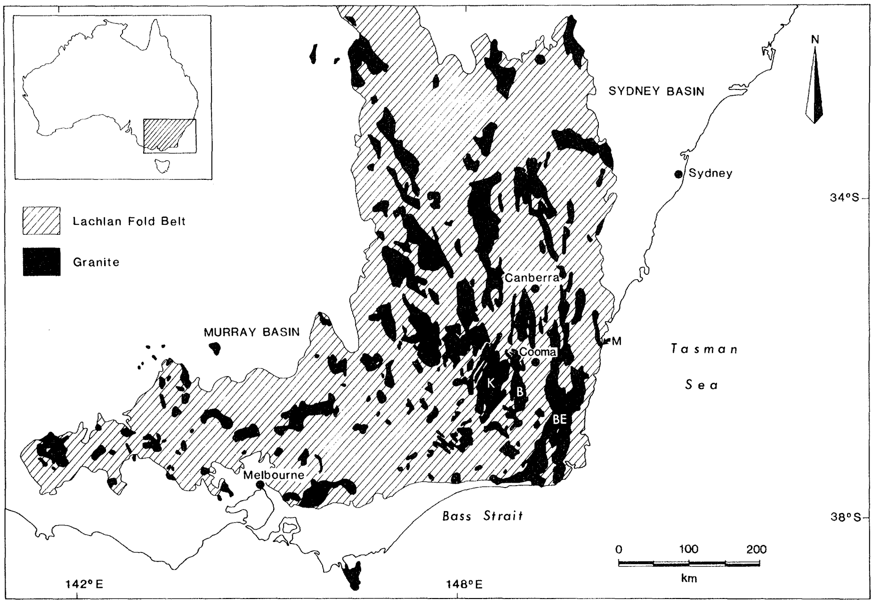

FIGURE 1. Map showing the distribution of the Lachlan Fold Belt in southeastern Australia, excluding Tasmania, and the occurrence of granites in that belt. K is the Kosciusko Batholith, B the Berridale Batholith, BE the Bega Batholith, and M the Moruya Batholith.

Large areas of the Lachlan belt are covered by Mesozoic and Cainozoic rocks and it is exposed over its full width only near its southern end (figure 1). Here, the belt is some 800 km wide perpendicular to the dominant structural trends. This is a much greater width than that of younger Mesozoic to Cainozoic fold belts. Radiometric ages on the granites are sparse but all data point to the emplacement of the granites over this large area during a restricted period of time. Most ages are in the 420 to 390 Ma interval with some younger plutons to 360 Ma in the central part of the belt north of Melbourne (see, for example, Williams *et al.* 1975; Compston & Chappell 1979; Richards & Singleton 1981). A small area in the Dundas Tablelands in the westernmost part of the belt, west of 142° E in figure 1, gives granite K–Ar mineral ages of 450–490 Ma (Richards & Singleton 1981). However, no granites of that age are known in the main part of the belt. In the most easterly part of the belt some 3000 km^2 of granite of Carboniferous age (Hercynian) is present; this is more correctly related to the younger New England Fold Belt, northeast of the Lachlan belt.

Modern geochemical studies of the granites in the Lachlan belt have so far been restricted to the easternmost 200 km of the belt. This is an area of relatively good exposure, uplifted as a series of plateaus up to 2100 m high since the Cretaceous. In this area east of longitude 148° E, granites make up 32950 km^2 or 36% of the total area of pre-granitic and granitic rocks (White & Chappell 1983). Related volcanic rocks cover another 15% of the area, so that half of the region is occupied by igneous rocks that were emplaced or erupted during a time interval of approximately 30 Ma. Further west, granites are less abundant (figure 1) but are still widely dispersed, making up some 12% of the area of the belt. The total area of the Lachlan Fold

Belt, including northeastern Tasmania, is close to 300000 km^2 and granites constitute 61000 km^2 or a little over 20% of this total area. For comparison, the total area of exposure of Caledonian Newer Granites in Britain and Ireland is 8300 km^2, with the largest unit, the Leinster Batholith, having an area of 1640 km^2.

Some significant conclusions about these granites can now be drawn. Their development through a lateral distance of 800 km across a fold belt in a relatively short time of 60 Ma, and dominantly during the second half of that interval, implies a massive transfer of heat into the crust. There is no obvious source of heat. In contrast to Mesozoic and younger fold belts, which were much narrower and in which melting may have been related to active subduction, this would seem to be ruled out in such a wide belt. Another significant feature of many younger fold belts is the common occurrence of mafic rocks, presumably mantle-derived, e.g. in the Peninsular Ranges Batholith of southern California (Larsen 1948). Likewise, in the Coastal Batholith of Peru, Cobbing & Pitcher (1972) report that gabbro makes up 'about 16%' of the plutonic rocks. In contrast, gabbros constitute less than 0.1% of the plutonic rocks in the Lachlan belt, and it is unlikely that heat was carried into the crust by mafic rocks on such a large scale. Thus the source of heat that resulted in the widespread magmatism is unknown. It is noted that the Lachlan magmatic activity was coeval with that of the Caledonian Newer Granites (see, for example, O'Connor *et al.* 1982), and it is becoming increasingly clear that there was a major melting event at 400 ± 20 Ma, implying a widespread transfer of heat from the mantle to segments of the crust before and at that time.

It is asserted that the Lachlan granites are of crustal derivation for the following reasons. First, as we shall see, approximately half of them are derived by partial melting of sedimentary rocks, with little or no evidence for any mantle component. Second, many of the granites, including mafic ones, involved melting at 'minimum' temperatures in equilibrium with quartz and two feldspars, so that the depth limit of feldspar stability was not exceeded. Third, most of the rocks are potassic, in contrast to the calcic granites of the Cordilleran and other young fold belts that might contain a component of mantle or subducted oceanic crust origin. Fourth, all oxygen isotopic compositions measured are significantly higher than mantle values and this must be regarded as an intrinsic or primary feature. Fifth, most Sr and Nd isotopic compositions are more evolved than mantle values. However, production within the crust does not imply, in all cases, the involvement of material that had undergone prior episodes of extensive igneous and sedimentary fractionation. Many of the granites are thought to have come from chemically rather primitive, but isotopically evolved, crust.

Granite suites

Over 400 individual granite plutons have been recognized in the eastern part of the Lachlan Fold Belt. These have been grouped into batholiths and complexes (White & Chappell 1983). The largest such unit is the Bega Batholith (Beams 1980; Beams *et al.* 1983), covering an area of 8600 km^2 and made up of more than 130 separate plutons. It has been found that many plutons can be grouped together on the basis of shared petrographic, chemical and isotopic features. These groupings are *suites* and are the basic unit in discussing most chemical and isotopic features. This concept is illustrated in figure 2 in which two suites from the Bega Batholith, Bemboka and Glenbog, are distinguished by plotting Sr on a Harker diagram. The Bemboka Suite consists of two plutons covering an area of 1050 km^2 near the centre of the batholith. The Glenbog Suite comprises fourteen separate plutons that are exposed over an area of 1540 km^2, running meridionally through a distance in excess of 250 km near the western edge of the batholith (figure 1).

Suites are thought to correlate with differences in source rock composition so that different suites result from different sources rather than different processes of crystallization or solidification. Conversely, a single suite is derived from effectively uniform source rocks. Suites are therefore crucial in discussing granite source rocks, and an effort has been made to develop techniques of calculating their source rock compositions. As a first step the data in figure 2 can be taken to imply that the Bemboka Suite was derived from more Sr-rich rocks than the Glenbog Suite. More precise estimates of composition can be attempted using the *restite model* of White & Chappell (1977) and these will be discussed below.

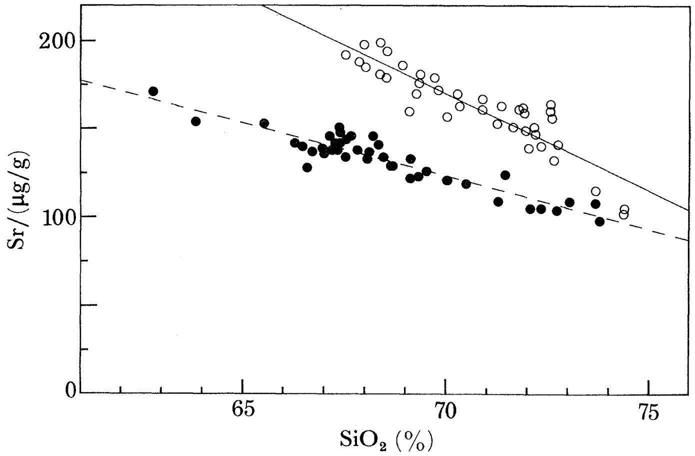

FIGURE 2. Harker Diagram showing Sr variation in the Bemboka Suite (open circles) and Glenbog Suite (solid circles) of the Bega Batholith.

I- AND S-TYPE GRANITES

The first-order subdivision of suites in the Lachlan Fold Belt is into two groups having mineralogical, chemical and isotopic properties indicating derivation from igneous rocks on one hand, and sedimentary rocks on the other. These are the I- and S-types of Chappell & White (1974). We are here less concerned with the properties of these two types *per se* and primarily interested in their source rocks, but a brief description of their properties is in order. A more detailed account of the types has been given recently in Chappell & White (1983).

Relative to the I-types, the S-type granites are low in Na, Ca and Sr, three elements which are lost during the conversion of feldspars to clay minerals by weathering, and are therefore low in pelitic rocks. The S-types are higher in Pb, Cr and Ni. The total Fe contents of the two types are comparable with Fe^{3+}/Fe^{2+} being significantly lower in the S-types, a feature which is thought to result from the presence of graphite in the source rocks (Flood & Shaw 1975). As a result of the lower Na and Ca, S-types are always corundum-normative or peraluminous and become more strongly so as the rocks become more mafic. Felsic I-types are mildly peraluminous and overlap the S-types, but more mafic I-type samples are metaluminous.

The mineralogy of the two types reflects their different chemical compositions. S-types contain Al-rich minerals such as muscovite, andalusite, cordierite, sillimanite or almandine; cordierite, some relict from the source and some precipitated from the melt, is particularly widespread although often altered. Hornblende never occurs and the most mafic S-types contain abundant biotite, up to 30%. Very felsic I-types contain muscovite and more mafic ones are characteristically hornblende-bearing. The opaque mineral content is generally different, with ilmenite occurring in S-types and magnetite in I-types, but exceptions are found (Whalen 1980). Isotopic properties of the two types will be discussed below in considering source rocks.

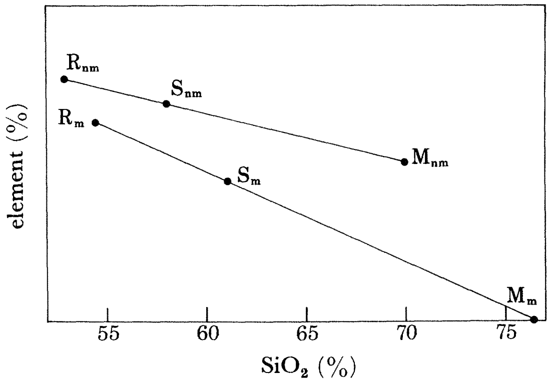

FIGURE 3. Diagram illustrating the partial melting of a source rock S_{nm} at non-minimum temperature or S_m at minimum temperature to produce restite R_{nm} or R_m and melt M_{nm} or M_m. Restite and melt together constitute the granite magma and separation of restite from the magma will generate rock compositions between S_{nm} and M_{nm}, or between S_m and M_m.

Two other important features of S-type granites must be noted. First, they generally occur as intrusive bodies surrounded by low-grade metamorphic rocks; examples related to high-grade regional metamorphism such as the Cooma Granodiorite (Pidgeon & Compston 1965) are uncommon. Thus S-type magmas are generally derived from deeper levels in the crust and have moved upwards as large volumes of magma, just as the I-types have. Second, as an extension of this, some S-type magmas were erupted, as did some I-types; three suites of S-type volcanic rocks have been described by Wyborn *et al.* (1981).

THE RESTITE MODEL

Granite melts form by the partial melting of a wide variety of source materials. These melts form from, and are in equilibrium with, solid material, or restite. When the amount of melt becomes sufficiently high, the rigid framework of restite will be broken and the whole mass will become fluid, or a magma. Relative to solid rocks of the same bulk composition, the magma will be less dense and its intrinsic buoyancy means that it will tend to move upwards to form a pluton, or to erupt. Because of the high viscosity and yield strength of granitic melts, the separation of restite is inhibited and in most, but not all, granites, some restite remains and forms part of the solidified granite or volcanic rock.

If the variation within a granite suite is largely or completely controlled by the proportions of restite in different samples, or the degree of restite unmixing, then source compositions can be more precisely defined. If the role of restite is minor or if it is absent, e.g. in the Tuolumne zoned pluton of the Sierra Nevada batholith (Bateman & Chappell 1979), then source compositions cannot be readily constrained. The relation between source rock and granite compositions in restite-controlled suites is shown in figure 3. Two cases are shown, one a source S_m that produces a 'minimum-temperature' melt M_m and its complementary restite R_m, the other a source S_{nm} that produces a higher temperature 'non-minimum temperature' melt M_{nm} plus restite R_{nm}. Compston & Chappell (1979) have suggested that the second case arises when insufficient minimum-melt components are present in the source to produce a fluid magma so that melting continues at a higher temperature. In both cases, the composition of derived granites will lie on the line joining melt to restite, passing through the source composition.

CALCULATION OF SOURCE COMPOSITIONS

The calculation of melt and restite compositions in figure 3 has been discussed by Compston & Chappell (1979). They calculated a *model restite* composition as the point where either normative quartz or K-feldspar disappeared as rock compositions were extrapolated to more mafic values. Values of M_{nm} were taken at 70% SiO_2, close to the most felsic compositions often observed in suites containing a non-minimum melt plus restite. Values of M_m can be calculated as the point where the extrapolated MgO content intersects the SiO_2 axis, since the MgO contained in minimum melts is very low (less than 0.05%). *Model source* compositions for non-minimum melt suites S_{nm} can be calculated by blending R_{nm} and N_{nm} in appropriate amounts, e.g. in proportions 3:1 if 25% melt is considered appropriate for the transition from rigid restite framework to fluid magma. Model source calculations for minimum-melt suites give minimum values for the SiO_2 content of the source since minimum-melt must be in equilibrium with restite containing quartz plus two feldspars, i.e. more siliceous than the model restite.

To overcome the problems of modelling minimum-melt suites, particularly since many S-type granites are of this type, a different method has been developed. If F is the fraction of melt that marks the transition from rigid restite framework to fluid magma, then F is the minimum amount of melt that the magma can contain and $(1-F)$ is the maximum amount of restite. If this magma moves up and differentiates to form a pluton of variable composition then the most mafic rock in that pluton will contain the maximum amount of restite, again $(1-F)$, and the minimum amount of melt, F. Thus, in a granite suite the most mafic possible composition (most restite-rich) will be the same as the source composition, within the limits of the model. Thus in any suite, the most mafic granite composition can be taken as the *model source* composition. Examples of this will be discussed below.

S-TYPE GRANITE SOURCE ROCKS

Complete data are not yet available on the S-type granites in the eastern part of the Lachlan Fold Belt, but twelve distinct S-type suites are recognized at this time, implying some variety in the composition of the sedimentary source rocks. Four of these suites and their source rock compositions will be discussed here, the Cooma, Bullenbalong, Ingebyrah and Dalgety suites.

Cooma Suite

The Cooma Granodiorite is a relatively small body (14 km²) occurring within a small regional metamorphic complex about 9 km wide where it is exposed on the western side. Metamorphism is of low pressure andalusite–sillimanite type. Pidgeon & Compston (1965)

TABLE 1. SELECTED GRANITE AND MODEL GRANITE ANALYSES FROM THE LACHLAN FOLD BELT

sample	1	2	3	4	5	6	7	8	9	10
SiO_2	72.00	68.13	65.32	74.07	67.68	73.48	68.21	58.91	55.50	64.89
TiO_2	0.54	0.56	0.76	0.28	0.64	0.22	0.53	1.41	0.70	0.48
Al_2O_3	13.72	14.46	15.06	13.22	14.70	13.41	14.25	16.91	18.63	14.85
Fe_2O_3	0.59	0.76	0.87	0.53	0.68	0.44	0.93	2.76	2.03	1.32
FeO	3.48	3.45	4.72	1.42	4.03	1.47	3.10	3.93	4.98	4.05
MnO	0.06	0.06	0.08	0.04	0.07	0.04	0.07	0.11	0.12	0.10
MgO	1.76	2.26	2.92	0.49	2.22	0.71	1.68	2.98	4.81	2.73
CaO	0.95	2.45	3.01	1.46	2.26	1.70	3.11	5.64	8.10	5.51
Na_2O	1.49	1.84	1.75	2.81	1.92	2.63	2.23	4.16	2.22	1.83
K_2O	3.73	3.97	3.14	4.38	3.60	4.63	3.77	1.55	0.95	2.55
P_2O_5	0.13	0.13	0.16	0.10	0.15	0.08	0.13	0.52	0.10	0.09
H_2O+	1.28	1.34	—	—	1.51	0.74	1.28	0.80	1.66	1.44
H_2O-	0.14	0.20	—	—	0.22	0.14	0.12	0.10	0.18	0.16
CO_2	0.13	0.12	—	—	0.12	0.11	0.29	0.23	0.06	0.07
total	100.00	99.73	97.79	98.80	99.80	99.80	99.70	100.01	100.04	100.07
trace elements/(μg/g)										
Ba	765	720	506	454	475	350	530	320	215	355
Rb	153	176	160	207	183	236	179	41	39	126
Sr	127	158	157	88	139	97	167	504	256	127
Pb	35	29	24	32	27	37	24	7	6	18
Th	22	20	19	18	19	19	16	6	4	14
U	4	3	3	3	4	6	3	2	1	2
Zr	201	170	197	143	187	100	158	246	68	109
Nb	9	11	13	8	13	10	12	18	5	8
Y	39	29	25	43	27	33	30	21	18	20
La	31	37	35	26	32	23	29	32	13	24
Ce	68	74	77	57	69	49	63	69	30	49
Nd	24	26	27	21	26	18	23	24	13	19
Sc	12	15	20	6	15	7	18	12	32	28
V	64	86	110	23	87	25	95	130	169	134
Cr	56	60	77	4	61	10	32	19	37	56
Co	15	17	20	5	17	6	14	25	26	20
Ni	24	21	27	4	20	4	10	13	15	11
Cu	11	18	23	4	17	3	11	48	8	17
Zn	71	71	92	33	82	28	57	76	76	71
Ga	15	17	19	14	18	14	16	17	17	16
isotopic data										
$^{87}Sr/^{86}Sr_i$	0.7180	—	—	—	0.7150	0.7108	0.7099	0.7038	0.7065	0.7119
ϵ_{Nd}	−9.2	—	—	—	−8.8	−8.0	−6.1	3.8	−3.7	−8.1
$\delta^{18}O$	12.0	—	—	—	11.6	10.2	9.6	7.9	7.3	9.0

sample details: (1) Sample Cl, Cooma Granodiorite, quartz-rich S-type granite; (2) Sample KB27, Back Swamp Granodiorite, sample from the Bullenbalong Suite with median FeO; (3) Model source content of the Bullenbalong Suite at total FeO of 5.5%; (4) Model melt content of the Bullenbalong Suite at total FeO of 1.9%; (5) Sample KB32, Jillamatong Granodiorite, a mafic sample from the Bullenbalong Suite; (6) Sample BB2, Numbla Vale Adamellite, a felsic S-type granite thought to represent a minimum-melt; (7) Sample BB9, Dalgety Granodiorite, an S-type granite with a relatively high ϵ_{Nd} value; (8) Sample MG16, Tuross Head Tonalite, the most mafic sample from the Moruya Suite; (9) Sample KB139, Grosses Plain Tonalite, the most mafic sample from the Jindabyne Suite; (10) Sample BB163, Finister Granodiorite, an I-type granite with a large negative ϵ_{Nd} value.

showed that the granite has the same Rb–Sr total rock age as the surrounding high-grade metamorphic rocks and similar initial $^{87}Sr/^{86}Sr$ ratios. McCulloch & Chappell (1982) made Nd isotopic analyses of a sample of granite and a high grade gneiss and obtained similar ϵ_{Nd} values of -9.2 and -8.3 respectively. All of these data are consistent with a model deriving the Cooma Granodiorite by essentially *in situ* melting of the surrounding Ordovician metamorphic rocks.

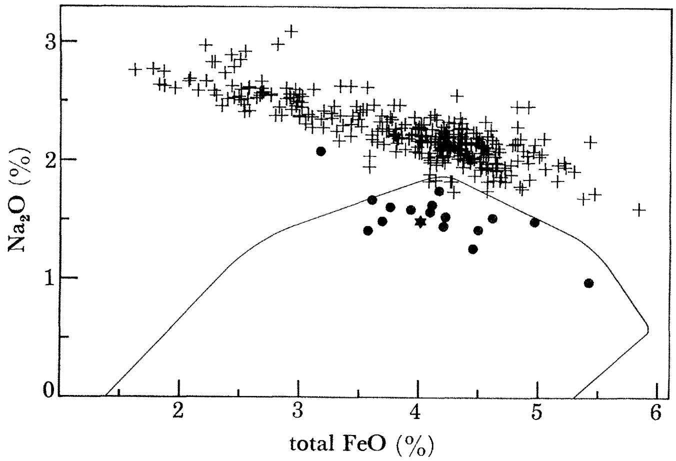

FIGURE 4. Plot of Na_2O against total iron as FeO for S-type granites from the eastern part of the Lachlan Fold Belt. The Cooma Granodiorite analysis (table 1) is shown as a star. The circles are 16 other rocks that chemically resemble the Cooma rock (Cooma Suite). The more abundant, more sodium-rich S-type granites are shown as crosses. The line at low Na_2O compositions encloses data for fifteen Ordovician sediments (Wyborn & Chappell 1983).

The Cooma Granodiorite (table 1) has a chemical composition that is distinctly different from most of the S-type granites in the Lachlan Fold Belt, containing significantly less Ca, Na and Sr. This is shown for Na_2O in figure 4, along with 16 other rocks from the Murrumbidgee and Maragle batholiths (White & Chappell 1983) that share these chemical characteristics, collectively referred to as the Cooma Suite. As with the isotopic data, the chemical data for this suite are again consistent with a derivation from the Ordovician quartz-rich greywackes and pelites which, as Wyborn & Chappell (1983) have pointed out, are low in Ca, Na and Sr.

Although their areal extent is small, the Cooma Suite rocks are significant in that they are the only granites in the Lachlan belt whose source rocks can also be directly examined. They are incontrovertibly of crustal origin. Their occurrence implies very high geothermal gradients, e.g. the high-grade metamorphic zones at Cooma crystallized at about 3 kbar† (White & Chappell 1983) and the problem of a heat source for these granites is particularly severe. A small body of pyroxene-bearing amphibolite occurs near the centre of the Cooma Granodiorite (Joplin 1939). This has a present-day $^{87}Sr/^{86}Sr$ of 0.7038 (Pidgeon & Compston 1965), is clearly mantle-derived, and may be significant in pointing to a heat source. However, it has already been noted that mafic rocks are very uncommon in the exposed Lachlan Fold Belt.

Bullenbalong Suite

The Bullenbalong Suite is the most widely developed S-type granite suite in the Lachlan belt. It is exposed over an area of 3100 km^2 and it extends meridionally through a distance of

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† 1 bar = 10^5 Pa.

150 km. The Bullenbalong Suite is one of several generally quite mafic S-type suites that together make up 11200 km² of the eastern Lachlan belt, one-third of the area of all exposed granites. Similar granites also occur further west in the belt, but their total abundance is not known at this time. Extensive volcanic equivalents occur, including the Hawkins Volcanics (Wyborn *et al.* 1981), which just north of Canberra have a total thickness of 2000 m.

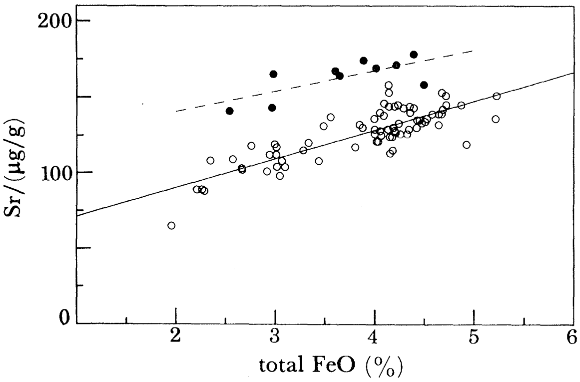
The minimum SiO_2 value determined for the Bullenbalong Suite is 65.9%. This is not as low as would be expected in such a mafic rock containing more than 25% biotite. This is a general feature of S-type granites and total iron provides a better index of the general composition. For this suite, total FeO ranges from 1.95% to 5.22% (75 samples) with a median value of 4.13% in KB27, nearer the more mafic end of the range of composition. An analysis of KB27 is given in table 1. Relative to the analysis of Cooma Granodiorite, KB27 is higher in Ca, Na and Sr indicating derivation from a more feldspar-rich source. In this respect, KB27 is typical of all S-type granites of the Lachlan belt, except the Cooma Suite. Wyborn (1977) pointed out that it is not possible to derive these S-type granites with higher Ca, Na and Sr from rocks similar to the exposed Ordovician (see figure 4).

The wide range in composition of the Bullenbalong Suite and the abundance of data makes it ideal for calculating model source compositions using the method discussed above. Figure 4 shows the range in total FeO content of all S-type granites and figures 5 and 6 the range for the Bullenbalong Suite. The maximum FeO content in figure 4 is 5.84% for a Cowra Granodiorite sample, not part of the Bullenbalong Suite; the latter has a maximum FeO of 5.22%. A value of 5.5% is taken for the model source and a complete composition calculated for other elements using this value in their regression parameters relative to total FeO, is given in table 1. The most felsic sample of Bullenbalong Suite contains 1.95% total FeO; and a felsic rock thought to be very close to an S-type primary melt, but not from the Bullenbalong Suite, is sample BB2 in table 1, containing 1.87% total FeO. A value of 1.9% is taken for the model melt composition of the Bullenbalong Suite and a complete melt composition calculated using this value is also shown in table 1.

Two samples for which isotopic data are available, KB32 and BB2, are also listed in table 1, to compare with the model source and melt compositions. The model source has a composition of a moderately feldspar-rich pelite. No rocks of this composition or average composition are known to be exposed in the Lachlan Fold Belt. For this general reason it was suggested by Wyborn (1977) that pre-Ordovician rocks more feldspar-rich than the exposed Ordovician greywackes and shales occur beneath the exposed Ordovician (see also Price 1983). These rocks are the presumed source of the bulk of the S-type granites. In relation to the subject of this symposium, as a major source of magma in the Lachlan belt, they are a continental crust source, with no evidence of a component of direct mantle or oceanic crust derivation. Such a view is supported by the Nd isotopic data (McCulloch & Chappell 1982) which show that two samples of Bullenbalong Suite, KB32 and KB31, have ϵ_{Nd} values of -8.8 and -8.0, close to the values of -9.2 for the Cooma Granodiorite and -8.3 for the associated gneiss (figure 7).

Ingebyrah Suite

The Ingebyrah Suite is another mafic S-type granite suite occurring as a group of five plutons totalling 410 km² in area, within the general area of exposure of the Bullenbalong Suite. The two suites are generally similar, but differ in some details, e.g. Ingebyrah is richer in Sr (figure 5). Neodymium isotopic compositions are also similar with the sample KB51 analysed by McCulloch & Chappell (1982) having an ϵ_{Nd} of -7.6. Strontium is distinctly less radiogenic with a value of 0.7106 for the initial $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}$ of KB51. This lower value may be related to the higher Sr content of this suite (figure 5) since, by inference, the source would have had a lower Rb/Sr ratio. The Ingebyrah Suite illustrates the type of chemical and isotopic fine-structure that exists within the S-type granites and their source rocks.



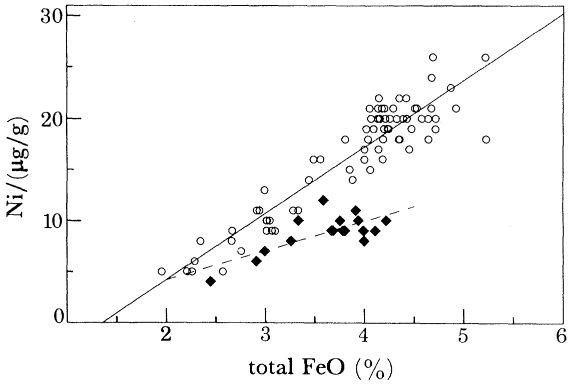


FIGURE 5. Plot of Sr against total iron as FeO for the Ingbeyrah Suite (solid circles) and the Bullenbalong Suite (open circles).

FIGURE 6. Plot of Ni against total iron as FeO for the Bullenbalong Suite (circles) and Dalgety Suite (diamonds).

Dalgety Suite

The Dalgety Suite consists of a single moderately felsic pluton in the Berridale Batholith, the Dalgety Granodiorite. With an area of 310 km², this is chemically and mineralogically unlike most of the S-type suites of the Lachlan belt. It is less peraluminous and never contains cordierite or altered cordierite. Both samples of this suite analysed by McCulloch & Chappell (1982) have less evolved Sr and Nd isotopic compositions than the Bullenbalong and Ingebyrah Suites, and consequently the model Nd ages are significantly younger than for the other S-type granites. On an ϵ_{Sr}–ϵ_{Nd} diagram (figure 7), the two Dalgety samples lie on a possible mixing line between a crustal component such as the Cooma gneiss or the more mafic S-type granites, and a mantle component. Such a mixed source is consistent with, but not required by, the isotopic data. However, some trace element data are not consistent with this model. For example, Ni is consistently lower in the Dalgety Suite than in the Bullenbalong Suite (figure 6), which would be unlikely if a mantle component were involved. It is concluded that this suite is derived from sedimentary source rocks that had a younger Nd model age and a different chemical composition than the source rocks of the Bullenbalong and other more mafic S-type suites.

Summary of S-*type suites and their source rocks*

For the Cooma Suite, an origin by partial melting of equivalents of the exposed Ordovician rocks is well established. For the mafic S-type suites such as Bullenbalong, such source rocks are not appropriate; the chemical and isotopic evidence points to another exclusively sedimentary source lacking any component of direct derivation from the mantle or subducted oceanic crust. In the case of the Dalgety Suite, the isotopic properties are transitional to those of the I-type granites and are consistent with a mixed sedimentary and igneous source. Such a source is not required by the isotopic features and such a source seems to be precluded by the chemical features of the Dalgety Suite.

I-TYPE GRANITE SOURCE ROCKS

The I-type granites of the Lachlan Fold Belt have a greater range in composition than the S-types, implying a wider range in source rock compositions. At the same time, individual I-type suites can be more precisely defined than their S-type equivalents, implying that the source rocks of each suite are more uniform. Three I-type suites and their source rocks will be considered here, the Moruya, Finister and Jindabyne suites. These represent the isotopically most primitive and evolved I-type suites, and an intermediate case.

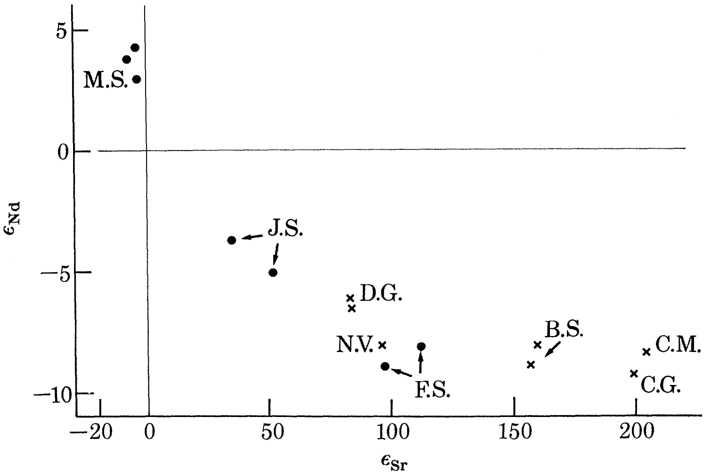


FIGURE 7. Plot of ϵ_{Sr} against ϵ_{Nd} for I- and S-type granites of the Lachlan Fold Belt. I-type granites are from the Moruya Suite (M.S.), the Jindabyne Suite (J.S.) and the Finister Suite (F.S.). S-type granites are from the Dalgety Granodiorite (D.G.), the Numbla Vale Adamellite (N.V.), the Bullenbalong Suite (B.S.) and the Cooma Granodiorite (C.G.). C.M. is a sample of Ordovician pelitic gneiss from the Cooma metamorphic complex. Data are from McCulloch & Chappell (1982) except for M.S. which are among the data referred to by McCulloch *et al.* (1982).

Moruya Suite

The Moruya Suite (Griffin *et al.* 1978) consists of eight separate plutons covering a total area of 194 km^2 at the eastern edge of the Lachlan belt (figure 1). The Nelligen Granodiorite pluton included in the suite by those authors is not now included, because of slight but significant Sr isotopic differences (Compston & Chappell 1979); those authors reported on average initial $^{87}Sr/^{86}Sr$ of 0.7043 for the Moruya Suite at 395 Ma. This ratio is close to that of chondritic upper mantle at that time (ϵ_{Sr} close to zero). The Nd and Sr isotopic compositions reported by McCulloch *et al.* 1982) include three samples for the Moruya Suite with slightly negative ϵ_{Sr} values and ϵ_{Nd} of +3.0, +3.8 and +4.3; these are plotted in figure 7. The Sr isotopic composition of the Moruya Suite is thus indistinguishable from a chondritic mantle value. The positive ϵ_{Nd} values imply that either the Moruya Suite granites, if they are mantle-derived, or their source rocks, if the suite is of crustal derivation, were obtained from a depleted mantle. The time of this derivation cannot be calculated since it depends on the time and magnitude of the prior depletion event, but it was in the interval 395 to 800 Ma, by using reasonable models for depleted mantle.

The isotopic data for the Moruya Suite thus leave open the two possibilities, one of direct derivation from a depleted mantle at 395 Ma, or production from crust of recent mantle derivation (less than 400 Ma). There is petrographic and chemical evidence that this suite is not of direct mantle derivation. The Moruya Suite ranges from felsic minimum-melt compositions through to mafic tonalites. Griffin *et al.* (1978) concluded that in all cases the melt was of felsic composition and that the mafic rocks contain a large proportion of recrystallized restite (White & Chappell 1977). This implies that all the components of this suite were produced by partial melting within the stability field of feldspar, that is, in continental crust. This crust was of relatively recent derivation (less than 400 Ma). Applying the method of calculating source-rock compositions developed above, the most mafic sample of Moruya Suite can be taken to represent the model source composition. The analysis of this sample, MG16 from the Tuross Head Tonalite, is given in table 1.

Finister Suite

The Finister Suite comprises two plutons, Finister and Merumbago, in the Berridale Batholith (figure 1), with a total exposed area of 48 km^2. Although this suite has relatively evolved Sr and Nd isotopic compositions (Compston & Chappell 1979; McCulloch & Chappell 1982) it is regarded as I-type on the basis of its chemistry and the occurrence of hornblende, and its oxygen isotopic composition (O'Neil & Chappell 1977), with four $\delta^{18}O$ values in the range 7.9–8.9‰.

Compston & Chappell (1979) reported initial $^{87}Sr/^{86}Sr$ ratios of 0.7102 and 0.7097 for the two plutons in this suite. They also calculated source rock Rb/Sr and $^{87}Rb/^{86}Sr$ values and the two points for this suite were at the high $^{87}Rb/^{86}Sr$ end of their source isochron for non-minimum melt granites of 1100 Ma at 420 Ma. McCulloch & Chappell (1982) studied a sample from each pluton (figure 7) and obtained Nd model ages of 1230 and 1270 Ma (chondritic mantle) and 1420 and 1440 Ma (depleted mantle). The preferred depleted mantle model age is close to the estimate of Compston & Chappell (1979) for this suite. These isotopic data clearly indicate derivation of the Finister Suite from old crust whose components, according to the chemical and oxygen isotopic data, had not been subjected to weathering at the Earth's surface. An analysis of sample BB163 from the Finister Granodiorite is given in table 1.

Jindabyne Suite

The Jindabyne Suite (Hine *et al.* 1978) consists of eight I-type plutons with a total area of 120 km^2, on the eastern side of the Kosciusko Batholith (figure 1). Compston & Chappell (1979) reported initial $^{87}Sr/^{86}Sr$ values for three plutons in this suite in the range 0.7066 to 0.7069 at 420 Ma. They ascribed these values to ageing of crustal source rocks with a $^{87}Rb/^{86}Sr$ of close to 0.3 over a period of 1100 Ma. McCulloch & Chappell (1982) obtained Nd model ages of 860 and 960 Ma (chondritic mantle) and 1210 and 1250 Ma (depleted mantle) for two samples from the Jindabyne Suite, all significantly less than the earlier estimate of Compston & Chappell (1979). Since that earlier study, a significantly more mafic sample from the Jindabyne Suite has been found, sample KB139 from the Grosses Plain Tonalite. If this composition is taken to define a model source composition, as discussed above, then revised estimates of the $^{87}Rb/^{86}Sr$ of the Jindabyne Suite source rocks can be made. With the Rb, Sr and initial $^{87}Sr/^{86}Sr$ values of KB139 (table 1) an $^{87}Rb/^{86}Sr$ value of 0.43 is obtained. Alternatively, with the SiO_2 content of KB139 defining the compositions of the Jindabyne Suite on regression lines for twenty six analysed samples, for Rb and Sr on Harker Diagrams (S_{nm} in figure 3), values of 47 μg/g Rb, 270 μg/g Sr and $^{87}Sr/^{86}Sr$ of 0.50 are obtained. Both these estimates of $^{87}Rb/^{86}Sr$ are higher than the values close to 0.3 of Compston & Chappell (1979).

With the value of 0.5 for $^{87}Rb/^{86}Sr$ for the source, the model Sr age (chondritic mantle) for KB139 is 820 Ma, in good agreement with the corresponding Nd model age of 860 Ma The older depleted mantle Nd model age of 1210 Ma is probably a better estimate of the true source age. These data again imply a two-stage production of the Jindabyne Suite from mantle, via deep crust, whose isotopic systems evolved for some 800 Ma before the melting event that produced the Jindabyne Suite.

The Jindabyne Suite data lie near the centre of the spectrum of I-type compositions on an ϵ_{Nd}–ϵ_{Sr} plot (figure 7). As McCulloch & Chappell (1982) noted, the covariation of ϵ_{Sr} and ϵ_{Nd} in that figure could result if the source rocks resulted from mixing of a young depleted mantle component (d.m.c.) and an old crustal component (c.c.) with $(Sr/Nd)_{dmc}$ $(Sr/Nd)_{cc}$ ≈ 7. Those authors pointed out that using reasonable values for Sr and Nd in d.m.c. and c.c. the isotopic composition of the Jindabyne Suite would require about 60% of c.c. in the source. They argued against this on chemical grounds; for example, an Rb content of 10 μg/g in d.m.c. and 150 μg/g in c.c. would give 94 μg/g in the Jindabyne Suite source, twice the estimate of 47 μg/g derived above. Likewise the $\delta^{18}O$ value of 7.3 in KB139 (table 1) would argue against such a significant metasedimentary crustal component in the source rocks. It is concluded that the old isotopic model ages of the Jindabyne Suite are the result of ageing of chemically rather primitive crust, as suggested by Compston & Chappell (1979).

Summary of I-*type suites and their source rocks*

The I-type suites of the Lachlan Fold Belt are rather diverse in composition, and by implication, were derived from a wide range of source compositions. In many cases, the rocks are felsic and were produced from melt-rich magmas formed by melting at low pressures, clearly implying an origin in the crust. Commonly, more mafic rocks appear to owe their more mafic character to the presence of abundant restite, and the melt involved was formed at low temperatures and at low pressures in the crust. Some of the more mafic suites, e.g. Finister and Jindabyne, owe their mafic character to the production of a higher temperature melt and a crustal origin is not required by the chemical data. However, in all cases of these that have been examined, both Sr and Nd isotopic compositions were significantly evolved above mantle values at the time of granite formation. Again, a crustal origin seems to be required.

Supracrustal and infracrustal granite sources

Chappell & White (1974) proposed that, based on studies in the Lachlan belt, two distinctive types of granite could be recognized, the S- and I-types. Ten years later, after fairly extensive additional studies, this subdivision is still clear in that region. Doubtful cases are not a result of a mixed source, but are the felsic types in which most chemical and mineralogical characters converge. It has become clear that the S-type granites of southeastern Australia are particularly distinctive and owe this character to derivation from relatively mature pelitic, but still feldspar-bearing, source rocks. Elsewhere, more feldspar-rich sedimentary sources would have produced S-type granites of a more subtle character. Such a character might have been present, for example, in the Scottish Caledonides, where Plant *et al.* (1983) have recently stated that the S- and I-type model is invalid. In the Scottish case, it must be remembered that those occurrences are a small sample (see earlier figures) and the largest granite body in Britain and Ireland, the Leinster granite, is probably S-type.

Chappell & White (1983) noted that for those I-type granites in which the variation is due to unmixing of melt and restite, which includes most I-types in the eastern part of the Lachlan Fold Belt, element variation diagrams show high degrees of correlation. For S-types, the opposite is the case, and the poorer correlation for these can be ascribed to more heterogeneous source rocks. This implies that I-type source rocks are relatively homogeneous, through volumes large enough to produce plutons up to 1000 km^2 in area in the Lachlan Fold Belt. 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). Chappell & White (1983) therefore suggested that the two types of granite come from source rocks of fundamentally different origin, one formed by deposition of the crust, the other by accretion beneath the crust, so that S-types were derived from supra-crustal source rocks and I-types generally from source rocks of infra-crustal origin.

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Discussion

P. R. SIMPSON (*Institute of Geological Sciences*, 64–78 *Grays Inn Road*, *London WC1X 8NG*, *U.K.*). In view of Dr Chappell's references to Scottish Caledonian granites which he appears to consider support his model, I should like to point out that the Caledonian alkalic uranium-rich granites such as the Cairngorm batholith are unequivocally I-type on trace element, geophysical and isotopic evidence but also have many primary S-type attributes (high alumina and potash, low soda and lime, predominantly high SiO_2 composition and increased contents of tin) (Plant *et al.* 1980).

Furthermore, many cases of apparently S-type two-mica granites, such as the Hercynian Cornubian Batholith of southwest England with elevated initial strontium ratios and associated Cu–Sn–U mineralization may originally have been I-type granites. It is thought that interaction with epizonal waters which have previously equilibrated with graphitic shales in the aureole transformed their mineralogy, trace element chemistry and isotope systems (Simpson *et al.* 1982).

In the circumstances, it was concluded that the I- and S-model for genesis of metalliferous and mineralized granites is not applicable in the Scottish Caledonian or English Hercynian Provinces and probably elsewhere.

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B. W. Chappell. My reference to Scottish Caledonian granites was to show that they are coaeval with those of the Lachlan belt, which could be significant in terms of heat sources and source rocks. I have also reminded the audience that the total area of Scottish granites is rather small, with the implication that care should be taken in extrapolating too widely from a small area. Even among the much more abundant granites of southeastern Australia, some types that are important elsewhere, are not strongly represented. We do though, have unequivocal evidence for two dominant sources: igneous and sedimentary. This is based on the widespread occurrence of rather mafic granites with two sets of distinctive chemical, isotopic and mineralogical properties.

The more felsic granites, those typically related to mineralization, are more difficult to assign, since with fractionation the chemical and mineralogical properties converge and can overlap, and more extensive isotopic studies are needed for characterization. However, it seems reasonable to suppose that the felsic granites of Cornubia and Malaysia, for example, are fractionated from more mafic S-type magmas, similar in many respects to those of the Lachlan belt. This is consistent with known chemical and isotopic data and on that basis more probable than an alteration of I-type granites.

Determination of the source magmas of felsic granites is not a straightforward problem and requires much more detailed studies in Britain, Australia, and elsewhere. It has recently been made perhaps more complex by the recognition of a less abundant but important third group, the 'A-type' granites (Collins *et al.* 1982), which could be the most significant type in relation to mineralization.

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