CHEMICAL EVOLUTION AND ORIGIN OF

GRANITES IN THE LACHLAN FOLD BELT

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CONTENTS

1. PUBLICATIONS BEING SUBMITTED FOR EXAMINATION

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2. White, A.J.R. & Chappell, B.W. 1977. Ultrametamorphism and granitoid genesis. *Tectonophysics* 43, 7-22.

3. O'Neil, J.R. & Chappell, B.W. 1977. Oxygen and hydrogen isotope relations in the Berridale batholith. *J. geol. Soc. Lond.* 133, 559-571.

4. Hine, R., Williams, I.S., Chappell, B.W. & White, A.J.R. 1978. Contrasts between I- and S-type granitoids of the Kosciusko Batholith. *J. geol. Soc. Aust.* 25, 219-234.

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6. Compston, W. & Chappell, B.W. 1979. Sr-isotope evolution of granitoid source rocks. *In* McElhinny, M.W. (ed.) *The Earth: Its Origin, Structure and Evolution*, Academic Press, London, pp. 377-426.

7. Wyborn, D., Chappell, B.W & Johnston, R.M. 1981. Three S-type volcanic suites from the Lachlan Fold Belt, southeast Australia. *J. geophys. Res.* 86, 10335-10348.

8. McCulloch, M.T. & Chappell, B.W. 1982. Nd isotopic characteristics of S- and I-type granites. *Earth planet. Sci. Lett.* 58, 51-64.

9. Collins, W.J., Beams, S.D., White, A.J.R. & Chappell, B.W. 1982. Nature and origin of A-type granites with particular reference to south-eastern Australia. *Contr. Miner. Petrol.* 80, 189-200.

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11. Chappell, B.W. 1984. Source rocks of I- and S-type granites in the Lachlan Fold Belt, southeastern Australia. *Phil. Trans. R. Soc. Lond.* A 310, 693-707.

PUBLICATIONS BEING SUBMITTED FOR EXAMINATION (continued)

12. Chappell, B.W. & White, A.J.R. 1984. I- and S-type granites in the Lachlan Fold Belt, southeastern Australia. *In* Xu Keqin & Tu Guangchi (eds) *Geology of Granites and Their Metallogenic Relations*, pp. 87-101. Science Press, Beijing.

13. Sawka, W.N. & Chappell, B.W. 1986. The distribution of radioactive heat production in I- and S-type granites and residual source regions: implications to high heat flow areas in the Lachlan Fold Belt, Australia. *Aust. J. Earth Sci.* **33**, 107-118.

14. Wyborn, D. & Chappell, B.W. 1986. The petrogenetic significance of chemically related plutonic and volcanic rock units. *Geol. Mag.* **123**, 619-628.

15. Chappell, B.W., White, A.J.R. & Wyborn, D. 1987. The importance of residual source material (restite) in granite petrogenesis. *J. Petrol.* **28**, 1111-1138.

16. Chappell, B.W. & Stephens, W.E. 1988. Origin of infracrustal (I-type) granite magmas. *Trans. R. Soc. Edinburgh: Earth Sciences* **79**, 71-86.

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2. INTRODUCTORY STATEMENT

The author has been involved in studying the granites of the Lachlan Fold Belt (LFB) since 1963 with this being the main focus of his scientific studies since 1973. This thesis brings together many of the publications that have arisen from that work and those 20 papers that are being submitted for examination are listed in Section 1 (pp. 2-3) and are bound together at the back of this volume. A complete list of the 114 publications for which this writer is an author is given in Section 10 (pp. 43-51). That list is comprehensive and again includes the 20 papers being examined. The remaining 94 papers are listed in support of the candidacy. Among those other papers, 37 deal with various aspects of granite studies, both in the LFB and elsewhere, and the remainder with a variety of geological and geochemical subjects.

Much of the work on the LFB has been carried out jointly with other persons. Most prominent among these is Professor A.J.R. White of the Australian National University (ANU) until 1971 and at La Trobe University (LTU) since 1972. Professor White has been a continuing source of stimulation and encouragement in this author's studies in the LFB. Dr J.A. McDonald, while at the ANU, also had an interest in the granites of the Wyangala Batholith and several BSc and one MSc project in the period 1973-1978 were carried out under his supervision. Three BSc theses that partly dealt with granites of the LFB were supervised by Dr R.A. Eggleton. Dr S.D. Beams continued his BSc study at the ANU as a PhD thesis at LTU. Dr L.A.I. Wyborn and Dr D. Wyborn both carried out PhD studies on the granites of the LFB and in the second case those studies have extended over a much longer period, based at the Bureau of Mineral Resources. Dr E.J. Reid submitted an MSc thesis at the ANU and a PhD thesis at the University of Tasmania and his results are known to the author. There have been 40 BSc honours, 2 MSc and 4 PhD theses submitted at the ANU dealing with granites of the LFB, mainly under the supervision of this author, and of A.J.R. White prior to 1972. At LTU, 35 BSc and 2 PhD theses have been available, through collaboration with A.J.R. White. Within the realm of the state government geological surveys, the author has benefited from discussions and from the provision of some rock samples, from Mr D. Pogson and Miss H. Basden of New South Wales, Dr F. VandenBerg of Victoria, and Dr M. McClenaghan of Tasmania.

The project to study the granites of the LFB has extended over 27 years and involved many persons. In connection with this thesis, this raises the question of this writers specific contributions to the project. The nature and scale of the LFB granite project has meant that much of the work has been collaborative. Only one paper being submitted for examination has single authorship. This author has been involved to some extent in most aspects of granite studies in the LFB, including field-work, rock sampling, petrography, modal analysis, and geochemistry; it is only in the area of isotopic studies that there has been no direct involvement in the laboratory acquisition of data. This thesis emphasises the geochemical aspects of the LFB study, since this writer can claim to have had the major involvement in all of that work. All chemical data that have been used in the LFB granite project have been obtained at the ANU. This includes samples from studies at LTU, which were either initially analyzed at the ANU, or re-analyzed for this project. Those samples of Dr E.J. Reid's

PhD thesis that have been used as part of this project were also analyzed at the ANU.

This thesis is concerned with ideas and interpretations that have resulted principally from the chemical studies of the LFB granites and this writer is responsible for most of that work. Table 1 provides the estimated proportion of the author's contribution to each of the 20 publications being submitted for examination. These figures have been arrived at in most cases by consultation with the joint authors.

An earlier PhD thesis to the ANU in 1966 was concerned with younger late Palaeozoic granites from the Moonbi district of the New England Fold Belt. That work was therefore geographically separated from the area now under consideration. However, that earlier study did contain the beginnings of some concepts that have been much further developed during studies of the LFB. Two of these must be noted. First, the Moonbi study concluded that the hornblende-bearing granites carried up mafic inclusions from their source, whose disaggregation provided the mafic component of the granites. According to that model, the composition of each particular sample reflected the proportion of that mafic material that was present. This was the beginning of what in a much more refined form was later called the "restite model". Second, in a brief comment at the end of that thesis, it was concluded that the two-mica granites north of Moonbi probably came from the partial melting of "sialic crust", in contrast to the presumed mafic source of the hornblende granites that were the main object of study. In retrospect, this was the first suggestion of the I-type and S-type granites, but its significance was not realized until the more diverse granites of the LFB came to be examined. The Chappell (1978) paper on the Moonbi granites, not included here for examination, did incorporate some of those later developments from studies of the LFB that are being submitted for examination in this thesis, and did not rely only on conclusions made much earlier in the PhD thesis.

TABLE 1. CONTRIBUTION OF THIS AUTHOR TO PUBLISHED PAPERS

Paper	%	comments
1. Chappell & White (1974)	50	Very much a shared paper
2. White & Chappell (1977)	50	Mainly BWC concept, developed further and mainly written by AJRW
3. O'Neil & Chappell (1977)	40	BWC responsible for geological aspects
4. Hine et al. (1978)	30	BWC responsible for most of geochemistry
5. Griffin et al. (1978)	30	BWC responsible for most of geochemistry
6. Compston & Chappell (1979)	40	BWC responsible for chemistry and modelling concept. Developed and written by WC
7. Wyborn et al. (1981)	30	BWC responsible for much of geochemistry
8. McCulloch & Chappell (1982)	40	BWC shared responsibility for interpretation
9. Collins et al. (1982)	25	BWC responsible for most of geochemistry
10. White et al. (1983)	40	BWC jointly responsible for work. First draft written by AJRW
11. Chappell (1984)	100	Invited paper at Royal Society symposium
12. Chappell & White (1984)	70	Invited paper at Nanjing symposium
13. Sawka & Chappell (1986)	40	Part of WNS PhD - he initiated most ideas. BWC responsible for geochemistry
14. Wyborn & Chappell (1986)	40	BWC partly responsible for ideas. Mainly written by DW
15. Chappell et al. (1987)	55	BWC responsible for initial concept, developed extensively through discussions with AJRW and DW. Organized and written by BWC
16. Chappell & Stephens (1988)	80	Invited paper at Hutton Symposium. First draft written while at St Andrews. WES mainly concerned with Caledonian
17. White & Chappell (1988)	35	AJRW invited paper at Hutton Symposium. BWC contributed to geochemistry and final draft
18. Chappell et al. (1988)	50	Ideas developed jointly, with evaluation of geochemical aspects mostly by BWC. Put together and written by BWC
19. White & Chappell (1989) 20. White et al. (1989)	35	BWC responsible for some mapping, all modal and chemical data and discussion of chemistry. Mostly written by AJRW

ARRANGEMENT OF THIS THESIS

This thesis comprises 20 publications arising from studies of granites in the LFB, and an accompanying text. The latter seeks to integrate those papers in terms of the current understanding of the evolution of granites in that belt. In Section 3 (pp. 9-11) the general occurrence and distribution of granites in the LFB is summarized. Section 4 (pp. 13-17) discusses the concept of granite suites and the causes of variation within suites. This includes a brief evaluation of the current status of the restite model in relation to other mechanisms for the production of variation in cogenetic granites. This leads in Section 5 (pp. 19-23) to a discussion of the I-type and S-type granites of the Lachlan Fold Belt. The concept of basement terranes is briefly discussed in Section 6 (p. 25). Because of its significance in developing an understanding of the origin of I-type granites, the information available on the large Bega Batholith and the inferences that can be drawn from those data, are treated in Section 7 (pp. 27-32). In Section 8 (pp. 33-38), the S-type granites of the Wagga Basement Terrane are discussed. This represents the most recent work on the granites in the LFB, and the interpretation of the geochemical data on those granites is almost entirely the work of the author. That work has very substantial implications for the origin of felsic S-type granites, including the two-mica granites, that are the igneous rock type associated with major tin deposits. The Wagga granites have provided the key to understanding in some detail the petrogenesis of the two-mica and related granites, which has previously been one of the outstanding and most difficult problems in granite genesis.

In Chapters 3-9 references to those publications being submitted for examination are by the number 1-20 in square brackets, with the number referring to the list on pp. 1-2. So, for example, a reference to [12] refers to Chappell & White (1984). All other papers are referred to in the normal way and those other references are listed in Section 9.

Section 10 lists all published papers of the author.

3. OCCURRENCE OF GRANITES IN THE LACHLAN FOLD BELT

That part of the Lachlan Fold Belt (LFB) exposed in southeastern Australia has a total area of close to 300,000 km^2. The full width is seen only in Victoria where it is some 750 km wide at right angles to the dominant structural trends. It was the site of very extensive igneous activity during late Silurian and Devonian times when abundant granites and related volcanic rocks were produced. The position of the LFB in relation to the other tectonic elements of eastern Australia is seen in Figure 1 of [16]. The distribution of granites in the belt is shown in Figure 1 of [18]. For the eastern third of the belt, in which the granites are more abundant, their occurrences are given in more detail in Figure 2 of [10], which paper also described the geological setting of the granites. All units recognized in Victoria were listed by White & Chappell (1988) and the location of all those units is shown on maps in that paper. Many of the regional features of the granites were discussed in the publication on the basement terrane concept [18]. Other general features of the LFB and its granites and their relation to other geological elements of eastern Australia have also been published [16]. That paper also discusses the extension of the LFB to the north beneath cover rocks, and south in Antarctica. Its total extension in eastern Australia could be regarded as being from latitude 13°S in Cape York to latitude 43°S in southeastern Tasmania. In Antarctica, granites of the same age as those in the LFB are restricted to the northern part of the Transantarctic Mountains. Prior to the opening of the Southern Ocean, the granites of this belt extended through a distance of some 3600 km with a width of up to at least 750 km [16]. This thesis is concerned with studies that have been made of those granites now occurring in south-eastern Australia and the term LFB used here refers to that region.

Granites outcrop over an area of 61,000 km^2 in the LFB and thus make up a little over 20% of the total area of that belt. Their distribution is not uniform, as they comprise 36% of the total area in the 108,400 km^2 east of 148°E and some 12% of the central and western parts. Related volcanic rocks are also abundant, covering 15% of the area of the eastern part of the belt [10].

Radiometric ages on granites of the LFB are sparse. Most ages are in the 420 to 390 Ma interval with some plutons to 360 Ma in the central part of the belt north of Melbourne (see, for example, Williams *et al.*, 1975; [6]; Richards & Singleton, 1981). The granites of western Tasmania (Taswegia Terrane) are distinctly younger than the main body of the LFB with a total range of ages from 380 to 330 Ma reported in the summary of McClenaghan *et al.* (1989). 2800 km^2 of granite of Carboniferous age (~ 320 Ma) is present in the most easterly part of the belt; this is more correctly related to the younger New England Fold Belt, northeast of the LFB.

White *et al.* (1974) subdivided granites according to their associated rocks into regional-aureole, contact-aureole and subvolcanic types. In the LFB, the country rocks are mostly of very low regional metamorphic grade and the plutons are generally contact-aureole types. In a few cases, the granites are regional-aureole types, surrounded by high-grade metamorphic rocks with which they are intimately related, e.g. at Cooma (Joplin, 1942; Pidgeon & Compston, 1965; Chappell & White, 1976; Munksgaard, 1988). The largest granite pluton in the LFB is the Bemboka Granodiorite in the Bega Batholith which is 970 km^2 in area with a small additional area covered by Devonian sedimentary rocks. Volcanic equivalents of some of the granites do occur, and sometimes the intrusions are subvolcanic, e.g. near its southern end, the Young Batholith intrudes the

Goobarragandra Volcanics with which it is chemically related [7].

More than eight hundred separate lithological units of granites (≈ plutons) have been recognized in the LFB. It has been conventional to group these lithological units into separate batholiths, particularly in the eastern part of the LFB, and this is here extended to cover the whole belt. The term "batholith" is used for a group of plutons that are contiguous or nearly so, with a total exposed area generally in excess of 500 km². Smaller units are referred to as "granite complexes" or "Granites"; these are sometimes excellent "mini-batholiths", such as Marulan, Moruya and Gingera. The term "Granites" is also used for an area of dispersed plutons, e.g. Bonang and Gulgong, that are sometimes in excess of 500 km² in area. In some cases the batholiths are naturally well-defined, e.g. Bathurst or Young; in other cases, the boundaries are poorly defined and arbitrary, e.g. Kosciusko *vs* Maragle. Batholiths generally include some adjacent but separated plutons and it seems undesirable to differentiate these as McClenaghan *et al.* (1989) have done, for example, in assigning a small area on the north-eastern corner of the Blue Tier Batholith to the "Eddystone Batholith". Historical usage must also be considered; for example, the Cooma Granodiorite could be assigned to the Murrumbidgee Batholith. However, it has for over fifty years been a focus of attention as the core rock of the Cooma Metamorphic Complex and this separate identity is retained here. While some aspects of this subdivision in batholiths and complexes are arbitrary it is nevertheless very useful in geographically subdividing plutons that cover such a large area.

The composite nature of the batholiths is exemplified by the Berridale Batholith, which although relatively small, consists of about forty separate plutons ranging up to 470 km² in outcrop area (White *et al.*, 1976b and [19, 20]). These structurally defined units may be grouped into twenty one lithologically distinct mappable units which appear as separate plutons, pairs of plutons, or groups of plutons. Screens of country rock hornfels often occur between adjacent plutons or between strings of plutons [10]. Contacts, where observed or inferred, are very steep.

A list of the separate batholiths and granite complexes recognized in the LFB is given in Table 2. The location of the first twenty of these is given in Figure 2 of [10]. Among the additional five, the Wagga Batholith comprises the very large area of granite in the Wagga Basement Terrane and east of the Melbourne Basement Terrane, shown in Figure 1 of [18], apart from the separate Maragle Batholith. Again with reference to [18], the Central Victoria Granites occupy the Melbourne Basement Terrane and the Western Victoria Granites the Stawell and Grampians-Stavely Basement Terranes. The Bassian Batholith comprises all of the granites extending from Wilsons Promontory across Bass Strait and through north-eastern Tasmania to Maria Island and the small exposure on the Forestier Peninsula, shown again in Figure 1 of [18]. A large part of that extensive area is covered by the waters of Bass Strait, but it seems desirable to group these rocks together rather than split them into many much smaller units. Throughout much of the Bassian Batholith there are occurrences of distinctive felsic fractionated S-type granites that sometimes contain concentrations of garnet, and these rocks should clearly be grouped into one structural unit. Finally, the Taswegia Granites are those of Devonian age in the Taswegia Basement Terrane, on the Tasmanian West Coast and King Island.

A comprehensive coloured map on a scale of 1:1 000 000, showing all granite units in the LFB, is being prepared and should be published in 1991.

TABLE 2. LACHLAN FOLD BELT GRANITE COMPLEXES

Batholith or complex	Area (km^2)	I	% of type S	A
1. GULGONG GRANITES	800	100	-	-
2. BATHURST BATHOLITH	1630	100	-	-
3. OBERON GRANITES	390	100	-	-
4. MARULAN GRANITES	220	100	-	-
5. MORUYA BATHOLITH	263	100	-	-
6. GABO ISLAND GRANITES	59	3	-	97
7. BEGA BATHOLITH	8620	99	<1	1
8. WOLOGORONG BATHOLITH	800	-	100	-
9. WYANGALA BATHOLITH	3180	29	69	2
10. MURRUMBIDGEE BATHOLITH	1470	42	32	-
11. COOMA COMPLEX	14	-	100	-
12. GINGERA GRANITES	260	21	79	-
13. BERRIDALE BATHOLITH	1670	46	51	-
14. BONANG GRANITES	435	62	16	22
15. KOSCIUSKO BATHOLITH	4000	6	94	-
16. YEOVAL BATHOLITH	1500	100	-	-
17. GRENFELL GRANITES	1040	100	-	-
18. YOUNG BATHOLITH	4090	1	99	-
19. TUMUT GRANITES	380	89	11	-
20. MARAGLE BATHOLITH	3940	22	78	-
21. WAGGA BATHOLITH	13800	~5	~95	
22. CENTRAL VICTORIA GRANITES	6400			
23. WESTERN VICTORIA GRANITES	2060	100	-	-
24. BASSIAN BATHOLITH	3590			
25. TASWEGIA GRANITES (West Coast)	715	?	?	-

4. GRANITE SUITES IN THE LACHLAN FOLD BELT

The recognition of lithological units and their chemical subdivision into suites has been discussed [10]. Granites assigned to a single suite share distinct textural, modal and chemical features and chemical criteria are a rigorous test of a suite. Rocks within a suite must also have the same isotopic composition and this is an excellent test because of the high precision available and the insensitivity to chemical composition, except where the age correction is large. Some of the suites in the LFB have been tested with Sr and Nd isotopes [6, 8]. Members of a suite are consanguinous but can have no simple relationship with another suite. Each suite is considered to correspond to a specific source-rock composition, with the variation within each suite resulting from processes such as restite-unmixing and fractional crystallization (see below). The concept of suites is well illustrated by the Bega Batholith in which fifty three suites have been recognized, some consisting of a single pluton that has a unique compositional character, while others are made up of several plutons. The suite concept is illustrated by plotting Sr *vs* SiO_2 for the 54 samples from the 14 plutons of the low-Sr Glenbog Suite and the high-Sr Candelo Suite of the Bega Batholith [11]. These chemical data fall into two distinct groups with different trends and distinguish the two suites. The 43 samples of Glenbog Suite come from 12 plutons in a belt extending for 275 km along the western margin of the batholith; considering this distance, the tight chemical coherence is most remarkable. Most of the analyzed granites in the LFB has been subdivided into suites on this basis. Those suites derived from igneous source rocks (I-type) tend to be better defined than those produced from sedimentary sources (S-type). This is thought to result from the I-type sources being of more uniform composition. It is thus possible to recognize more compositional fine-structure among the I-type granites whereas the S-type suites are less numerous and individually cover larger areas. Some suites can be grouped with others that share broadly similar chemical features, but differ in detail. These broader groupings are called *supersuites*. As an example, the Glenbog Suite discussed above is placed within a Glenbog Supersuite along with other suites that have similar but not precisely the same features as that suite.

The suites and supersuites are analogous to the units and super-units recognized in the Coastal Batholith of Peru by Pitcher (1978). Pitcher, working in an area of excellent exposure, emphasized relative ages determined in the field, modes, texture, and fabric, with confirmation to be sought from the chemistry. Bateman & Dodge (1970) again emphasized age relations in applying the term sequence to related rocks in the Sierra Nevada Batholith. Granites of the LFB are not so well exposed and hence the chemical composition is emphasized in erecting suites and supersuites.

Whitten *et al.* (1987) carried out a cluster analysis of chemical data from the Bega Batholith supplied by this author and were not able to find a wholly objective (to them) set of criteria for identifying suites in that complex. They were able to separate five of the suites recognized by Beams (1980) using the stepwise analysis of variation diagrams for the elements Cr, Sr, K_2O and/or Na_2O, and SiO_2, but cluster analysis could not retrieve all of those suites completely and correctly. They concluded that these suites should be abondoned, or defined differently. Inspection of Figures 2 and 5 in [11] will show that suites can be clearly separated among the granites of the Bega Batholith. That this can not be done "objectively" using methods of cluster analysis is more an argument against

applying that technique in this way, rather than against the suite concept as used in the LFB. A problem with the computer methods has been pointed out to this writer by Dr W.E. Stephens; this can be illustrated by an example that would be consistent with the data plotted in Figure 2 of [11]. If four rocks contain 68%, 68%, 73% and 73% SiO_2 and 130, 200, 110 and 140 ppm Sr, respectively, then cluster analysis will group these in two pairs, with the first two together and the last two together. However, the Figure 2 in [11] shows clearly that the first and third should be grouped, and the second and fourth, as nature provides a natural negative correlation of Sr and SiO_2 abundances. A method that relies on absolute differences, and does not take into account correlations between the variation of the different components of the kind seen within cogenetic rocks, is not suitable for this sort of analysis. Also, it cannot be assumed that all elements will be of equal usefulness in separating suites; for example, in the LFB, Sr is by far the most valuable element to use in that way. Likewise, one group of elements might separate one pair of suites, while another group of elements might better separate another pair. Assuming that Whitten *et al.* (1987) knew of and used the best technique available to the mathematical geologist, it is clear that these subdivisions are at this time best done graphically. It is unfortunate that those authors may have created a different impression, and if their conclusions have created misconceptions about the usefulness of the suite concept.

Suites are the fundamental unit as far as any discussion of variation within and between different batches of granite magma is concerned. Differences between suites can be ascribed to differences in source rock compositions. Various mechanisms are invoked to account for the within-suite variation found in granites, including fractional crystallization, restite unmixing, magma mixing and assimilation.

FRACTIONAL CRYSTALLIZATION

This is the classic mechanism for producing variation in rock suites, going back to the studies of Bowen (1928) who was determined to derive all igneous rocks by the fractional crystallization of basalt. He had a great deal of success in that aim. Present workers would invoke a greater variety of source magmas; in the case of granites, most petrologists would involve primary magmas formed by partial melting of crustal rocks, sometimes sedimentary. Studies in the LFB show clearly that fractional crystallization of granite magmas is not the universal process which some people believe it to be [2, 15]. In this thesis it is assigned an important but subsidiary role, as follows: (a) rarely in producing the complete range of compositional variation within a suite, e.g. in the Boggy Plain Supersuite (Wyborn *et al.*, 1987) which varies from gabbro to aplitic granite in composition; (b) in a subordinate way to restite unmixing, when minor growth of new crystals and their separation from melt may occur, particularly in magmas formed at higher temperatures (non-minimum-melt compositions); (c) following the separation of restite when a felsic melt dominated by quartz and feldspar components forms (haplogranitic), from which the continuing fractionation of feldspar crystals leads to changes in trace element compositions without significant changes in the major element abundances (see later discussion of S-type granites of the Wagga Batholith, pp. 33-37).

RESTITE UNMIXING

This is the dominant process producing variation with granite suites in the LFB [2]. A more comprehensive, updated and detailed account of the *restite model* has been published [15]. According to this model, the high viscosity and high yield strength of felsic crustal melts means that the melt phase might not be extracted to form a body of completely molten magma. Instead, a magma (in the original sense of that term), rich in material residual from melting, or *restite*, is formed and varying degrees of separation of the two may then occur as the magma moves up through the crust. According to the restite model, the composition of a rock formed in this way will be a function of the composition of the melt and restite, and of the degree of separation between the two.

Some aspects of [15] have recently been critically discussed by Clemens (1989). In view of this continuing controversy, a summary of the rationale behind the restite model is given here, from Chappell & White (1990). "It is widely accepted that most granite magmas result from partial melting of the crust. A mechanism of partial melting implies that a silicate melt must, at least initially, coexist with residual unmelted material or restite. Debate about the role of restite in granite genesis (Chappell *et al.*, 1987 [reference 15]; Wall *et al.*, 1987), must revolve around the extent to which that silicate melt is completely removed from its restite at an early stage in the evolution of the magma. It is our contention that all degrees of separation are possible, so that there is a spectrum of restite involvement. At one extreme is the classical situation in which the granites formed from a largely or completely liquid magma (Bateman & Chappell, 1979; Wyborn *et al.*, 1987). The opposite case is that in which the magmas retained varying amounts of solid residual source material within a low-temperature silicate melt (Griffin *et al.*, 1978 [reference 5]; Chappell, 1978)."

It has never been proposed that all variation in granites results from varying degrees of restite separation, and the publications of Bateman & Chappell (1979) and Wyborn *et al.* (1987) in fact document the other case of dominant fractional crystallization. The contention has been that restite separation was a dominant factor in producing variation in the granites of the LFB, and that the importance of such a process should be assessed elsewhere. The restite model is based on several diverse lines of evidence [15]. Clemens (1989) asserts that some of these could be interpreted differently. That individual pieces of evidence could be interpreted in another way in not in dispute; what is significant is the whole assemblage of evidence in reference [15].

One particular point of Clemens (1989) is in error and must be corrected. He states that "Chappell *et al.* (1987, p. 1130) [reference 15] suggested that granitoids (in the Lachlan Fold Belt, Australia) that have Rb contents >250 ppm and Sr and Ba < 70 and 200 ppm respectively, represent 'magmatic systems where fractional crystallization has occurred', the remainder of rocks (in a given suite) being explained by restite unmixing. The basis for this belief appears to be the rapid increases observed in Rb/Sr and Rb/Ba ratios in the more felsic rocks of some suites." Figure 1 of Clemens (1989) shows how these ratios change in a range of rocks in which the individual elements vary in a linear way. This effect is well known and it is a simple theorem that the ratios of two variables which individually show linear correlation against a third variable, do not also show a linear variation. Variations in ratios have not been used in assessing restite fractionation *versus* fractional crystallization. It is the variation in *single elements* that must and has been used; reference to Figure 2 of this thesis (p. 37) illustrates this point. That figure also shows the contrast between a supersuite

in which fractional crystallization has modified the composition of the more felsic rocks (Koetong), and one in which it has not (Bullenbalong). The variation of Rb and P_2O_5 for the Bullenbalong Supersuite in Figure 2 is precisely of the type that, combined with other evidence, has lead to the suggestion that the compositional variation in such cases was the result of restite fractionation. This type of information also shows that the concluding statement of Clemens (1989) that "Harker diagrams are close to impotent as tools for *process* diagnosis" is absurd.

One line of evidence in support of the restite model in [15] was the presence of 'old' zircon in granites, which was taken to represent solid material brought from the source. That conclusion is now receiving powerful support by more detailed studies using the SHRIMP ion microprobe (Williams *et al.*, 1988; Williams, 1989). These have shown that in some I-type granites of the Bega Batholith, old zircons occur as cores surrounded by wide rims having the magmatic crystallization age of around 400 Ma. Total-rock isotopic and chemical data show that these old zircons cannot have resulted from late-stage accidental contamination and must have come from the source rocks. This evidence for the zircon crystals being a restite component is discussed briefly below (p. 32).

MAGMA MIXING

Many of the features that can be accounted for by the restite model could also result from the mixing of mafic and felsic magmas (see Reid *et al.*, 1983, for a discussion). Such features would include linear variation diagrams, the occurrence of mafic inclusions (Vernon, 1983) sometimes with quasi-igneous textures, and possibly the occurrence of calcic plagioclase cores surrounded by strongly zoned rims. However, magma mixing cannot account for all of the features explained by the restite model. Magma mixing encounters particularly difficult problems in accounting for the variation in those granites that are derived from sedimentary rock sources, in which the mafic inclusions are metasedimentary and modified igneous inclusions are not found, and where the granites become more peraluminous or sedimentary in chemical character as they become more mafic. In the case of the I-type granites, detailed chemical and isotopic studies of suites from the Bega Batholith show that while some suites show evidence for mixing of an igneous and a sedimentary component, such mixing must have occurred *before* partial melting of the source rocks (see pp. 30-32).

HYBRIDIZATION AND ASSIMILATION

Rocks of intermediate composition could be generated by the assimilation of mafic material by felsic melts, or vice versa. In a similar way to magma mixing, assimilation of solid mafic material by felsic melts could produce many of the features accounted for by the restite model. While localized assimilation of this type is possible, it is unlikely to have occurred on a large scale as proposed for example by Wilkinson *et al.* (1964), and that particular case, at least, is more satisfactorily interpreted using the restite model. In the LFB and other Palaeozoic fold belts, mafic rocks are rare and are therefore an unlikely component in the granites. Such a process of mafic rock assimilation also fails to account for the mafic granites of peraluminous composition (S-types). Large-scale assimilation of sedimentary material cannot be invoked in those cases because both the

sedimentary inclusions and the granites containing them have chemical and isotopic compositions unlike those of the surrounding Ordovician rocks. A restite source at depth is preferred in the case of the LFB.

SUMMARY: VARIATION WITHIN SUITES IN THE LACHLAN FOLD BELT

In the LFB, differences between suites is ascribed to different source rock compositions. Variation within suites is accounted for as follows:

(a) Dominantly by varying degrees of separation of melt from residual mafic material, or restite. A small amount of fractional crystallization may accompany restite separation, involving removal of crystals precipitated from the melt.

(b) Rarely, completely by fractional crystallization. This does sometimes occur, e.g. in the Boggy Plain Supersuite.

(c) By feldspar fractionation, after all restite has been removed by (a) or a felsic composition has been arrived at by (b).

SOME IMPLICATIONS OF THE RESTITE MODEL

The general implications of the restite model and the fact that many granite magmas carry with them solid source material both as enclaves and individual crystals, have been discussed in [15]. These may be placed into four groups, and summarized as follows (from Chappell & White, 1990). First, for those suites to which the restite model is applicable, constraints can be placed on the composition of the melt phase and of the primary restite composition and also on the composition of the source material from which the granites were derived, since these three must lie on the compositional trend defined by the granites. In this way, source rock compositions and the partial melting process can be modelled with a degree of precision that is not possible in those rock suites in which the composition is not determined by restite abundance. Second, the thermal characteristics of more mafic granite magmas containing abundant restite differ from chemically equivalent magmas containing no restite, since the former will exist at much lower temperatures. This probably accounts for the minor nature of contact metamorphic effects around some mafic S-type granites in the Lachlan Fold Belt. The presence of restite also means that much less heat is needed to produce a magma, both since lower temperatures are required and since the magma is only partly melt. This eases some of the problems associated with obtaining the heat necessary for the production of voluminous granite magmas over large areas, as in the LFB. Third, the restite model implies that some elements may be present at a significant concentration in granite magmas despite their very low solubility in granite melts. For example, much of the light rare-earth elements in S-type granites can be present in crystals of restite monazite, so that the more mafic rocks are relatively LREE-enriched. Fourth, the restite model implies that many granite magmas move bodily away from their source rather than by a process of early separation of melt from solid material. In such a case, the whole source volume including melt, enclaves and restite minerals moves upward, at least initially. This contrasts with the other situation involving the early separation of melt, in which melt moves up through solids residual from melting, that are themselves moving down. The former scenario represents a classic diapiric

mechanism and may have structural implications in the surrounding rocks.

5. GRANITE TYPES IN THE LACHLAN FOLD BELT

The concept of a twofold subdivision of granites into those derived from igneous and sedimentary source rocks (the I- and S-types) was introduced by Chappell & White [1]. Such a subdivision followed naturally from the concept of suites of granites being closely related to source rock compositions. The occurrence of peraluminous granites within the LFB had long been recognized (Baker, 1940), although their significance was not appreciated. The fact that these could be related to source rocks of the same character was recognized by Joyce (1970, 1973) in applying the earliest versions of the restite model developed by this author to the S-type granites of the Murrumbidgee Batholith. It was as a result of mapping of the Berridale Batholith, where both types of granites with their contrasting properties are closely related in the field, that the significance of the subdivision was recognized. The early statements on the characteristics of both types [1] were based on studies in that area, with a subsequent extension to include the granites of the Kosciusko Batholith in the vicinity of Jindabyne [4]. An update of the original paper [1] was prepared for the 1982 Nanjing meeting on "Geology of Granites and their Metallogenic Relations" and this has been published [12]. Unfortunately, that paper has not had a wide circulation. Prior to 1982, most of the work in the LFB was in its eastern part and some of the results of looking more broadly at the whole belt are discussed below. However, most of the concepts in [12] are still current but there have been some developments in our understanding of the two granite types and these will also be discussed.

In general, most of the granites of the LFB show bimodal mineralogical, chemical and isotopic properties corresponding to these two types, with suites generally clearly representative of either the I-type or S-type group. The more mafic rocks can be easily separated, but the properties of the two types tend to converge in more felsic rocks as haplogranite compositions are approached. When such felsic melts were fractionated it can be very difficult to distinguish the two types. However, fractionated I-type granites are rare but not completely unknown in the LFB and strongly fractionated granites are mostly S-type; this observation may itself may be significant in a more general way.

A third group of granites, the A-types, was later recognized in the LFB [9]. A fourth category, "IS-type" is proposed for the unusual Murrumbucka Suite of the Murrumbidgee and Berridale Batholiths; these are though to be derived from a mixed igneous plus sedimentary source and will not be discussed further here.

INFRACRUSTAL AND SUPRACRUSTAL SOURCE ROCKS

The separation of the more mafic granites of the LFB into I-type and S-type groups is quite clear. There has, however, been a tendency by others to *assume* that the two types ought to be transitional - this is particularly so among isotope geologists. For example, Gray (1984) presented a mixing model to explain the isotopic characteristics of these granites. He argued that all Sr and Nd isotopic data published at that time for the granites of the LFB lay on a mixing line between basalt and a granite magma derived from metasediments. This is one possible interpretation of the isotope data. However, it had previously been shown in [8], for example, that the rather isotopically evolved character of the I-type Jindabyne Suite could not be the result of mixing with sedimentary

material since the chemical composition of this suite does not show evidence of the presence of the large amount of sediment that would be necessary to explain the isotopic composition [16]. The relatively evolved isotopic character of the Jindabyne Suite [6, 8] resulted from the aging of primitive source materials prior to partial melting at about 400 Ma BP. It is aging of source materials in that way that is the alternative, and more viable, interpretation of the isotope data.

It can be shown very easily that variation within the S-type granite suites such as Bullenbalong was not the result of incorporation of varying amounts of more mafic and more isotopically primitive mafic material, as this is not consistent with the observation that the more mafic rocks within such suites are the more peraluminous [17]. Likewise, the variation within the isotopically evolved I-type suites on the western side of the Bega Batholith cannot be the result of varying proportions of a basaltic and sedimentary component, since all rocks of a single suite have approximately the same isotopic composition, irrespective of their chemical composition (see further discussion in Section 7).

In general, the chemical data for the LFB granites are not consistent with their derivation from sources consisting of mixtures of primitive and sedimentary end-members. This point is illustrated by the examples that have just been given. However, one case is known in which isotopic differences between suites and the associated changes in chemical composition, were due, at least in part, to progressively greater amounts of sedimentary material in the source rocks. This is the Bega Batholith in which the suites show impressive chemical and isotopic regularities that imply the presence of an increasing sedimentary component towards the western side of the batholith. The presence of such a component is supported by the presence of old zircons in those rocks (Williams *et al.*, 1988; Williams, 1989). The systematic character of the suites in the Bega Batholith shows that the sources were homogeneous in narrow strips over distances of up to 300 km. This implies that the sedimentary component in the granites of the Bega Batholith was incorporated into the source rocks before partial melting occurred (Section 7, pp. 30, 32).

The arguments for favouring an infracrustal source produced by underplating the crust as the source of I-type granites have been given in detail in [16]. The implication from studies of the Bega Batholith is that truly infracrustal source rocks can contain a sedimentary component. For that reason the terminology I = infracrustal rather than I = igneous, is to be preferred. This also emphasizes the fundamentally different origins of the I-type and S-type granites, not just their chemical, mineralogical and other features.

In a similar way, it has been pointed out in section 4.4 of [17] that supracrustal detrital rocks will generally be peraluminous, even when derived as immature sediments from rocks such as andesite. If such rocks are the source of granites then the latter will retain the peraluminous composition of the source rocks, at least at more mafic compositions. Granites formed from such supracrustal source rocks will exhibit the whole package of S-type characteristics. Again the terminology S = supracrustal rather than S = sedimentary is preferred, to emphasize the fundamentally different nature of the source rocks, relative to the I-type granites.

The use of "infracrustal" and "supracrustal" in this way, rather than "igneous" and "sedimentary", was first suggested in the conclusions of [12]. It is because of this fundamental difference between the source rocks of I-type and S-type granites, that granites showing transitional

characteristics are rare in the LFB.

I-TYPE AND S-TYPE GRANITE COMPOSITIONS

Average compositions of 1078 I-type, 609 S-type and 42 A-type granites analyzed from the LFB are given in Table 3. These represent samples collected from all of that area, except for some samples from the Bassian Batholith which have been collected but not yet completely analyzed. Since S-type granites are slightly more abundant than I-type granites in the whole belt, the intensity of collection of the latter has clearly been greater. This is mainly the result of the poor exposures in the dominantly S-type and very large Wagga Batholith, and to a lesser extent, elsewhere. The unalyzed Bassian granites are also mainly S-type. Granites that have not yet been classified by type are not included in the mean values. Since most of these are relatively felsic rocks, this means that final averages will be slightly more felsic than those in Table 3.

The first significant feature of the average I-type and S-type compositions in Table 3 is that the differences for many elements are not great. The major elements SiO_2, Al_2O_3, total FeO and MgO have similar concentrations. Among the trace elements, Th, U, Zr, Nb, Y, La, Ce, Sc, V, Co, Cu and Ga are likewise similar. Relative to the I-types, the S-types are lower in CaO, Na_2O and Sr; this is fundamental and a consequence of the removal of those three elements in solution when feldspars are weathered to form clay minerals. Source rocks that include a clay mineral component, or its metamorphosed equivalent, will produce granites low in these elements. Much of the detailed variation between different S-type suites is caused by variations in the abundance of these three elements, reflecting varying amounts of a clay mineral component in the source rocks. The only other elements that are distinctly lower in the S-type average are Ba and Mn; the reasons for this are not known.

Relative to the I-types, the S-types are high in TiO_2, K_2O, P_2O_5, Rb, Pb, Cr, Ni and Zn. For Cr and Ni, the cause of this is clear. The I-type granites are largely derived from source rocks low in those two elements, that is from fractionated rocks that contained more of the haplogranite components. The S-type granites, on the other hand, came from rocks containing more of these elements, typically relatively high in shales. The high Pb content of the S-types is surprising since one would have expected loss of this element during the weathering of feldspars to clay minerals. The high abundance may be a local feature for the LFB, reflecting a high Pb value in the igneous rocks that were weathered to give the S-type source rocks. In fact, a similar explanation probably accounts for all the differences, apart from the fundamentally different CaO, Na_2O and Sr levels.

The S-type granites also have a distinctly lower average $Fe^{3+}:Fe^{2+}$ ratio although there is overlap in this parameter between individual samples of the two groups. The more reduced character of the S-type granites is thought to be due to the presence of graphite in the sedimentary source rocks (Flood & Shaw, 1975).

The various mineralogical differences between the two granite types are a consequence of these chemical differences. Thus S-type granites are always peraluminous and contain an Al-rich biotite often with other Al-rich minerals, generally cordierite or its alteration products, and sometimes muscovite, andalusite, sillimanite or garnet. Only the most felsic I-type granites are peraluminous, reflecting the fact that all lowest temperature silicate melts have that property. More mafic I-type

granites are metaluminous and consequently contain hornblende. The generally more reduced Fe in the S-types corresponds to the common occurrence of ilmenite in those rocks rather than magnetite in the I-types, but this is not a firm criterion.

Isotopic features are useful in distinguishing the two granite types. The differences in oxygen isotopic composition were first documented by O'Neil & Chappell [3]. The separation that they found in the Berridale Batholith with I-type and S-type granites having oxygen isotopic compositions less than and greater than 10‰ respectively, relative to SMOW, is supported by a large amount of additional unpublished data on granites of the LFB. Oxygen isotopic compositions are the best single discriminant between the two granite types.

Compston & Chappell [6] showed that the I-type granites of the LFB have a wide range of initial $^{87}Sr/^{86}Sr$ ratios, from 0.704 to 0.712 in the rocks that they examined. They ascribed this range to varying ages of mantle derivation of I-type source rocks, so that I-type granites were derived from chemically primitive crust which had evolved isotopically to varying degrees with time. This was confirmed by McCulloch & Chappell [8] in their study of Nd isotopic compositions. The more isotopically evolved I-type granites overlap in those parameters with the S-type granites and consequently isotopic compositions cannot always be used to discriminate between the two types.

A-TYPE GRANITE COMPOSITIONS

The average composition of the forty two analyzed A-type granites from the LFB is listed in Table 3. This average composition shows very clearly the fundamental differences between A-type and I-type granites. These include:

1. The A-type granites are more felsic. They are therefore high in SiO_2 and the alkalis and low in FeO, MgO, CaO, V, Cr and Ni.

2. Zr, Nb, Y, La, Ce, Zn and Ga are significantly more abundant in the A-type granites.

3. Ba is very similar in both the I-type and A-type average, showing that fractionation of feldspars is not a significant factor in the differences in composition.

In a recent discussion of these differences, White *et al.* (1985) have ascribed the distinctive features of the A-type granites to the presence of high F in the melt which distorts the melt framework and allows the large cations to enter the melt phase. They consider that the conditions for producing such melts could arise when anhydrous crust from which a granite melt has previously been extracted, is subjected to a second melting event. Clemens *et al.* (1986) carried out experimental studies on an A-type granite from the LFB, the Watergums Granite. They concluded that their data supported an origin by direct, high-temperature partial melting of a melt-depleted source rock in the lower crust.

TABLE 3. AVERAGE COMPOSITIONS OF I-TYPE, S-TYPE AND A-TYPE GRANITES FROM THE LACHLAN FOLD BELT

	I-type	S-type	A-type
Number of samples	1078	609	42
SiO_2	68.95	70.44	73.39
TiO_2	0.43	0.47	0.30
Al_2O_3	14.31	14.07	12.88
Fe_2O_3	1.06	0.56	0.90
FeO	2.35	2.80	1.66
MnO	0.07	0.06	0.06
MgO	1.53	1.37	0.30
CaO	3.28	1.97	1.07
Na_2O	3.12	2.43	3.49
K_2O	3.39	4.01	4.61
P_2O_5	0.12	0.15	0.08
Trace elements (ppm)			
Ba	525	465	545
Rb	155	222	188
Sr	247	118	97
Pb	19	27	27
Th	18	18	24
U	4	4	5
Zr	147	164	325
Nb	11	12	26
Y	28	32	71
La	30	28	55
Ce	64	63	131
Sc	13	12	12
V	62	54	9
Cr	25	33	2
Mn	550	450	430
Co	11	11	3
Ni	9	13	2
Cu	10	10	5
Zn	49	62	95
Ga	16	17	22

6. BASEMENT TERRANES IN THE THE LACHLAN FOLD BELT

The provincial character of the granites of the LFB started to manifest itself fairly early in the study of those rocks. The first case was that of the central screen of the Berridale Batholith which separated a mixture of I- and S-type granites to the west from exclusively I-type granites on the eastern side. This was termed the IS-line by White *et al.* (1976a) and those authors suggested that it represents the eastern limit of thick crystalline crust in eastern Australia, possibly of Precambrian age. Other similar lines later became apparent, most notably those in Victoria that separate the granites of what has now been called the Melbourne Basement Terrane [18] from the granites to both east and west. The granites of that Terrane are a mixture of both I- and S-types, both of which are extremely reduced and have very high Ba contents. The granites to the east are dominantly S-type and those further west are exclusively I-type, and in neither case are the rocks as reduced or as rich in Ba as those in the Melbourne Basement Terrane.

The use of granites in this way and the development of the basement terrane concept in the LFB had its beginnings in a lithosphere symposium conducted by the Victorian Division of the Geological Society of Australia (Chappell & White, 1985). It became apparent from preparing that contribution that granites are a useful tool for studying the compositional characteristics of the deep crust of the LFB, and its variations on a regional scale. The granites of the LFB can be shown to have strongly provincial characters with compositional features that are relatively constant over large areas, separated by sharp discontinuities. This is analogous to the recognition of tectonostratigraphic terranes, except that we are dealing with chemical features and the major faults between the terranes are not seen. It has been suggested in [18] that such terranes do occur at depth in the LFB beneath the Ordovician cover-rocks and that these were the distinct sources of the different granite provinces. The ten basement terranes that can be recognized in the LFB and the distinctive characters of each are given in [18] and that paper provides a full account of the basement terrane applied to the LFB.

7. INFRACRUSTAL GRANITES

The I-type granites of the LFB have in recent years been studied less intensively than the S-type granites. This has been because the latter are in some ways an unusual occurrence, they can be related more specifically to possible source rock compositions, they are widely misunderstood and misinterpreted elsewhere despite earlier descriptions in the literature and there is a consequent need to document them, and because they have a closer relationship to known and potential mineralization. In contrast, the I-type granites of the LFB are in many respects similar to those of other fold belts, particularly of Palaeozoic age. However, there are points of particular interest among the I-type granites of the LFB. These include the recognition of suites on a chemical basis with a relationship to source compositions (Section 4) and the provincial character of these granites within the different basement terranes (Section 6). Variation in restite content is an important factor in determining composition [15] but not a universal mechanism (Wyborn *et al.*, 1987). Strongly fractionated I-type granites are rare in the LFB, but not unknown, e.g. the very felsic Coles Bay Granite in the Bassian Batholith. Finally, the Bega Batholith is particularly important as a large I-type complex adjacent to the present continental margin, which shows distinct compositional asymmetries and whose origin, when fully understood, will help in refining solutions of the general problem of the origin of I-type granites. Some of these compositional features of this batholith will be discussed later in this section.

In addition to these specific features of the LFB I-type granites, there are some more general conclusions that have come from observations on these rocks over many years; most of these have been discussed in [16]. Briefly, they are summarized here:

(a) The I-type granites of the LFB are part of an extensive world-wide occurrence of such rocks with ages close to 400 Ma, the Caledonian-age of Europe.

(b) These rocks were derived from chemically primitive source rocks showing a range of isotopic evolution, mainly through aging in the crust.

(c) These source rocks are considered to be infracrustal and to have been produced by underplating an older crust. Detailed arguments favouring such an underplated source are given in section 5.1 of [16].

(d) In at least some cases, sedimentary material may have been incorporated in such a source (see Bega Batholith, below).

(e) The I-type granites are generally potassic and that respect are similar to those of Britain and Ireland. However, they generally do not have the high Na content of the European rocks, and differ in detail. They may be complementary to the Caledonian granites of Scotland and Ireland, with perhaps the eastern part of the LFB, rifted away during the opening of the Tasman Sea, having been more similar to those European granites [16].

(f) Caledonian-age granites, including the LFB, are distinctly different from those of the Cordillera, which are often more calcic and closer in composition, but not identical to, the compositions of modern arc rocks.

(g) The distinction in (f) was recognized by Pitcher (1982) who proposed the terms

I-(Caledonian) type and I-(Cordilleran) type. The terms I-(granodioritic) and I-(tonalitic) were suggested in [16] as alternatives to these, since although the Caledonian and Cordilleran granites are generally distinctive, granodioritic or "Caledonian" type rocks are found in the Cordillera, for example the rather potassic and very voluminous granites in the main range of the Sierra Nevada (e.g. Bateman & Chappell, 1979).

(h) The composition of I-type granites reflects to a degree that of their source rocks, so that such granodioritic rocks in the Cordillera resulted from the partial melting of older crust, probably Proterozoic in age, whereas the tonalitic rocks were derived from young crust or lithosphere (Silver & Chappell, 1988), or possibly from greater depth. As stated in [16], "In a sense, the eastern and central Sierra Nevada Batholith is a batholith of Palaeozoic character which did not form until the necessary heat sources appeared in the Mesozoic" (p. 81). If rocks identical to the more easterly parts of that batholith were present in the LFB, they would not be out of character and would simply be indicative of yet another basement terrane.

(i) The term "remagmatization" has been introduced to refer to cases in which partial melting of source rocks without subsequent fractionation of melt from restite produces younger rocks at a higher level in the crust, with the same chemical character as those source rocks. The mafic rocks of the Moruya Suite [5,16] provide an example, so that the Tuross Head Tonalite has a composition very similar to that of its older source. This implies that the chemical composition of that rock cannot be used in considering the tectonic environment at the time of its formation (380 Ma), but reflects the tectonic regime at the time of formation of the source rocks (?600 Ma suggested by ion probe zircon ages). In general, one must be careful in using chemical criteria to argue about the tectonic environment in which granites formed, since the composition of granites is often determined dominantly by their source materials, which may be much older.

(f) The term M-type should be restricted to granites with the compositional character of modern arc-rocks (quartz diorite), generally occurring in close association with such rocks. These are the only granites that have had a direct origin in the mantle or mantle wedge. These granites do not occur in the LFB, and in fact are rather rare elsewhere.

(g) It was suggested in [16] that the composition of the exposed continental crust might have evolved by the progressive development of M-, I-(tonalitic) and I-(granodioritic) magmas with the last two being derived by the partial melting of its predecessor. This is a sequence from quartz diorite (andesite to basaltic andesite) to tonalite (dacite) to granodiorite (rhyodacite). It may be helpful in the future to look at the development and evolution of post-Archaean continental crust in these terms.

THE BEGA BATHOLITH

This author's contribution to the Bega Batholith project has only been part of the total effort put into that study, but because of the importance of this complex to our present understanding of the I-type granites of the LFB, and its probable future implications for other areas, this work is briefly summarized here.

The Bega Batholith is located within the Bega Basement Terrane in the southeastern corner of mainland Australia, east of the I-S line. It extends for 300 km north from Bass Strait to the latitude

TABLE 4. SUPERSUITES IN THE BEGA BATHOLITH

Name	Number of units	Number of suites	Area (km^2)	At 68% SiO$_2$ % Na$_2$O	At 68% SiO$_2$ ppm Sr	Avge $\delta^{18}O‰$
1. Moruya	9	2	263	4.04	321	8.2
2. Cobargo	7	4	370	3.63	384	8.8
3. Kameruka	6	5	1354	3.44	299	8.9
4. Candelo	9	7	1199	2.65	315	9.1
5. Bemboka	13	8	1850	2.51	188	9.6
6. Glenbog	17	6	1752	2.67	136	8.7
7. Tonghi	7	4	573	2.41	191	9.1

of Canberra, where it terminates abruptly at the boundary of the Bathurst Basement Terrane. Much of our knowledge of this area comes from the work of Beams (1980), although he has not been involved with later studies. Beams (1980) mapped the batholith on a regional scale and recognized more than 150 separate plutons. He sampled extensively and the chemical data and some of its interpretation was done in collaboration with this author. Later studies on the oxygen isotopes have been done jointly with J.R. O'Neil, on Sr and Nd isotopes with M.T. McCulloch, and the U-Pb zircon dating project is jointly with I.S. Williams and W. Compston. This batholith combined with the small Moruya Batholith [5] and the Gabo Island Granites has a total area of 8940 km^2, which is greater than the total area of Caledonian-age granites in Britain and Ireland. The total complex contains several small A-type granite plutons (179 km^2) and very minor S-type bodies (70 km^2) but is dominated by a variety of I-type granites, which show very striking chemical and isotopic asymmetry ([5]; Beams, 1980; McCulloch et al., 1982; unpublished data). From east to west, seven supersuites are recognized, each possessing distinctive properties. The most significant changes are in Na and Sr which decrease markedly westward (Table 4). Al and P decrease to a lesser extent. Ca and Sc increase significantly to the west, while Rb and V increase slightly. All of these changes refer to rocks of constant SiO$_2$ content. There is no detectable change in K across the batholith. Initial $^{87}Sr/^{86}Sr$ ratios increase from around 0.704 to 0.709 and ε_{Nd} values decrease from +4 to -9 (McCulloch et al., 1982). More recently, old cores with a range of ages have been discovered in some zircon crystals in samples from the central and western parts of the batholith using the SHRIMP ion microprobe (Williams et al., 1988; Williams 1989). This shows that the observed changes result, at least in part, from a component of old material in the rocks of the western side of the batholith.

As far as is known, the details of the lateral compositional changes in the Bega Batholith are unique. However they are closely analogous to asymmetries that have been observed in various Cordilleran batholiths, such as the Peninsular Ranges Batholith (PRB) (Baird et al., 1984; Silver & Chappell, 1988). Tonalites are the most abundant rocks in the PRB and are represented throughout the batholith. Within that rock type, all of the 29 elements studied by Silver & Chappell (1988) vary

systematically across the batholith, and the direction of change is constant for all elements except Ti. In both the PRB and the Bega Batholith, the chemical changes are ascribed dominantly to corresponding changes in source rock compositions (there was some mineralogical control of REE abundances across the PRB; Gromet & Silver, 1983). The problem of the asymmetries is largely one of elucidating the development of such variations in the crust and perhaps also the uppermost mantle in the case of the PRB. Each batholith represents the petrological genealogy of its particular segment of lithosphere (Silver & Chappell, 1988). The general character of the changes in both areas are similar, although more profound in terms of the number of elements in the case of the PRB. However, the details are quite different. The resolution of the fundamental problem represented here will probably need studies on other areas, integrated of course with data obtained on the chemical polarity observed across many modern island arcs.

The problems raised by the compositional asymmetries across the Bega Batholith have concerned this writer for the past ten years and these studies are continuing. The relevant data and conclusions that can be drawn from those data at this time are summarized in the following:

(a) The Bega Batholith shows striking asymmetries for some elements and for all isotopic systems that have been examined. These parameters change in a direction perpendicular to the present, and also presumably the mid-Palaeozoic, continental margin. Gradients in these properties are quite sharp, in great contrast to their constancy over some 300 km in the north-south direction.

(b) At its eastern side, rocks of the Bega Batholith include mafic tonalites very similar in chemical composition to the dominant tonalites of the Cordillera. Proceeding west, there are some distinctive chemical changes, most notably decreasing Na and Sr.

(c) Felsic granites having compositions that are thought to be primary melts occur throughout the batholith, indicating that the granite magmas were derived from the crust.

(d) Nd and Sr isotopic compositions are relatively primitive on the eastern side and become markedly more evolved towards the west (Table 4).

(e) Recent ion probe data show that old zircon cores occur throughout the batholith but in the eastern suites these do not exceed about 1000 Ma in age. These relatively young inherited zircons are thought to have been derived from an underplated protolith of igneous composition. There is a component of of very old zircon towards the western side of the batholith, showing that at least some of the lateral changes in composition must be ascribed to the presence of a greater component of sedimentary material in the more westerly rocks.

(f) A detailed examination of the variation in isotopic composition of some of the western suites, shows that any significant amounts of sedimentary component must have been added before any fractionation of felsic from mafic components in the magmas. Data from 10 separate plutons of the Glenbog Suite (Fig. 2) shows that there is no correlation between the Fe content and the Nd isotopic composition. If the evolved isotopic systematics of the Glenbog Suite were the result of mixing of basalt and a granite magma derived from metasediments as proposed in the general model of Gray (1984), then there would be a strong correlation betweeen these two components, with the less isotopically evolved samples (higher ε_{Nd}) being more Fe-rich. There is some scatter in the isotopic composition of this suite, which is to be expected with the samples coming from 10 separated plutons each sampling different sources during separate fusion events, with the two most
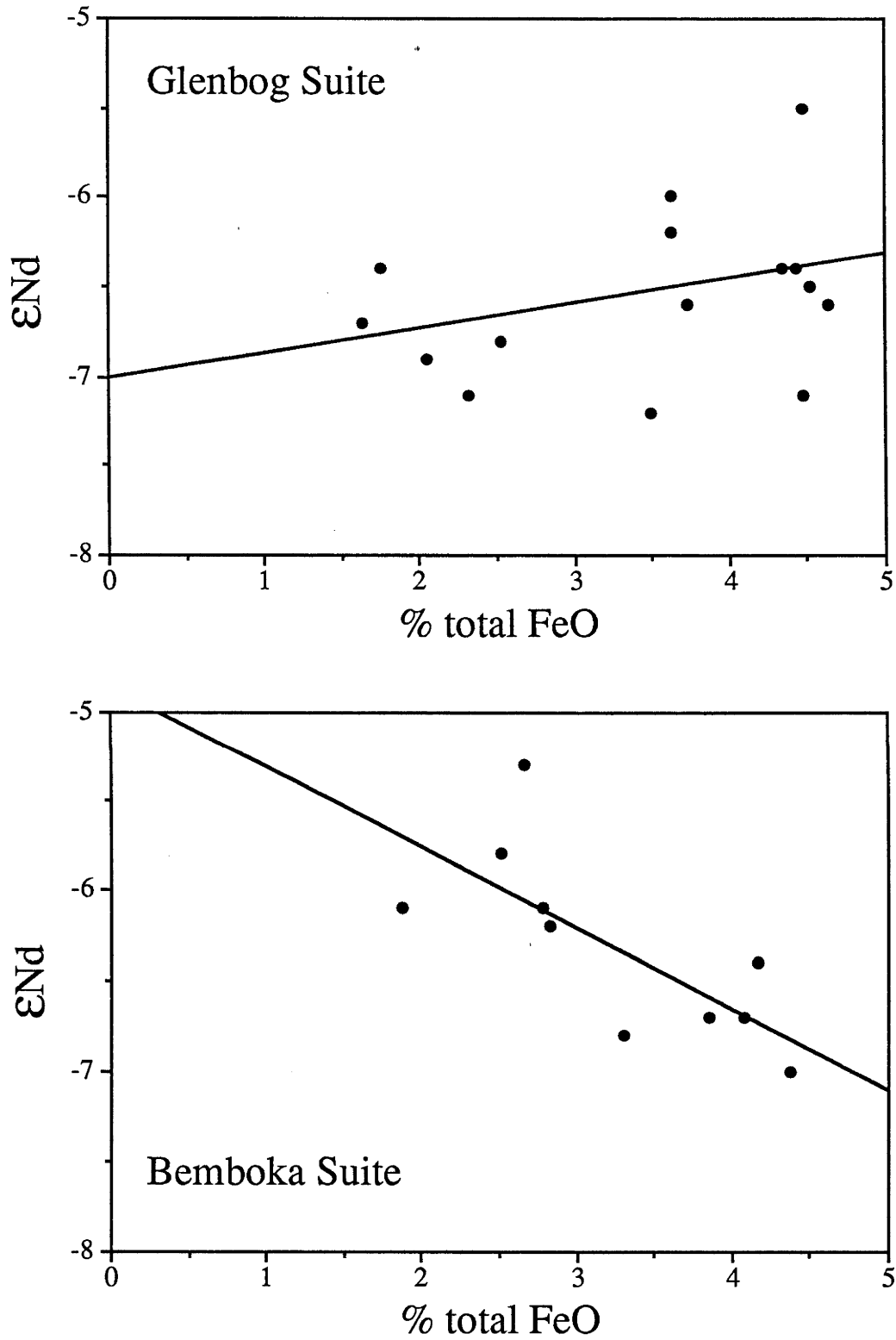
Figure 1. Relative variation in ɛNd and total FeO in two suites of the Bega Batholith, using isotopic data provided by Dr M.T. McCulloch.

distant samples plotted in Figure 1 being separated from each other by 207 km. For the single large Bemboka pluton (980 km^2), Figure 2 shows that there is a correlation between chemical and isotopic composition (coefficient = -0.73) but it is in in the opposite direction to that which would be produced by mixing a more isotopically evolved felsic crustal component with a mafic mantle end-member.

(g) The old zircon cores were derived from the sedimentary component, shown to have been added to the source before partial melting. This shows that the cores represent true crystals of restite from the source rocks and are not the result of accidental contamination (see p. 16).

(h) Oxygen isotopic compositions are all significantly above mantle values and within the range of I-type granites of [3]. Average values are for each supersuite in Table 4, show that the $\delta^{18}O$ is lowest on the eastern side and increases sytematically towards the west in the next four supersuites, before dropping slightly in magnitude in the two most westerly supersuites.

(i) Simple attempts to model the source rocks of the Bega Batholith have shown that it is not the result of the partial melting of a series of sources produced by mixing two end-members each of fixed composition. While there is firm evidence of a greater sedimentary component on the western side, the metaluminous nature of the western rocks implies a source also having that character, that is of dominantly igneous composition. The distinctive chemical features of the western rocks partly resulted from this igneous component having been different in composition to the primitive Cordilleran tonalite composition of the source rocks on the eastern side.

Despite the amount of documentation of the Bega Batholith, details of its origin remain an enigma. During 1990, more information will become available in the following areas. First, there will be more chemical information on 60 samples representative of the batholith by additional methods of analysis, including neutron activation analysis. Second, ion probe analyses of zircon will be completed on two samples from each supersuite and of four samples from associated country rock sediments. Third, additional Sr and Nd isotopic data will be available to better define the variation and systematics within the isotopically evolved western suites in relation to their chemical composition. Fourth, Pb isotopic analyses on samples representative of the variation across the batholith will be completed. When these additional data become available, detailed modelling may resolve the problems of the origin of this complex.

The Bega Batholith illustrates the complexities that can exist within I-type granites and their source rocks. At the present time, this writer feels that a source region probably resulting dominantly from underplating, and changing laterally and very systematically in composition and perhaps age, and containing progressively greater amounts of a sedimentary component towards the western side, will account for the observed changes in the granites. Beams (1980) showed that the western suites of the batholith were derived from source rocks possessing many of the compositional features of continental tholeiites. Hergt *et al.* (1989) have recently argued that the features of the dolerites of Tasmania that require a crustal component in the source rocks, were most likely derived by the introduction of a small quantity of subducted sediment into a mantle source. Perhaps such a mechanism will be shown to be appropriate in producing the progressively more sedimentary character of the source rocks towards the western side of the Bega Batholith.

8. SUPRACRUSTAL GRANITES

The S-type granites of the LFB are of particular interest partly because of their extensive development. Also, unlike the S-type granites of many fold belts, they are generally allochthonous with respect to their source rocks and the magmas were mostly intruded into high levels of the crust, or erupted. The S-type granites are more commonly associated with areas of known mineralization in the LFB than are the I-type granites, and this has also resulted in more interest in these rocks as a group. They provide a means of looking at the character of the deeper and unexposed crust of large parts of the LFB. Since S-type magmas must have been derived from a *fertile* sedimentary protolith [17], the composition of the source rocks is relatively constrained (compare the problems of constraining the source rocks of the Bega Batholith in section 7). This provides the opportunity to study the whole process of granite formation in more detail than is possible with other granites, through from partial melting to emplacement or eruption, including the mechanisms of fractionation both during and subsequent to partial melting.

Many of the features of the S-type granites in the LFB have recently been summarized and reviewed [17]. Such granites make up a little over 50% of the total area of granite in the belt and their distribution is not uniform. They occur in five of the nine basement terranes of the LFB (Kosciusko, Wagga, Melbourne, Bassian and Taswegia) with a few small bodies formed at relatively high levels in the crust occurring in the Bega Basement Terrane. The following discussion will mainly be concerned with a comparison of S-type granites in the Kosciusko Basement Terrane (KBT) and in the Wagga Basement Terrane (WBT). In a few cases, the S-type granites occur in a regional metamorphic environment, notably at Cooma (Joplin, 1942; Chappell & White, 1976) and at places in the Wagga Metamorphic Belt within the WBT. Almost all of these granites occur in a batholithic and subvolcanic environment, the *batholithic* S-type granites of [17]. Volcanic equivalents occur and were an important part of the original magmatic activity ([7, 14]; Clemens *et al.*, 1984).

The origin of the Cooma granite has recently been discussed [17]. That occurrence is contrasted in that paper with the batholithic Bullenbalong Suite [4, 8, 11, 15]. The latter suite occurs extensively within the KBT and shares with other granites of that province, compositional variations that are completely dominated by restite separation. An account of the type of chemical variation found in such S-type systems can be found in [17]. A major study is now under way on other cases in which the compositional variation was dominantly the result of fractional crystallization, at least at more felsic compositions. In the following, a brief summary of this unpublished work is presented, since it is an important part of the current understanding of granite genesis in the LFB, and because it has thrown light on the controversial problem of the origin of strongly peraluminous felsic granites. Such felsic granites are an important component of the Wagga, Bassian and Taswegia Basement Terranes and it is the study of the first of these regions that has to date been the most fruitful.

S-TYPE GRANITES OF THE WAGGA BASEMENT TERRANE

The unique feature of the S-type granites of the WBT, relative to other such rocks in the LFB,

is that they range continuously in composition through from comparatively mafic varieties to very felsic two-mica granites. The most mafic rocks contain abundant biotite and cordierite and sometimes almandine-rich garnet, and have a composition thought to be close to that of their sedimentary source rocks. These mafic rocks occur mainly as two groups, in the Cooma and Koetong Supersuites. The granites of the Cooma Supersuite are restricted to part of this area, contain relatively low amounts of Na_2O and CaO, are always comparatively mafic in composition with no felsic representatives. They have compositions similar to that of the Cooma Granodiorite [17]. These granites resulted from the partial melting of sedimentary rocks similar in composition to the exposed Ordovician mudrocks, which comprise the matrix between the granites of the LFB. In contrast, the Koetong Supersuite is exposed over an extensive area within the WBT. These granites have chemical compositions that are significantly different from those of the Ordovician country rocks, in that the more mafic varieties contain more Na_2O and CaO than the Cooma Supersuite, and they are thought to have been derived from unexposed pre-Ordovician sediments. In this respect they resemble the Bullenbalong Supersuite of the KBT [17]. Within the Koetong Supersuite, there is a continuous and complete gradation in composition through from mafic to very felsic granites. It is this range in composition that gives these granites their special interest, since the mafic granites are precursors to the felsic ones, and the complete process of fractionation that produced the felsic granites can be examined. This is particularly useful in studying the genesis of other felsic two-mica granites that are not associated with more mafic rocks, for example, those occurring in the Cornubian Batholith of south-western England.

The distribution of granites in the WBT is shown in Figure 1 of [18]. These granites are a rather diverse group and occur over an area of 17,740 km^2, comprising 22% of the total area of granites in the LFB. S-type granites comprise about 90% of this area. The granites of this basement terrane are distinguished from those of the KBT to the east by the fact that most of the more felsic S-type granites in the former are relatively "fractionated", with higher concentrations of elements such as Rb and Nb [18]. The Melbourne Basement Terrane to the west is distinguished from this and all other basement terranes of the LFB by the extremely low $Fe^{3+}:Fe^{2+}$ ratios and high Ba contents of all granites in that region, both I-type and S-type [18].

The large area of fairly continuous exposure in the south-eastern corner of the WBT [18] is referred to as the Maragle (or Corryong) Batholith. The remainder of the granites shown on that figure can be assigned to the Wagga Batholith. Apart from members of the Cooma Supersuite, the S-type granites of the Maragle Batholith are indistinguishable both petrographically and chemically, from the more mafic granites of the Wagga Batholith. Most of the S-type granites of the Maragle Batholith, and the large Wantabadgery Granodiorite and the Ganmain Granodiorite in the Wagga Granites, belong to the Tom Groggin Suite which has the largest area of any suite in the LFB (5000 km^2). This suite resembles the more mafic S-type suites of the KBT, such as Bullenbalong [17], but differs in detail. Other mafic S-type granites north of the Wantabadgery unit belong to the Ungarie Suite and these also show the chemical characteristics of the Tom Groggin Suite, extending them to slightly more felsic compositions. These trends are carried even further in some of the more felsic and widely developed S-type granites among the Wagga Batholith in the Grong Grong, Kikoira, Kyeamba and Koetong Suites. All of these suites together form a continuous and well-defined

group, named the Koetong Supersuite. The distinctive feature of this supersuite is the progressive development of highly "fractionated" rocks, containing for example, up to 500 ppm Rb in the most felsic examples. In contrast, two other bodies of granite within this basement terrane, Collingullie and Galore, do not share that character and they are placed in the Collingullie Suite. One analysis of the Yabba body south-west of Koetong is rather felsic (73.6% SiO_2) and unfractionated, and therefore is also not part of the Koetong Supersuite.

For most elements, the more mafic rocks of the Koetong Supersuite (<68% SiO_2) are similar in chemical composition to analogous rocks of the Bullenbalong Supersuite. Al is distinctly higher in amount in about one half of the Koetong samples, Ca is a little lower, Mg abundances are in the lower part of the Bullenbalong range while the Na contents of Koetong are restricted to the upper half of those of the Bullenbalong Suite. Cr abundances are somewhat lower in Koetong which also contains marginally less Sc and V. Some samples of Koetong contain relatively high amounts of Sr, and Pb and Nb tend to be a little more abundant in that supersuite. These differences are, however, all relatively small and the principal feature of these mafic rocks is their overall similar compositions.

In contrast to the above, the more felsic rocks of the two supersuites are distinctly different in composition for many elements. Beginning at around 69% SiO_2, the abundances of many elements diverge between the two supersuites, with the magnitude of the separation increasing progressively as the rocks become more felsic. The elements that increase strongly in the Koetong Supersuite, relative to their abundances in the Bullenbalong Supersuite, are Rb, U, Nb, Ga and Sn, while Al, K, P, Pb and Zn show a less marked relative increase. Many elements, namely Ti, Fe, Mg, Sr, Th, Zr, LREE, Sc, V, Cr, Co and Ni show a slight decrease in relative concentrations, while Ca, Ba, Y and the HREE show a marked decrease. These changes are illustrated for Rb and P in Figure 2.

Two points about the compositions of the most felsic Koetong rocks are fundamental in explaining their origin. First, the normative compositions lie very close to the experimentally determined minimum-temperature composition in the system Q-Ab-Or-H_2O at 50 MPa (Tuttle & Bowen, 1958). This shows that the compositions were produced by processes involving equilibrium between quartz, feldspars, and a silicate liquid at high temperature. Second, the abundances of Rb (Fig. 2) increase, and of Sr and Ba decrease, as the rocks become more felsic. This is consistent with prolonged fractionation of quartz and feldspars from a melt close to the minimum-temperature composition (McCarthy & Hasty, 1976). The fractionation of such a mineral assemblage, which is neither oversaturated or undersaturated with respect to Al, results in originally mildly peraluminous liquids becoming strongly peraluminous. This increasing Al oversaturation leads to an increasing solubility of P in the felsic melt (Mysen *et al.*, 1981) and accounts for the increasing levels of P_2O_5 in these rocks as they become more fractionated (Fig. 2).

The source rocks of the Koetong Supersuite were close in composition to the most mafic granites in that suite, since it is those rocks that correspond to magma compositions in which little or no separation of melt and restite occurred [11]. Modification of that primary magma involved the sequential operation of restite fractionation and fractional crystallization, with a small degree of overlap. All of the chemical features of the Koetong Supersuite can be accounted for by the operation of these processes on a magma derived from a normal sediment containing sufficient of the components Q, ab, or and H_2O to produce significant amounts of silicate melt at high temperatures,

TABLE 5. Average composition of Cornubian granites and of a granite from the Lachlan Fold Belt

	CNG	VB140		CNG	VB140
SiO_2	72.35	72.48	Rb	483	419
TiO_2	0.26	0.25	Sr	74	65
Al_2O_3	14.52	14.50	Ba	176	220
Fe_2O_3	0.30	0.29	Zr	113	99
FeO	1.56	1.33	Nb	17	20
MnO	0.05	0.03	Y	18	14
MgO	0.41	0.47	La	29	20
CaO	0.79	0.66	Sc	4	4
Na_2O	2.96	2.80	V	15	15
K_2O	5.12	5.20	Cr	8	10
P_2O_5	0.25	0.33	Co	3	4
			Ni	6	4
Norm C	3.23	3.85	Cu	5	11
			Zn	44	77
			Ga	24	20
			Sn	16	25
			Pb	28	36
			Th	21	14
			U	13	11

CNG is an average of 26 analyses of Cornubian granite by this author, combined with analyses in the literature. VB140 is an analysis of the Granya Granite of the Wagga Batholith from the Tallangatta 1:100 000 sheet, 100 m grid reference 288021.

that is "fertile" in the sense of [17]. The point at which fractional crystallization became the dominant process (~ 69% SiO_2) can be determined by comparing the trends for Rb in both the Koetong and Bullenbalong Supersuites in Figure 2. The cause of the difference in behaviour of these supersuites is not known. The provincial character of the differences is remarkable, with the Bullenbalong Suite magmas in the KBT resisting fractional crystallization, in contrast to most magmas in the WBT (it was noted above that the relatively small Collingullie Suite in the WBT is unfractionated). The lack of fractionation in Bullenbalong is presumably related to a relatively high viscosity and/or yield strength of those magmas, which could be related to a relatively low H_2O-content; a conspicuous feature of the granites within the KBT is the almost complete absence of aplitic rocks. Magmas of the Koetong Supersuite may have initially been more H_2O-rich, and the concentration of that component may have increased at a sufficiently early stage through the precipitation of anhydrous minerals, to significantly lower the viscosity of the melts. The provincial character of this behaviour between the
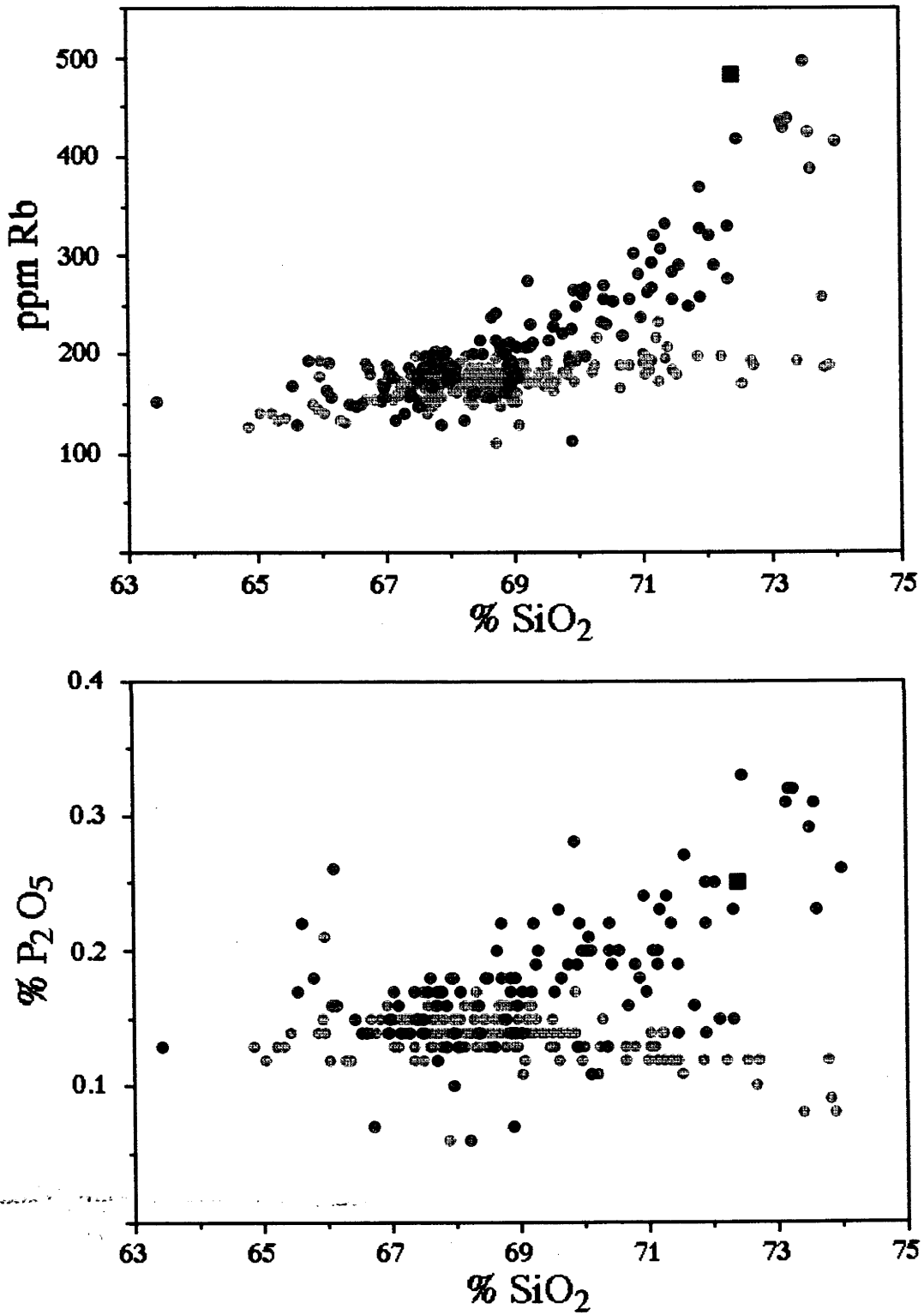
Figure 2. Harker Diagrams for Rb and P_2O_5 for the Bullenbalong (blue circles) and Koetong (red circles) Supersuites. The average composition of biotite granites from the Cornubian Batholith (CNG) is also shown (green square)

KBT and the WBT probably implies that these differences were related back to features of the source rock compositions.

Price (1983) studied the geochemistry of the Koetong Suite, an important component of the Koetong Supersuite. He concluded that those granites were derived from a metasedimentary source, with the observed compositions resulting from separation of the melt and refractory residue components of the magma. He stated that processes such as fractional crystallization and crystal accumulation may have operated locally. The range of Rb content for the five analyses quoted by Price (1983) is from 204 to 274 ppm which is just above the level at which fractional crystallization occurred in the Koetong Supersuite (Fig. 2). The present observations therefore essentially confirm the conclusions of Price (1983) and place his work in context in terms of the total range of variation of the Koetong Supersuite.

The genesis of felsic and strongly peraluminous granites such as those of the Cornubian Batholith has been in some dispute in recent years. Most studies of these rocks have assigned a major role to late stage alteration in producing the present compositions. While there are some cases of rocks of extreme composition as a result of alteration, most have chemical compositions that resemble closely those of the more felsic rocks of the Koetong Supersuite. An average composition CNG for the dominant biotite granites (as opposed to the Li-mica granites) of the Cornubian Batholith is listed in Table 5 (Chappell & Hine, 1990). This average was obtained by combining 26 new analyses of the Dartmoor, Bodmin Moor, St Austell, Carnmenellis and Land's End bodies with all data in the literature considered to be of good quality. For the major elements, the number of other analyses used varied from 54 for SiO_2 to 13 for P_2O_5, and for the trace elements listed in Table 5, the numbers ranged from 481 for U to 2 for Co. The analysis of sample VB140 of the Granya Granite, from the Koetong Supersuite, is also listed in Table 5. This is the analysis from that supersuite that matches CNG most closely, and it can be seen that for most elements the agreement is striking. This suggests very strongly that the felsic Cornubian granites were produced by the type of fractionation processes that can be observed in detail in the Koetong Supersuite. The way in which the Cornubian compositions lie on the trends established for Koetong is shown by the position of CNG for Rb and P_2O_5 in Figure 2. Modelling of the CNG composition shows that, for all elements, it can be produced by the separation of a partial melt from a fertile sediment, followed by fractional crystallization (Chappell & Hine, 1990). It is not necessary to invoke a sedimentary source for those rocks that has any unusual chemical characteristics, except that it must be fertile in terms of producing a significant amount of partial melt, in the sense of [17].

The discovery of the chemical characteristics of the Koetong Supersuite has been the most significant new information to come from granite studies in the LFB in recent years. As stated earlier (p. 8), those rocks have provided the key to understanding in some detail the petrogenesis of the two-mica and related granites, which has previously been one of the outstanding and most difficult problems in granite genesis.

9. GENERAL REFERENCES

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