GRANITES OF THE LACHLAN FOLD BELT

Bruce W. Chappell
GEMOC, Macquarie University, NSW 2010

The Palaeozoic Lachlan Fold Belt (LFB) occupies the southeastern corner of the Australian continent and it has a total area of close to 300,000 km^2. There was very extensive igneous activity in the LFB in Silurian and Devonian times, and during the Carboniferous in the northeastern corner of the belt. Massive quantities of granitic magma were produced and we currently recognise 875 lithological units of granite, the locations of most of which are shown on the map of Chappell *et al*. (1991). Volcanic rocks are also important and most of the 100 such units that are recognised are also shown on that map. With an outcrop area of 61,000 km^2 the granites comprise a little more than 20% of the LFB and they are more abundant in the eastern part, where volcanic rocks are also important. Most of the granites were emplaced into low-grade flysch sediments of Ordovician age, or else into older granites, or volcanic rocks of the same general magmatic episode.

Following are some of the petrogenetic outcomes of granite studies in the LFB in the last forty years:

- The granite plutons can be grouped into suites, which share field, petrographic and compositional features (Hine *et al*., 1978; Griffin *et al*., 1978; White *et al*., 2001). Suites are the basic unit for considering the petrogenesis of the granites.
- The granites form images of their source rocks (Chappell, 1979).
- Characteristics of the distinctive granite provinces were correlated with corresponding differences in their source rocks in the deep crust, or *basement terranes*, by Chappell *et al*. (1988).
- The first-order subdivision of the suites is into the I- and S-types (Chappell & White, 1974, 1992, 2001), derived by the partial melting of older igneous and sedimentary source rocks.
- Compositional variation within most of the suites resulted from varying degrees of separation of crystals entrained from the source from a partial melt, the *restite model* of White & Chappell (1977) and Chappell *et al*. (1987).
- The felsic granites of some suites evolved by fractional crystallisation after mafic restite had been removed (Chappell & White, 1998; Chappell, 1999).
- Some 5% of the granites in the LFB evolved from mafic to felsic composition completely by fractional crystallisation. These are rocks of the Boggy Plain Supersuite (Wyborn, 1983; Wyborn *et al*., 1987) and the Marulan Batholith (Carr *et al*., 1992).
- The granites can be subdivided into low- and high-temperature groups, on the basis of the presence or absence of inherited zircon in the more mafic granites on a suite (less than ~ 68% SiO_2). These groups correspond to those that evolved by restite fractionation sometimes followed by low-temperature fractional crystallisation, and those that evolved completely by fractional crystallisation (Chappell *et al*., 1998, 2000).
- The distinctive A-type granites are the high-temperature felsic granites (Collins *et al*., 1982; King *et al*., 1997, King *et al*., 2001).
- Volcanic rocks can be grouped into suites and into I- and S-types (Owen & Wyborn, 1979; Wyborn *et al*., 1981).
- For what are now termed the low-temperature granite suites, both the associated volcanic and plutonic rocks have essentially the same range of compositions and the compositions of relatively fresh volcanic rocks can be matched very closely with those of particular granites (Wyborn & Chappell, 1986). In the high-temperature Boggy Plain

Supersuite, the volcanic rocks are felsic rhyolites with compositions that complement those of the more mafic cumulate granites of that supersuite (Wyborn *et al*., 2001).

- Development of the SHRIMP ion microprobe has facilitated the study of zircon age inheritance and has shown that it is ubiquitous in the S-type granites and widespread in the I-type granites (Williams, 1995, 2001).
- Appreciable economic mineralisation associated with granites of the LFB is limited to those granites whose compositions were modified by fractional crystallisation (Blevin & Chappell, 1992, 1995).
- Debate about the source rocks of the dominant *batholithic* S-type granites (White & Chappell 1988) is unresolved. Chappell *et al*. (2000) favoured a sedimentary source rock that was more feldspathic than those exposed at the surface.
- The formation of the dominant Silurian and Devonian granites of the LFB is not considered to have been related directly to subduction (Chappell, 1998).

References

Blevin P.L. & Chappell B.W. 1992. The role of magma sources, oxidation states and fractionation in determining the granite metallogeny of eastern Australia. *Transactions of the Royal Society of Edinburgh: Earth Sciences* 83, 305-316.

Blevin, P.L. & Chappell, B.W. 1995. Chemistry, origin and evolution of mineralized granites in the Lachlan Fold Belt, Australia: the metallogeny of I- and S-type granites. *Economic Geology* 90, 1604-1619.

Carr, P.F., Chappell, B.W. & Jones, B.G. 1992. Geochemical contrasts between intersecting Devonian and Carboniferous magmatic belts in the eastern Lachlan Fold Belt (Abstract). *Transactions of the Royal Society of Edinburgh: Earth Sciences* 83, 487.

Chappell, B.W. 1979. Granites as images of their source rocks. *Geological Society of America Program with Abstracts* 11, 400.

Chappell, B.W. 1998. Tectonic evolution of the eastern Australian fold belts from a granite-based perspective: 1998 Mawson Lecture. *The Australian Geologist* 109, 24-30.

Chappell, B.W. 1999. Aluminium saturation in I- and S-type granites and the characterization of fractionated haplogranites. *Lithos* 46, 535-551.

Chappell, B.W., Bryant, C.J., Wyborn, D., White, A.J.R. & Williams, I.S. 1998. High- and low-temperature I-type granites. *Resource Geology* 48, 225-236.

Chappell, B.W., English, P.M., King, P.L., White, A.J.R. & Wyborn, D. 1991. *Granites and related rocks of the Lachlan Fold Belt (1:1 250 000 scale map)*. Bureau of Mineral Resources, Geology and Geophysics, Australia.

Chappell, B.W. & White, A.J.R. 1974. Two contrasting granite types. *Pacific Geology* 8, 173-174.

Chappell, B.W. & White, A.J.R. 1992. I- and S-type granites in the Lachlan Fold Belt. *Transactions of the Royal Society of Edinburgh: Earth Sciences* 83, 1-26.

Chappell, B.W. & White, A.J.R. 1998. Development of P-rich granites by sequential restite fractionation and fractional crystallisation: the Koetong Suite in the Lachlan Fold Belt. *Acta Universitatis Carolinae, Geologica* 42, 23-27.

Chappell, B.W. & White, A.J.R. 2001. Two contrasting granite types – 25 years later. *Australian Journal of Earth Sciences* 48, 489-499.

Chappell, B.W., White, A.J.R. & Hine, R. 1988. Granite provinces and basement terranes in the Lachlan Fold Belt, southeastern Australia. *Australian Journal of Earth Sciences* 35, 505-521.

Chappell, B.W., White, A.J.R., Williams, I.S., Wyborn, D. & Wyborn, L.A.I. 2000. Lachlan Fold Belt granites revisited: high- and low-temperature granites and their implications. *Australian Journal of Earth Sciences* 47, 123-138.

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

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. *Contributions to Mineralogy and Petrology* 80, 189-200.

Griffin, T.J., White, A.J.R. & Chappell, B.W. 1978. The Moruya Batholith and geochemical contrasts between the Moruya and Jindabyne Suites. *Journal of the Geological Society of Australia* 25, 235-247.

Hine, R., Williams, I.S., Chappell, B.W. & White, A.J.R. 1978. Contrasts between I- and S-type granitoids of the Kosciusko Batholith. *Journal of the Geological Society of Australia* 25, 219-234.

King, P.L., Chappell, B.W., White, A.J.R. & Allen, C.M. 2001. Are A-type granites the high temperature felsic granites? Evidence from fractionated granites of the A-type Wangrah Suite. *Australian Journal of Earth Sciences* 48, 501-513.

King, P.L., White, A.J.R., Chappell, B.W. & Allen, C.M. 1997. Characterization and origin of the aluminous A-type granites of the Lachlan Fold Belt, southeastern Australia. *Journal of Petrology* 38, 371-391.

Owen, M. & Wyborn, D. 1979. Geology and geochemistry of the Tantangara and Brindabella 1:100 000 sheet areas. *Bulletin of Mineral Resources, Australia, Bulletin* 204, 52 pp, five microfiche.

White, A.J.R., Allen, C.M., Beams, S.D., Carr, P.F., Champion, D.C., Chappell, B.W., Wyborn, D. & Wyborn, L.A.I. 2001. Granite suites and supersuites of southeastern Australia. *Australian Journal of Earth Sciences* 48, 515-530.

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

White, A.J.R. & Chappell, B.W. 1988. Some supracrustal (S-type) granites of the Lachlan Fold Belt. *Transactions of the Royal Society of Edinburgh: Earth Sciences* 79, 169-181.

Williams, I.S. 1995. Zircon analysis by ion microprobe: the case of the eastern Australian granites. *Leon T. Silver 70th Birthday Symposium and Celebration*, The California Institute of Technology, 27-31.

Williams, I.S. 2001. Response of detrital zircons and monazite, and their U-Pb isotopic systems, to regional metamorphism and host-rock partial melting, Cooma Complex, southeastern Australia. *Australian Journal of Earth Sciences* 48, 557-580.

Wyborn, D. 1983. Fractionation processes in the Boggy Plain zoned pluton. PhD thesis, Australian National University, Canberra (unpubl.).

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

Wyborn, D., Chappell, B.W. & Johnston, R.M. 1981. Three S-type volcanic suites from the Lachlan Fold Belt, southeast Australia. *Journal of Geophysical Research* 86, 10335-10348.

Wyborn, D., Chappell, B.W. & James, M. 2001. Examples of concective fractionation in high-temperature granites from the Lachlan Fold Belt. *Australian Journal of Earth Sciences* 48, 531-541.

Wyborn, D., Turner, B.S. & Chappell, B.W. 1987. The Boggy Plain Supersuite: a distinctive belt of I-type igneous rocks of potential economic significance in the Lachlan Fold Belt. *Australian Journal of Earth Sciences* 34, 21-43.

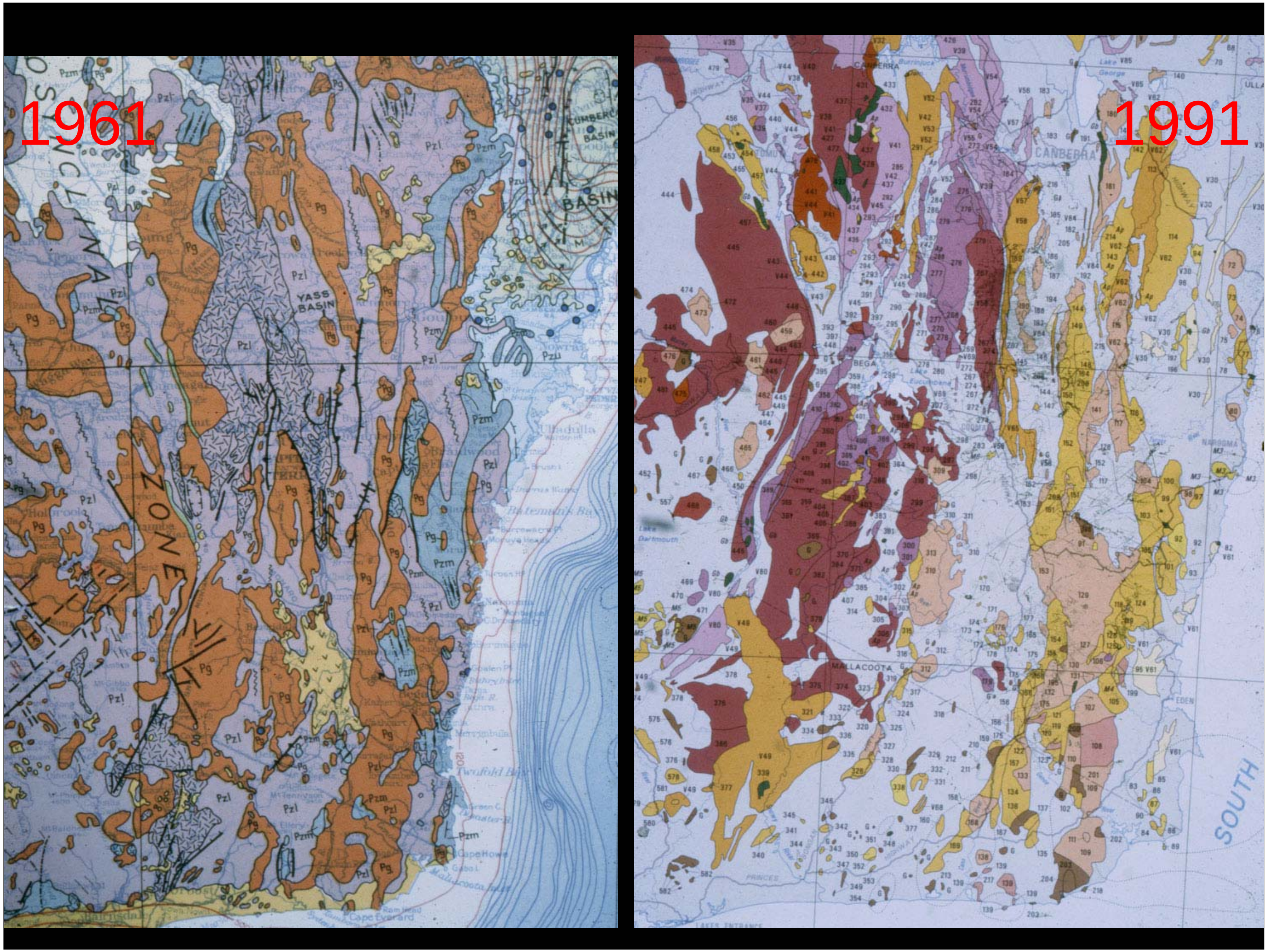
GRANITES OF THE LACHLAN FOLD BELT

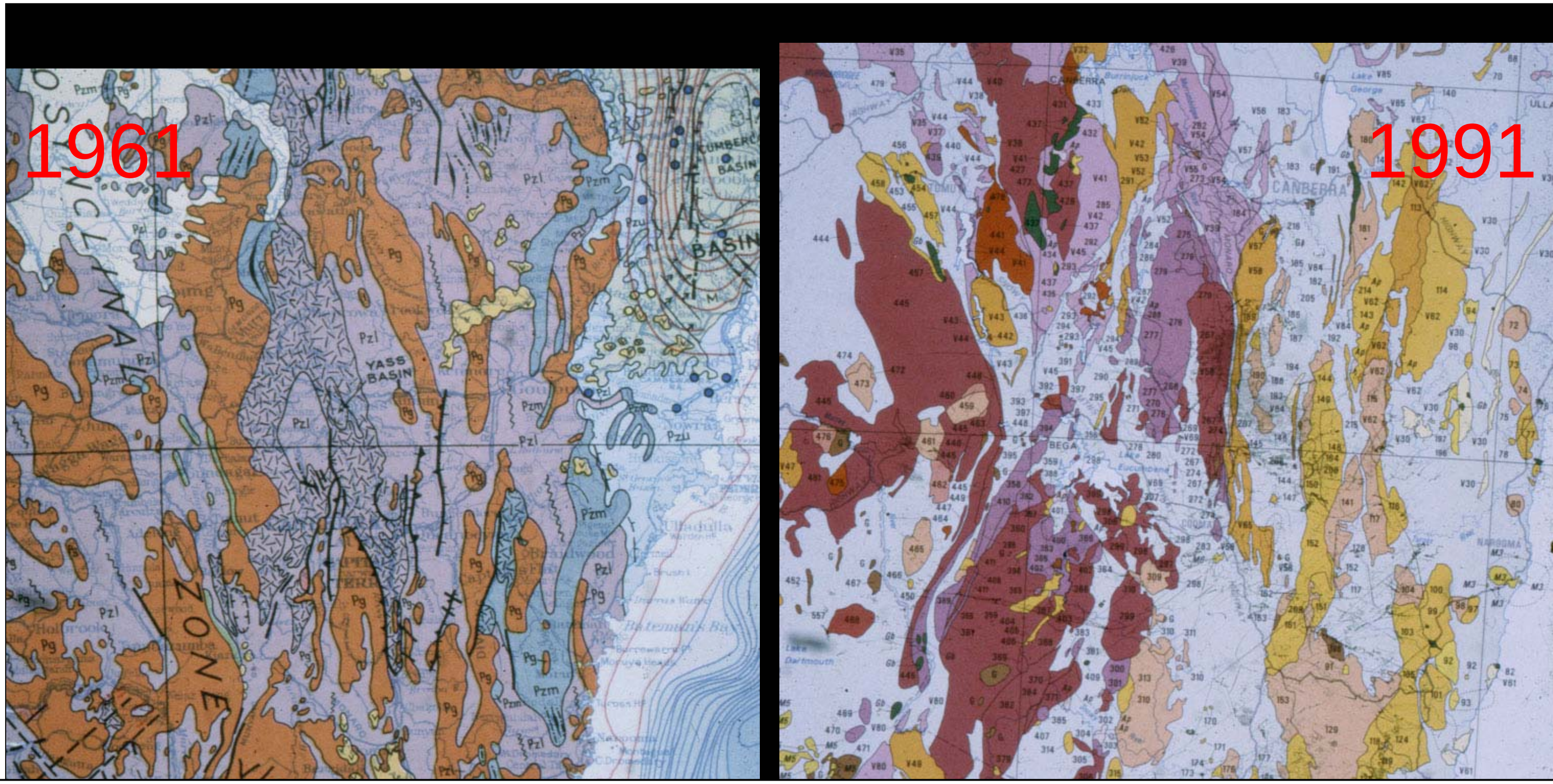
Bruce Chappell

GEMOC

LACHLAN FOLD BELT

- Total area of LFB ~ 200,000 km^2
- Part of a more extensive N-S belt
- Granites = 61,000 km^2 in area
- Widespread volcanics in eastern part
- Mainly Silurian and Devonian in age
- Part of "Caledonian" magmatic event
- Carboniferous age in NE part
  - granites similar to New England
- 875 lithological units of granite
- 100 volcanic units
- Matrix generally low-grade Ordovician sediments, older granites, or volcanics
- Probably the most extensive composit-ional data for an area of this size

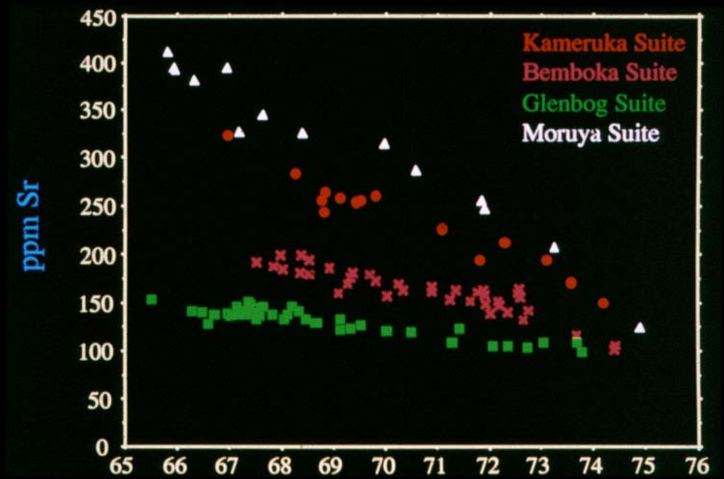

1961
1991
YASS BASIN
ZONE
BEGA
MALLACOOTA
CANBERRA
SOUTH

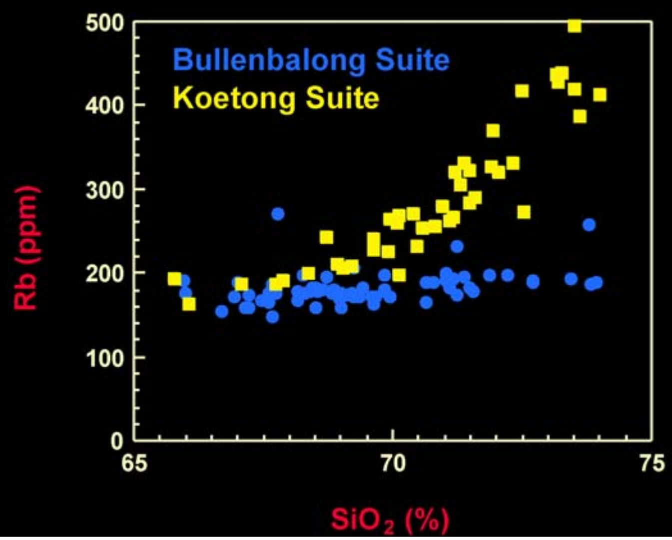


The left side map is part of the so-called "Tectonic Map of Australia" published in the early 1960's. That on the right is from the map published by the Bureau of Mineral Resources, now Geoscience Australia, in 1991.

Chappell, B.W., English, P.M., King, P.L., White, A.J.R. & Wyborn, D. 1991. *Granites and related rocks of the Lachlan Fold Belt (1:1 250 000 scale map)*. Bureau of Mineral Resources, Geology and Geophysics, Australia.

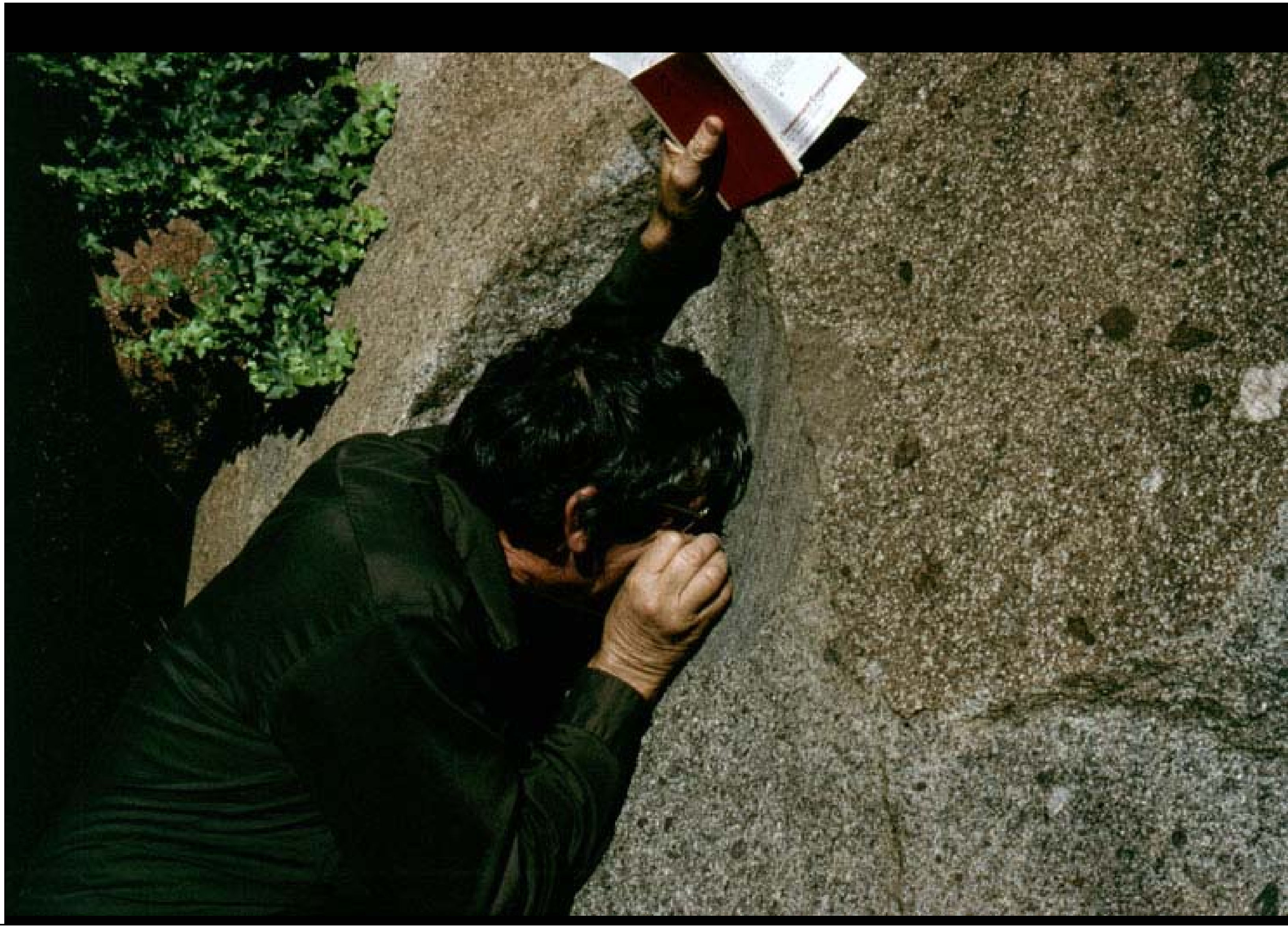
GRANITE SUITES





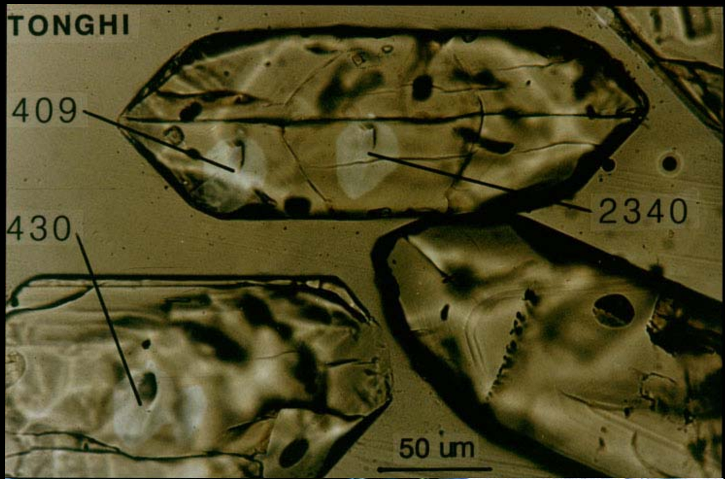
The granite plutons can be grouped into *suites*, which share field, petrographic and compositional features (White *et al*., 2001). Suites are the basic unit for considering the petrogenesis of the granites.

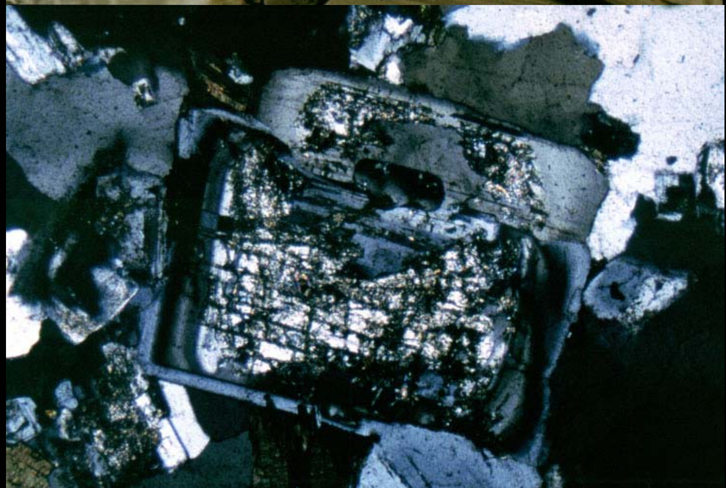
On a broader scale, the suites can be grouped into *supersuites*, which may also contain associated volcanic rocks.



Photograph of Allan White assigning the Cowra Granodiorite to its appropriate suite.

THE RESTITE MODEL

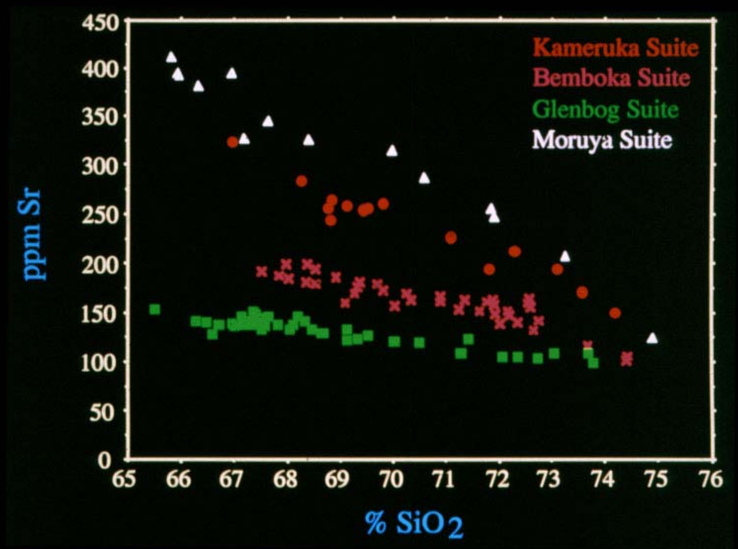


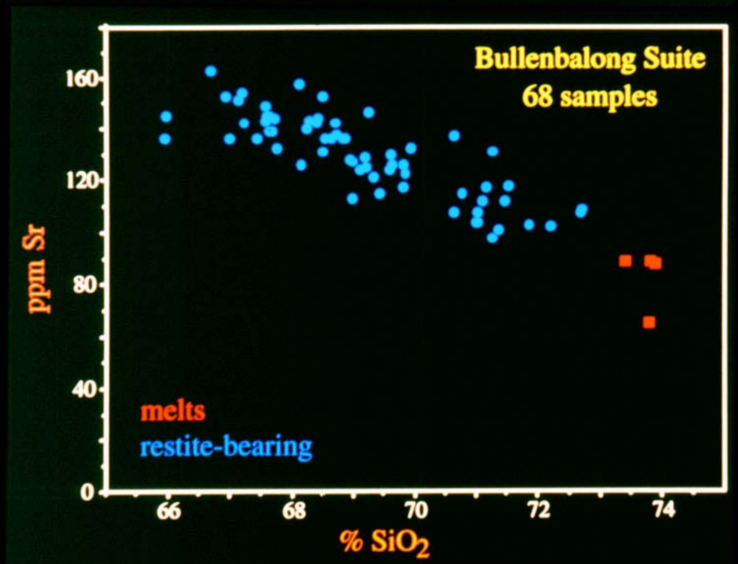


The *restite model* was developed to account for features of many granite suites that cannot be readily accounted for using other models such as magma mixing and fractional crystallisation (White & Chappell, 1977; Chappell *et al*., 1987).

Among the features of many granites that the restite model can readily account for, are the older zircon cores and the relatively uniform cores of plagioclase crystals.

Granites that form in this way evolve from a magma that initially comprised a partial melt mixed with crystals carried from the source.





High correlations between element abundances, giving “linear” variations on Harker Diagrams, are a feature of many granite suites. Variation within such suites is interpreted as resulting from the separation of varying amounts of a restite component from the magma. The composition of the partial melt lies at the felsic end of these trends, or its extrapolation, while the composition of the original source rock is located near the mafic end of the trends.

These variations could be accounted for by magma mixing or mingling, but such a process cannot account for the correlation in abundances at either end of the variation within suites, illustrated here for Sr in some suites of the Bega Batholith. Fractional crystallisation could not produce such linear variations, because of the preferential incorporation of that element into precipitating feldspars.

The higher scatter for the Bullenbalong Suite in these two figures is typical of S-type suites and results from greater heterogeneity of the source materials. An implication is that I-type granites were derived from rather uniform sources.

IMAGES OF THEIR SOURCE ROCKS

Chappell (1978) pointed out that granites form "images" of their source rocks. This is clearly the case for suites in which the compositional variation was controlled by varying degrees of separation of restite from melt. In such a case, the more mafic rocks would have compositions close to those of the source materials. We refer to these as *direct images*. In the case of granites that formed at higher temperatures from complete melts, the quality of those images will be lower, and we refer to them as *indirect images*. As an example, we have the high Cu, Sr and Ba contents of the Boggy Plain Supersuite.

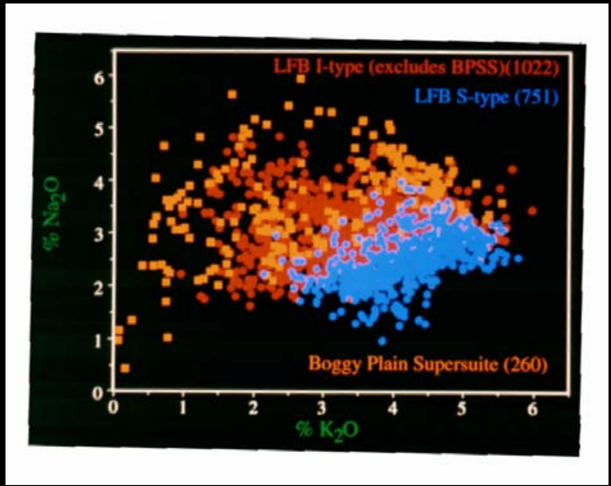
Isotopic compositions of the heavier elements should not be significantly affected by processes of partial melting and crystallisation, so the imaging quality is high.

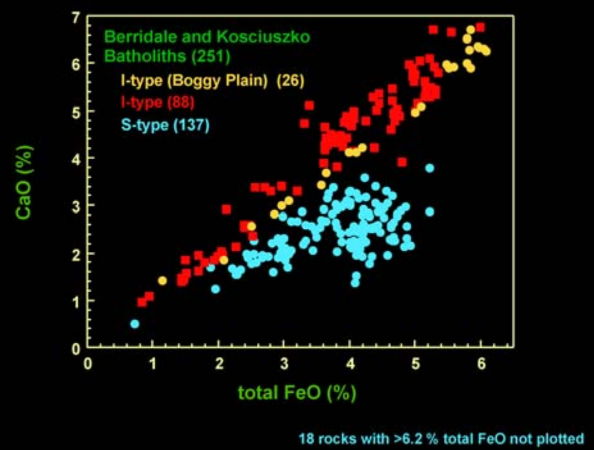
The more mafic granites of low-temperature origin, that are restite-rich, may also form a good mineralogical image of their source rocks. For example, a source rock of tonalitic composition, comprising dominantly quartz + plagioclase + biotite + hornblende, may become magmatic by partial melting to produce a restite assemblage of plagioclase + orthopyroxene + clinopyroxene, seen as the phenocryst assemblage in some volcanic rocks, e.g. the Kadoona Dacite. With slower cooling, these minerals would react with the hydrous melt to produce a group of minerals with abundances close to those of the source, e.g. the Tuross Head Tonalite.

Chappell, B.W. (1979). Granites as images of their source rocks. Geological Society of America, Program with Abstracts **11**, 400.

See also references listed previously for the restite model.

I- AND S-TYPE GRANITES



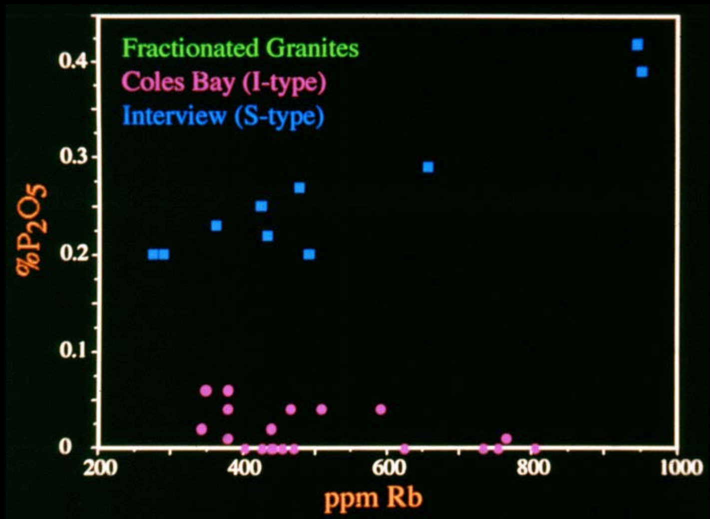


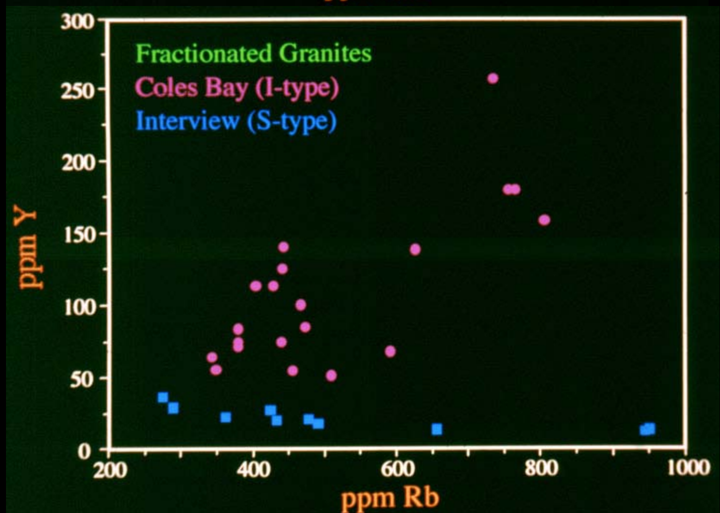
An immediate consequence of the imaging property of granite magmas is that granites that formed from older igneous or sedimentary rocks will share compositional characteristics with their source materials, and hence two groups of granites can be recognised.

S-type granites have lower Na and Ca contents than I-type granites because of the loss of those elements to the oceans during chemical weathering.

As a consequence, S-type granites are always oversaturated in Al, never contain hornblende, and commonly carry cordierite and muscovite and sometimes aluminosilicate minerals.

FRACTIONATED I- AND S-TYPE GRANITES

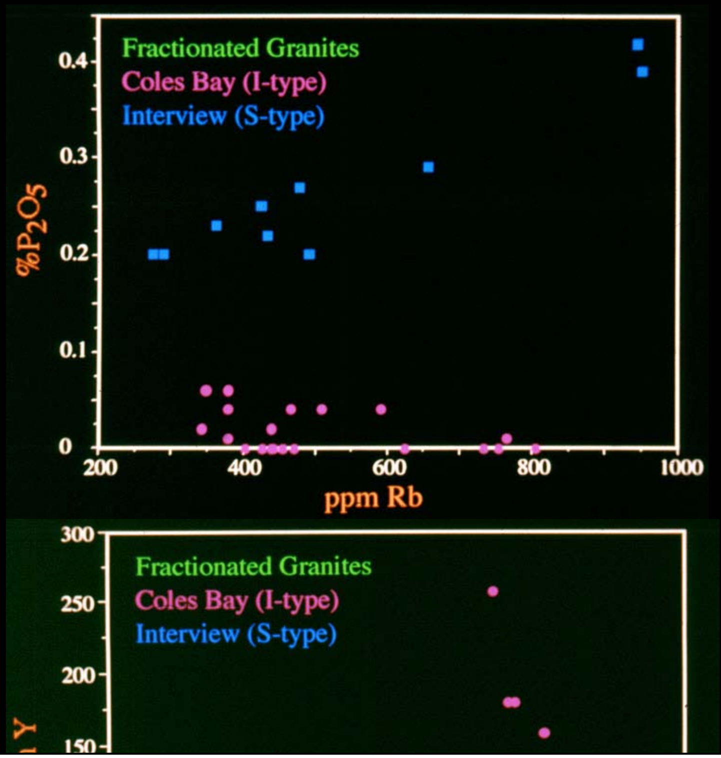




S-type granite melts are always saturated in Al, but when fractional crystallisation occurs, the abundance of excess Al can increase to much higher levels, expressed as normative corundum, up to about 4%. Montel *et al*. (1988) showed that P is soluble in such melts and the data of Wolf & London (1994) for the solubility of P, show that the abundances of P_2O_5 of up to ~ 0.4% are always less than saturation. Under such conditions P increases in abundance with fractionation (upper figure), and trace elements that form minerals with P, such as monazite, become saturated and decrease (lower figure).

There are some excellent examples of this contrasting behaviour of I- and S-type granites in the LFB, discussed by Chappell (1999). This again confirms the I- and S-type separation.

FRACTIONATED I- AND S-TYPE GRANITES



S-type granite melts are always saturated in Al, but when fractional crystallisation occurs, the abundance of excess Al can increase to much higher levels, expressed as normative corundum, up to about 4%. Montel *et al*. (1988) showed that P is soluble in such melts and the data of Wolf & London (1994) for the solubility of P, show that the abundances of P_2O_5 of up to ~ 0.4% are always less than saturation. Under such conditions P increases in abundance with fractionation (upper figure), and trace elements that form minerals with P, such as monazite, become saturated and decrease (lower figure).

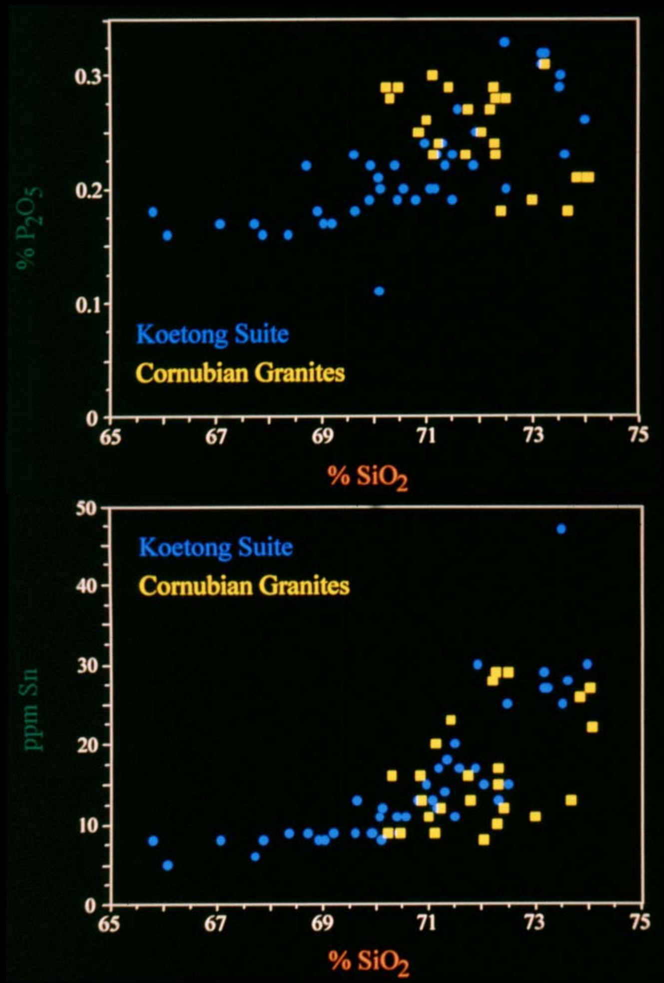
There are some excellent examples of this contrasting behaviour of I- and S-type

Montel, J.M., Mouchel, R. & Pichavant, M., 1988. High apatite solubility in peraluminous melts. *Terra Cognita* **8**, 71.

Wolf, M.B. & London, D., 1994. Apatite dissolution into peraluminous haplogranitic melts: an experimental study of solubilities and mechanisms. *Geochimica et Cosmochimica Acta* **56**, 4127-4145.

Chappell, B.W. 1999. Aluminium saturation in I- and S-type granites and the characterization of fractionated haplogranites. *Lithos* **46**, 535-551.

"TIN GRANITES"



Until some ten years ago, the so-called "tin granites" represented a major problem in petrology. These rocks show:

- extreme excess of Al (~ 4% Al_2O_3)
- extreme enrichment in certain elements
  - B, Rb, Sn, Cs, W and U
- association with rich mineralisation
- sometimes a very high heat flow
- generally not associated more mafic rocks

The LFB provides perhaps a unique perspective on the tin granites, with such granites of the Koetong Suite of the Wagga Batholith that match those of the Cornish Batholith very closely, showing a complete transition to quite mafic compositions. Here the whole process of evolution from the primary magmas can be examined.

All of the distinctive features of these rocks can be readily accounted for by the strong fractional crystallisation of S-type leucogranites. Processes such as metasomatism were not significant.

IS-LINES AND BASEMENT TERRANES

The S-type granites of the Kosciuszko region have a sharp eastern limit that can be drawn down the centre of the Berridale Batholith, extending south to Bass Strait, and north to the edge of the exposed LFB. White *et al*. (1976) called this the I-S line. Chappell *et al*. (1988) noted that this line is but one example of a type of boundary that is characteristic of the LFB. Granites of that region have a distinct provincial character, with sharp discontinuities occurring between provinces that internally are of rather constant character. Because of the "imaging" property of granites, noted earlier, these breaks are thought to correspond to analogous discontinuities in the deeper parts of the crust.

Province boundaries do not correspond to changes in surface lithologies, which are dominated by Ordovician- to Silurian-aged flysch deposits that are of rather constant character. Chappell *et al*. (1988) stated that "breaks of this type are thought to correspond to sharp changes in the composition of the deep crust that correspond to unexposed or *basement terranes*". They speculated that these terranes correspond to fragments of continental crust that were assembled prior to deposition of the presently exposed sedimentary rocks.

IS-LINES AND BASEMENT TERRANES

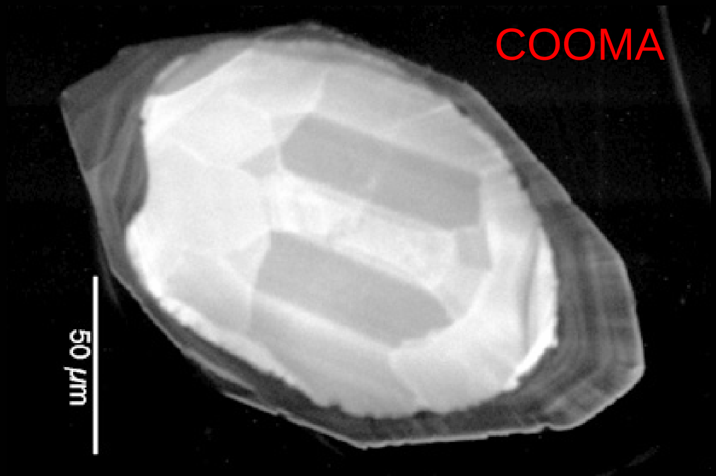
The S-type granites of the Kosciuszko region have a sharp eastern limit that can be drawn down the centre of the Berridale Batholith, extending south to Bass Strait, and north to the edge of the exposed LFB. White *et al*. (1976) called this the I-S line. Chappell *et al*. (1988) noted that this line is but one example of a type of boundary that is characteristic of the LFB. Granites of that region have a distinct provincial character, with sharp discontinuities occurring between provinces that internally are of rather constant character. Because of the "imaging" property of granites, noted earlier, these breaks are thought to correspond to analogous discontinuities in the deeper parts of the crust.

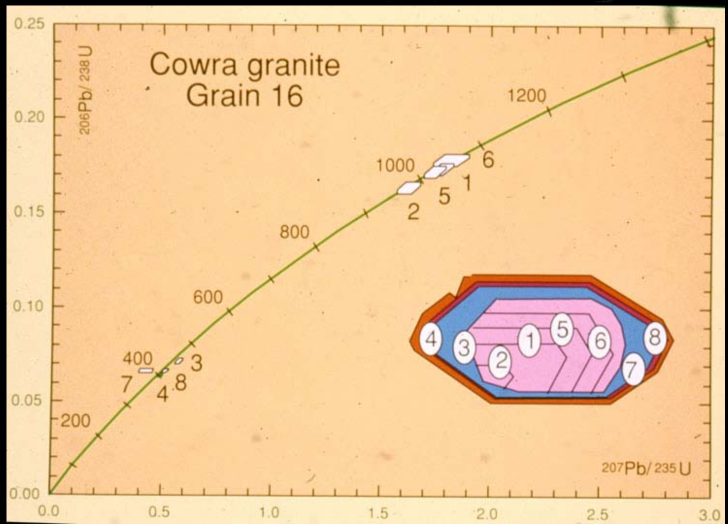
Province boundaries do not correspond to changes in surface lithologies, which are dominated by Ordovician- to Silurian-aged flysch deposits that are of rather constant character. Chappell *et al*. (1988) stated that "breaks of this type are thought to correspond to sharp changes in the composition of the deep crust that correspond to unexposed or *basement terranes*". They speculated that these terranes correspond to fragments of continental crust that were assembled prior to deposition of the presently

White, A.J.R., Williams, I.S. & Chappell, B.W. 1976. The Jindabyne Thrust and its tectonic, physiographic and petrogenetic significance. *Journal of the Geological Society of Australia* **23**, 105-112.

Chappell, B.W., White, A.J.R. & Hine, R. 1988. Granite provinces and basement terranes in the Lachlan Fold Belt, southeastern Australia. *Australian Journal of Earth Sciences* **35**, 505-521.

THE SHRIMP AND ZIRCON AGE-INHERITANCE

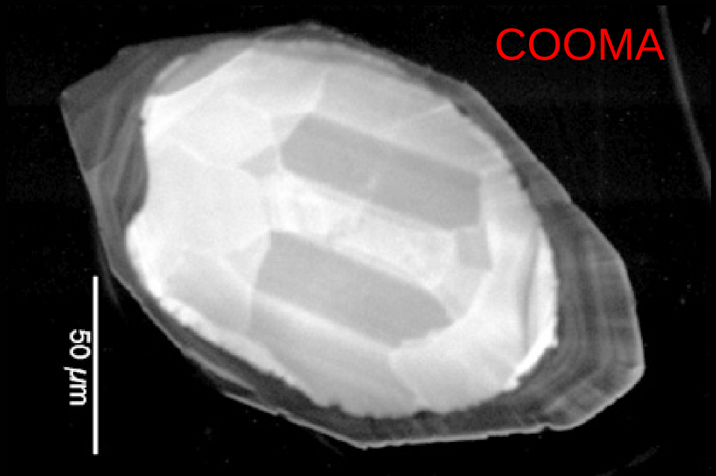


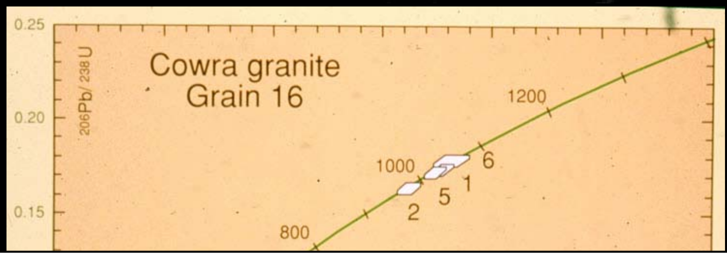


Development of the SHRIMP ion probe by Bill Compston and co-workers has had a major impact on the development of our understanding of the LFB granites. Detailed studies by Ian Williams have shown that zircon age inheritance is ubiquitous in the S-type granites and widespread in the I-type granites (Williams, 1995, 2001). The occurrence of older zircon. There are distinct age maxima in the older crystals at ~ 500 to 600 Ma (Delamarian or Pan-African) and at ~ 1000 Ma (Grenville).

The presence of older zircon in a granite shows that the magma was always saturated in that mineral. This confirms bulk rock trends for Zr and in the more mafic rocks this ha been critical in development of the concept of low- and high-temperature granite types.

THE SHRIMP AND ZIRCON AGE-INHERITANCE





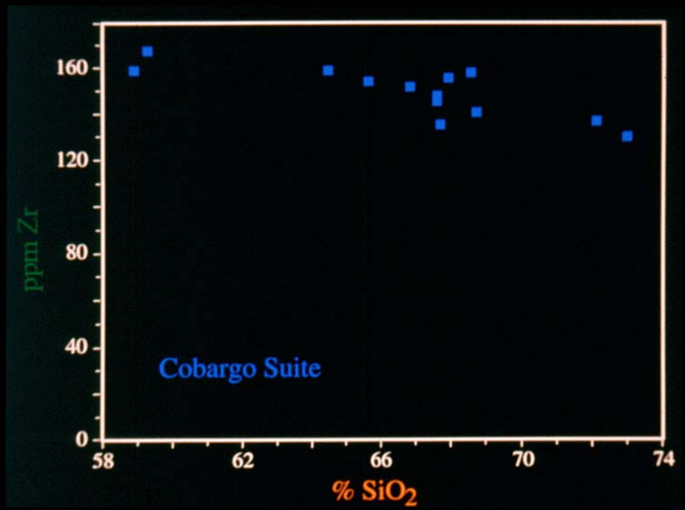
Development of the SHRIMP ion probe by Bill Compston and co-workers has had a major impact on the development of our understanding of the LFB granites. Detailed studies by Ian Williams have shown that zircon age inheritance is ubiquitous in the S-type granites and widespread in the I-type granites (Williams, 1995, 2001). The occurrence of older zircon. There are distinct age maxima in the older crystals at ~ 500 to 600 Ma (Delamarian or Pan-African) and at ~ 1000 Ma (Grenville).

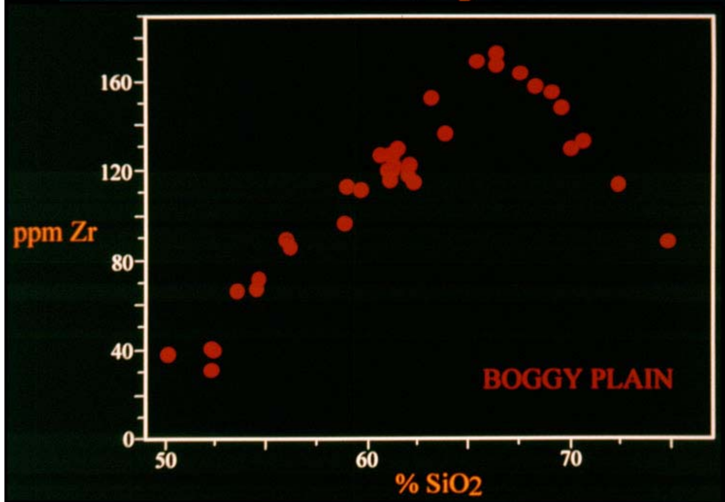
The presence of older zircon in a

Williams, I.S. 1995. Zircon analysis by ion microprobe: the case of the eastern Australian granites. *Leon T. Silver 70th Birthday Symposium and Celebration*, The California Institute of Technology, 27-31.

Williams, I.S. 2001. Response of detrital zircons and monazite, and their U-Pb isotopic systems, to regional metamorphism and host-rock partial melting, Cooma Complex, southeastern Australia. *Australian Journal of Earth Sciences* **48**, 557-580.

LOW- AND HIGH-TEMPERATURE GRANITES

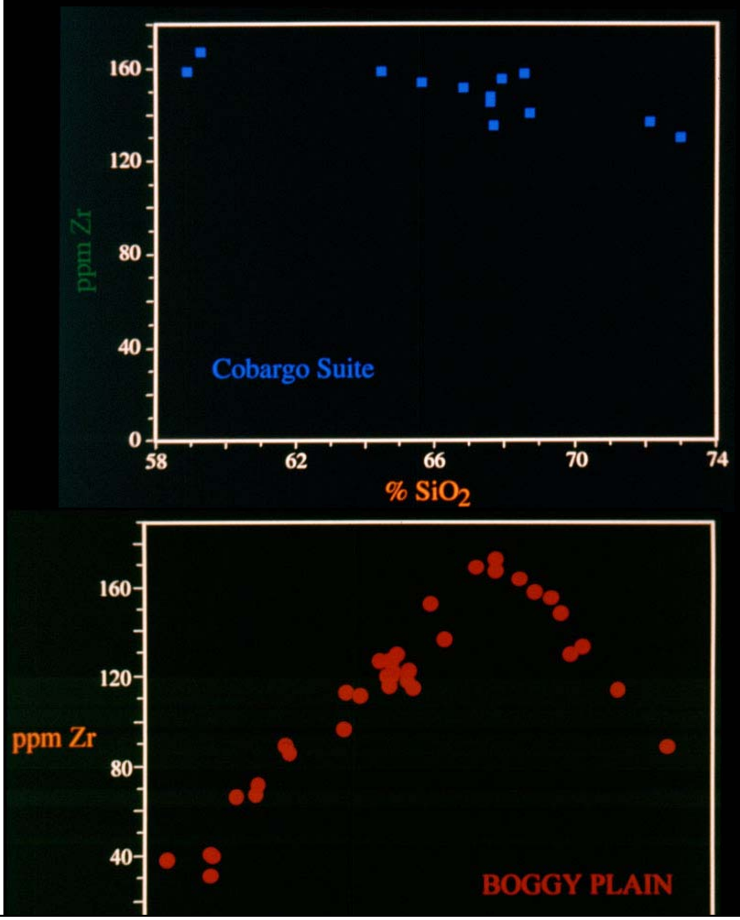




These two figures illustrate the two contrasting patterns of variation of Zr among the LFB granites. For the Cobargo Suite, Zr abundances decrease progressively with increasing SiO_2 and the rocks were always saturated in zircon, and must have existed as magmas at relatively low temperatures. For the high-temperature Boggy Plain pluton, the magmas were initially not saturated in zircon, and were at much higher temperatures.

The low-T granites formed from source rocks that contained sufficient low-T melt components for enough melt to form so that the magma could be extracted at relatively low temperatures. For the high-T granites, melting continued to higher temperatures before the magma could depart the source. Low-T granites, which include all S-types, form from heating of older crust; the high-T granites form from more primitive and less evolved crust.

LOW- AND HIGH-TEMPERATURE GRANITES



These two figures illustrate the two contrasting patterns of variation of Zr among the LFB granites. For the Cobargo Suite, Zr abundances decrease progressively with increasing SiO_2 and the rocks were always saturated in zircon, and must have existed as magmas at relatively low temperatures. For the high-temperature Boggy Plain pluton, the magmas were initially not saturated in zircon, and were at much higher temperatures.

The low-T granites formed from source rocks that contained sufficient low-T melt components for enough melt to form so that the magma could be extracted at relatively low temperatures. For the high-T granites, melting continued to higher temperatures before the magma could depart the source. Low-T granites, which include all S-types, form from heating of older crust; the high-T granites form

Chappell, B.W., Bryant, C.J., Wyborn, D., White, A.J.R. & Williams, I.S. 1998. High- and low-temperature I-type granites. *Resource Geology* **48**, 225-236.

A-TYPE GRANITES:
THE HIGH-TEMPERATURE FELSIC GRANITES

The Lachlan Fold Belt contains some excellent examples of true A-type granites, although they comprise only 0.6% of the total area of granite outcrop. They were initially described in the Mumbulla and Gabo Island Suites by Collins *et al*. (1982), and have since been discussed by King *et al*. (1997, 2001). The major element compositions of all types of felsic granite converge to the haplogranite minimum-temperature composition of Tuttle & Bowen (1958), so that while the major element compositions of the A-type granites are distinctive, they are not necessarily diagnostic. These rocks are distinguished by high abundances of Zr (~ 500 ppm in the Gabo Island and Danswell Creek Suites), which show that they formed at higher temperatures than other felsic granites. These higher temperatures are interpreted to result from the partial melting of a H_2O-poor source, so that in a sense these are the analogues of high-temperature tonalites, for example, which form from source rocks that are low in K, another minimum-temperature melt component. Other elements present in unfractionated A-type granite at high abundances are Nb, the REE and Ga. These "true" A-type granites must be distinguished from other granites that are commonly called A-type, where the REE and Ga contents may be high as a result of fractional crystallisation, and are not a primary feature.

A-TYPE GRANITES: THE HIGH-TEMPERATURE FELSIC GRANITES

The Lachlan Fold Belt contains some excellent examples of true A-type granites, although they comprise only 0.6% of the total area of granite outcrop. They were initially described in the Mumbulla and Gabo Island Suites by Collins *et al*. (1982), and have since been discussed by King *et al*. (1997, 2001). The major element compositions of all types of felsic granite converge to the haplogranite minimum-temperature composition of Tuttle & Bowen (1958), so that while the major element compositions of the A-type granites are distinctive, they are not necessarily diagnostic. These rocks are distinguished by high abundances of Zr (~ 500 ppm in the Gabo Island and Danswell Creek Suites), which show that they formed at higher temperatures than other felsic granites. These higher temperatures are interpreted to result from the partial

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. *Contributions to Mineralogy and Petrology* **80**, 189-200.

King, P.L., Chappell, B.W., White, A.J.R. & Allen, C.M. 2001. Are A-type granites the high temperature felsic granites? Evidence from fractionated granites of the A-type Wangrah Suite. *Australian Journal of Earth Sciences* **48**, 501-513.

King, P.L., White, A.J.R., Chappell, B.W. & Allen, C.M. 1997. Characterization and origin of the aluminous A-type granites of the Lachlan Fold Belt, southeastern Australia. *Journal of Petrology* **38**, 371-391.

VOLCANIC ROCKS: SUITES & SUPERSUITES, I- & S-TYPES

It was field and related studies by the BMR (Owen & Wyborn, 1979) which showed that the volcanic rocks of the LFB are closely related to the granites. The volcanic rocks can be placed into suites and supersuites with the granites, and I- and S-type volcanic rocks can also be recognised.

It is rare to find the volcanic rocks in a pristine condition, but when such rocks are found, their chemical compositions may match those of selected granites very closely (see next slide). When cogenetic volcanic and plutonic rocks are found, the former tell us about the mineralogical composition of the granite at an earlier time. This can be useful genetically, for example in showing that much of the mafic mineralogy that we see in the granites is secondary from earlier pyroxene-bearing assemblages.

Granites, in general, provide the better chemical information, as they are remarkably resistant to bulk chemical modifications during cooling. The volcanic rocks supply crucial mineralogical data. The latter provide the best information that we have for the depth of partial melting (for the S-types ~ 17 km), and for temperatures of eruption.

Owen, M. & Wyborn, D. 1979. Geology and geochemistry of the Tantangara and Brindabella 1:100 000 sheet areas. *Bureau of Mineral Resources, Australia, Bulletin* **204**, 52 pp, five microfiche.

S-TYPE PLUTONIC AND VOLCANIC ROCK COMPOSITIONS

	granite	dacite
SiO_2	69.29	69.26
TiO_2	0.66	0.62
Al_2O_3	14.79	14.67
Fe_2O_3	0.76	0.88
FeO	3.77	3.63
MnO	0.06	0.06
MgO	2.09	2.09
CaO	2.50	2.73
Na_2O	2.09	2.07
K_2O	3.62	3.64
P_2O_5	0.15	0.15

	granite	dacite
Rb	178	171
Sr	133	139
Ba	535	530
Zr	191	188
Nb	13	12
Y	33	33
La	33	33
Sc	15	15
V	90	100
Cr	51	57
Ni	22	22
Cu	13	14
Zn	64	72
Ga	18	18
Sn	4	4
Th	21	19
U	4	4

granite = avge of 4 analyses of Cowra Gd.
Q + Or + Plag + Bi + Cord +Alm (<1)

dacite = SV51 from Hawkins Dacite.
Q(20) + Pl(20) + Bi(10) + Opx(5) + Cord (5) + Alm(2) + gmass (40)

I-TYPE PLUTONIC AND VOLCANIC ROCK COMPOSITIONS

	granite	dacite
SiO_2	67.66	66.86
TiO_2	0.56	0.60
Al_2O_3	14.73	14.67
Fe_2O_3	1.93	1.82
FeO	2.93	3.44
MnO	0.09	0.09
MgO	1.95	2.21
CaO	4.64	4.77
Na_2O	2.49	2.49
K_2O	2.78	2.77
P_2O_5	0.09	0.11

	granite	dacite
Rb	136	125
Sr	141	170
Ba	422	445
Zr	143	164
Nb	8	9
Y	27	29
La	23	26
Sc	20	21
V	107	118
Cr	15	17
Ni	5	5
Cu	6	9
Zn	68	61
Ga	16	17
Sn	4	4
Th	15	16
U	3	3

granite = avge of 6 analyses of Yalgatta Gd.
Q(31) + Or(10) + Plag (40) + Bi (14) + Hb (5)

dacite = BV5 from Kadoona Dacite.
Q(17) + Pl(31) + Bi(3) + Opx(5) + Cpx (2) + Opq(2) + gmass (40)

VOLCANIC ROCKS: LOW- AND HIGH-TEMPERATURE

The previous slide shows that chemical compositions of some I- and S-type granites and volcanic rocks can be matched very closely. That is the case for what are now call the low-temperature suites, for which both the associated volcanic and plutonic rocks have essentially the same range of compositions and the compositions of relatively fresh volcanic rocks can be matched very closely with those of particular granites (Wyborn & Chappell, 1986). The volcanic rocks of these suites are invariably porphyritic, and the bulk of the phenocrysts are interpreted as crystals as restite.

In the high-temperature Boggy Plain Supersuite, the volcanic rocks are felsic and without phenocrysts, with compositions that complement those of the more mafic cumulate granites of that supersuite (Wyborn *et al*., 2001). The high-temperature Mountain Creek Volcanics include very felsic rocks up to 76.5% SiO_2 (rhyolites), that erupted at temperatures ~ 1050 °C.

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

Wyborn, D., Chappell, B.W. & Johnston, R.M. 1981. Three S-type volcanic suites from the Lachlan Fold Belt, southeast Australia. *Journal of Geophysical Research* **86**, 10335-10348.

GRANITES OF THE LFB AND MINERALISATION

It would be fair to comment that for such a large area of plutonic rocks (of Silurian to Carboniferous age), the amount of related mineralisation in the LFB is rather small. Appreciable economic mineralisation associated with granites of the LFB is limited to those granites whose compositions were modified by fractional crystallisation (Blevin & Chappell, 1992, 1995). Since most of the granite suites did not evolve in that way, there is a ready explanation for the lack of mineralisation.

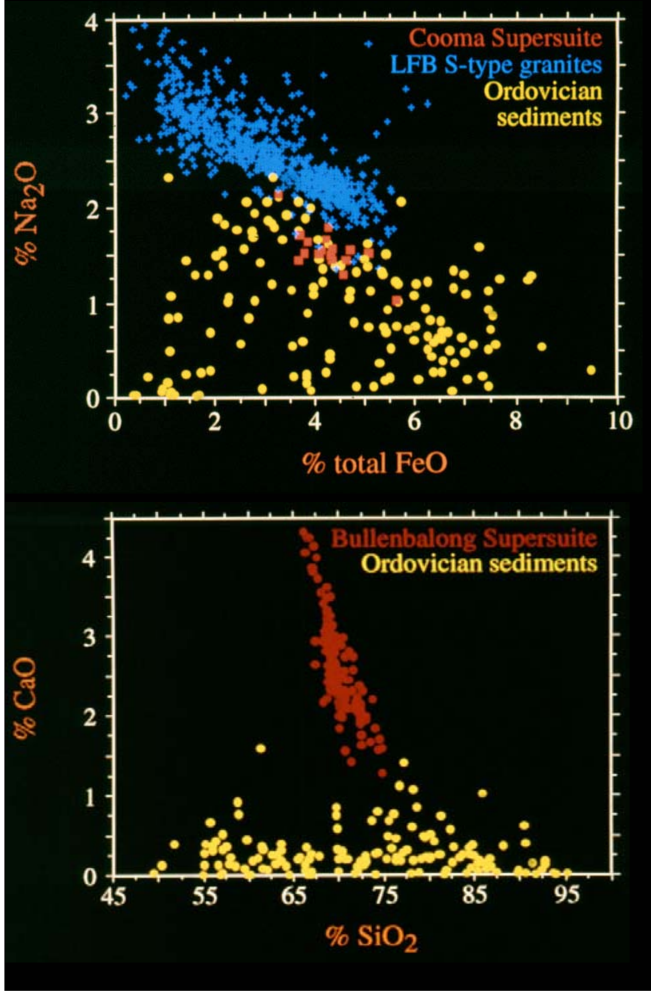
Tin mineralisation, which is associated with fractionated granites, is significant but production has not been too substantial by world standards. But the very close analogy between some granites of the Wagga Batholith and the Cornubian Batholith, will be of interest if tin were ever to regain significant status as a commodity.

Phil Blevin has studied the metallogenic aspects of the Lachlan granites in detail and this will be part of his presentation to-morrow.

Blevin P.L. & Chappell B.W. 1992. The role of magma sources, oxidation states and fraction-ation in determining the granite metallogeny of eastern Australia. *Transactions of the Royal Society of Edinburgh: Earth Sciences* **83**, 305-316.

Blevin, P.L. & Chappell, B.W. 1995. Chemistry, origin and evolution of mineralized granites in the Lachlan Fold Belt, Australia: the metallogeny of I- and S-type granites. *Economic Geology* **90**, 1604-1619.

SOURCE OF THE BATHOLITHIC S-TYPE GRANITES — A PROBLEM

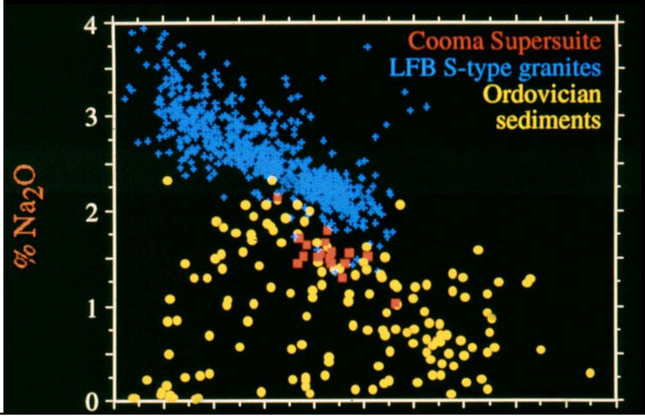


Debate about the source rocks of the dominant *batholithic* S-type granites (White & Chappell 1988) is unresolved. The abundances of Na and Ca in the Ordovician sediments are far too low for those rocks to have been the source materials for those granites – the components of the sediments were too strongly weathered and feldspars have been destroyed (see figures).

Gray (1984) and Collins (1998), for example, have proposed that the Na and Ca levels seen in these S-type granites was derived from a mafic component that was added to the Ordovician sediments.

Chappell *et al*. (2000) favoured a sedimentary source rock that is more feldspathic than those exposed at the surface. Such material is found as enclaves on the S-type granites, and there are no mafic materials associated with these granites, not even as enclaves. Also, the S-type supersuites are fairly uniform over large areas, not consistent with a mixed source.

SOURCE OF THE BATHOLITHIC S-TYPE GRANITES — A PROBLEM



Debate about the source rocks of the dominant *batholithic* S-type granites (White & Chappell 1988) is unresolved. The abundances of Na and Ca in the Ordovician sediments are far too low for those rocks to have been the source materials for those granites – the components of the sediments were too strongly weathered and feldspars have been destroyed (see figures).

Gray (1984) and Collins (1998), for example, have proposed that the Na and Ca levels seen in

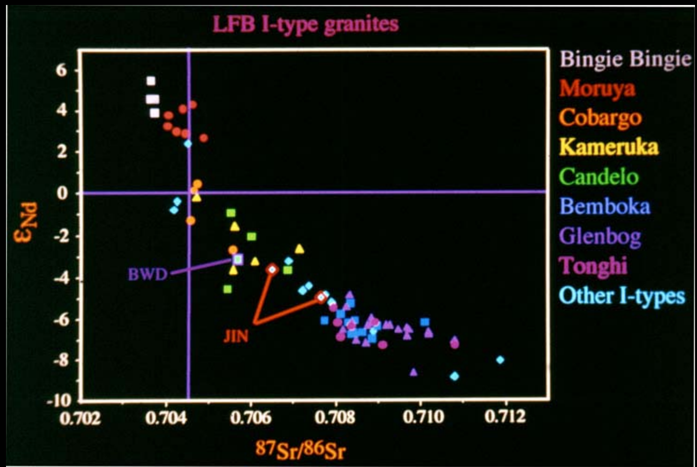
Gray, C.M. 1984. An isotopic mixing model for the origin of granitic rocks in southeastern Australia. *Earth and Planetary Science Letters* **70**, 47-60.

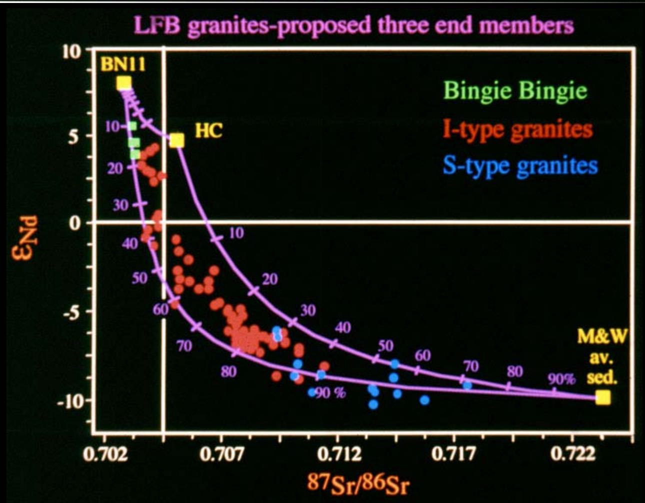
Chappell, B.W., White, A.J.R., Williams, I.S., Wyborn, D. & Wyborn, L.A.I. 2000. Lachlan Fold Belt granites revisited: high- and low-temperature granites and their implications. *Australian Journal of Earth Sciences* **47**, 123-138.

Collins, W.J. 1998. Evaluation of petrogenetic models for Lachlan Fold Belt granitoids: implications for crustal architecture and tectonic models. *Australian Journal of Earth Sciences* **45**, 483-500.

White, A.J.R. & Chappell, B.W. 1988. Some supracrustal (S-type) granites of the Lachlan Fold Belt. *Transactions of the Royal Society of Edinburgh: Earth Sciences* **79**, 169-181.

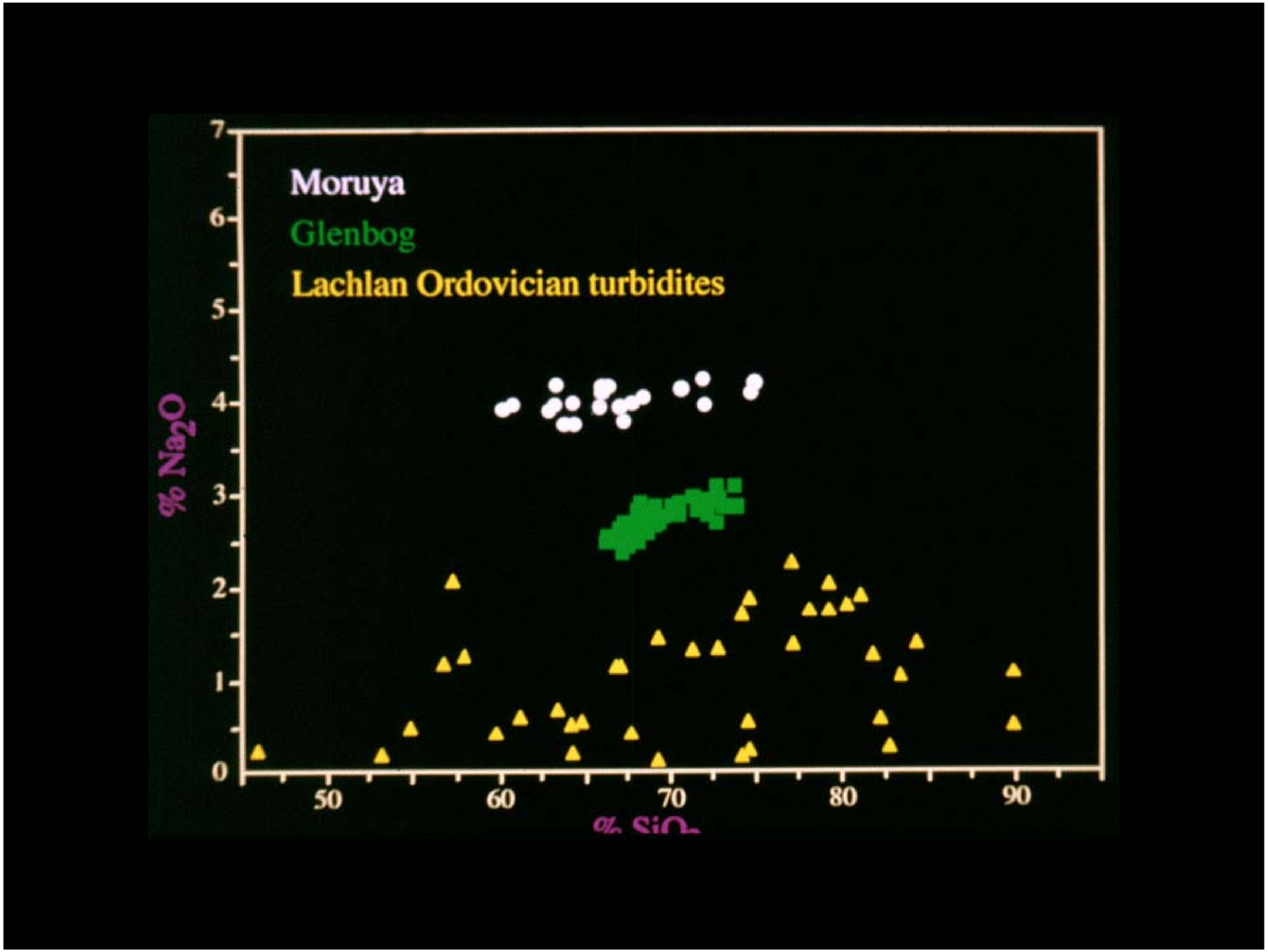
THE QUESTION OF MIXED SOURCES

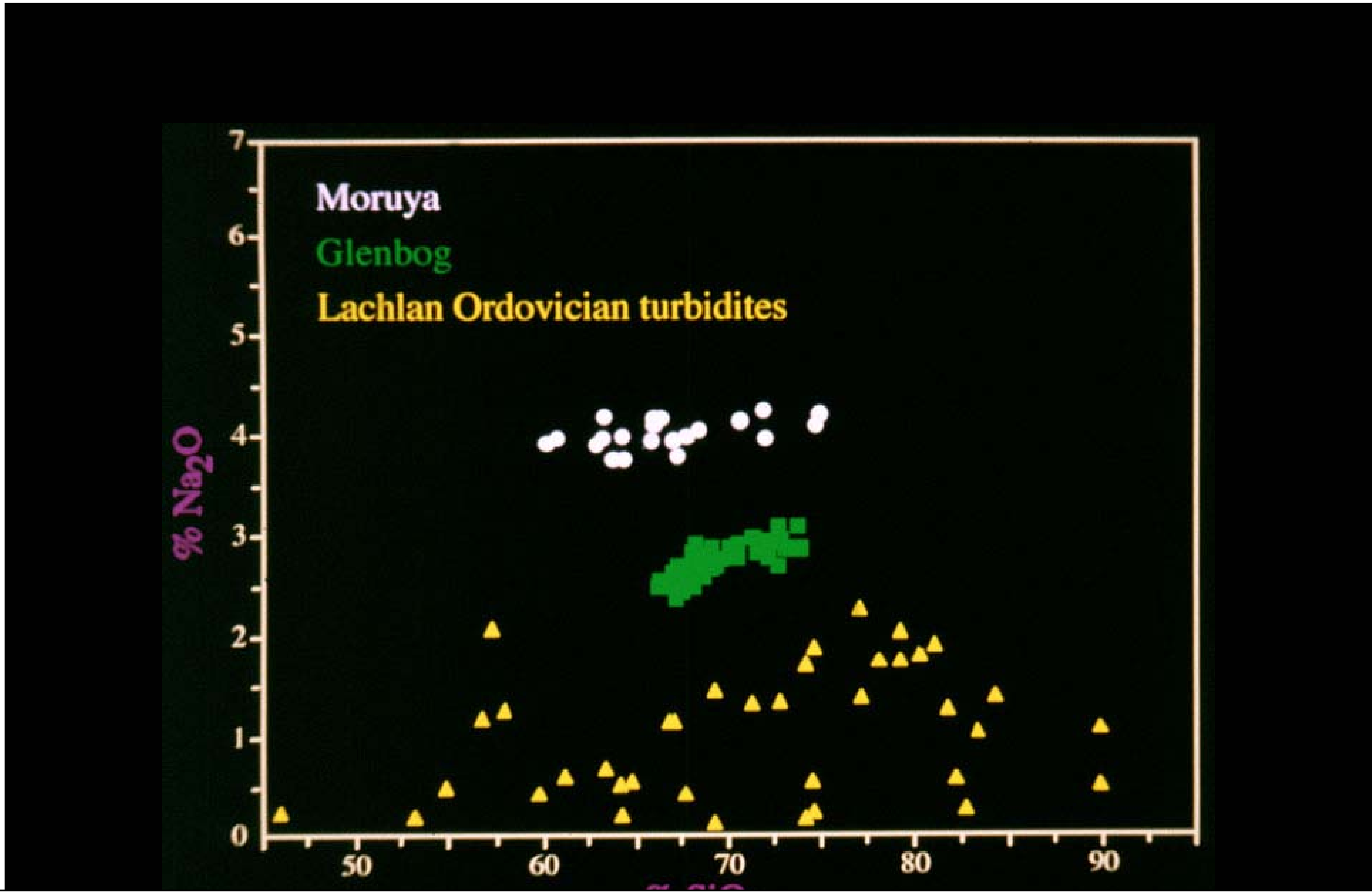




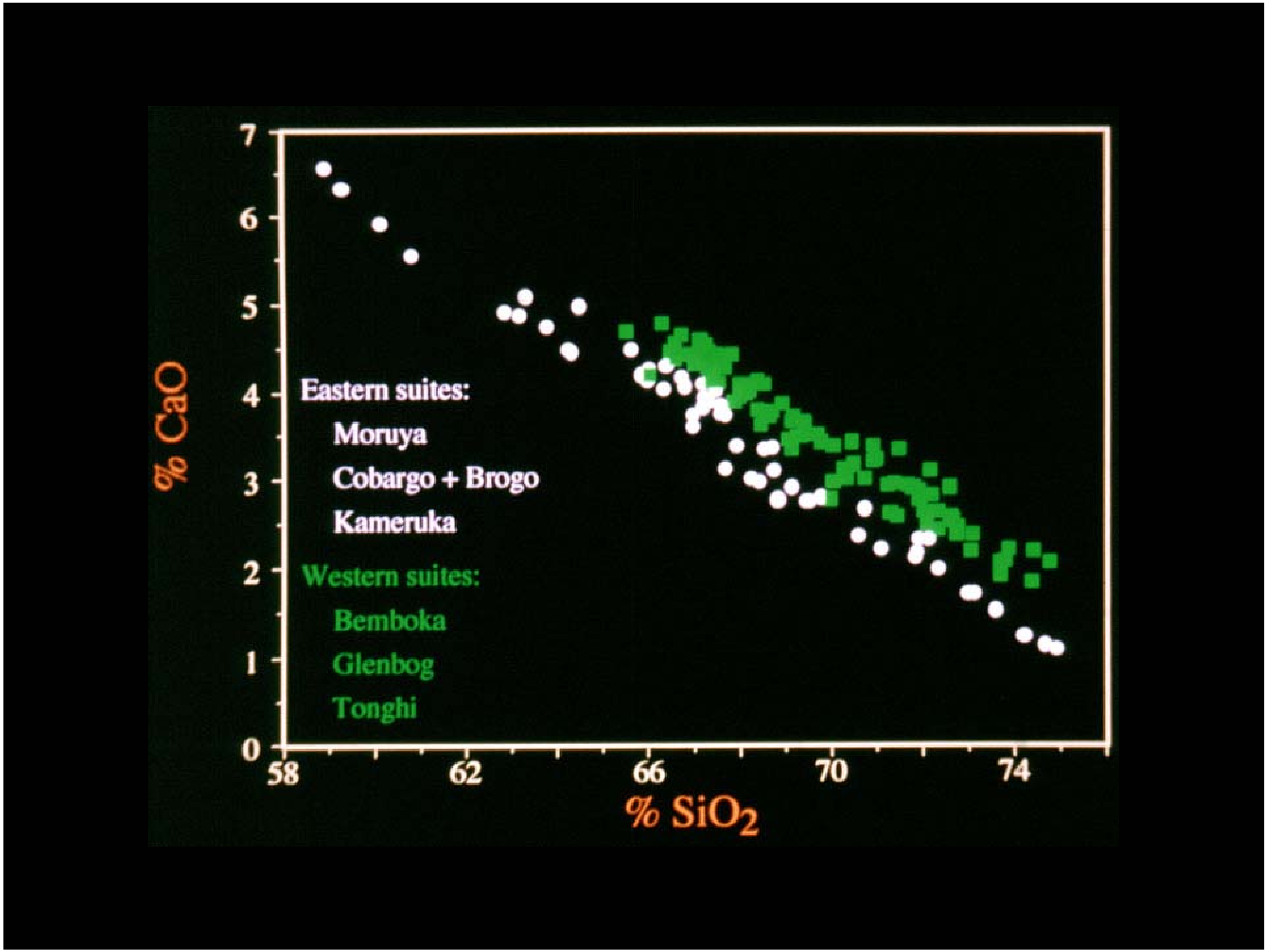
Sr and Nd isotopic compositions of the LFB granites are gradational and plot as a "mixing line" on a ε_{Nd}-Sr_i diagram. Gray (1984) stated that all granites of the LFB, both I- and S-type, form a single broad family produced by the mixing of two end-members, one mantle-derived, the other the Ordovician sediments. This was refined by Keay *et al*. (1997) who proposed three end-members.

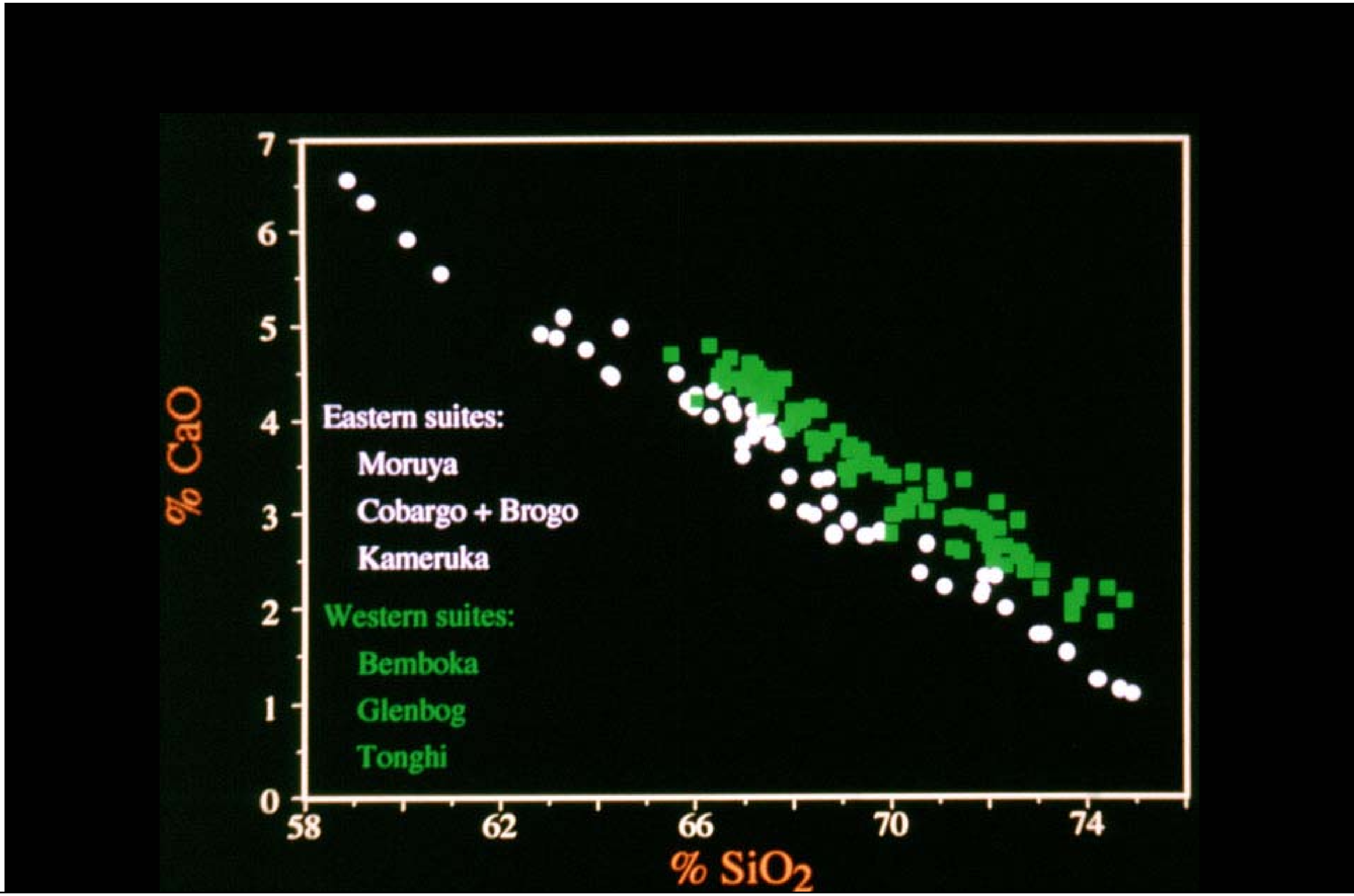
These models have inconsistencies with the elemental compositions. For example, Glenbog is more isotopically evolved and its lower Na contents is consistent with a sedimentary component, but its Ca content is higher than Moruya. This is shown on the following two slides. Also, some I-type granites, such as Jindabyne, require too large a sedimentary component to be consistent with the chemical features.


Moruya
Glenbog
Lachlan Ordovician turbidites
% Na2O
% SiO2
0
1
2
3
4
5
6
7
50
60
70
80
90



Granites of the Glenbog Suite are both more isotopically evolved and contain less Na than granites of the Moruya Suite. These observations would be consistent with the incorporation of Ordovician sediments with the low Na contents seen on this figure. But the reverse is the case for Ca, seen in the next slide.


% CaO
% SiO2
7
6
5
4
3
2
1
0
58
62
66
70
74
Eastern suites:
Moruya
Cobargo + Brogo
Kameruka
Western suites:
Bemboka
Glenbog
Tonghi



The western suites of the Bega Batholith contain more Ca than do the eastern suites. This is not consistent with incorporation of the very low Ca Ordovician sediments to account for the more isotopically evolved nature of the western suites.

NO DIRECT ROLE FOR SUBDUCTION

Formation of the dominant Silurian and Devonian granites of the LFB was not related directly to subduction (Chappell, 1998). This is controversial. However, we have the following petrological evidence (or lack thereof):

- Apart from the small Marulan Batholith, the Silurian and Devonian igneous rocks do not include any analogs of the distinctive Cordilleran tonalitic plutonic rocks. I-type tonalites are present, e.g. at Tuross Head, with compositions like those of the Cordillera, but they are parts of low-temperature suites.
- Widespread S-type granites (>50% of the LFB granites), involving chemically and isotopically rather-evolved source rocks, are not a feature of younger subduction-related belts, and require the presence of thick (~ 20 km) metasedimentary crust.
- The volcanic rocks are also mostly low-temperature, dacites to rhyolites. The high-temperature volcanic rocks are dominated by felsic rhyolites.
- The LFB granites were emplaced into a slate belt. Are there any subduction-related sediments of Ordovician to Devonian age, such as mélange?
- Are there any verified post-Cambrian blueschists in the LFB?

The LFB contrasts markedly with the New England Fold Belt in all of these respects.

NO DIRECT ROLE FOR SUBDUCTION

Formation of the dominant Silurian and Devonian granites of the LFB was not related directly to subduction (Chappell, 1998). This is controversial. However, we have the following petrological evidence (or lack thereof):

- Apart from the small Marulan Batholith, the Silurian and Devonian igneous rocks do not include any analogs of the distinctive Cordilleran tonalitic plutonic rocks. I-type tonalites are present, e.g. at Tuross Head, with compositions like those of the Cordillera, but they are parts of low-temperature suites.
- Widespread S-type granites (>50% of the LFB granites), involving chemically and isotopically rather-evolved source rocks, are not a feature of younger subduction-related belts, and require the presence of thick (~ 20 km) metasedimentary crust.
- The volcanic rocks are also mostly low-temperature, dacites to rhyolites. The high-temperature volcanic rocks are dominated by felsic rhyolites.
- The LFB granites were emplaced into a slate belt. Are there any subduction-related sediments of Ordovician to Devonian age, such as mélange?
- Are there any verified post-Cambrian blueschists in the LFB?

Chappell, B.W. 1994. Lachlan and New England: fold belts of contrasting magmatic and tectonic development (47th Clarke Memorial Lecture). *Journal and Proceedings of the Royal Society of New South Wales* **127**, 47-59.

Chappell, B.W. 1998. Tectonic evolution of the eastern Australian fold belts from a granite-based perspective: 1998 Mawson Lecture. *The Australian Geologist* **109**, 24-30.

LACHLAN GRANITE DATABASE

A little more than 3500 chemical analyses of rocks from the Lachlan Fold Belt including approximately 2200 granites, plus associated plutonic and volcanic rocks, Ordovician mafic rocks, igneous rocks from the Mesozoic complexes, and sedimentary rocks. Will be made freely available following an earlier release of comparable New England data.

GEMOC