CAUSES OF VARIATION IN GRANITE SUITES

Bruce Chappell
GEMOC, Macquarie University, NSW 2010

Granite suites each have characteristic compositional features and show regular transitional internal variations in composition. When two elements are plotted against each other the compositional changes reveal themselves as smooth curves, sometimes linear, sometimes curved (White *et al*., 2001)) Isotopic compositions of suites will normally vary within narrow limits, but may be more variable as a reflection of analogous differences in heterogeneous source rocks. A granite suite will possess characteristic mineralogical features and may also have a distinctive textural character. Single suites may be comagmatic, or else may be cogenetic, both in terms of source and processes. A prime concern in studying granite suites is the process which produced the compositional variation in each case. Following are various possible mechanisms for producing such variation, following Chappell (1996a):

1. Variation inherited from heterogeneous source rocks
2. Varying degrees of partial melting
3. Magma mixing and/or mingling
4. Assimilation or contamination
5. Restite separation, generally restite crystal fractionation
6. Fractional crystallisation (a type of crystal fractionation)
7. Hydrothermal alteration

These processes could operate alone, or sometimes simultaneously (e.g. 4 and 6 in the AFC process), or in some cases sequentially (e.g. 5 followed by 6, or 6 followed by 7). They will be evaluated on the basis of observations that have been made on the granites of eastern Australia.

These different mechanisms will be considered, particularly 3, 5 and 6, those to which a major role has most often been ascribed in producing variation within granite suites.

Magma mixing and/or mingling

This is an extremely popular mechanism for producing compositional variations. A current widely accepted model (e.g. Barbarin, 1991) envisages melt from the mantle partly melting the crust as it crystallises and cools. The two components then mingle to produce a range of rock compositions. Most of the types of evidence cited in support of this model are seen among the granites of the large I-type Bega Batholith (8940 km^2) of the eastern Lachlan Fold Belt (LFB). These include the presence of mafic enclaves that are generally more abundant in the more mafic host rocks, hybrid rocks at Tuross Head, striking examples of linear chemical variations, noting that Wall *et al*. (1987) have stated that “mixing is the classic cause of linear variation in major and trace element Harker diagrams”, and variations in isotopic compositions that can readily, although not necessarily correctly, be accounted for on the basis of mixing of various end-member compositions. However, the rocks of this batholith show compositional features that are not consistent with the variation within suites having been produced in that way. When the compositions of pairs of suites are compared, any differences seen at either end of the range in composition are also seen at the other limit, so that both the most mafic and felsic rocks show similar relative abundances of particular elements (Chappell, 1996b). The probability that mafic and felsic end-member components would so consistently choose mixing/mingling partners that share their particular compositional features relative to other mixing pairs is so small that it can be rejected. Furthermore, while the rocks of the Bega Batholith show isotopic compositions that could be produced by mixing of discrete end-members (e.g. Keay *et al*., 1997), the isotopic variations within suites are relatively small and not of a type that would have been produced by the mixing of more isotopically evolved crust with more primitive mantle-derived components (Chappell & McCulloch, 1990). We are forced to agree with Pitcher (1993, p. 136) who stated that "For all their eye-catching display in outcrop, mingling and mixing in the higher levels of the crust represent but second-order processes in the diversification of the granitic rocks”.

These arguments and such a conclusion apply to variations with granite suites of the LFB, but are not directly applicable to the question of the granites having been derived from mixed source rocks, as has been proposed by Gray (1984, 1990), Collins (1996) and Keay *et al*. (1997). Since considerations of such broader scale mixing processes are not relevant to the questions of compositional variations within suites of granites, they are not part of this present discussion.

Assimilation or contamination

Some contamination of granite plutons by components from the country rocks would be expected; it is a question of scale and the amount by which this process contributes significantly to variations within granite suites. Assimilation has been detected in the Boggy Plain pluton (34 km^2), where initial $^{87}Sr/^{86}Sr$ ratios increase from an average of 0.70441 in the marginal diorites and the granodiorites (29% of area), to an average of 0.70479 in the monzogranites (70%), to 0.70554 in one sample from the central aplitic rocks (0.9%) (Wyborn, 1983). Even in this most favourable case of a relatively hot and initially completely molten magma, the amount of assimilation was very small, and did not contribute significantly to the overall compositional variation.

The presence of cordierite in the granites of the LFB that are now called S-type, has long been recognized, most notably by Baker (1940), who favoured an origin resulting from enrichment of the granite magma in Al by assimilation of argillaceous country rock. Snelling (1960) subdivided granites of the Murrumbidgee Batholith of the LFB into "contaminated" and "uncontaminated" types, and suggested that the "contaminated" granites were derived from a parental magma akin to the "uncontaminated" granites in composition by the incorporation of country rocks at depth. Both of Snelling's groups are S-type. With the recognition of the I- and S-type groups by Chappell & White (1974), is has become generally accepted that the cordierite in the S-type granites is either a product of the process that lead to partial melting of the source rocks (e.g. Chappell *et al*., 1987), or else precipitated from melts that acquired a strongly peraluminous composition during the partial melting of sedimentary source materials (Clemens & Wall, 1981). However, Collins (1996) has stated that “LFB S-type magmas are heavily contaminated I-type magmas”.

Fractional crystallisation

This is the process by which the removal of crystals that have precipitated from a melt leads to progressive changes in composition of that melt. This is a mechanism that has been widely used to account for variation in igneous rock suites ever since it was introduced into petrology by Becker (1897). While this process did not operate as widely in the LFB as is sometimes thought, that region does provide some excellent examples. These include the granites and volcanic rocks of the Boggy Plain Supersuite (BPS) (Wyborn *et al*., 1987), the felsic I-type granites of the Freycinet Peninsular of Tasmania, and felsic S-type granites of the Koetong Suite and Tasmania. Distinctive characteristics of this process are non-linear element abundances on variation diagrams, extreme enrichments or depletions in some trace elements in cases of strong fractionation, the development sometimes of cumulate rocks, the production of the strongly peraluminous “tin granites”, and a more common association with mineralisation than for rock suites that evolved in other ways.

Rocks produced by fractional crystallisation will either have the composition of melts from which crystals have been removed, or else will have compositions that reflect the addition to or concentration of crystals in a melt. In the latter case it is useful to distinguish between *cumulate* rocks in which the precipitated crystals formed a framework with the spaces filled with melt, and *cumulative* rocks in which crystals have been concentrated relative to the melt. The latter term can also be used collectively for both processes.

The Koetong Suite and the "tin granites". At SiO_2 contents above about 70%, the granites of the Koetong Suite in the Wagga Batholith provide an excellent and instructive example of fractional crystallisation, with the rock compositions corresponding to Bowen's *liquid line of descent*. The most felsic granites of the Koetong Suite have compositions that project close to those of experimentally determined "minimum-temperature" melts. For the five analysed samples that contain more than 90% of normative $Q + ab + or$ in the system Q-Ab-Or-H_2O (Tuttle & Bowen, 1958), the average proportions of those three components are $Q_{39}ab_{28}or_{33}$. This compares with the experimentally determined H_2O-saturated value of $Q_{40}ab_{29}or_{31}$. It is noteworthy that those five samples from the Koetong Suite are also strongly corundum-normative with an average value of 3.57% C. That those rocks represent melt compositions, with at most very little modification by hydrothermal alteration, is firmly established. Unlike many of the relatively felsic granites of other S-type suites of the LFB, those of the Koetong Suite show clear compositional evidence of fractional crystallisation, with abundances of elements such as Rb, Nb and Cs rising, and Sr and Ba falling, in all cases by factors of three or more, as the rocks become more felsic. P_2O_5 contents also rise with increasing fractionation, which is a distinctive feature of fractionated S-type granites (Chappell & White 1998). Those authors also regarded granites that are associated with the Koetong Suite and which contained much higher Sr abundances as cumulative rocks; however isotopic data have since shown that those rocks are not comagmatic and must be assigned to a separate suite. A detailed study of all S-type granite analyses from the LFB has shown that, apart from a very unusual and restricted example from the Blue Tier Batholith, there are no cumulate or cumulative compositions among the analysed S-type granites of the LFB (see below). That such rocks must exist at depth is implied by the occurrence of fractionated melt compositions. Such cumulative S-type granites are known from elsewhere, e.g. in Malaysia and among the European Hercynian granites.

Studies of the evolution of the Koetong Suite have lead to a much better understanding of the origin of the "tin granites". Such rocks were a significant problem in petrogenesis, with their very felsic, fractionated and strongly Al-oversaturated compositions, the very high abundances of several elements such as B, Rb, Sn, Cs, W and U, and generally a lack of associated less felsic rocks. The Koetong Suite shows a complete transition from quite mafic S-type granites to fractionated compositions that match those of "tin granites" such as Cornwall very closely. This has confirmed that fractional crystallisation is the dominant process in producing the "tin granites".

The Boggy Plain Supersuite. In contrast to the evolution of the Koetong Suite along a liquid line of descent, the rocks of the concentrically zoned Boggy Plain pluton correspond to a sequence of cumulate rocks that crystallised at the contracting boundary between melt and previously crystallised material. That process produced a continuous variation in compositions from 50.1% to 74.8% SiO_2, with one break between the outer contact and the aplitic rocks located near the centre of the pluton. Most of these cumulate rocks would not be recognised as such on textural or individual compositional grounds. However, some compositionally distinctive rocks do occur, with high Cr and low Zr and Ba contents, and a positive Eu anomaly in one case. The most mafic rock of the BPS, a plagioclase-rich cumulate from the Yeoval Batholith, has a very distinctive composition and contained very small amounts of melt, with the bulk rock containing 13.6% CaO, 0.06% K_2O, 0.01% P_2O_5 and 13 ppm Zr. The complementary fractionated melts of the BPS occur as felsic volcanic rocks and as plutons (Wyborn *et al.*, 2001).

Fractional crystallisation in haplogranites. Chappell (1999) discussed the process of fractional crystallisation in felsic haplogranites and contrasted the behaviour of strongly fractionated I- and S-type granites. In all of these rocks the contents of the major elements are very similar and do not change with fractionation, being governed by equilibrium between melt and crystals in the Tuttle & Bowen (1958) haplogranite system. However, trace element abundances change markedly with fractionation, and in ways that can differ between the I- and S-types. The I-type granites of the Coles Bay Suite of the Tasmanian east coast and of the S-type Interview Suite of western Tasmania include some strongly fractionated compositions. In all cases the abundances of elements that occur in mafic minerals, and Ca, which have low abundances, decrease further with fractionation, as do Sr and Ba, while Rb and Cs increase. For the Interview Suite the abundances of P increase while elements that occur in P-bearing accessory minerals other than apatite, such as Th, Y and the REE, decrease to low abundances, while for the Coles Bay Suite granites show the opposite trends.

How common are the products of fractional crystallisation in the LFB? There are some granite suites in the LFB that clearly evolved through fractional crystallisation, but they represent a small fraction of the total, certainly less than one quarter. They comprise the high-temperature granite suites (5% of LFB granites) and the fractionated haplogranites of the low-temperature suites. However, the view is commonly held that the variations within rock suites of the LFB and elsewhere are almost universally the result of fractional crystallisation. For example, Clemens (2003, p. 14), in discussing fractional crystallisation, has stated that "it seems safe to say that crystal fractionation (sic) probably plays a major role in the differentiation of very many granite magmas…". He also states that minor mechanisms include magma mixing, wall-rock assimilation and restite unmixing.

Cumulate and cumulative granites in the LFB. Clemens (2003) takes the view that the more mafic granites of the LFB are products of crystal accumulation. While that is the case for mafic rocks of high-temperature granite suites (Chappell *et al*., 1998), which are always I-type, it does not seem to be the case for the much more abundant low-temperature I-type suites in the LFB, and for the S-type granites, for four reasons. (1) Low-silica rocks closely associated with granites, apart from those of the BPS and the Marulan Batholith, have a very low abundance in the LFB. Among rocks of the BPS, 26% contain less than 59% SiO_2. Excluding the high-temperature granites of the Marulan Batholith and the Carboniferous granites in the east of the LFB, a few of which are possibly the high-temperature type, no other I-type rocks contain less than 55.5% SiO_2 and only 0.8% contain less than 59% SiO_2. For the analysed S-type granites there are no SiO_2 values less than 63%, except for one analysis of a granite with a concentration of garnet, which is distinct from the other most mafic S-type granites of the LFB, which contain abundant quartz, cordierite, biotite and plagioclase. For all other analysed granites, mafic minerals such as biotite (SiO_2 ~ 35%), hornblende (SiO_2 ~ 47%), pyroxenes (SiO_2 ~ 50%) or cordierite (SiO_2 ~ 50%) did not concentrate, at least in rocks at the present levels of exposure, to the exclusion of minerals such as plagioclase (SiO_2 = 66.3% at An_{50}) and quartz. Rocks of the BPS have bimodal SiO_2 contents, with mafic cumulate rocks and the complementary fractionated melt compositions being the most abundant, with only 10.4% of analysed rocks having compositions between 65% and 70% SiO_2. For the other I-type and the S-type granites, 39.8% and 42.3% of the analyses, respectively, lie in that interval. (2) Chemical equivalence of plutonic and volcanic rocks in the low-temperature granite suites of the LFB strongly suggests that none of the former are cumulative. Wyborn *et al.* (1981) pointed out that the general compositions of some plutonic and volcanic suites of the LFB can be matched fairly closely, and that the compositional differences between plutonic suites are also found in the volcanic suites. The volcanic rocks are not more felsic with a greater proportion of melts from which early-formed crystals had been removed, as would be expected if the more mafic granites are cumulative. Wyborn & Chappell (1986) considered the significance of that observation in more detail, and showed that comagmatic plutonic and volcanic rocks of the LFB can be divided into two groups. In the first group, the plutonic and volcanic rocks can be equated in composition, whereas in the second the volcanic rocks are more felsic than the related plutonic rocks. The first instance includes the low-temperature suites and Wyborn & Chappell (1986) argued that those rocks must represent true magma compositions and cannot be cumulative rocks produced during fractional crystallisation (cf. Clemens 1989). In the second case, the more mafic plutonic rocks represent crystal cumulates and the volcanic rocks and the exclusively felsic plutons, the complementary fractionated liquid. This second situation is illustrated by the BPS which includes rhyolitic lavas, the Mountain Creek Volcanics, that are much more felsic than the comagmatic or cogenetic cumulate plutonic rocks. (3) Apart from the granites of the BPS and the Marulan Batholith, the variations for many elements within granite suites of the LFB are not consistent with those rocks having formed progressively as cumulates. In no I-type suites that are referred to as low-temperature do elements such as P, Zr and Ba that may appear as an important component of new liquidus phases during continuing fractional crystallisation, show inflexions on Harker diagrams, e.g. for Ba in the Cobargo Suite which ranges through SiO_2 contents from 59% to 73%. In that and some other suites of the Bega Batholith, Ba increases in abundance as the granites become more, whereas precipitation of the minerals now present in the rocks would have lead to a depletion in the Ba content of the melt, and therefore in subsequently formed rocks, just as is observed for the Boggy Plain pluton at $SiO_2 > 66\%$. Chappell (1996a) has modeled the variations of some trace elements in I-type suites of the Bega Batholith and the S-type Bullenbalong Suite and shown those variations are not consistent with the rocks forming as cumulates by fractional crystallisation. (4) Rock suites that extend from felsic to mafic compositions without compositional discontinuities. If the more mafic members of the low-temperature granite suites of the LFB are cumulative rocks, then the fractionated melts produced by that process should be represented within the felsic rocks of those suites. Furthermore, the compositions of those felsic granites must represent melt rather than cumulative compositions. This is seen in the felsic S-type granites where compositions enriched in the elements contained in monazite such as Th and the light REE, and in the Sr and Ba contained in precipitated feldspars, which are present in cumulative S-type granites in other areas, do not occur. Among the felsic I-type granites, the distinctive high Sr, Ba and heavy REE that are characteristic of such rocks when they are cumulative, are not seen among any of the low-temperature rock suites that extend to more mafic compositions. If the more mafic rocks of those suites, and of the S-type suites, are cumulative, then compositional discontinuities should be widespread for elements, such as Sr, that partition strongly into cumulative rocks, in passing from felsic melt compositions to more mafic cumulative compositions. These are not seen, which confirms that the mafic rocks are not cumulative.

LFB granites as products of fractionated melts. Collins (1996), for example, has proposed that the granite suites of the LFB represent a series of melt compositions produced by fractional crystallisation from a melt with an initial composition matching that of the most mafic rock in a suite. This eliminates some of the difficulties for the cumulative model, but others persist. Three of these will be discussed. (1) The compositional variation within suites is unlikely to be consistent with fractional crystallisation. This argument is analogous to the third argument above, but it is more difficult to make in this case because the crystals that are presumed to have been removed from the melt are not seen. But a strong general argument can be made, which is that the strong "linear" variations that are seen for many elements would not be expected to result from processes in which the precipitating minerals would be continually varying in relative proportions and in compositions. (2) Complementary cumulative batholiths at depth. A general argument against more mafic granite compositions representing melt compositions was made by McCarthy & Groves (1979) who proposed that the granites of the Blue Tier Batholith are cumulate rocks, and pointed out that the alternative scenario in which the granites represent melt compositions, would imply that "each pluton was formed by a vast number of small separate intrusions, analogous to separate lava flows, each one different from the others". Further, they noted that this "demands a second magma chamber at depth where fractional crystallization occurred". On a broader scale, such a mechanism would require that all of the batholiths of the LFB are underlain by extensive cumulative rocks. (3) Occurrence of inherited zircons. The presence of older zircons in many of the more mafic I-type granites, and in all of the more mafic S-type granites of the LFB, shows that those rocks cannot represent melt compositions (Chappell, 2003). The zircon saturation temperatures (Watson & Harrison, 1983) for the most mafic rocks of various suites are all close to 800°C, which within the limits of the method, represents the maximum temperature at which zircon crystals could be present in equilibrium with a melt of those compositions. That is clearly too low a temperature for such a composition to be completely molten, by a very long way, yet the rocks contain old zircons and the variation of Zr in the suite is also consistent with zircon having been present, as a phase in which the magma was saturated. It is clear that the mafic rocks of these suites cannot have been melts, and consequently the compositional variation within those suites cannot correspond to a series of melts produced by fractional crystallisation.

Varying degrees of partial melting

Beyond the point where progressive melting of a granite source rock leads to the removal of one of the components of that melt (Q + ab + or), the temperature of melting will rise and the compositions of the melt will change as the fraction of melt increases. This is a potential mechanism for the generation of variation within rock suites that probably has not received the attention that it merits. It is approximately the reverse of the process of fractional crystallisation for cases in which extreme enrichments or depletions of trace elements have not been produced by that other process. It is possible that variations within the high-temperature granites of the Marulan Suite of the LFB (Carr *et al*., 1992) were produced in way, but there would not seem to be any other possible cases in the LFB. It has not been favoured as a general mechanism for any of those granites partly because of their distinctive patterns of linear compositional variation, in contrast to Marulan. But in particular, the fact that the variation within single plutons is parallel to that produced by groups of plutons within a suite, would imply that this mechanism can only have operated if every detail of compositional variation within plutons corresponded to different fractions of melt that had been generated by varying degrees of melting. This process seems to be better suited to producing suites that comprise plutons of different but individually relatively uniform compositions.

Restite separation or fractionation

This is a process of crystal fractionation in which the crystals that are separating from the melt were entrained in the melt at its source. This model for compositional variation was first proposed by White & Chappell (1977) to account for observations that had been made on granites of southeastern Australia. A more detailed account of this process was given by Chappell *et al*. (1987).

Many of the granite suites of southeastern Australia show distinctive linear trends for various elements on Harker diagrams. This has been confirmed by Collins (1996) who referred to "the remarkable linear chemical trends" in those granites. Such linear trends are not consistent with a mechanism of crystal fractionation through fractional crystallisation, as has been seen above. Now that extensive magma mingling can be discounted as a mechanism for the production of these variations (Chappell, 1996b), the mechanism of restite fractionation must be considered. In fact it provides an elegant solution to this problem. A mixture of felsic melt and mafic residual material would result from partial melting of the crust, with different degrees of separation of those two components producing linear correlations between elements. This is a process of fractionation of restite crystals from a melt with in which they were initially distributed following partial melting and with which they were in equilibrium. This would be much easier to achieve, at least on a large scale, than the mingling of molten and solid material that would have different physical properties and, at least initially, would not be in equilibrium. It also accounts for the observed correlations in abundances between the mafic and felsic compositions of various suites, since both were derived from the same material.

The veracity of the restite model has received powerful support from the observation of the widespread occurrence of age inheritance in zircon crystals of the granites of the LFB (Williams, 1995), which lead to development of the concept of high- and low-temperature granites by Chappell *et al*. (1998) (see Chappell, 2003).

Hydrothermal alteration

Subsolidus hydrothermal alteration may alter the composition of a granite as feldspars are replaced by sheet silicates and the loss of those elements that cannot be accommodated in the latter, principally Na, Ca and Sr, while K and Rb could be added from circulating solutions. The primary evidence for alteration is generally petrographic; however chemical data generally show that its effects are overrated. Many rocks in which there are clear petrographic signs of alteration plot in a very tight field or array on chemical diagrams, which would not be expected if their compositions were in part the result of low temperature alteration. Also, for most felsic granites of this type, the compositions are generally very close to the minimum-temperature compositions for hydrous melts in equilibrium with quartz and feldspars (Tuttle & Bowen 1958).

Variation inherited from heterogeneous source rocks

Suites of I-type granites in the LFB often show a remarkable compositional coherence, e.g. Sr in the Glenbog Suite shows extremely regular variation throughout 12 plutons that occur over a distance of more than 250 km. While homogeneity in a single pluton could be ascribed to thorough mixing at an early stage, for the Glenbog Suite this implies a relatively homogeneous distribution of Sr in the source rocks that must have contributed separately to the different plutons. The capacity to recognise suites depends on the internal variations within two source materials being small relative to the overall differences between them. A corollary of the very precise suite definitions that can be made in many cases in southeastern Australia, is that either the source materials were very homogeneous, or were mixed thoroughly at an early stage in the production of the suite, that latter situation being unlikely when a suite comprises several dispersed plutons. Because sedimentary source rocks are more heterogeneous than those of I-type granites, S-type suites individually show more scatter in element concentrations about the dominant trend for a suite. Also, when the more mafic members of S-type suites have compositions close to those of their source rocks, it is possible that they might show variations inherited from those source materials.

References

Baker, G. 1940. Cordierite granite from Terip Terip, Victoria. *American Mineralogist* **25**, 543-548.

Barbarin, B. 1991. Enclaves of the Mesozoic calc-alkaline granitoids of the Sierra Nevada Batholith, California. In: Didier, J. & Barbarin, B. (eds) *Enclaves and Granite Petrology*. Elsevier, Amsterdam, pp. 135-153.

Becker, G.F. 1897. Fractional crystallization of rocks. *American Journal of Science* Fourth Series **4**, 257-261.

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. 1996a. Compositional variation within granite suites of the Lachlan Fold Belt: its causes and implications for the physical state of granite magma. *Transactions of the Royal Society of Edinburgh: Earth Sciences* **87**, 159-170.

Chappell, B.W. 1996b. Magma mixing and the production of compositional variation within granite suites: evidence from the granites of southeastern Australia. *Journal of Petrology* 37, 449-470.

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. 2003. High- and low-temperature granites. *This volume*.

Chappell, B.W. & McCulloch, M.T. 1990. Possible mixed source rocks in the Bega Batholith: constraints provided by combined chemical and isotopic studies. *Seventh ICOG Meeting, Geological Society of* ***Australia, Abstracts*** 27**, 17.**

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. & Wyborn, D. 1987. The importance of residual source material (restite) in granite petrogenesis. *Journal of Petrology* **28**, 1111-1138.

Clemens, J.D. (1989). The importance of residual source material (restite) in granite petrogenesis: a comment. *Journal of Petrology* **30**, 1313-1316.

Clemens, J.D. & Wall, V.J. (1981). Origin and crystallization of some peraluminous (S-type) granitic magmas. *Canadian Mineralogist* **19**, 111-131.

Collins, W.J. 1996. Lachlan Fold Belt granitoids: products of three-component mixing: Transactions of the Royal Society of Edinburgh: Earth Sciences **87**, 171-26.

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.

Gray, C.M. 1990. A strontium isotopic traverse across the granitic rocks of southeastern Australia: petrogenetic and tectonic implications. *Australian Journal of Earth Sciences* **37**, 331-349.

Keay, S., Collins, W.J. & McCulloch, M.T. 1997. A three-component Sr-Nd isotopic mixing model for granitoid genesis, Lachlan fold belt, eastern Australia. *Geology* **25**, 307-310.

McCarthy, T.S. & Groves, D.I. (1979). The Blue Tier Batholith, northeastern Tasmania. *Contributions to Mineralogy and Petrology* **71**, 193-209.

McCarthy, T.S. & Hasty, R.A. (1976). Trace element distribution patterns and their relationship to the crystallization of granitic melts. *Geochimica et Cosmochimica Acta* **40**, 1351-1358.

Pitcher, W.S. 1993. *The Nature and Origin of Granite*. Blackie Academic & Professional, Glasgow, 321 pp.

Tuttle, O.F. & Bowen, N.L. (1958). Origin of granite in the light of experimental studies in the system $NaAlSi_3O_8$-$KAlSi_3O_8$-SiO_2-H_2O. *The Geological Society of America Memoir* **74**.

Wall, V.J., Clemens, J.D. & Clarke, D.B. 1987. Models for granitoid evolution and source compositions. *Journal of Geology* **95**, 731-749.

Watson, E.B. & Harrison, T.M. (1983). Zircon saturation revisited: temperature and composition effects in a variety of crustal magma types. *Earth and Planetary Science Letters* **64**, 295-304.

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.

Snelling, N.J. 1960. The geology and petrology of the Murrumbidgee Batholith. *Quarterly Journal of the Geological Society of London* **116**, 187-215.

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 eastern 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.

Wyborn, D. (1983). Fractionation processes in the Boggy Plain zoned pluton. Ph.D. Thesis, The Australian National University.

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

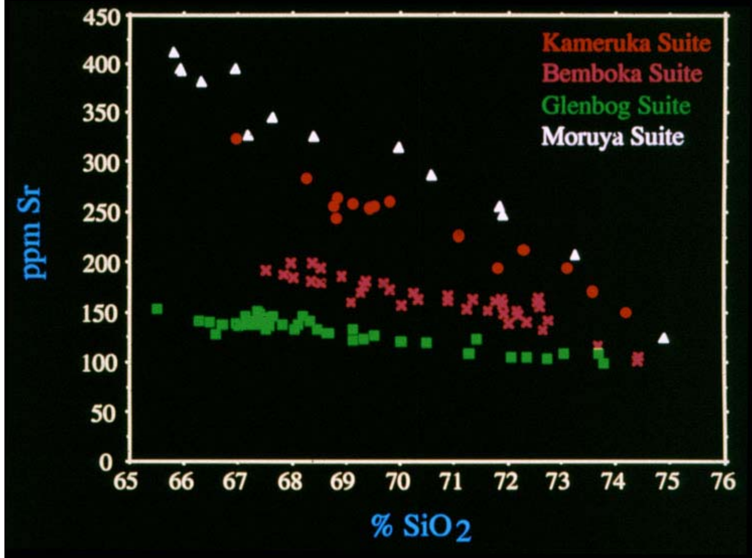
Wyborn, D., Chappell, B.W. & Johnston, R.M. (1981). Three S-type volcanic suites from the Lachlan Fold Belt, southeast Australia. *Journal of Geophysical Research* **86**, 10335-10348.

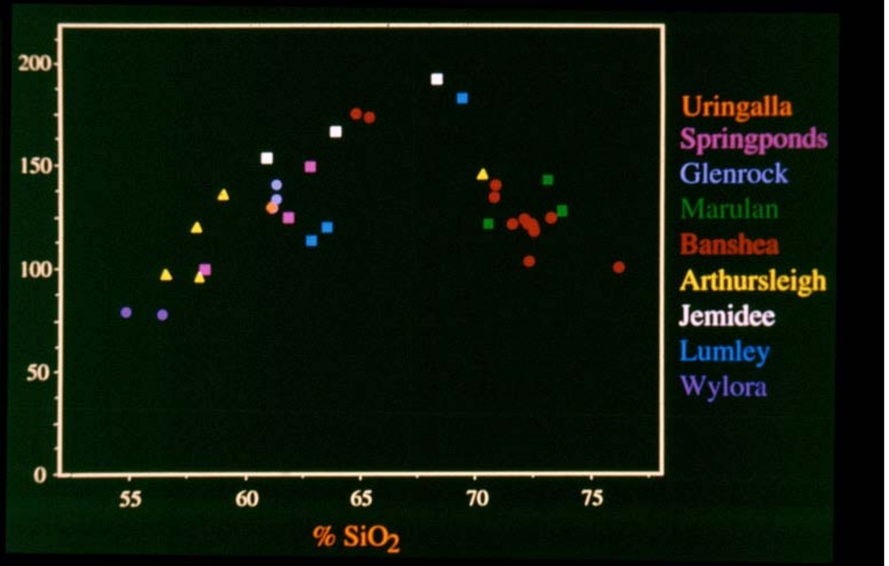
Wyborn, D., Turner, B.S. & Chappell, B.W. 1987. The Boggy Plain Supersuite: a distinctive belt of I-type igneous rocks of potential economic significance in the Lachlan Fold Belt. *Australian Journal of* ***Earth Sciences*** 34**, 21-43.**

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

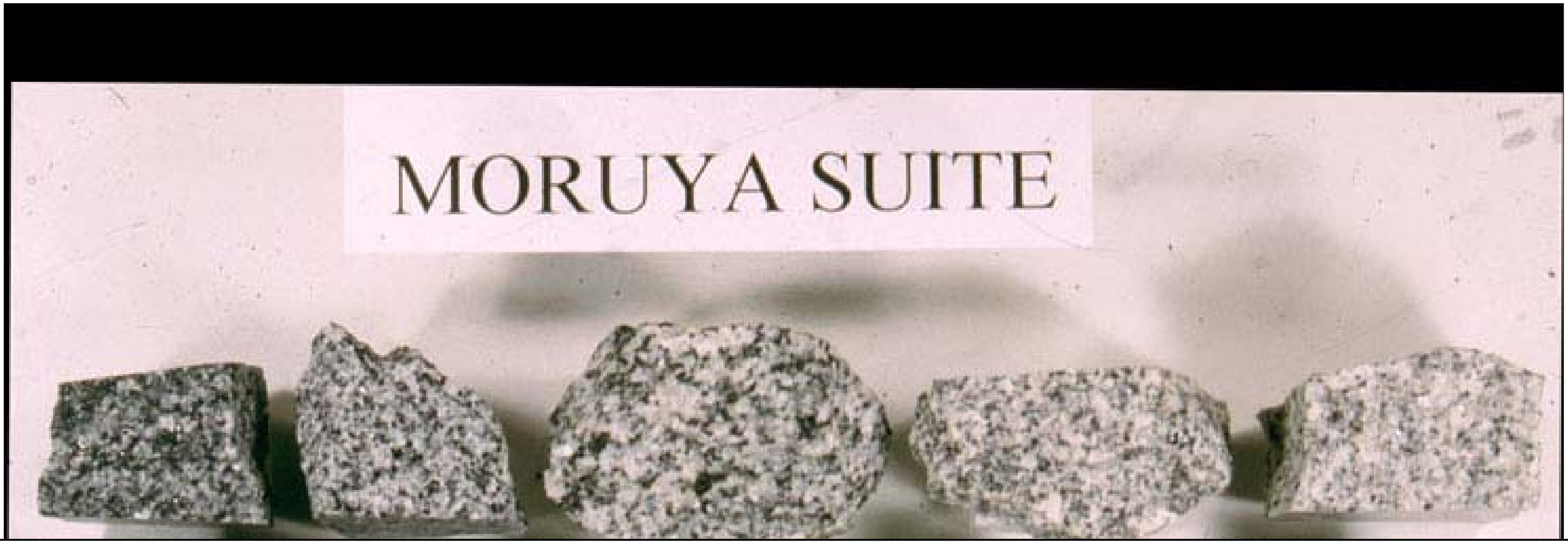
CAUSES OF VARIATION WITHIN GRANITE SUITES

Bruce Chappell






MORUYA SUITE
60
63
67
72
75
% SiO_2



The Moruya Suite comprises xx bodies of I-type granite occurring at the eastern margin of the Lachlan Fold Belt on the south coast of New South Wales. This slide illustrates the wide range in composition within this suite.

What are the causes of variation in composition of this and other granite suites?

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.

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 eastern Australia. *Australian Journal of Earth Sciences* **48**, 515-530.

GRANITE SUITES

Granite suites are characterised by regular transitions in composition. When two elements are plotted against each other the compositional changes reveal themselves as smooth curves, sometimes linear, sometimes curved.

Isotopic compositions of suites will normally vary within narrow limits, but may be more variable, reflecting analogous differences in heterogeneous source rocks.

A granite suite will possess characteristic mineralogical features and may also have a distinctive textural character.

Granite suites may be grouped into supersuites, for which the criteria are less rigid.

Single suites may be comagmatic, or else may be cogenetic, both in terms of source and processes.

Volcanic rocks that are comagmatic or cogenetic with a suite of granites, would be included in that suite, or more commonly, supersuite.

A prime concern in studying granite suites is the process that produced the compositional variation in each case.

MECHANISMS THAT MAY PRODUCE VARIATION WITHIN GRANITE SUITES

1. Variation inherited from heterogeneous source rocks
2. Varying degrees of partial melting
3. Magma mixing and/or mingling
4. Assimilation or contamination
5. Restite separation, generally restite crystal fractionation
6. Fractional crystallisation (a type of crystal fractionation)
7. Hydrothermal alteration

These processes could operate alone
- but sometimes simultaneously (e.g. 4 and 6 in the AFC process),
or in some cases sequentially (e.g. 5 followed by 6, or 6 followed by 7)

MECHANISMS THAT MAY PRODUCE VARIATION WITHIN GRANITE SUITES

1. Variation inherited from heterogeneous source rocks
2. Varying degrees of partial melting
3. Magma mixing and/or mingling
4. Assimilation or contamination
5. Restite separation, generally restite crystal fractionation

The various mechanisms that have been proposed to account for the variations within granite suites are listed in this slide. Mechanisms 5 and 6, both forms of crystal fractionation, are regarded as the dominant processes. Nos 1 and 2 are also important. Nos 3, 4 and 7 may be locally significant but cannot be invoked to account for large scale compositional variations.

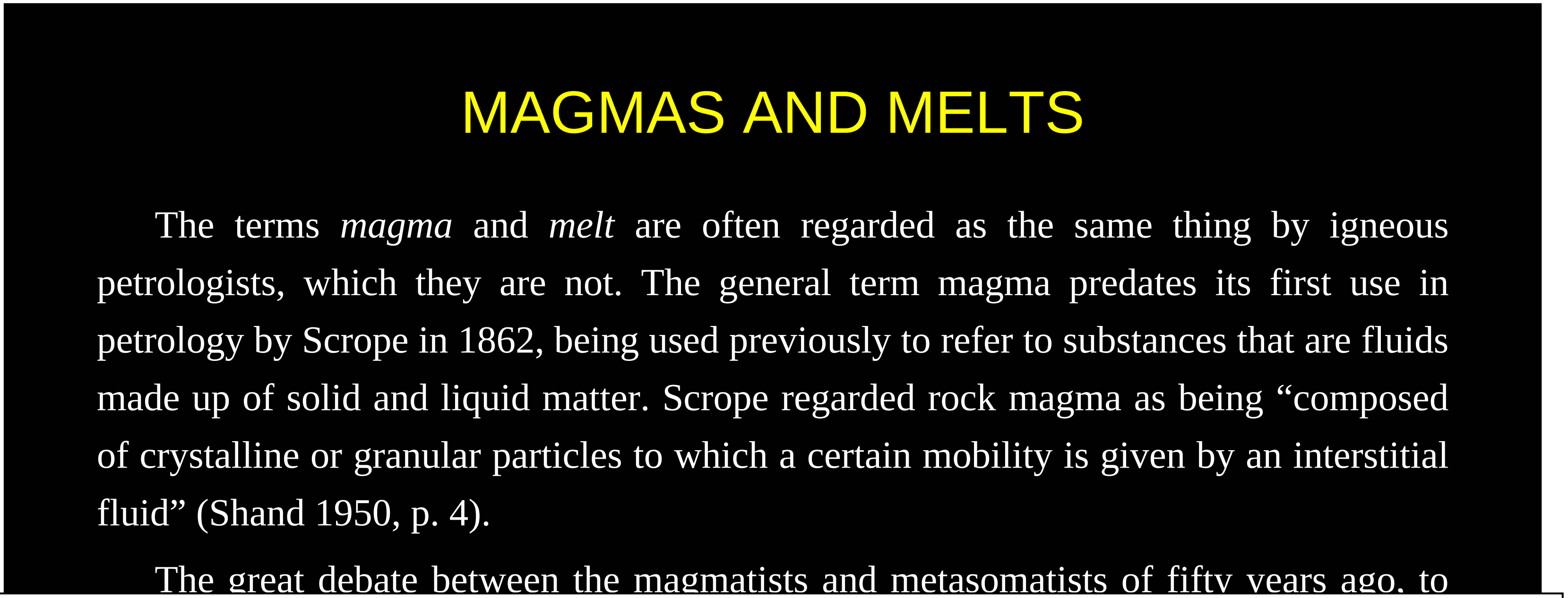
Chappell, B.W. 1996. Compositional variation within granite suites of the Lachlan Fold Belt: its causes and implications for the physical state of granite magma. *Transactions of the Royal Society of Edinburgh: Earth Sciences* **87**, 159-170.

MAGMAS AND MELTS

The terms *magma* and *melt* are often regarded as the same thing by igneous petrologists, which they are not. The general term magma predates its first use in petrology by Scrope in 1862, being used previously to refer to substances that are fluids made up of solid and liquid matter. Scrope regarded rock magma as being “composed of crystalline or granular particles to which a certain mobility is given by an interstitial fluid” (Shand 1950, p. 4).

The great debate between the magmatists and metasomatists of fifty years ago, to some extent revolved around a misunderstanding of the term magma, shown by Read’s (1948) statement “The *igneous* rocks are those produced by consolidation of *magma*, which is a completely fluid rock substance”, presumably meaning completely molten. Grout (1948) at the same symposium, gave what is perhaps the pre-eminent definition of magma, stating among other criteria, that it is a natural fluid. His complete definition is given in the notes.

This misunderstanding still effects our understanding of granite evolution.



MAGMAS AND MELTS

The terms *magma* and *melt* are often regarded as the same thing by igneous petrologists, which they are not. The general term magma predates its first use in petrology by Scrope in 1862, being used previously to refer to substances that are fluids made up of solid and liquid matter. Scrope regarded rock magma as being “composed of crystalline or granular particles to which a certain mobility is given by an interstitial fluid” (Shand 1950, p. 4).

The great debate between the magmatists and metasomatists of fifty years ago, to

Grout’s (1948, p. 46) definition of magma:

Magma is defined as a natural fluid in or on the Earth, generally very hot, made up largely of a mutual solution of silicates, with some oxides, sulfides, and water, held in solution be pressure; the water may reduce the viscosity of a fluid, but heat is the main factor in its fluidity. The term magma may properly include fluids in which crystals may be residual from melting, or in process of growth, so long as the amount of solid matter does not give the aggregate notable rigidity.

On the same page, Grout also gives what is the best definition of *granitisation*.

Grout, F.F. 1948. Origin of granite. *In* Gilluly, J. (ed.) *Origin of granite*, Geological Society of America Memoir **28**, 45-54.

As an example of the correct use of “magma”, the older zircon crystal in a granite that are widely accepted as crystals that have been entrained from the source are properly regarded as magmatic.

Other references:

Read, H.H. 1948. Granites and granites. *In* Gilluly, J. (ed.) *Origin of granite*, Geological Society of America Memoir **28**, 1-19.

Shand, S.J. 1950. *Eruptive rocks* (4th ed.). Murby, London.

THE CRITICAL MELT FRACTION

A *magma* ceases to be a magma when the fraction of solid material increases to the point that a solid framework of crystals develops which no longer permits its free movement, and it ceases to be a fluid. In reverse, what can be termed a *migma*, becomes a *magma* when the fraction of melt increases to that fluid proportion. This transition was studied experimentally by van der Molen & Paterson (1979), who defined a *critical melt fraction* (CMF) to separate framework-controlled flow behaviour from suspension-like behaviour, which occurs at approximately 30 to 35% melt. Arzi (1978) referred to the same melt fraction as the “rheological critical melt percentage”.

Rushmer (1995) has used the CMF in a different sense, to refer to “the minimum amount of melt needed before it can effectively segregate”. This different usage of what is a very useful term is unfortunate, and was probably driven by the widely held perception that all granite magmas are extracted from their source rocks as pure melts (e.g. Clemens & Mawer, 1992), so that the previous definition can be considered irrelevant. Studies such as those of Rushmer (1995) and Clemens & Mawer (1992) are concerned with an important end-member in the spectrum of granite magmas, which overall may contain any fraction of melt between the CMF and 100%. There is abundant evidence that the other extreme case in which the whole mass initially moves bodily as a crystal-rich magma, once the restite framework is broken at the CMF, is also important.

THE CRITICAL MELT FRACTION

A *magma* ceases to be a magma when the fraction of solid material increases to the point that a solid framework of crystals develops which no longer permits its free movement, and it ceases to be a fluid. In reverse, what can be termed a *migma*, becomes a *magma* when the fraction of melt increases to that fluid proportion. This transition was studied experimentally by van der Molen & Paterson (1979), who defined a *critical melt fraction* (CMF) to separate framework-controlled flow behaviour from suspension-like behaviour, which occurs at approximately 30 to 35% melt. Arzi (1978) referred to the same melt fraction as the "rheological critical melt percentage".

Rushmer (1995) has used the CMF in a different sense, to refer to "the minimum amount of melt needed before it can effectively segregate". This different usage of what is a very useful term is unfortunate, and was probably driven by the widely held perception that all granite magmas are extracted from their source rocks as pure melts (e.g. Clemens & Mawer, 1992), so that the previous definition can be considered irrelevant. Studies such as those of Rushmer (1995) and Clemens & Mawer (1992) are

van der Molen, I. & Paterson, M.S. (1979). Experimental deformation of partially-melted granite. *Contributions to Mineralogy and Petrology* **70**, 299-318.

Arzi, A.A. 1978. Critical phenomena in the rheology of partially melted rocks. *Tectonophysics*, **44**, 173-184.

Rushmer, T. (1995). An experimental deformation study of partially molten amphibolite: application to low melt fraction segregation. *Journal of Geophysical Research* **100**, 15681-15695.

Clemens, J.D. & Mawer, C.K. 1992. Granitic magma transport by fracture propagation. Tectonophysics **204**, 339-360.

1. MAGMA MIXING/MINGLING

Magma mixing or mingling is an attractive and extremely popular mechanism for explaining some features of granites and for producing compositional variations within suites of granites.

The term *mixing* refers to "the homogenisation of melt phases and the conversion of any pre-existing crystals to minerals stable in the hybrid melt, or their armouring by stable minerals" (Vernon, 1983). Mingling is a combination of two components where they retain some of their identity, such as the case of basalt mingling with a granite magma to produce mafic enclaves. However, the term mixing has frequently, and incorrectly, been used in an inclusive way in the literature.

A current widely accepted model for magma mingling (e.g. Barbarin, 1991) envisages melt from the mantle partly melting the crust as it crystallises and cools. The two components then mingle to produce a range of rock compositions.

Vernon, R.H., 1983. Restite, xenoliths and microgranitoid enclaves in granites. *Journal and Proceedings of the Royal Society of New South Wales* **116**, 77-103.

Barbarin, B., 1991. Enclaves of the Mesozoic calc-alkaline granitoids of the Sierra Nevada Batholith, California. In: Didier, J. & Barbarin, B. (eds) *Enclaves and Granite Petrology*. Amsterdam: Elsevier, pp. 135-153.

EVIDENCE CITED IN SUPPORT OF MAGMA MIXING/MINGLING

- **Volcanic and subvolcanic rocks**. Composite lavas are produced by the simulataneous eruption of felsic and more mafic magmas at many volcanic centres. Tephra comprising an intimate mixture of two or more contrasting compositions of magma are a common feature of felsic pyroclastic deposits, again pointing to the presence of liquids (Sparks *et al*., 1977).
- **Mafic enclaves**. There is a general view that the widespread mafic or microgranular enclaves represent the product of quenching of basaltic liquid by an I-type granite magma. A summary of the arguments supporting that view has been given by Zorpi *et al*. (1989)
- **Local hybrids**. There are numerous descriptions of hybrid rocks that are mixtures of felsic and mafic material that could be interpreted as magma mingling, e.g. at Tuross Head by Vernon *et al*. (1988)
- **Linear patterns of chemical variation**. These are clearly suggestive of magma mixing or mingling, and have been widely so interpreted. For example, Wall *et al*. (1987) stated that “mixing is the classic cause of linear variation in major and trace element Harker diagrams”.
- **Isotope variations**. These are sometimes cited as evidence of mixing, e.g. by Gray (1984) who argued from variations in initial ^{87}Sr/^{86}Sr values in granites of the LFB, that basaltic material and granitic melt derived from the Ordovician sedimentary rocks had mixed to produce all the granitic rocks, ranging from hornblende tonalites to cordierite granodiorites.

See Chappell (1996) for a fuller discussion of the above.

EVIDENCE CITED IN SUPPORT OF MAGMA MIXING/MINGLING

- **Volcanic and subvolcanic rocks**. Composite lavas are produced by the simulataneous eruption of felsic and more mafic magmas at many volcanic centres. Tephra comprising an intimate mixture of two or more contrasting compositions of magma are a common feature of felsic pyroclastic deposits, again pointing to the presence of liquids (Sparks *et al*., 1977).
- **Mafic enclaves**. There is a general view that the widespread mafic or microgranular enclaves represent the product of quenching of basaltic liquid by an I-type granite magma. A summary of the arguments supporting that view has been given by Zorpi *et al*. (1989)
- **Local hybrids**. There are numerous descriptions of hybrid rocks that are mixtures of felsic and mafic material that could be interpreted as magma mingling, e.g. at Tuross Head by Vernon *et al*. (1988)
- **Linear patterns of chemical variation**. These are clearly suggestive of magma mixing or

Sparks, R.S.J., Sigurdsson, H. & Wilson, L., 1977. Magma mixing: a mechanism for triggering acid explosive eruptions. *Nature* **267**, 315-318.

Zorpi, M.J., Coulon, C., Orsini, J.B. & Cocirta, C., 1989. Magma mingling, zoning and emplacement in calc-alkaline granitoid plutons. *Tectonophysics* **157**, 315-329.

Vernon, R.H., Etheridge, M.A. & Wall, V.J., 1988. Shape and microstructure of microgranitoid enclaves: indicators of magma mingling and flow. *Lithos* **22**, 1-11.

Wall, V.J., Clemens, J.D. & Clarke, D.B., 1987. Models for granitoid evolution and source comp-ositions. *Journal of Geology* **95**, 731-749.

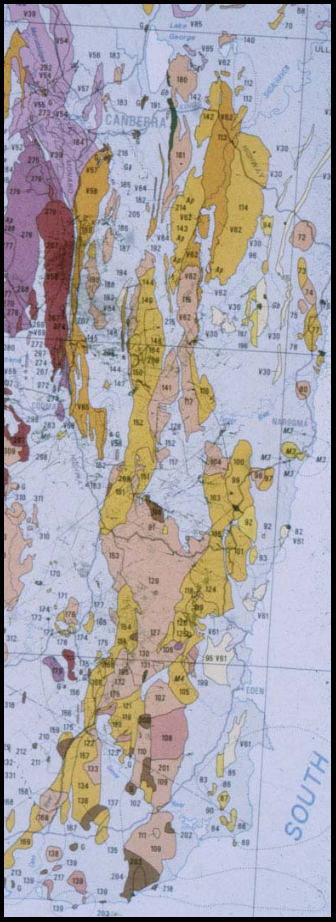
Gray, C.M., 1984. An isotopic mixing model for the origin of granitic rocks in southeastern Australia. *Earth and Planetary Science Letters* **70**, 47-60.

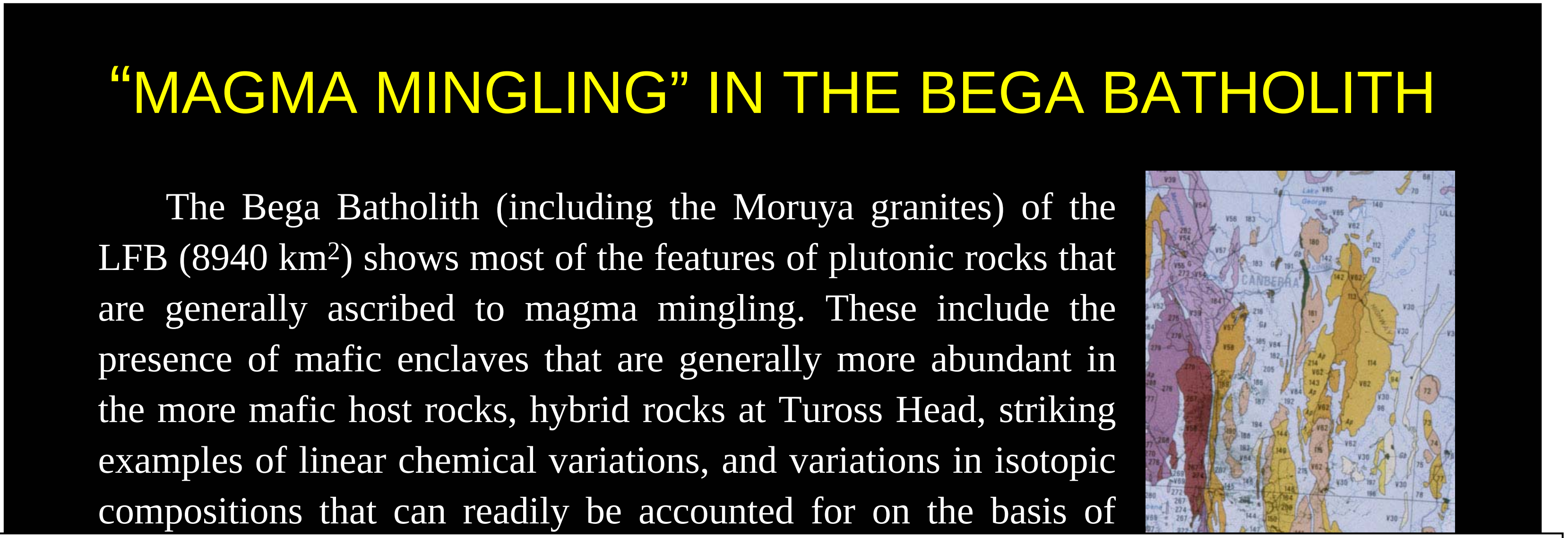
“MAGMA MINGLING” IN THE BEGA BATHOLITH

The Bega Batholith (including the Moruya granites) of the LFB (8940 km^2) shows most of the features of plutonic rocks that are generally ascribed to magma mingling. These include the presence of mafic enclaves that are generally more abundant in the more mafic host rocks, hybrid rocks at Tuross Head, striking examples of linear chemical variations, and variations in isotopic compositions that can readily be accounted for on the basis of mixing of various end-member compositions.

However, the rocks of this batholith show compositional features that are not consistent with the variation within suites having been produced in that way.

The following figures show some of the features that point to magma mingling and those that effectively exclude it as a possible mechanism for producing the major variations in compositions within the suites of this large batholith.





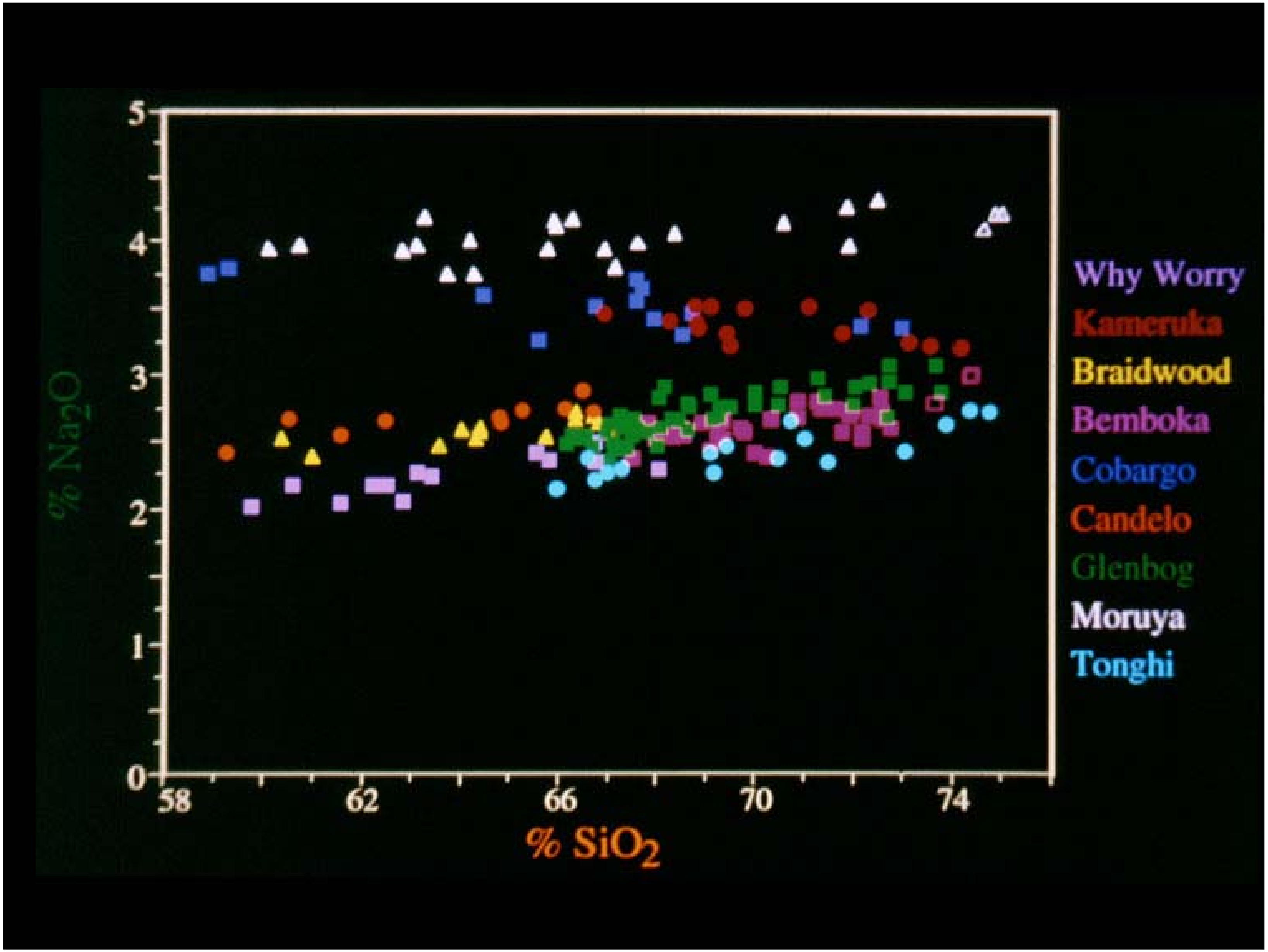
"MAGMA MINGLING" IN THE BEGA BATHOLITH

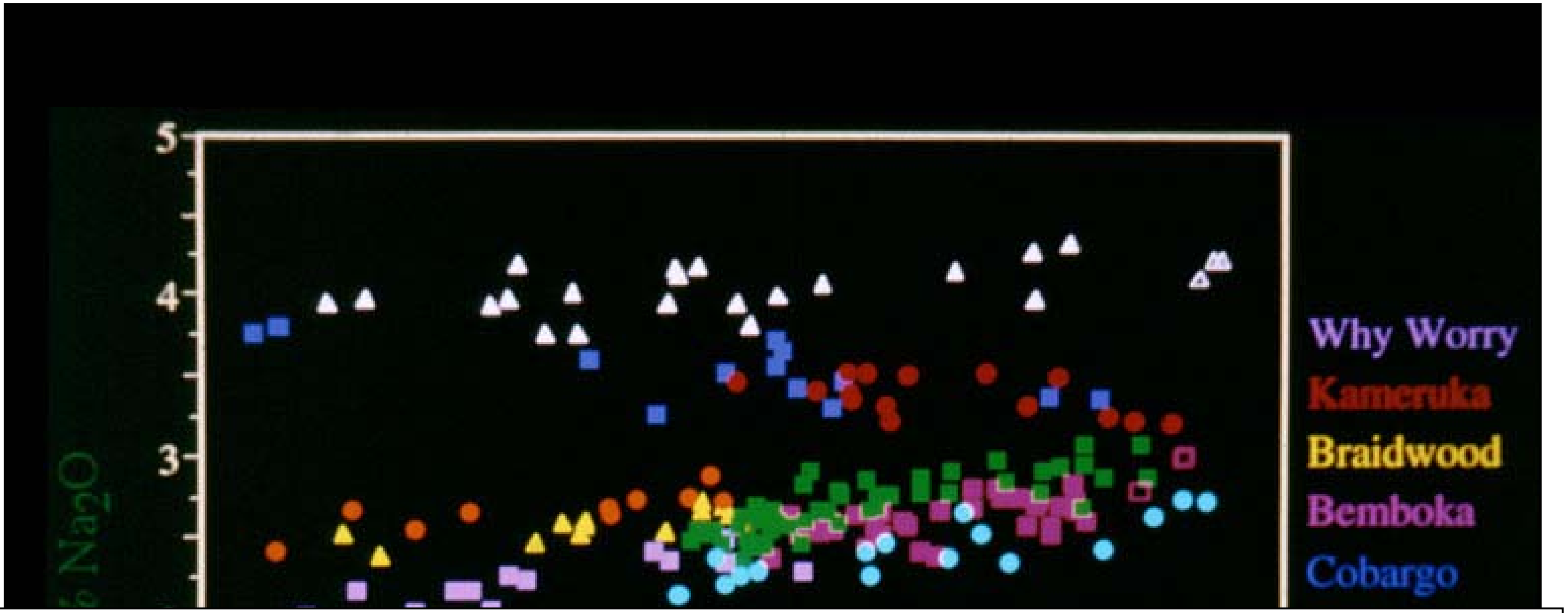
The Bega Batholith (including the Moruya granites) of the LFB (8940 km^2) shows most of the features of plutonic rocks that are generally ascribed to magma mingling. These include the presence of mafic enclaves that are generally more abundant in the more mafic host rocks, hybrid rocks at Tuross Head, striking examples of linear chemical variations, and variations in isotopic compositions that can readily be accounted for on the basis of

Vernon *et al*. (1988) described an example of magma mingling in the Tuross Head Tonalite, part of the Moruya Suite whose chemical variation will be consid-ered below. They noted that rocks of that suite show linear geochemical variations which had been interpreted by Griffin *et al*. (1978) as a type example of restite unmixing, but they pointed out that linear geo-chemical trends could also result from mixing bet-ween two magmas. They later state that the widespread mingling at Tuross Head is strong evidence against res-tite unmixing for producing the different magma batches at that locality.

Vernon, R.H., Etheridge, M.A. & Wall, V.J., 1988. Shape and microstructure of microgranitoid enclaves: indicators of magma mingling and flow. *Lithos* **22**, 1-11.

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.

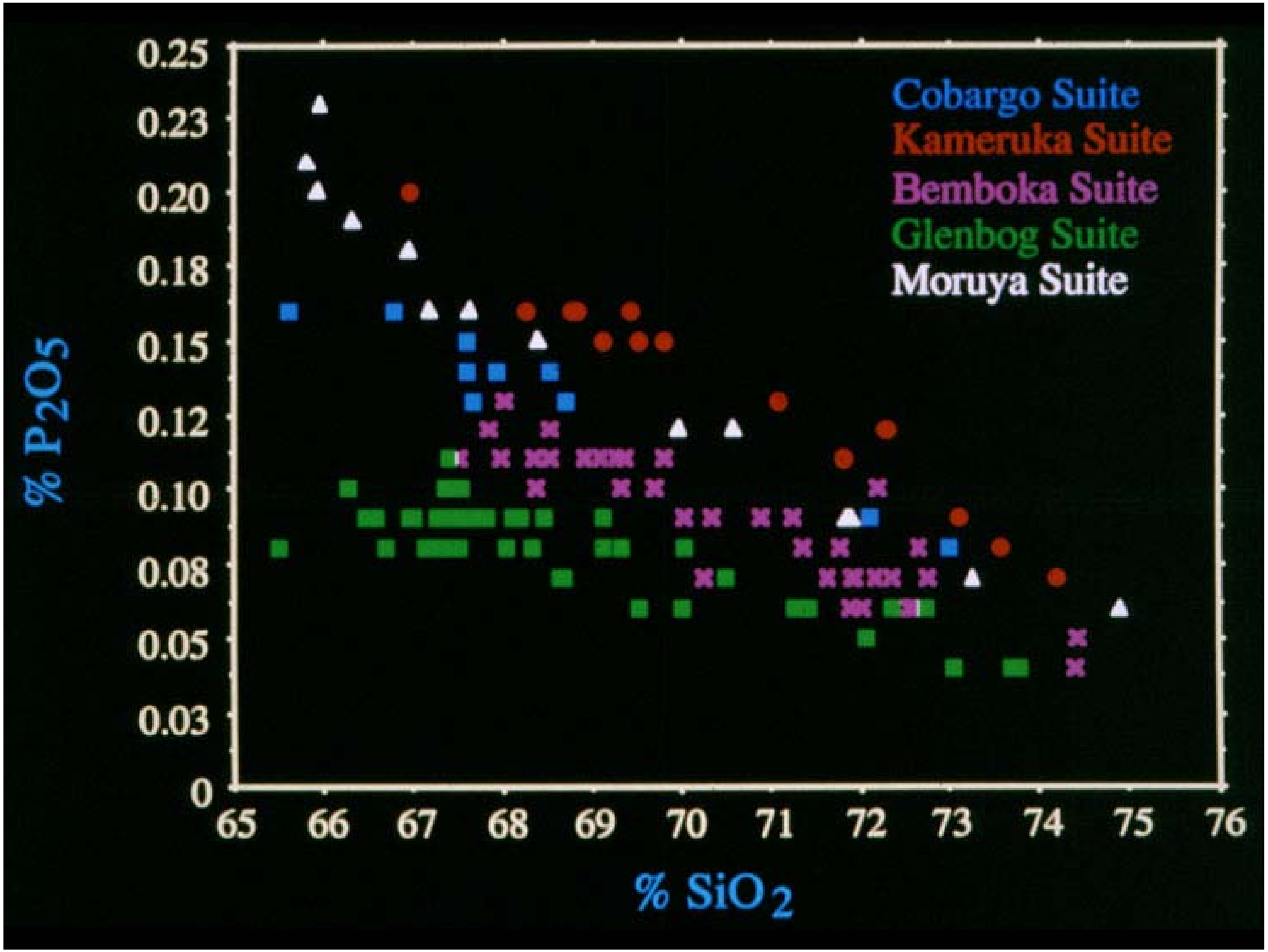

5
4
3
2
1
0
% Na2O
58
62
66
70
74
% SiO2
Why Worry
Kameruka
Braidwood
Bemboka
Cobargo
Candelo
Glenbog
Moruya
Tonghi

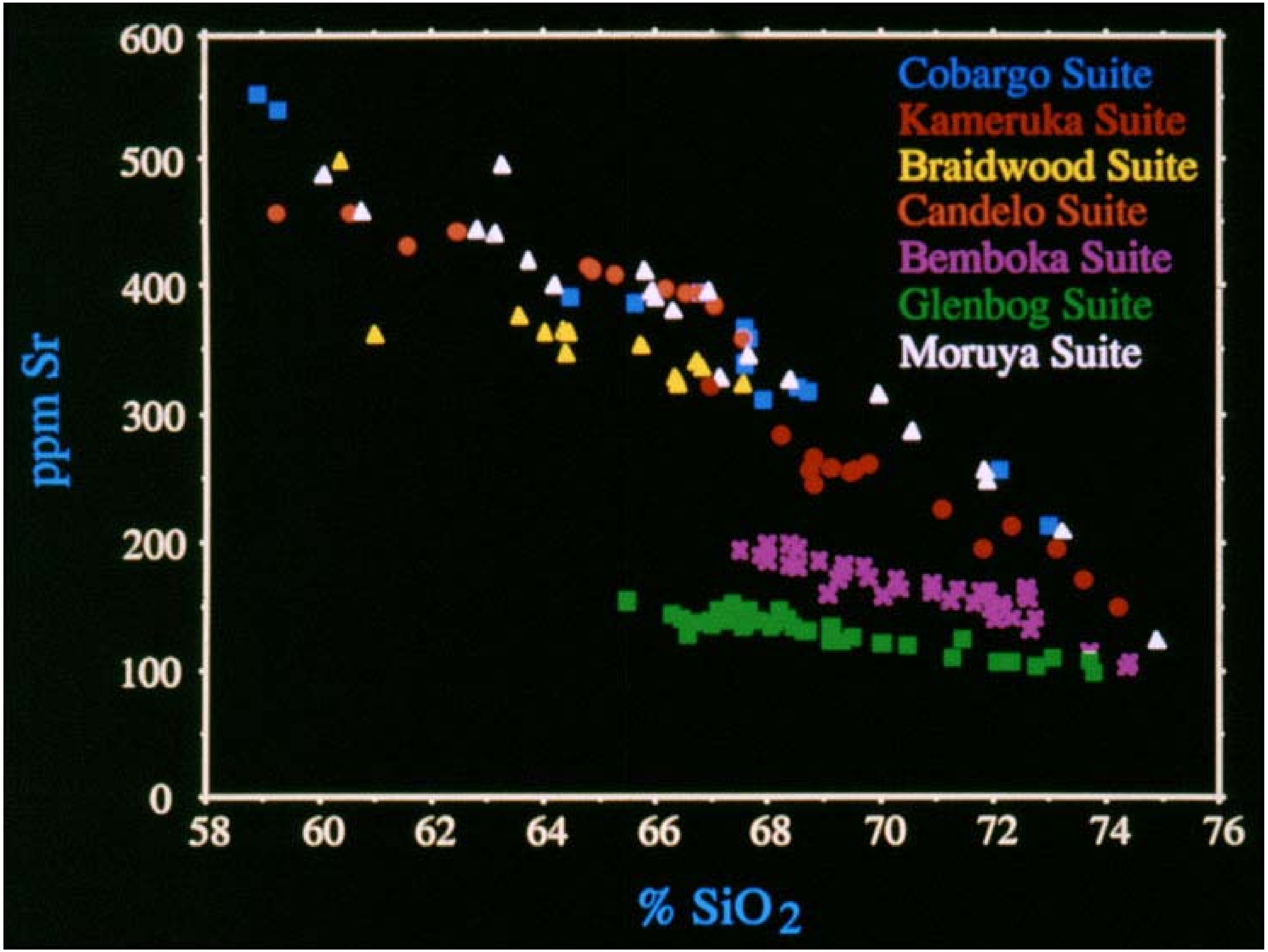


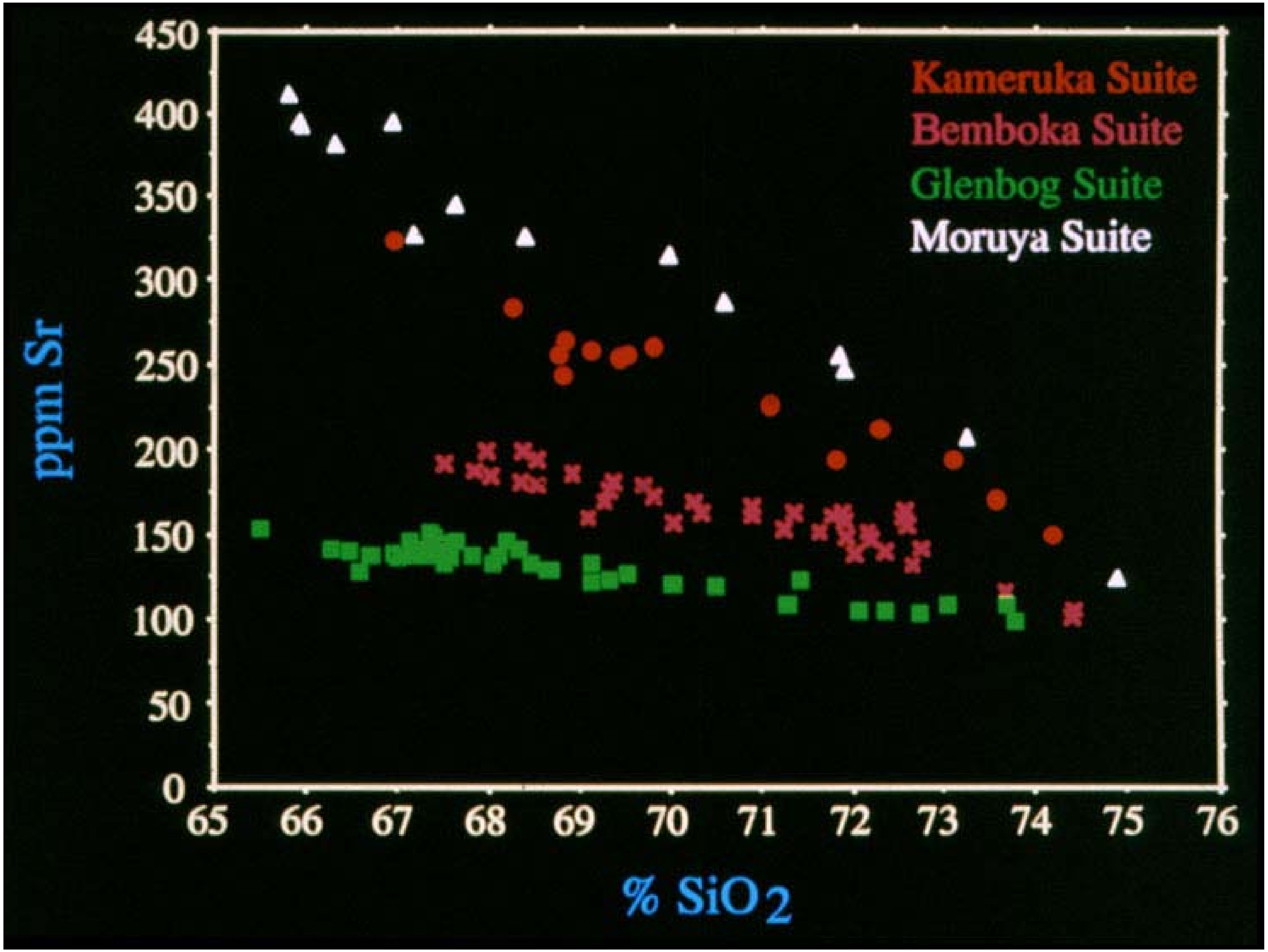
Refer to this and the following diagrams.

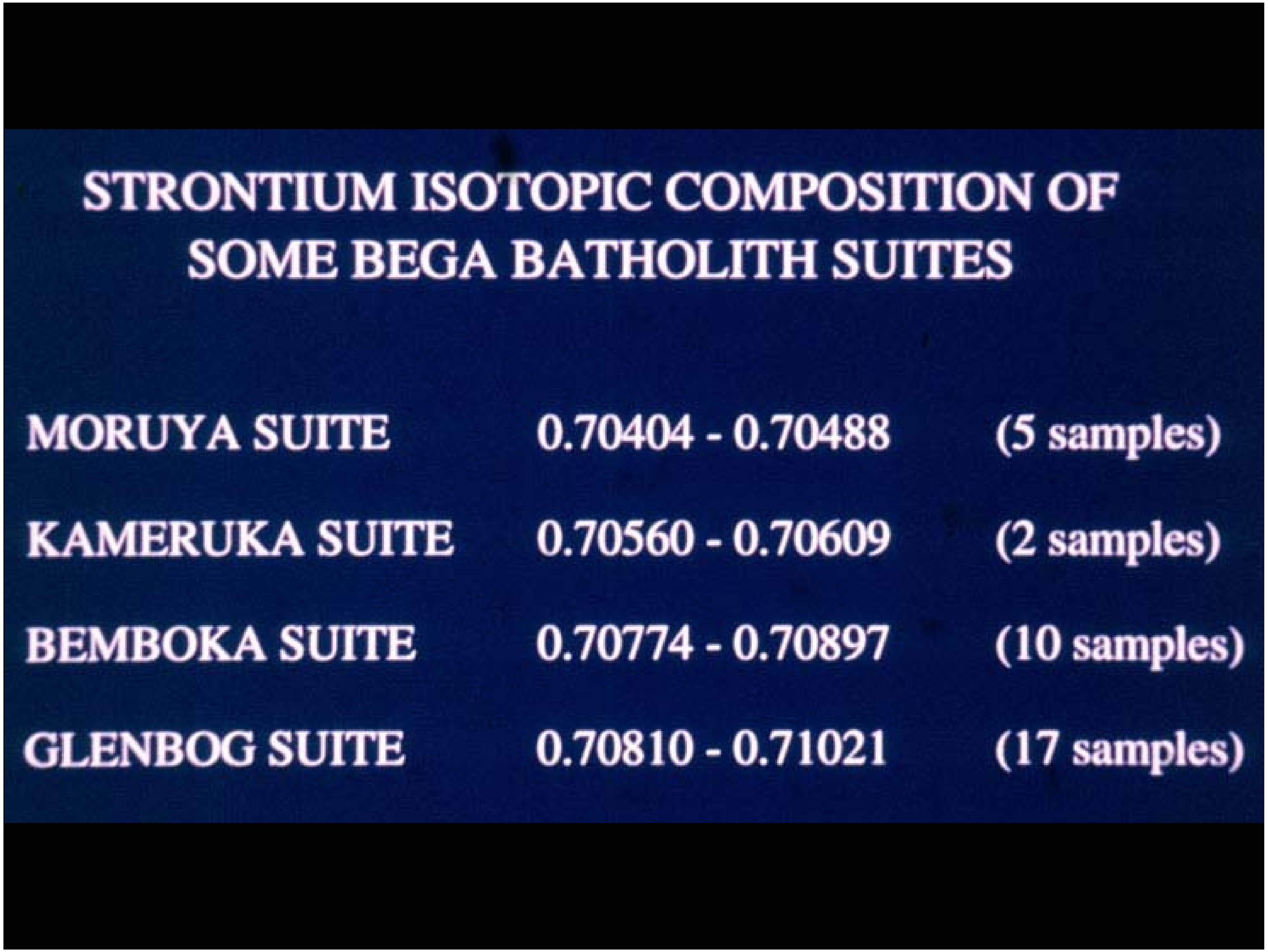
When the compositions of pairs of suites are compared, any differences seen at either end of the range in composition are also seen at the other limit, so that both the most mafic and felsic rocks show similar relative abundances of particular elements (Chappell, 1996). The probability that mafic and felsic end-member components would so consistently choose mixing/mingling partners that share their particular compositional features relative to other mixing pairs is so small that it can be rejected.

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.


Cobargo Suite
Kameruka Suite
Bemboka Suite
Glenbog Suite
Moruya Suite
% P2O5
0.25
0.23
0.20
0.18
0.15
0.12
0.10
0.08
0.05
0.03
0
65
66
67
68
69
70
71
72
73
74
75
76
% SiO2


600
500
400
300
200
100
0
58
60
62
64
66
68
70
72
74
76
ppm Sr
% SiO2
Cobargo Suite
Kameruka Suite
Braidwood Suite
Candelo Suite
Bemboka Suite
Glenbog Suite
Moruya Suite


Kameruka Suite
Bemboka Suite
Glenbog Suite
Moruya Suite
ppm Sr
% SiO2
450
400
350
300
250
200
150
100
50
0
65
66
67
68
69
70
71
72
73
74
75
76



STRONTIUM ISOTOPIC COMPOSITION OF SOME BEGA BATHOLITH SUITES

MORUYA SUITE	0.70404 - 0.70488	(5 samples)
KAMERUKA SUITE	0.70560 - 0.70609	(2 samples)
BEMBOKA SUITE	0.70774 - 0.70897	(10 samples)
GLENBOG SUITE	0.70810 - 0.71021	(17 samples)

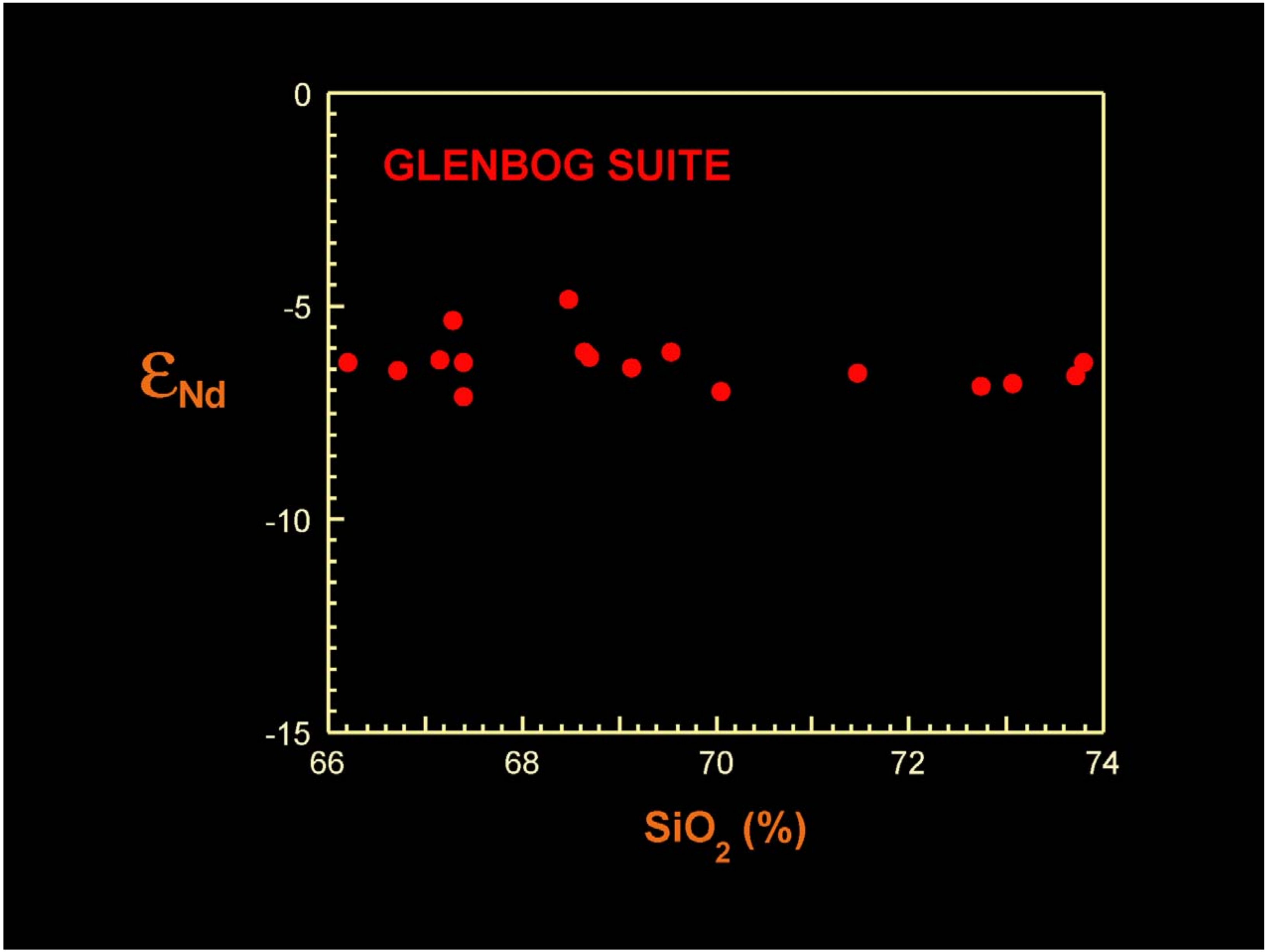
STRONTIUM ISOTOPIC COMPOSITION OF SOME BEGA BATHOLITH SUITES

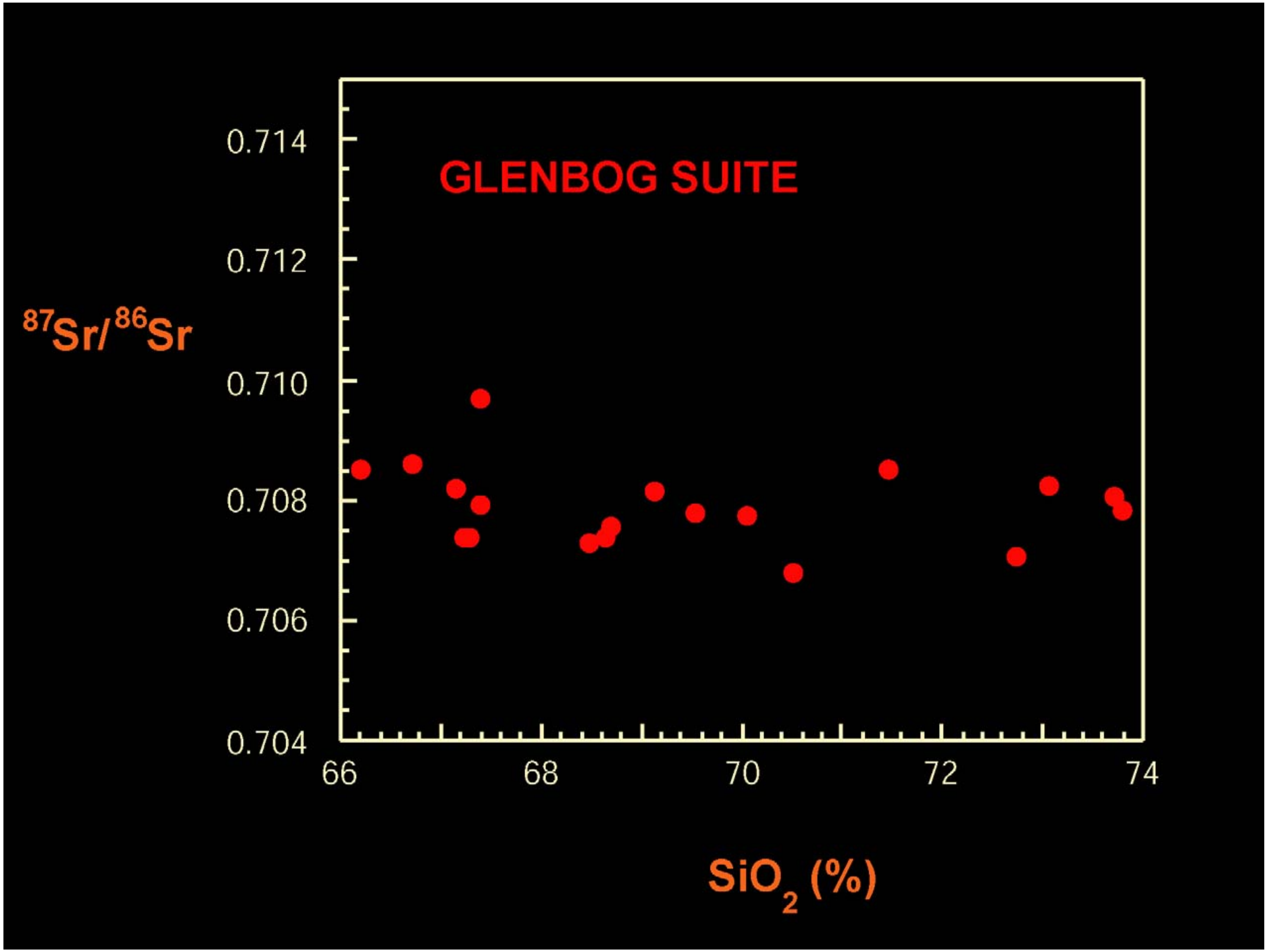
MORUYA SUITE 0.70404 - 0.70488 (5 samples)

While the rocks of the Bega Batholith show isotopic compositions that could be produced by mixing of discrete end-members (e.g. Keay *et al*., 1997), the isotopic variations within suites are relatively small and not of a type that would have been produced by the mixing of more isotopically evolved crust with more primitive mantle-derived components (Chappell & McCulloch, 1990).

Chappell, B.W. & McCulloch, M.T., 1990. Possible mixed source rocks in the Bega Batholith: constraints provided by combined chemical and isotopic studies. *Seventh International Conference on Geochronology, Cosmochronology and Isotope Geology, Geological Society of Australia, Abstracts* **27**, 17.

See also the two following diagrams.


GLENBOG SUITE
0
-5
-10
-15
εNd
66
68
70
72
74
SiO2 (%)


GLENBOG SUITE
87Sr/86Sr
0.714
0.712
0.710
0.708
0.706
0.704
66
68
70
72
74
SiO2 (%)

MAGMA MIXING/MINGLING: A CONCLUDING STATEMENT

Much of the evidence in favour of magma mixing and mingling refers to phenomena that have been documented only on a small scale (mixed volcanic rocks and hybrid plutonic rocks), or can be interpreted according to alternative models (linear chemical variation), may not be relevant to the associated granites, or could be interpreted differently (enclaves), or have been presented generally without supporting evidence from, and may be in conflict with, chemical variations (isotopic changes).

It is concluded that this is not a significant process in producing the compositional variations seen in large bodies of granite. “For all their eye-catching display in outcrop, mingling and mixing in the higher levels of the crust represent but second-order processes in the diversification of the granitic rocks” (Pitcher, 1993, p. 136).

We can conclude by quoting from Harker (1909, p. 359), who stated “Finally, it should be remarked that, when admixture takes place, it belongs to a late stage in the genetic history of a rock-magma, either to the epoch of intrusion (or extrusion) or to the time immediately following that. Any peculiar variety of rock which may result does not make a starting-point for the elaboration of new varieties. In short, like other hybrids, these *hybrid rocks are barren”*.

These comments refer strictly to compositional variations within rock suites and do not necessarily apply to the question of mixed source rocks for granites of the LFB – see notes.

MAGMA MIXING/MINGLING:
A CONCLUDING STATEMENT

Much of the evidence in favour of magma mixing and mingling refers to phenomena that have been documented only on a small scale (mixed volcanic rocks and hybrid plutonic rocks), or can be interpreted according to alternative models (linear chemical variation), may not be relevant to the associated granites, or could be interpreted differently (enclaves), or have been presented generally without supporting evidence from, and may be in conflict with, chemical variations (isotopic changes).

It is concluded that this is not a significant process in producing the compositional

Pitcher, W.S., 1993. *The Nature and Origin of Granite*. Blackie Academic & Profes-sional, Glasgow, 321 pp.

Harker, A., 1909. *The Natural History of Igneous Rocks*. Methuen, London, 384 pp.

These arguments and such a conclusion apply to variations within granite suites of the LFB, but are not directly applicable to the question of the granites having been derived from mixed source rocks, as has been proposed by Gray (1984, 1990), Collins (1996) and Keay *et al*. (1997). Since considerations of such broader scale mixing processes are not relevant to the questions of compositional variations within suites of granites, they are not part of this present discussion, and we be considered later.

Collins, W.J. 1996. Lachlan Fold Belt granitoids: products of three-component mixing: Transactions of the Royal Society of Edinburgh: Earth Sciences **87**, 171-26.

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.

Gray, C.M. 1990. A strontium isotopic traverse across the granitic rocks of southeastern Australia: petrogenetic and tectonic implications. *Australian Journal of Earth Sciences* **37**, 331-349.

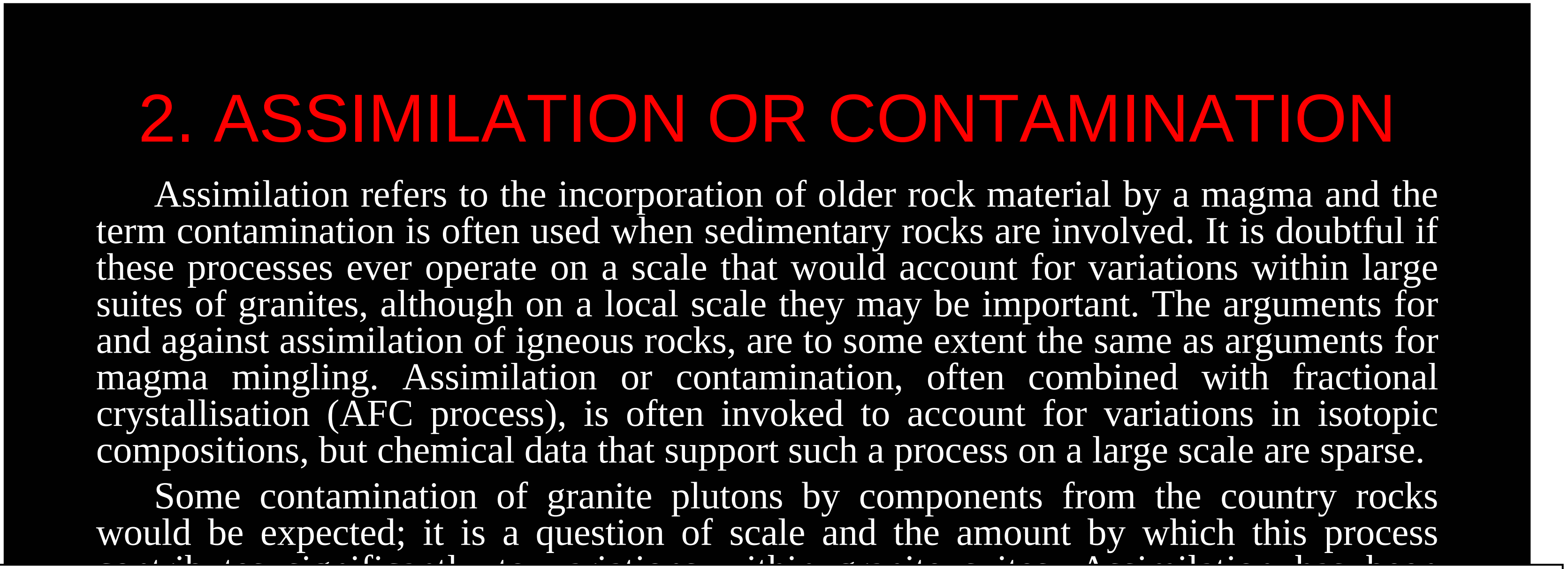
Keay, S., Collins, W.J. & McCulloch, M.T. 1997. A three-component Sr-Nd isotopic mixing model for granitoid genesis, Lachlan fold belt, eastern Australia. *Geology* **25**, 307-310.

2. ASSIMILATION OR CONTAMINATION

Assimilation refers to the incorporation of older rock material by a magma and the term contamination is often used when sedimentary rocks are involved. It is doubtful if these processes ever operate on a scale that would account for variations within large suites of granites, although on a local scale they may be important. The arguments for and against assimilation of igneous rocks, are to some extent the same as arguments for magma mingling. Assimilation or contamination, often combined with fractional crystallisation (AFC process), is often invoked to account for variations in isotopic compositions, but chemical data that support such a process on a large scale are sparse.

Some contamination of granite plutons by components from the country rocks would be expected; it is a question of scale and the amount by which this process contributes significantly to variations within granite suites. Assimilation has been detected using Sr isotopes in the Boggy Plain pluton (34 km^2) (see notes). Even in this most favourable case of a relatively hot and initially completely molten magma intruded into sedimentary rocks, the amount of assimilation was very small, and did not contribute significantly to the overall compositional variation.

The presence of cordierite in some granites of the LFB, has long been recognised, most notably by Baker (1940), who favoured an origin by assimilation of argillaceous country rock. With the recognition of the I- and S-type Chappell & White (1974), is has become generally accepted that cordierite in the S-type granites is either a product of the process that lead to partial melting of the source rocks (e.g. Chappell *et al*., 1987), or else precipitated from melts that acquired a strongly peraluminous composition during the partial melting of sedimentary source materials (Clemens & Wall, 1981).



2. ASSIMILATION OR CONTAMINATION

Assimilation refers to the incorporation of older rock material by a magma and the term contamination is often used when sedimentary rocks are involved. It is doubtful if these processes ever operate on a scale that would account for variations within large suites of granites, although on a local scale they may be important. The arguments for and against assimilation of igneous rocks, are to some extent the same as arguments for magma mingling. Assimilation or contamination, often combined with fractional crystallisation (AFC process), is often invoked to account for variations in isotopic compositions, but chemical data that support such a process on a large scale are sparse.

Some contamination of granite plutons by components from the country rocks would be expected; it is a question of scale and the amount by which this process

In the Boggy Plain pluton, the initial $^{87}Sr/^{86}Sr$ ratios increase from an average of 0.70441 in the marginal diorites and the granodiorites (29% of area), to an average of 0.70479 in the monzogranites (70%), to 0.70554 in one sample from the central aplitic rocks (0.9%) (Wyborn, 1983).

Baker, G. 1940. Cordierite granite from Terip Terip, Victoria. *American Mineralogist* **25**, 543-548.

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

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.

Clemens, J.D. & Wall, V.J. (1981). Origin and crystallization of some peraluminous (S-type) granitic magmas. *Canadian Mineralogist* **19**, 111-131.

Wyborn, D. (1983). Fractionation processes in the Boggy Plain zoned pluton. Ph.D. Thesis, The Australian National University.

FRACTIONATION AND CRYSTAL FRACTIONATION

The term *fractionation* is frequently used to refer to processes by which the abundances of elements are changed, for example in the purification of a compound in the laboratory. It can be applied to the natural processes that change the chemical compositions of various components of the Earth, including igneous rocks such as granites. In general, the term fractionation refers to any process by which material of a particular composition is broken up into two or more parts with contrasting compositions. Particularly with igneous rocks, the analogous term *differentiation* is often used.

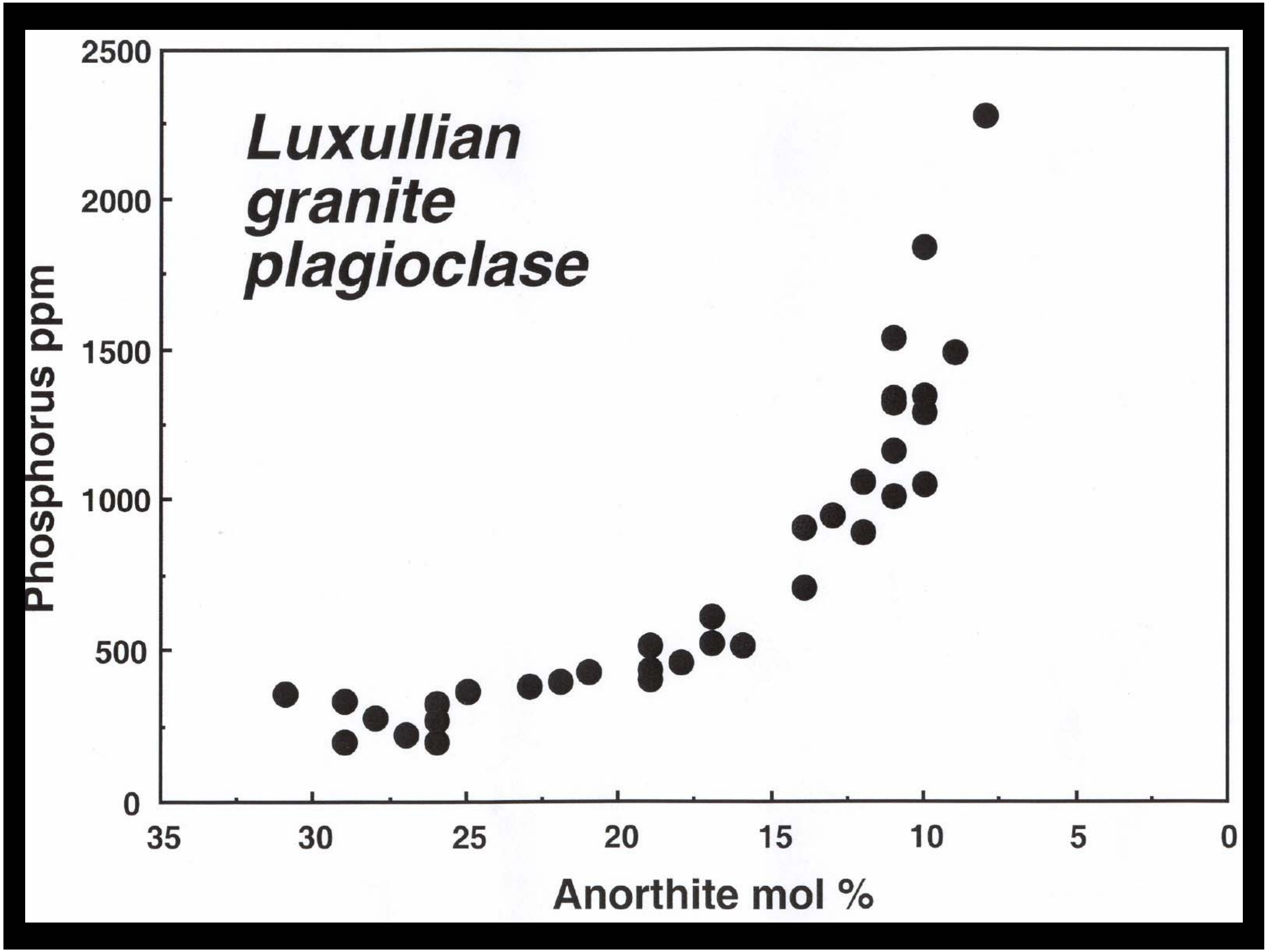
One example of fractionation is that of the removal of crystals from a mixture of crystals and liquid with a certain bulk composition, which changes that composition. This also results in a new composition comprising the removed crystals probably mixed with some melt. The original mixture has been *fractionated* into two different compositions. This mechanism of *crystal fractionation* is the most common way by which the compositions of igneous rocks evolve. One case is *fractional crystallisation* in which the crystals that are removed to concentrate elsewhere were precipitated from the melt. Alternatively, the crystals that are removed could have been entrained in the magma at its source.

Wilson, M., 1993. Magmatic differentiation. *Journal of the Geological Society* **150**, 611-624.

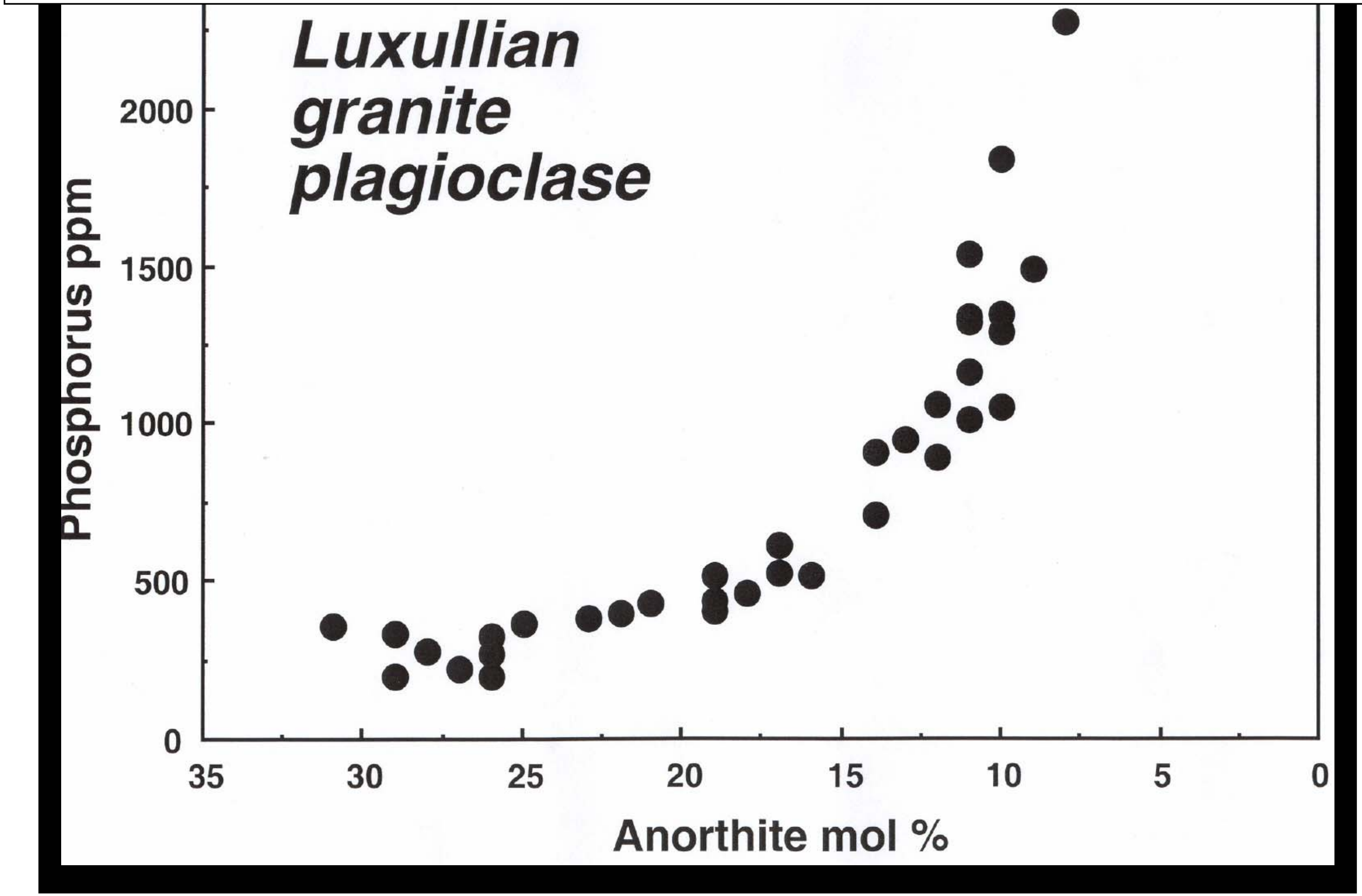
3. FRACTIONAL CRYSTALLISATION

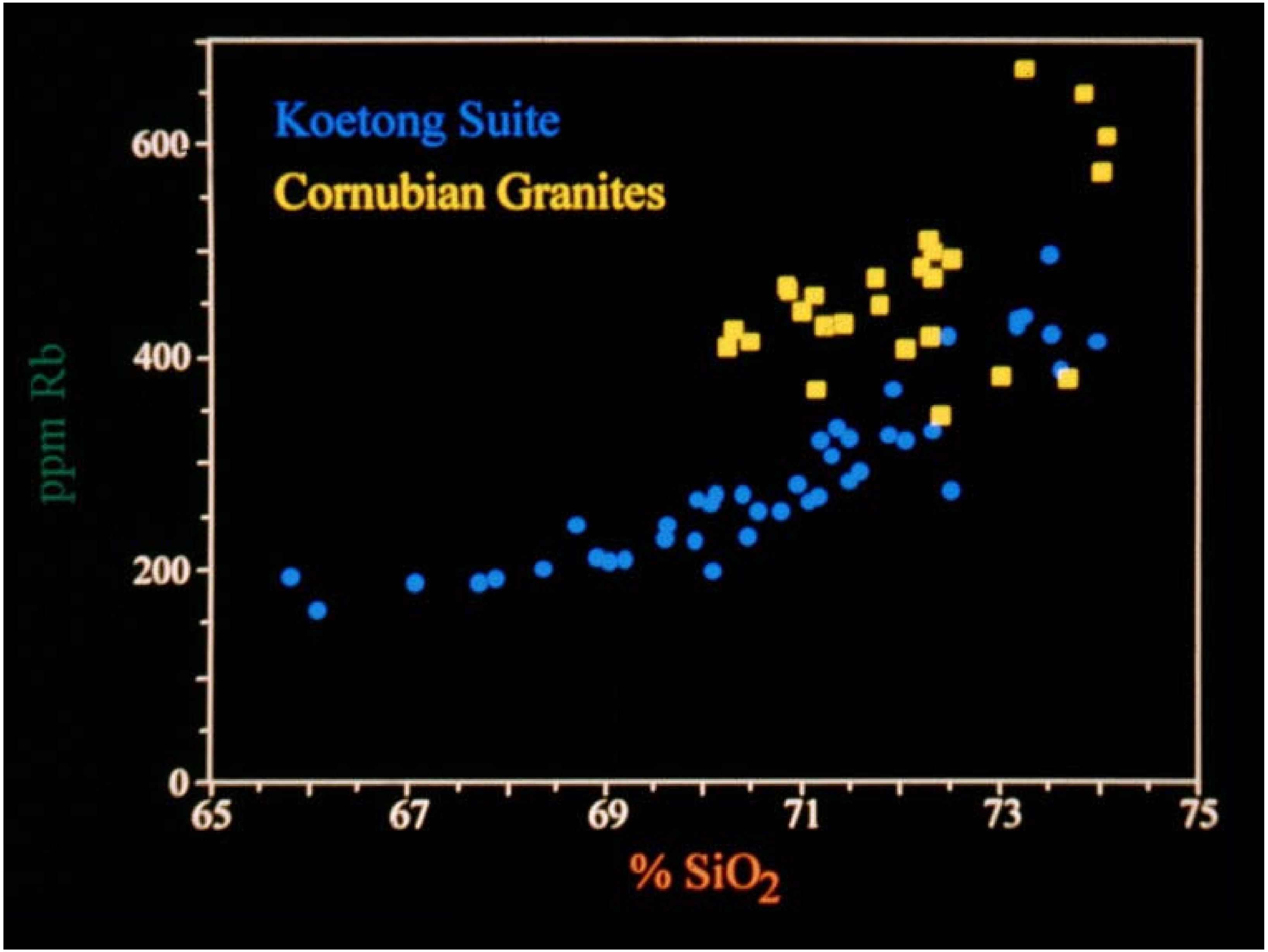
- The bulk composition of crystals precipitating from a solution differs from that of the solution
- If these crystals are removed after they form, then the composition of the solution changes progressively
- This *fractional crystallisation* has long been used to purify crystals
- The important exception is the case of a eutectic solution, e.g. the Tuttle & Bowen minimum-temperature melt (for the major components)
- Marie Curie separated 100 mg of $RaCl_2$ from 2000 kg of pitchblende, $RaSO_4$ being less soluble than $BaSO_4$ – this was a 25% recovery of pure Ra
- Darwin observed the concentration of olivine crystals in a basaltic dyke
- Becker (1897) introduced the term fractional crystallisation into petrology
- A single zoned crystal is a good simple example
- Normally used in petrology to describe the progressive evolution of melts, e.g. in a series of lavas – N.L. Bowen's *liquid line of descent*
- But the complementary cumulate or cumulative rocks must also occur, and for plutonic rocks this is a possibility that must be considered

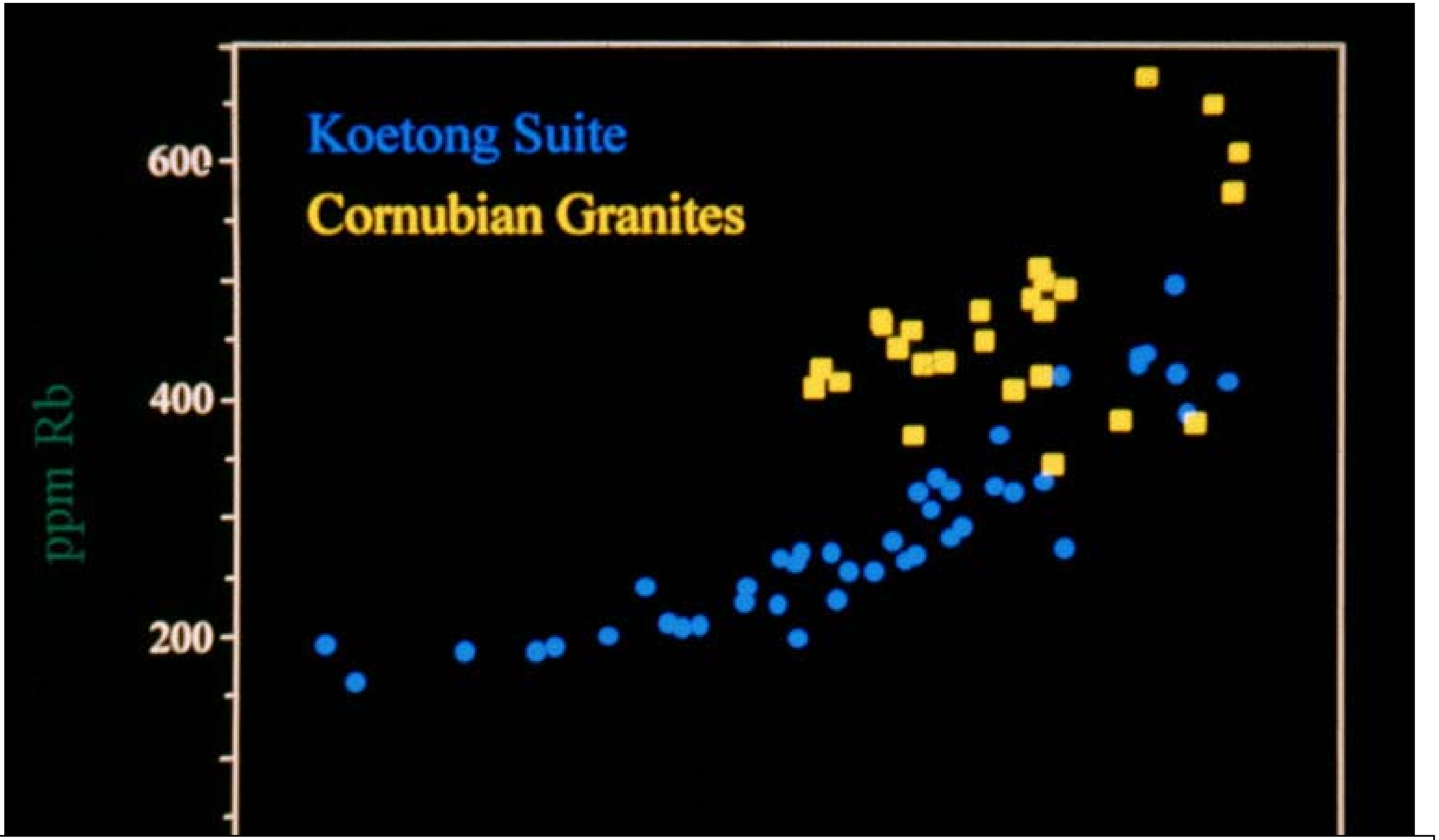
Becker, G.F. (1897). Fractional crystallization of rocks. *American Journal of Science* FOURTH SERIES **4**, 257-261.


Luxullian
granite
plagioclase
Phosphorus ppm
2500
2000
1500
1000
500
0
35
30
25
20
15
10
5
0
Anorthite mol %

These data were measured on a sample of Cornish granite from the Luxullian Quarry and show how the P contents of the plagioclase increase in the outer more Na-rich zones of the plagioclase crystals.




Koetong Suite
Cornubian Granites
ppm Rb
600
400
200
0
65
67
69
71
73
75
% SiO$_2$



Above about 69% SiO_2 the Rb contents of the Koetong Suite of the Wagga Batholith increase progressively due to fractional crystallisation. A comparison with the granites of the Cornubian Batholith of SW England, for this and other elements, when combined with the observation that those rocks have compositions matching the Tuttle & Bowen minimum temperature compositions very precisely, shows that those rocks formed in the same way.

BOWEN’S LIQUID LINE OF DESCENT

When crystals are precipitated from a melt, the composition of that melt will normally change. Those crystals may then be mechanically separated from the melt, which will change progressively in composition. The products of such changes may be seen, for example, among the lavas erupted from a volcano. Bowen (1928) termed such a sequence of rock compositions a *liquid line of descent*. The types of changes that are typically seen in such cases are:

- Major elements such as Si K and generally Na increase in abundance
- Major elements such as Ti Fe Mg Ca decrease
- Ratios Mg/Fe Ca/Na decrease
- Trace elements such as F Rb Sn Cs W and U rise
- Trace elements such as V Cr Ni Zn Sr fall
- Some trace elements may rise or fall depending on whether or not the melt is saturated in the dominant mineral containing that element, e.g. Zr and Ba
- In some cases mineral saturation in felsic melts depends on whether the melt is I- or S-type. The most important example is apatite saturation which is a feature of felsic I-type melts (P falls) but not of the more strongly peraluminous S-type melts (P rises). The removal of monazite from S-type melts causes the abundances of Th and the LREE to fall, whereas Th increases with fractional crystallisation in the I-type melts. The HREE rise sharply with fractionation of felsic I-type melts because they are apparently not saturated in any HREE-rich mineral.

Bowen, N.L. 1928. *The Evolution of the Igneous Rocks*. Princeton University Press, Princeton, 334 pp.

CUMULATE AND CUMULATIVE ROCKS

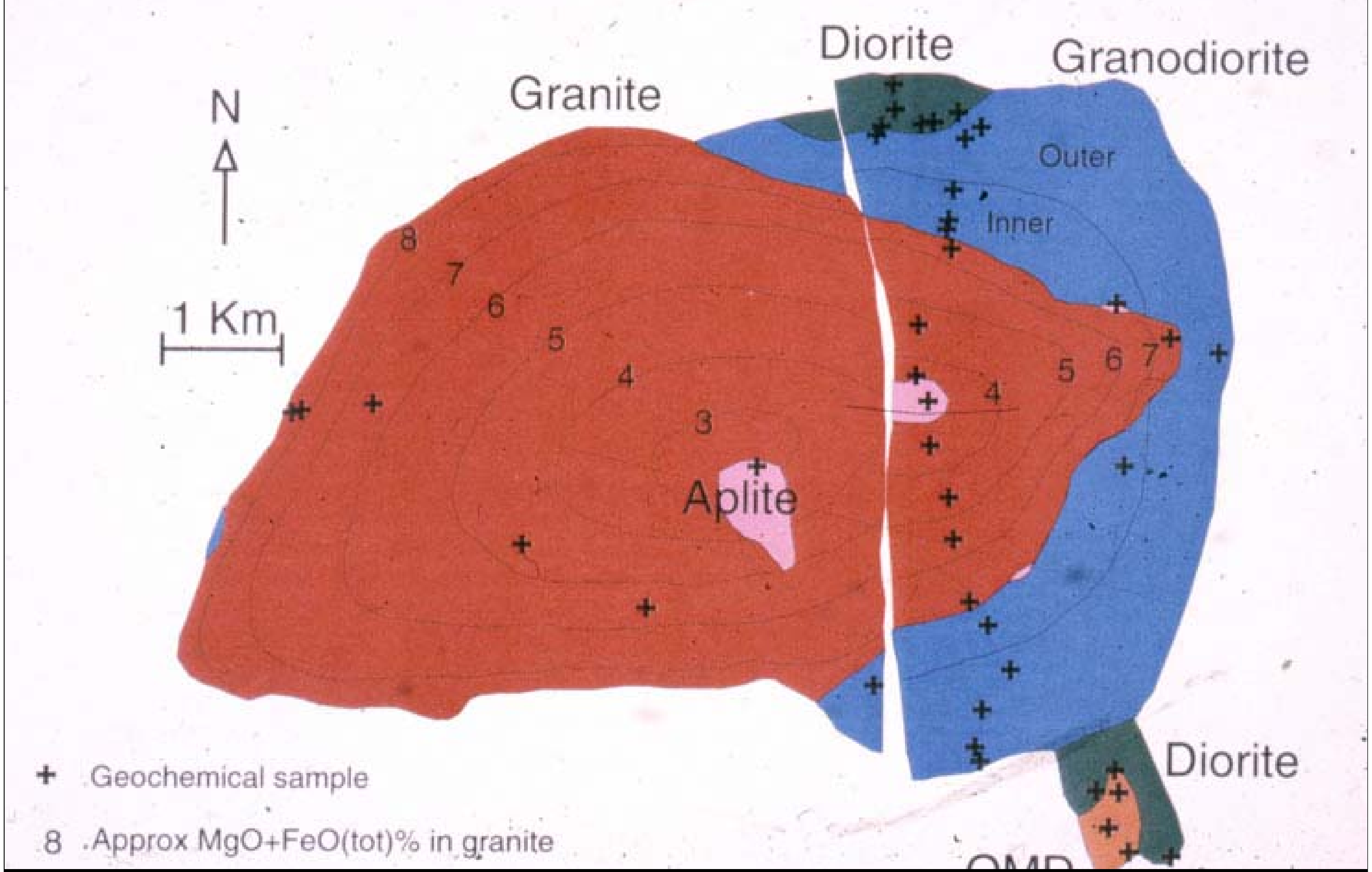
- The process of fractional crystallisation must also produce cumulative rocks, in addition to changing melt compositions.
- These rocks have compositions that vary in a much more complex way than those of rocks lying on a liquid line of descent.
- The term *cumulate* can be applied to rocks that formed from a framework of precipitated crystals and trapped interstitial melt, e.g. the rocks of most of the Boggy Plain pluton. These rocks are equivalent to the cumulate rocks formed from mafic magmas (e.g. Irvine, 1982), except that the variation is generally in a horizontal direction in granites.
- The term *cumulative* can be used to refer to rocks in which crystals have been concentrated in a melt relative to their original proportions.
- More mafic cumulate granites are characterised by very low abundances of elements contained in minerals not saturated in the melt, e.g. P Zr and Ba.
- Felsic cumulative granites contain high abundances of those elements that are removed during evolution along a liquid line of descent, e.g. Sr and Ba, with Th and the LREE in S-type granites, and conversely, e.g. low HREE in I-type granites.

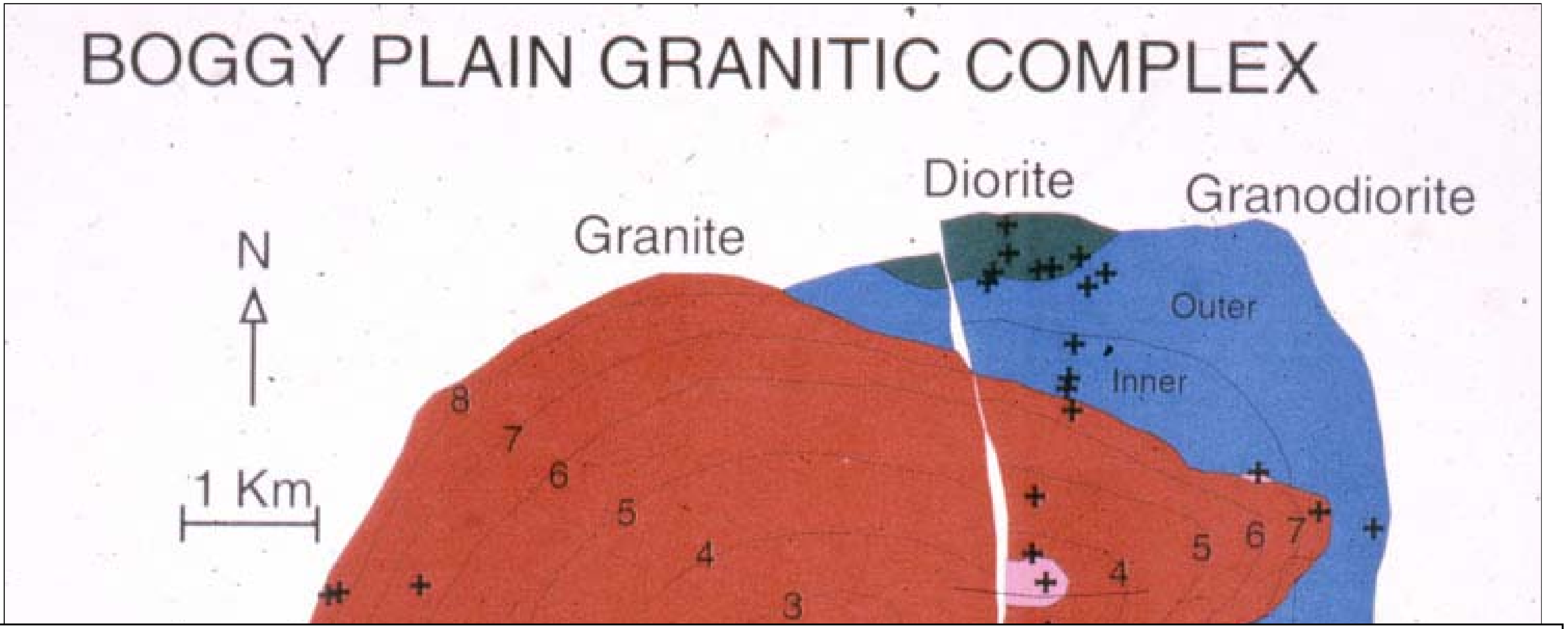
More detailed arguments against the common occurrence of cumulative and cumulate rocks in the LFB, apart from the Boggy Plain Supersuite where they are common, are given in the abstract for this meeting. We will now examine an example of cumulate rocks, in the Boggy Plain pluton from the northern part of the Kosciuszko National Park (Wyborn, 1983).

Irvine, T.N. 1982. Terminology for layered intrusions. *Journal of Petrology* 23, 127-162.

Wyborn, D. 1983. Fractionation processes in the Boggy Plain zoned pluton. Unpublished Ph.D. Thesis, The Australian National University (unpublished).

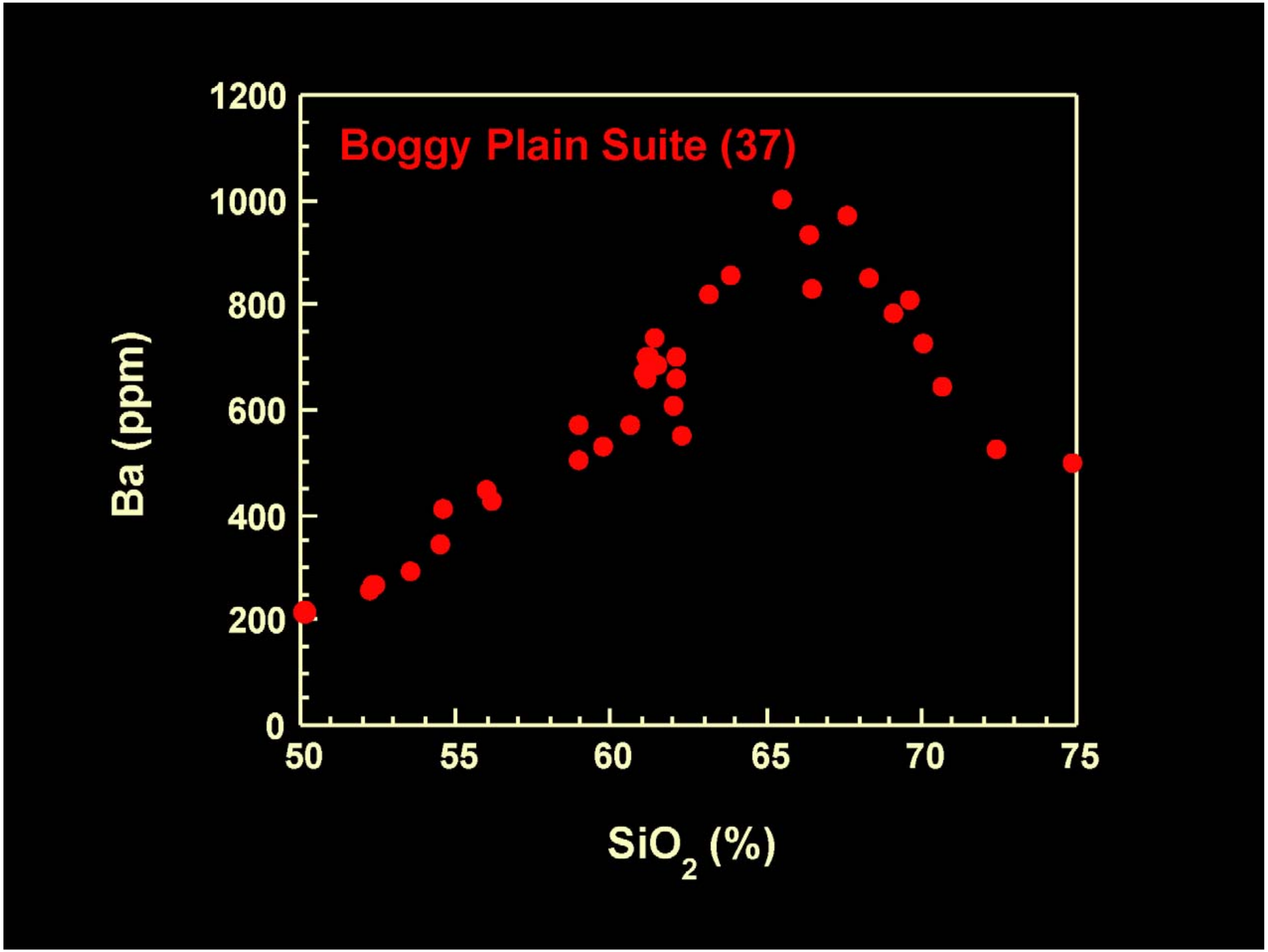
BOGGY PLAIN GRANITIC COMPLEX

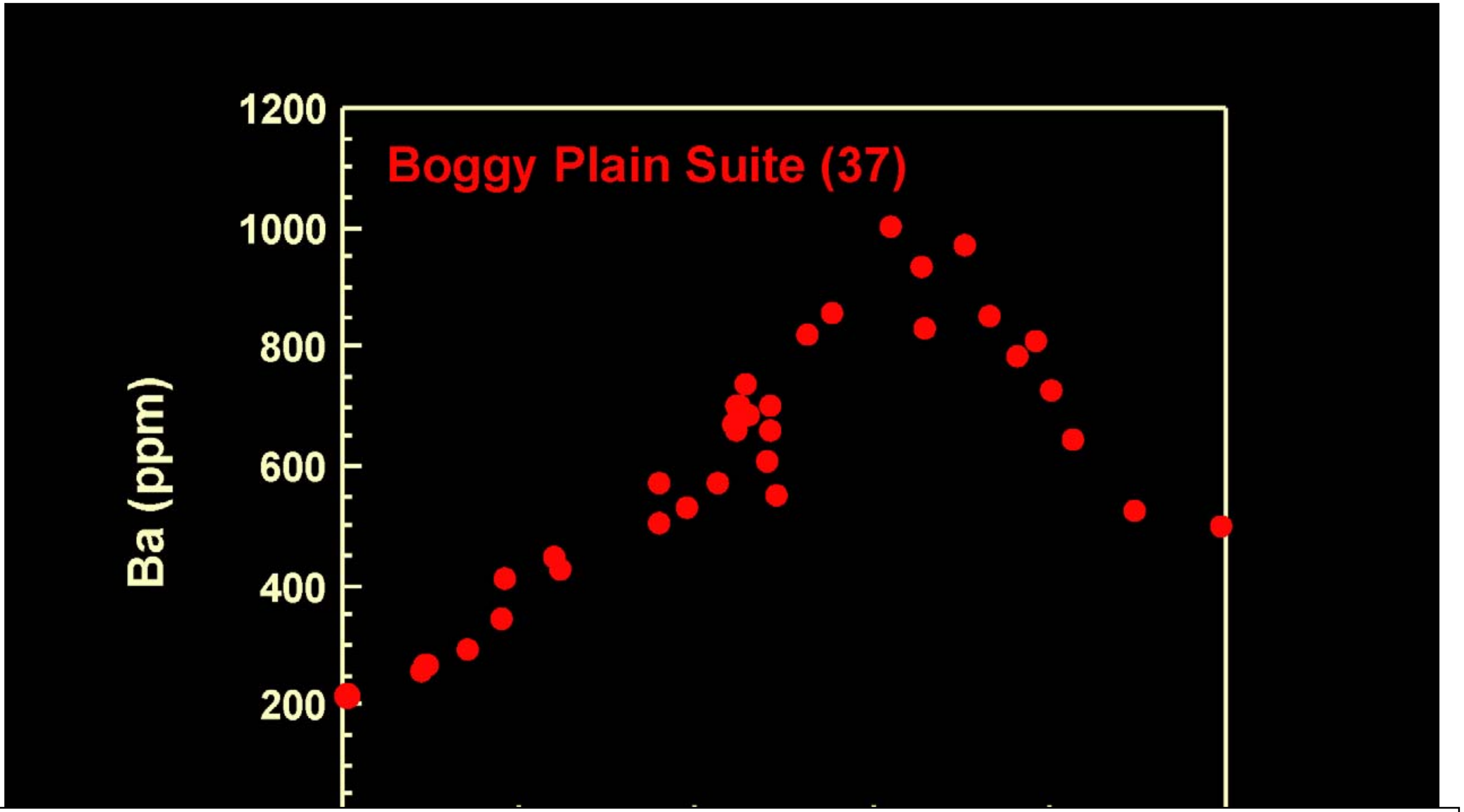




The Boggy Plain pluton is a normally zoned pluton, 34 km^2 in area, in the Kosciuszko Batholith in the northern part of the Kosciuszko National Park. It is zoned progressively from mafic rocks at the margins, through granodiorite and monzogranite, to aplitic rocks at the centre. There is one internal contact with the main body, shown as the boundary between blue and red on the map. Zoned bodies such as this are not uncommon among more potassic or "monzonitic" granites, in contrast to tonalites, that are rarely zoned. They form when the precipitating crystals nucleate at the margins of the pluton and the residual melt is displaced into the molten central parts of the body (in some cases much of the melt moves buoyantly upwards to form higher level felsic plutons and felsic volcanic rocks, but that did not happen in this case). Compositional changes in this pluton are indicated by the total MgO + FeO numbers on the map. For a general description see pp. 533-537 of Wyborn *et al*. (2001).

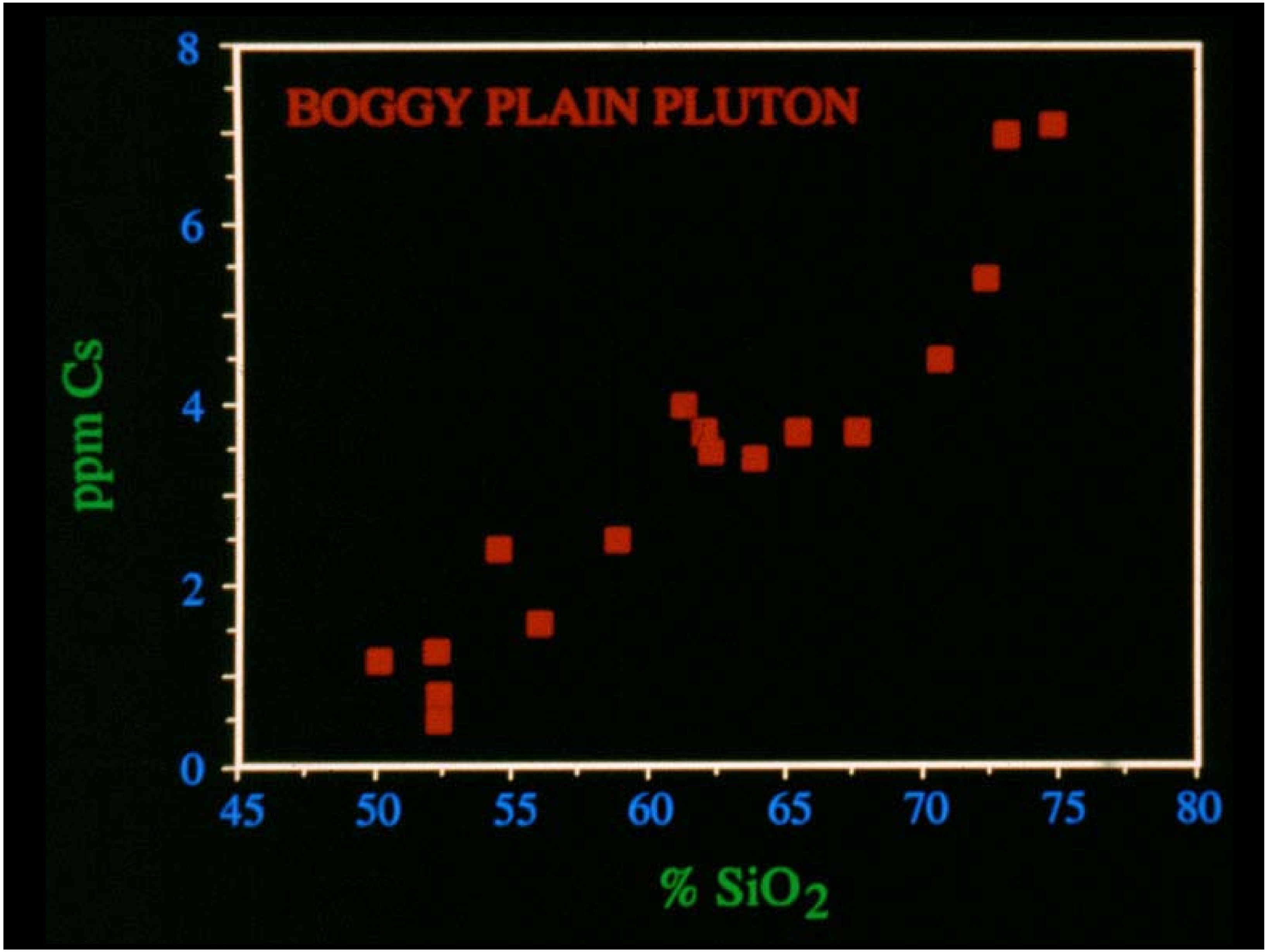
Wyborn, D., Chappell, B.W. & James, M. 2001. Examples of convective fractionation in high-temperature granites from the Lachlan Fold Belt. *Australian Journal of Earth Sciences* **48**, 531-541.

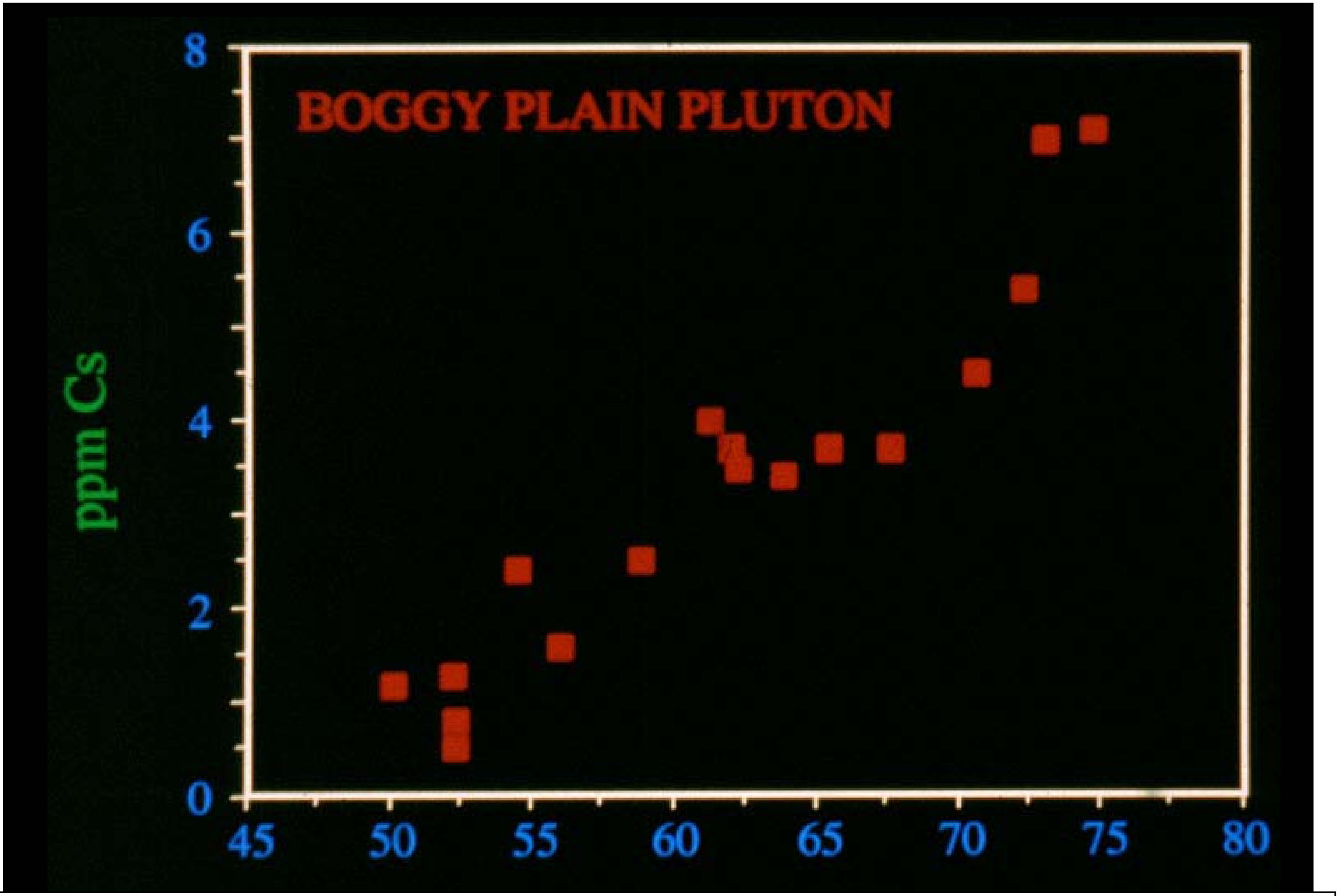

Boggy Plain Suite (37)
Ba (ppm)
1200
1000
800
600
400
200
0
50
55
60
65
70
75
SiO2 (%)



The inflection in Ba contents was apparently caused by the appearance of biotite as a liquidus phase during crystallisation of the pluton ((see p. 536 of Wyborn *et al*. (2001).

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


BOGGY PLAIN PLUTON
ppm Cs
0
2
4
6
8
45
50
55
60
65
70
75
80
% SiO$_2$



Cs increases in abundance by a factor of 10 times in the Boggy Plain pluton, as a result of fractional crystallisation.

PROBLEM OF THE “TIN GRANITES”

As another examples of fractional crystallisation we can consider the “tin granites”. These are named from their association with rich tin mineralisation, e.g. in Cornwall, Malaysia, and parts of central Europe such as the Erzgeberge. They occur in the Lachlan Fold Belt, e.g. in the Koetong Suite of the Wagga Batholith. They have in the past represented a major problem in granite petrogenesis, because of some remarkable features, which include:

- Extreme oversaturation in Al, with ~ 3-4% excess Al_2O_3 or normative corundum, so that they contain muscovite ± andalusite etc – “two-mica granites”.
- Extreme enrichments in B P Rb Sn Cs W U
- Associated with major mineralisation, e.g. 2,500,000 tonnes of Sn in Cornwall.
- Extreme heat flow in Cornwall ~ 130 mW/m^2 *vs* 60 typically in continents

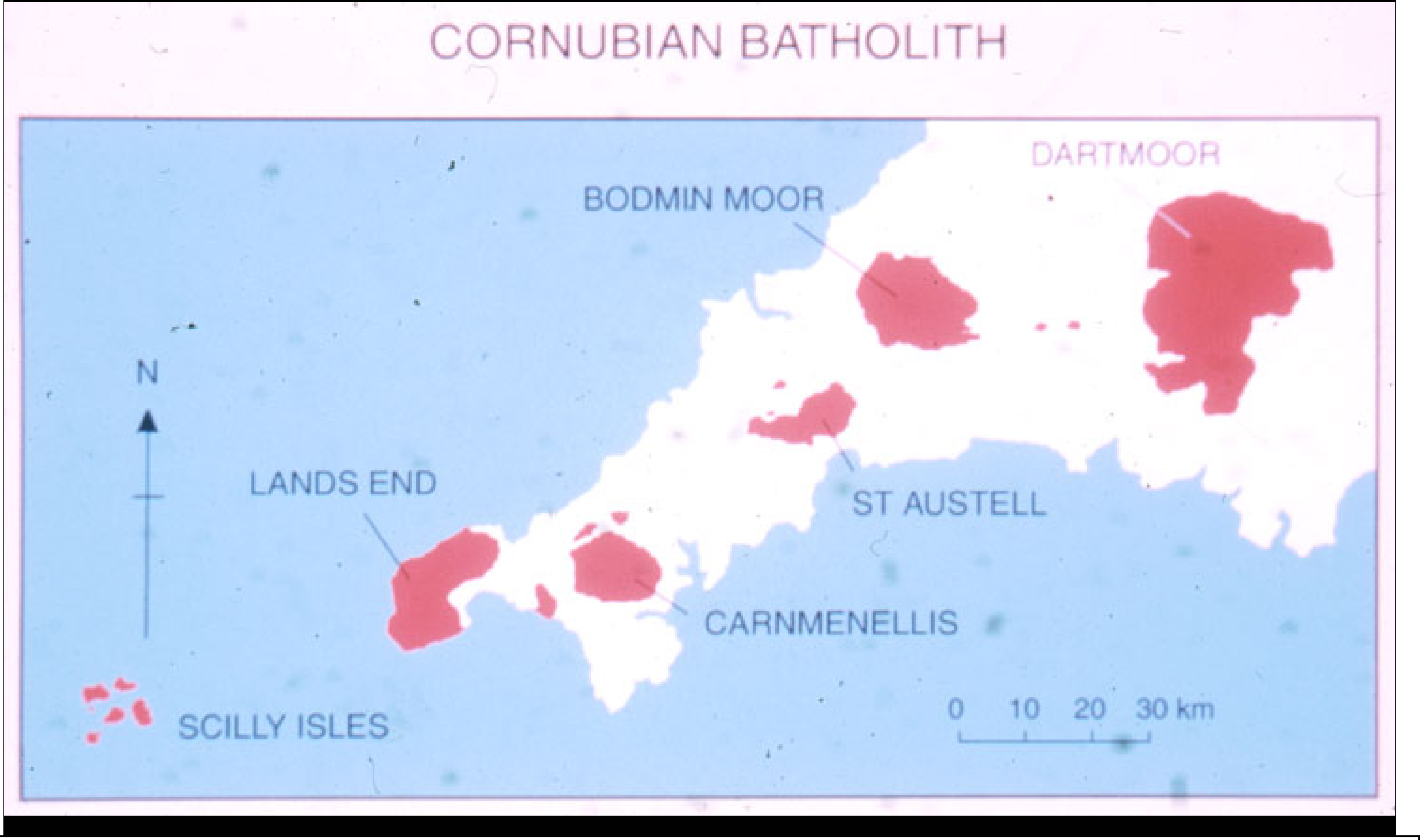
ARE THESE ROCKS MAGMATIC OR METASOMATIC?

“TIN GRANITES” - continued

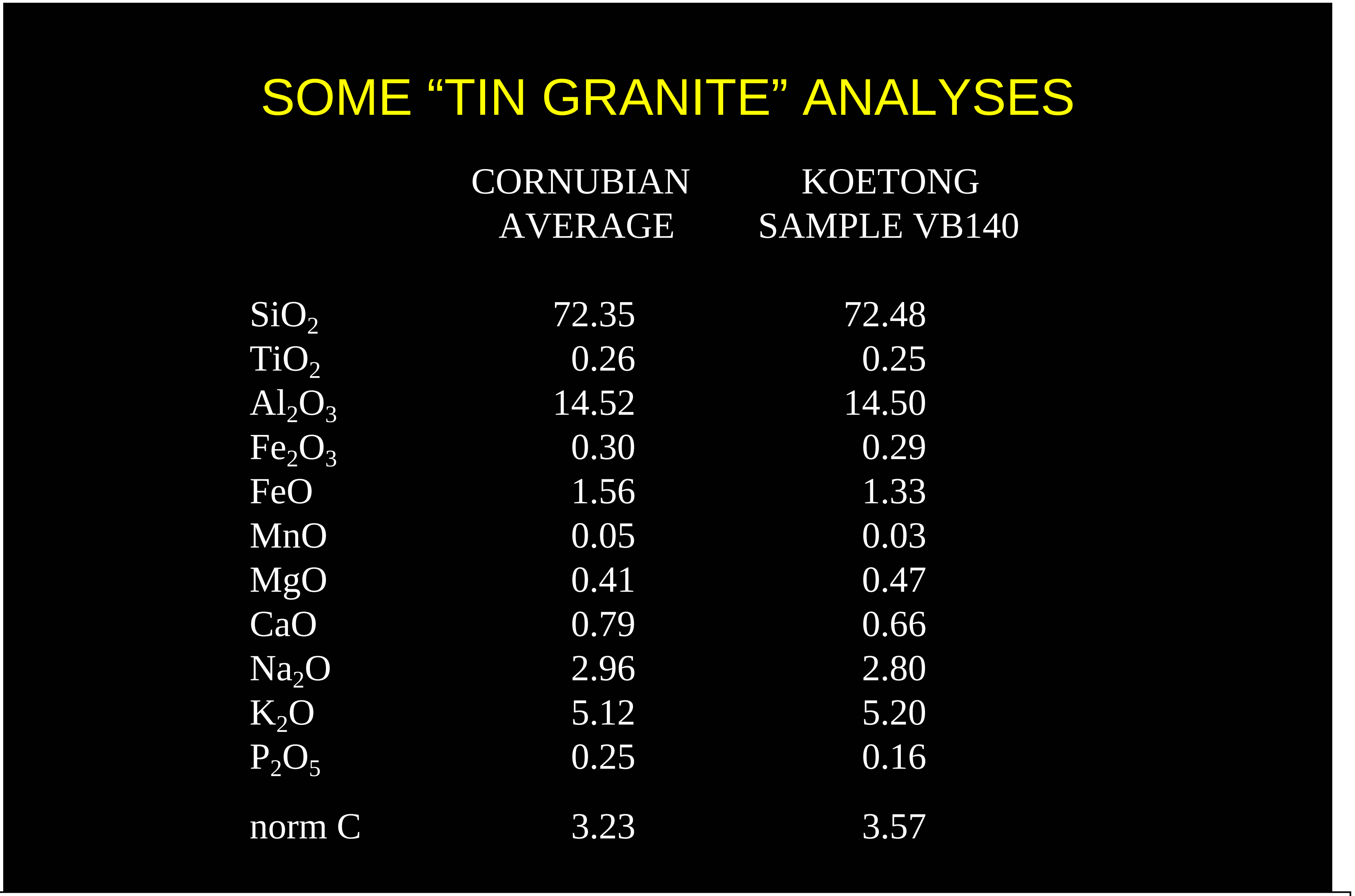
An additional problem with the “tin granites” is that they are not generally associated with less felsic granites. For example, among the classic “tin granites” of Devon and Cornwall, the range in SiO_2 contents is from 70% to 74%. However, in the Lachlan Fold Belt, the “tin granites” of the Koetong Suite lie towards the more felsic end of a continuously varying suite of rocks that range from 66% to 74% SiO_2. That occurrence provides an opportunity to examine the origin of these rocks in more detail.

CORNUBIAN BATHOLITH

This batholith comprises six plutons that extend along the Cornubian Peninsula of SW England to the offshore occurrence of the Isles of Scilly.



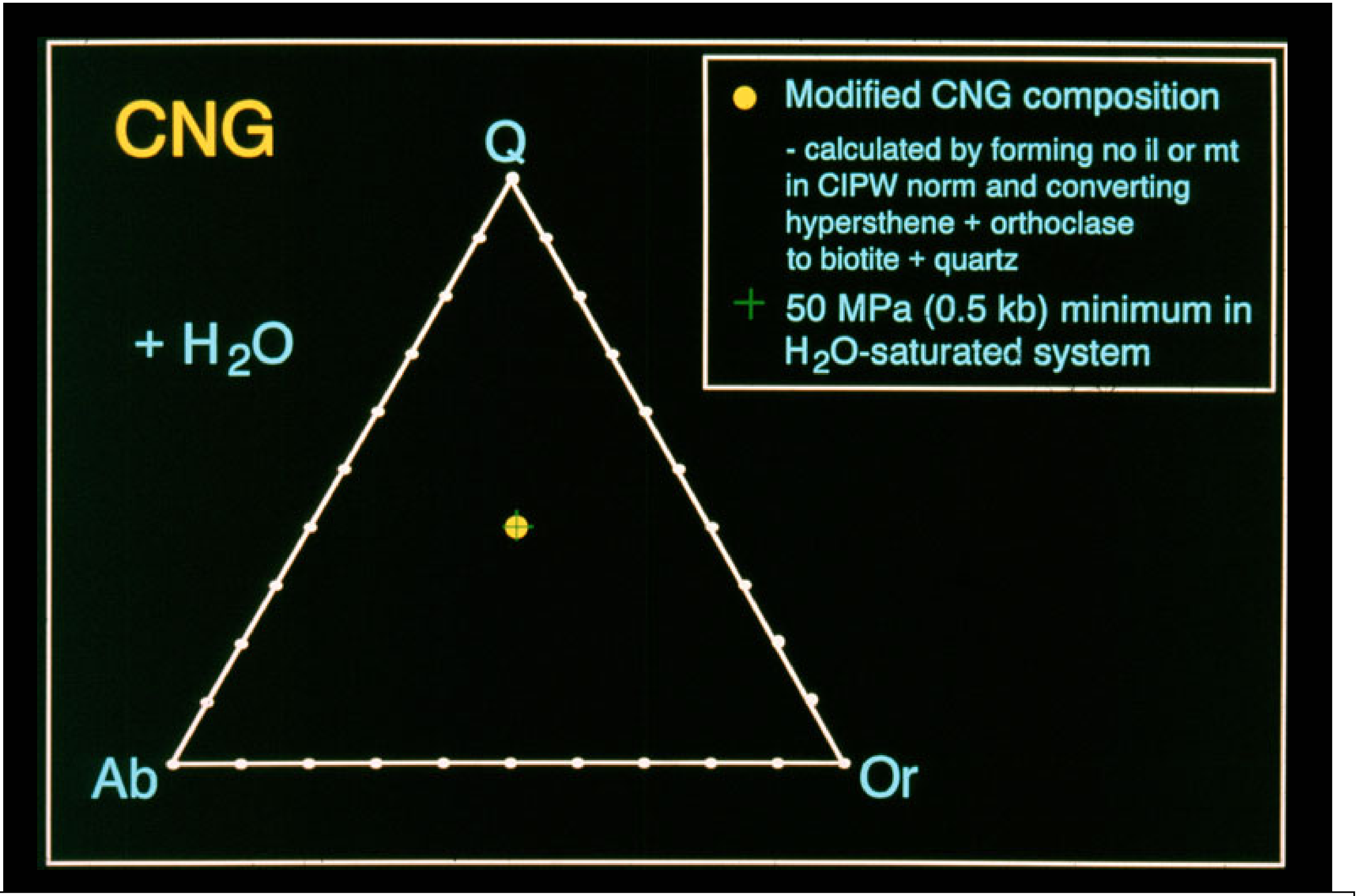
The Cornubian Batholth comprises six major bodies of granite in SW England.



SOME “TIN GRANITE” ANALYSES

	CORNUBIAN AVERAGE	KOETONG SAMPLE VB140
SiO_2	72.35	72.48
TiO_2	0.26	0.25
Al_2O_3	14.52	14.50
Fe_2O_3	0.30	0.29
FeO	1.56	1.33
MnO	0.05	0.03
MgO	0.41	0.47
CaO	0.79	0.66
Na_2O	2.96	2.80
K_2O	5.12	5.20
P_2O_5	0.25	0.16
norm C	3.23	3.57

An average composition of the granites of the Cornubian Batholith compares very closely in composition with sample VB140 of the Granya granite, from the Koetong Suite.

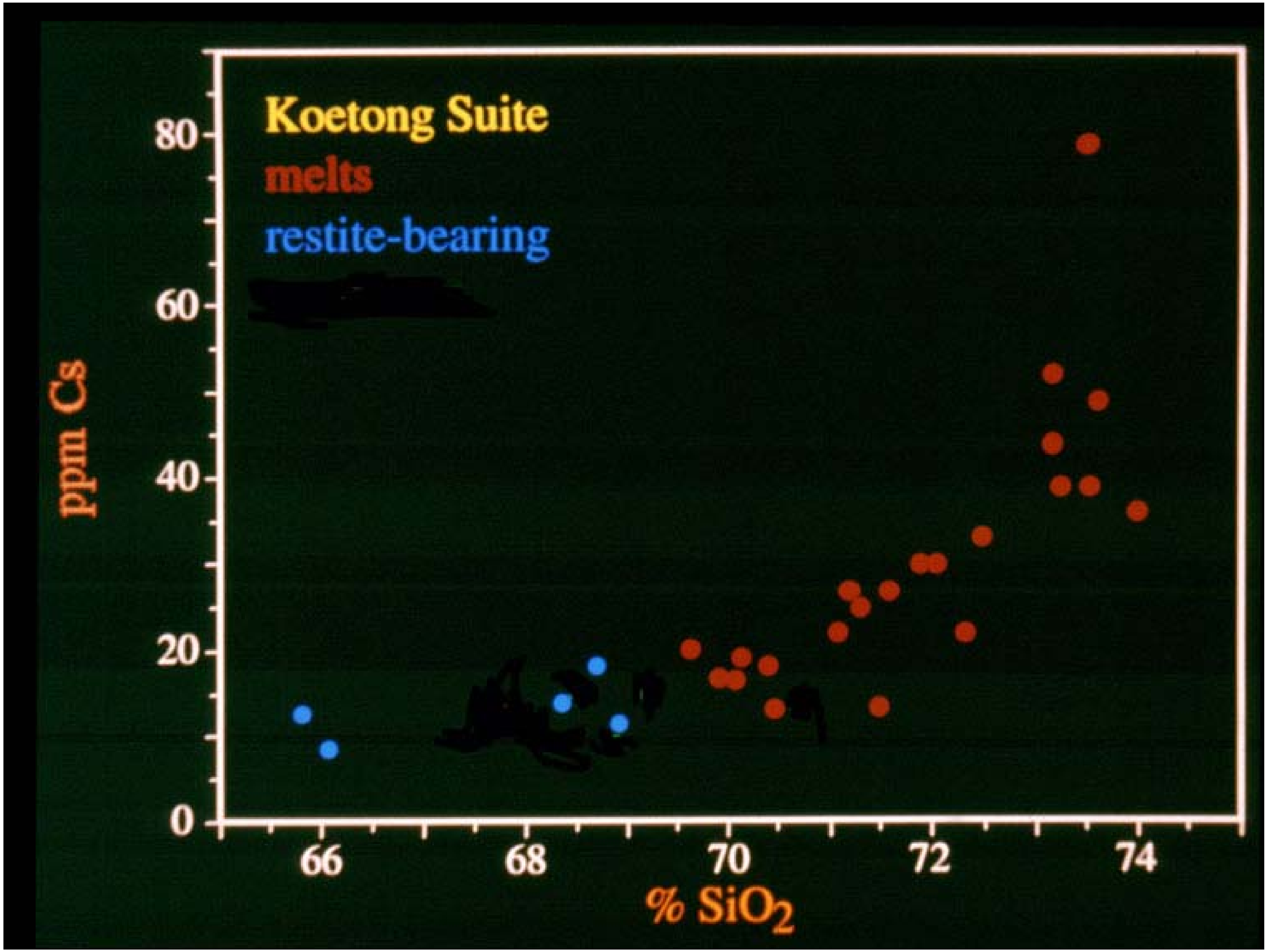


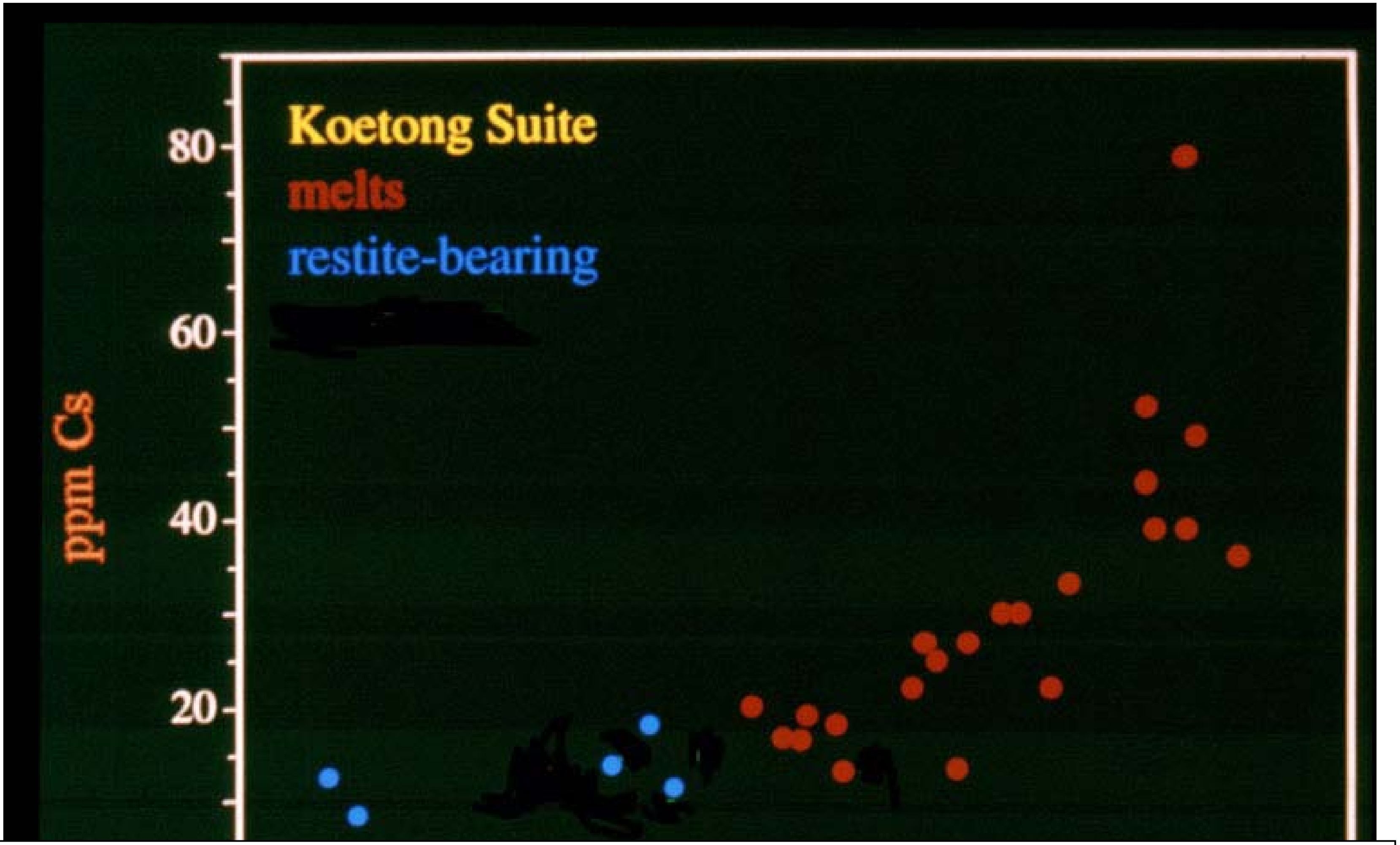
The average composition of the Cornubian granites lies precisely at the minimum-temperature composition of Tuttle & Bowen (1958) at 50 MPa.

TRACE ELEMENTS

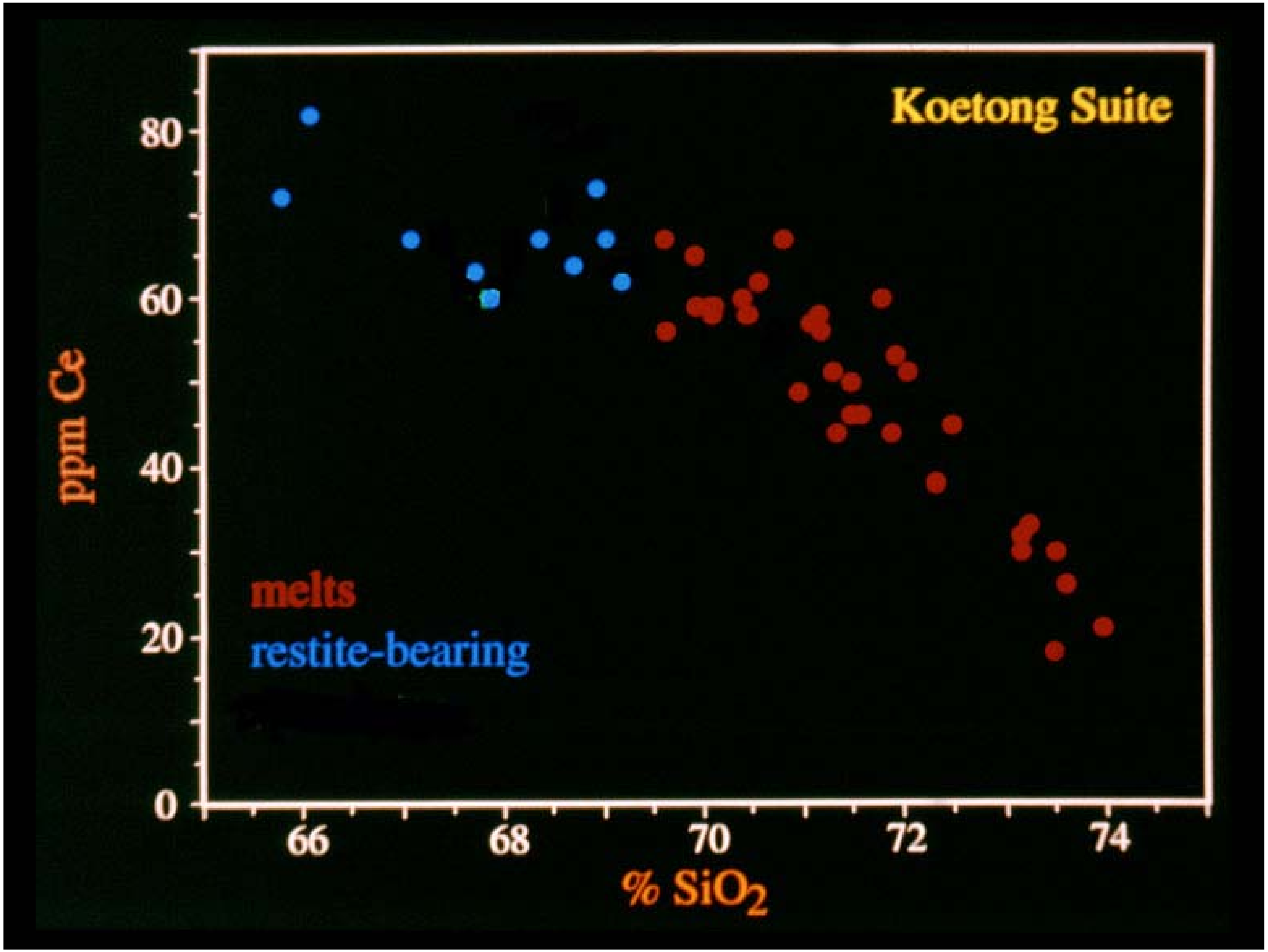
	CNG	**VB140**		**CNG**	**VB140**
B	320	120	Cr	8	9
Rb	483	419	Co	3	4
Cs	49	33	Ni	6	4
Sr	74	65	Ga	24	20
Ba	176	220	As	22	7
Zr	113	99	Sn	16	25
Nb	17	20	W	15	13
Y	18	14	Pb	28	36
Ce	63	48	Th	15	15
V	15	15	U	13	11

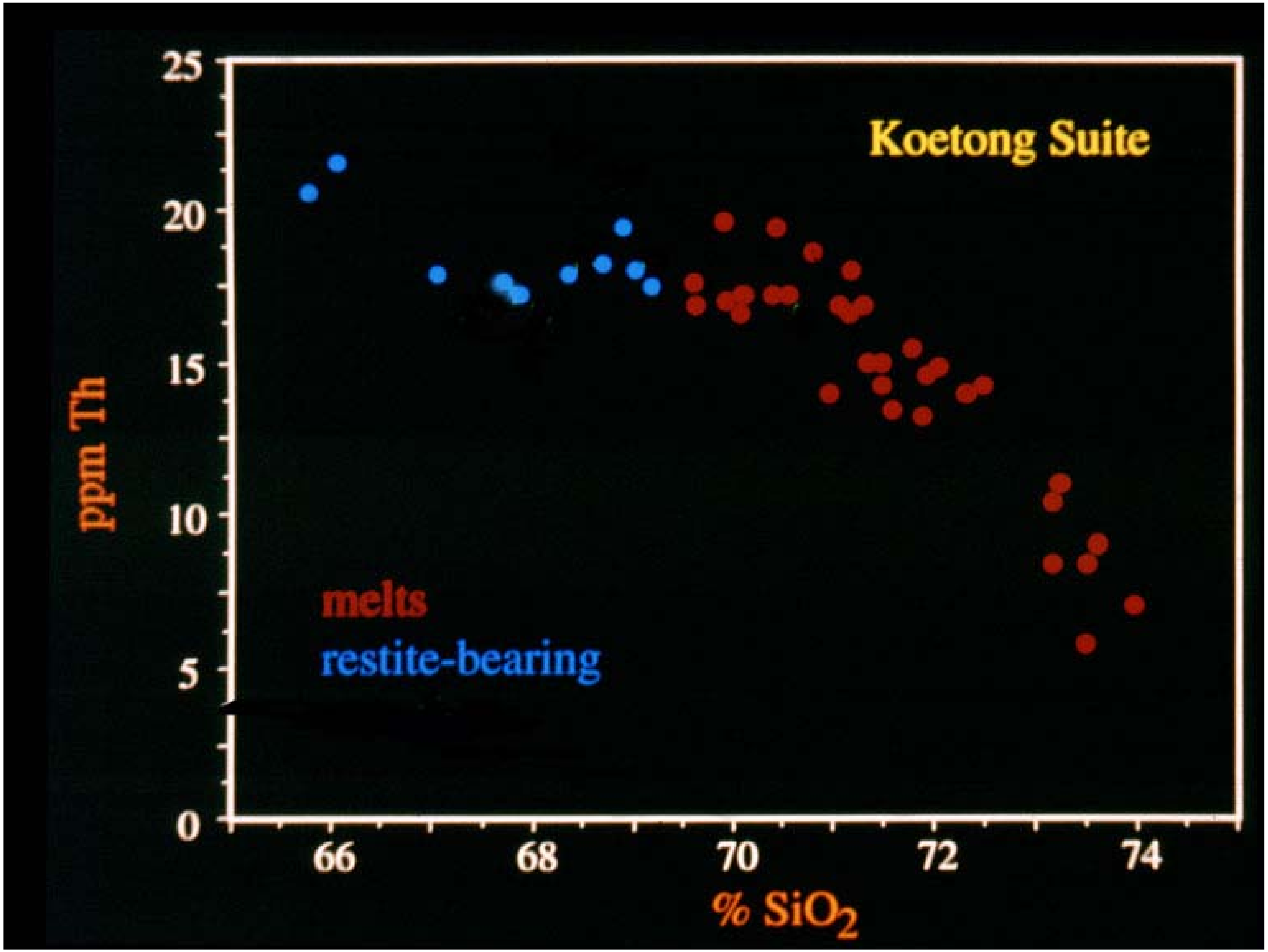
CNG is an average Cornubian granite composition, VB140 is the sample of Granya granite. The agreement in trace element compositions is quite good, except for B, which has a high abundance in the Cornubian granites, and As, which is low in amount in all granites of the LFB. The lower Ce content of VB140 reflects slightly more intense monazite fractionation.

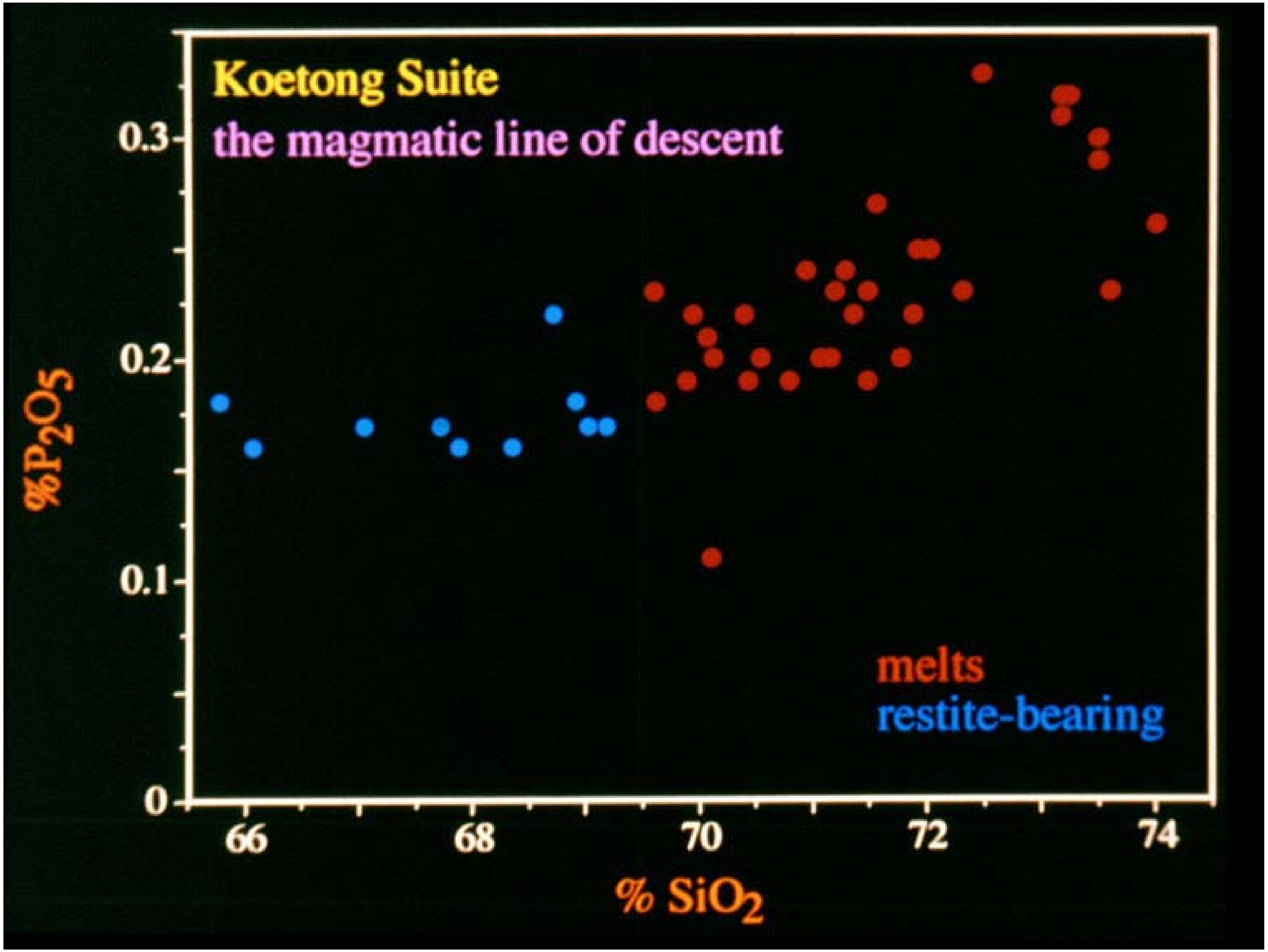

Koetong Suite
melts
restite-bearing
[redacted]
ppm Cs
80
60
40
20
0
66
68
70
72
74
% SiO_2

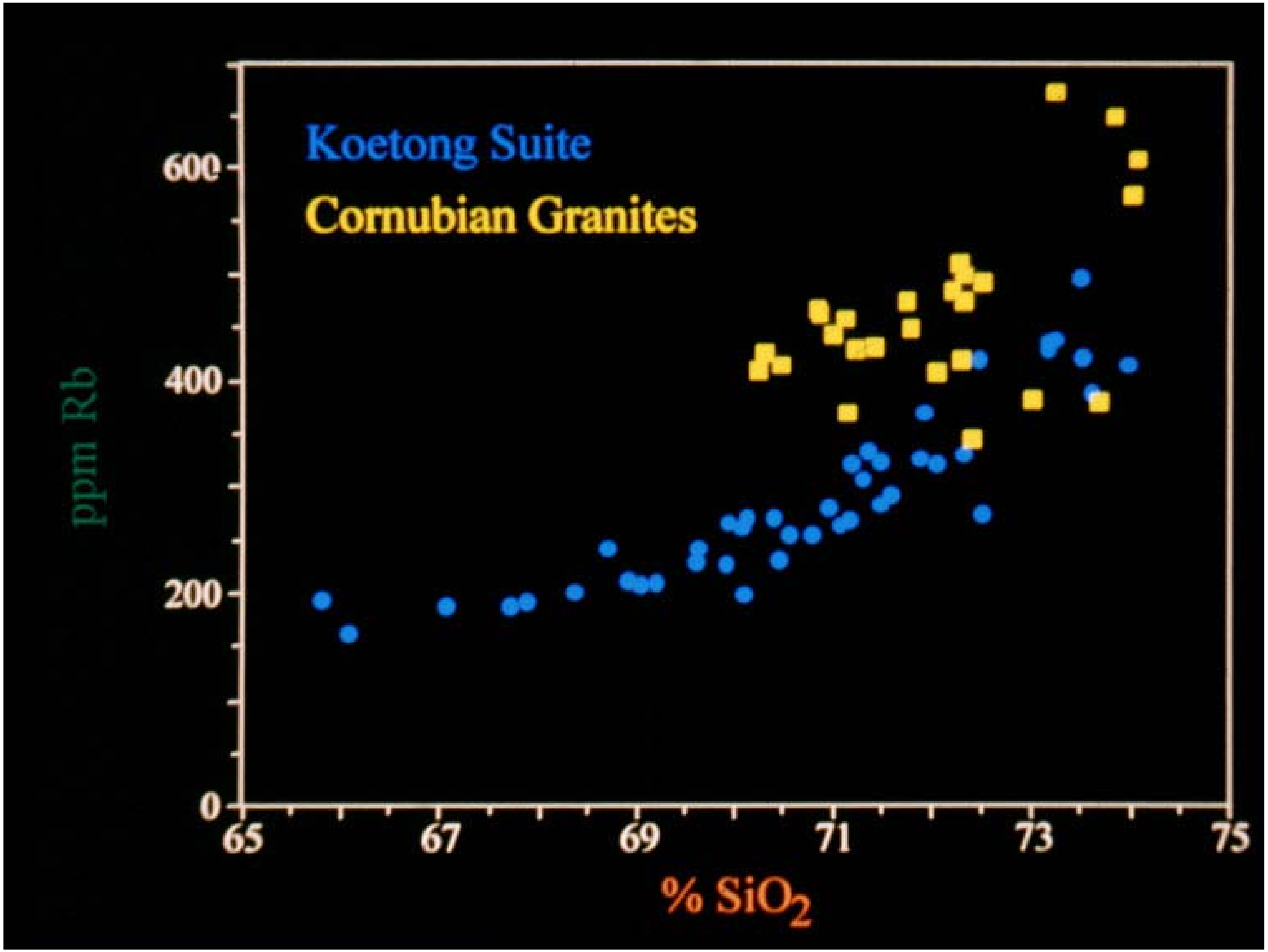


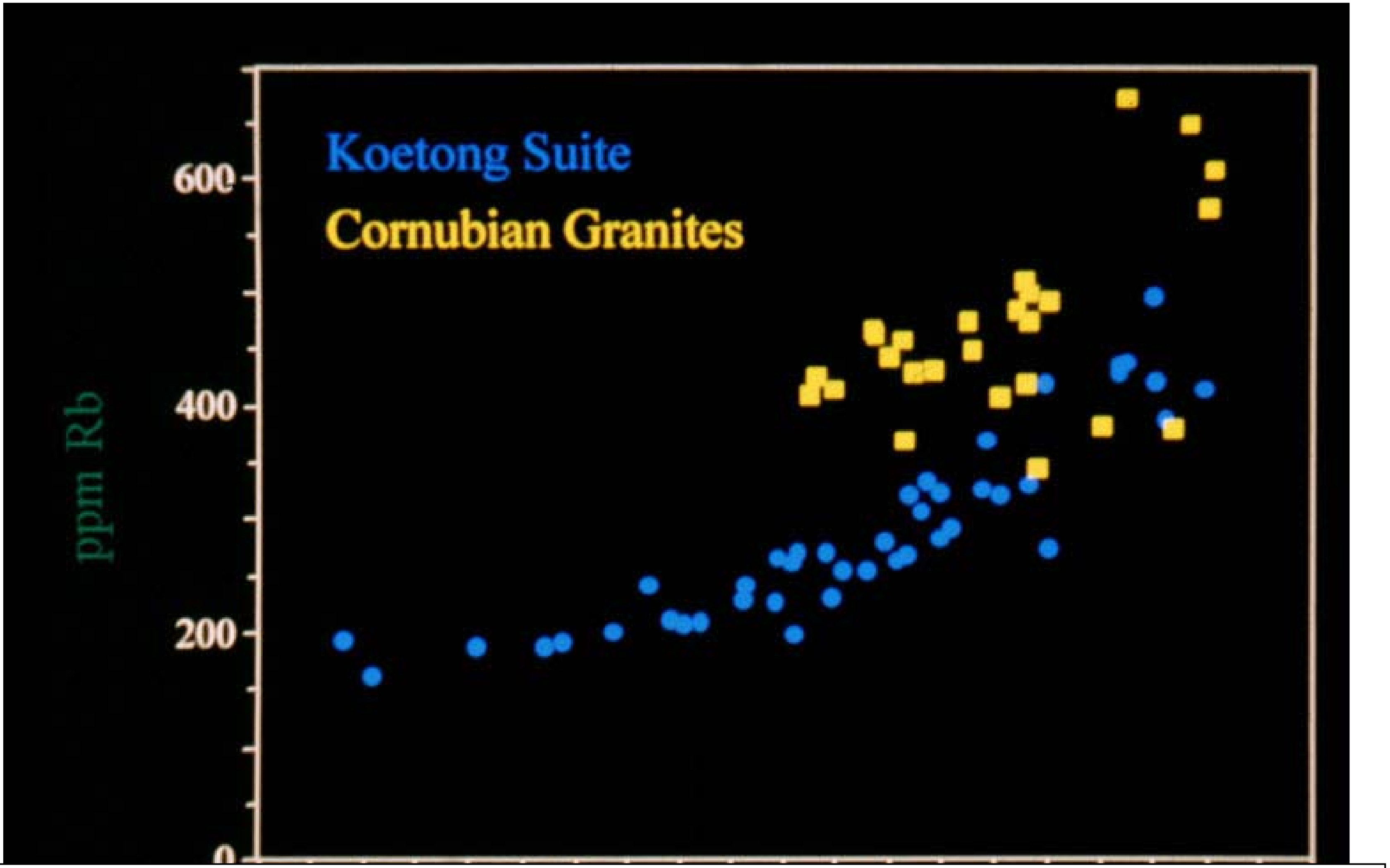
This and the following three slides show the effects of fractional crystallisation in the Koetong Suite following the separation of the primary melt with ~ 69% SiO_2 from its restite. The compositional variation of the granites more mafic than 69% SiO_2 appears to be due to the fractionation of restite crystals. The red points define a liquid line of descent and all of the points comprise a magmatic line of descent.


Koetong Suite
ppm Ce
80
60
40
20
0
66
68
70
72
74
% SiO$_2$
melts
restite-bearing

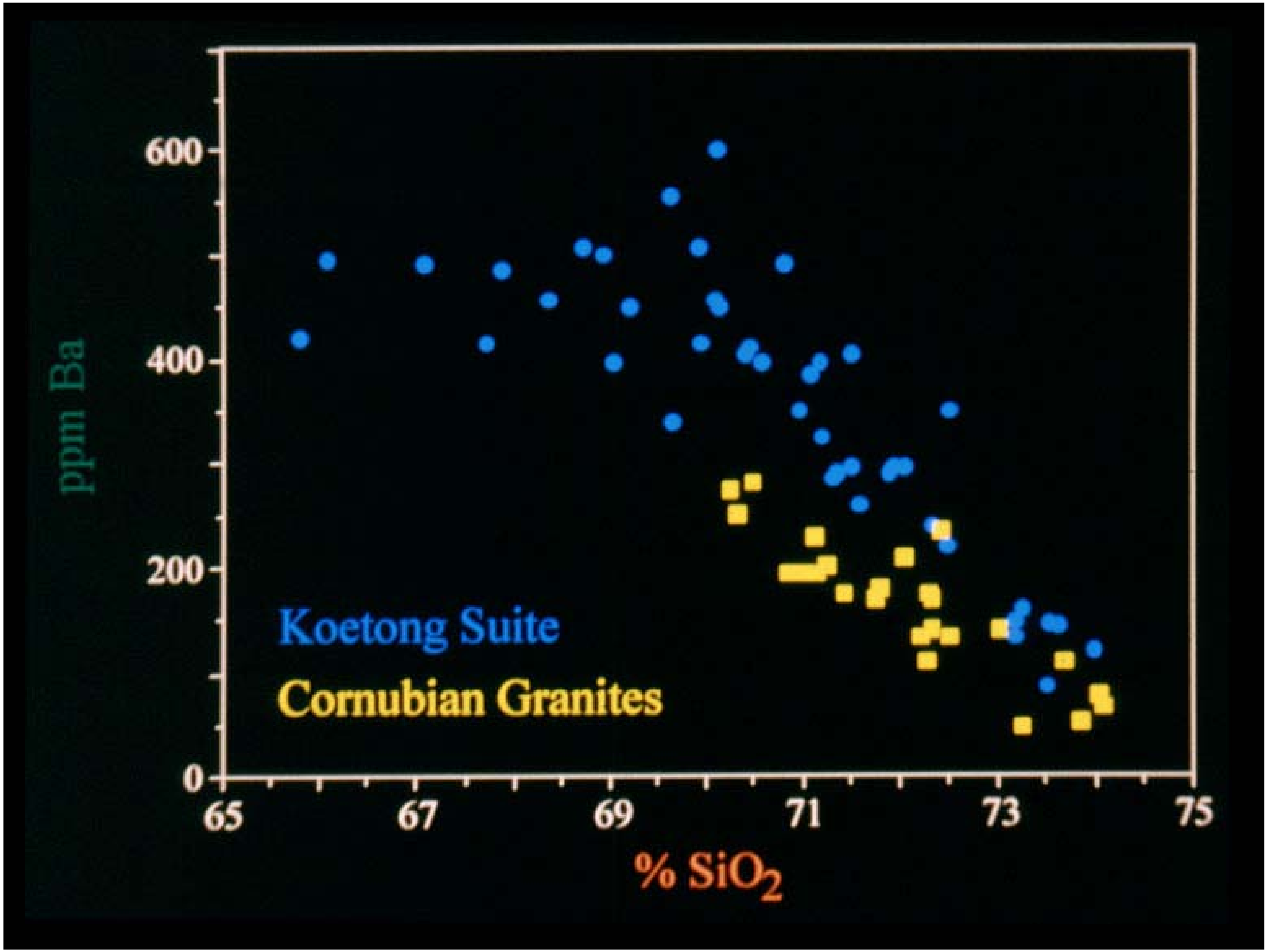

Koetong Suite
melts
restite-bearing
ppm Th
% SiO$_2$
0
5
10
15
20
25
66
68
70
72
74

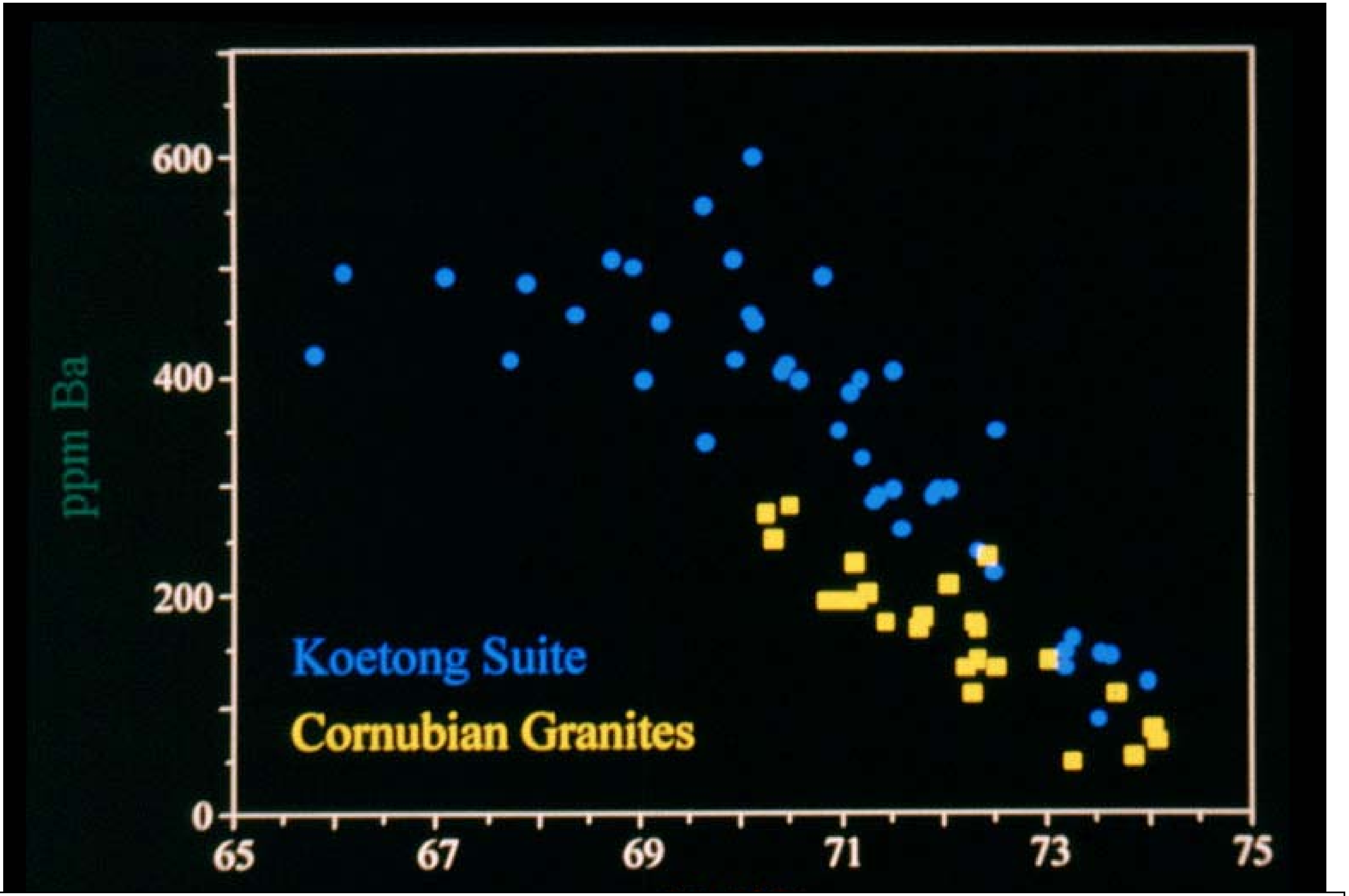

Koetong Suite
the magmatic line of descent
0.3
0.2
0.1
0
%P2O5
66
68
70
72
74
% SiO2
melts
restite-bearing


Koetong Suite
Cornubian Granites
ppm Rb
600
400
200
0
65
67
69
71
73
75
% SiO2

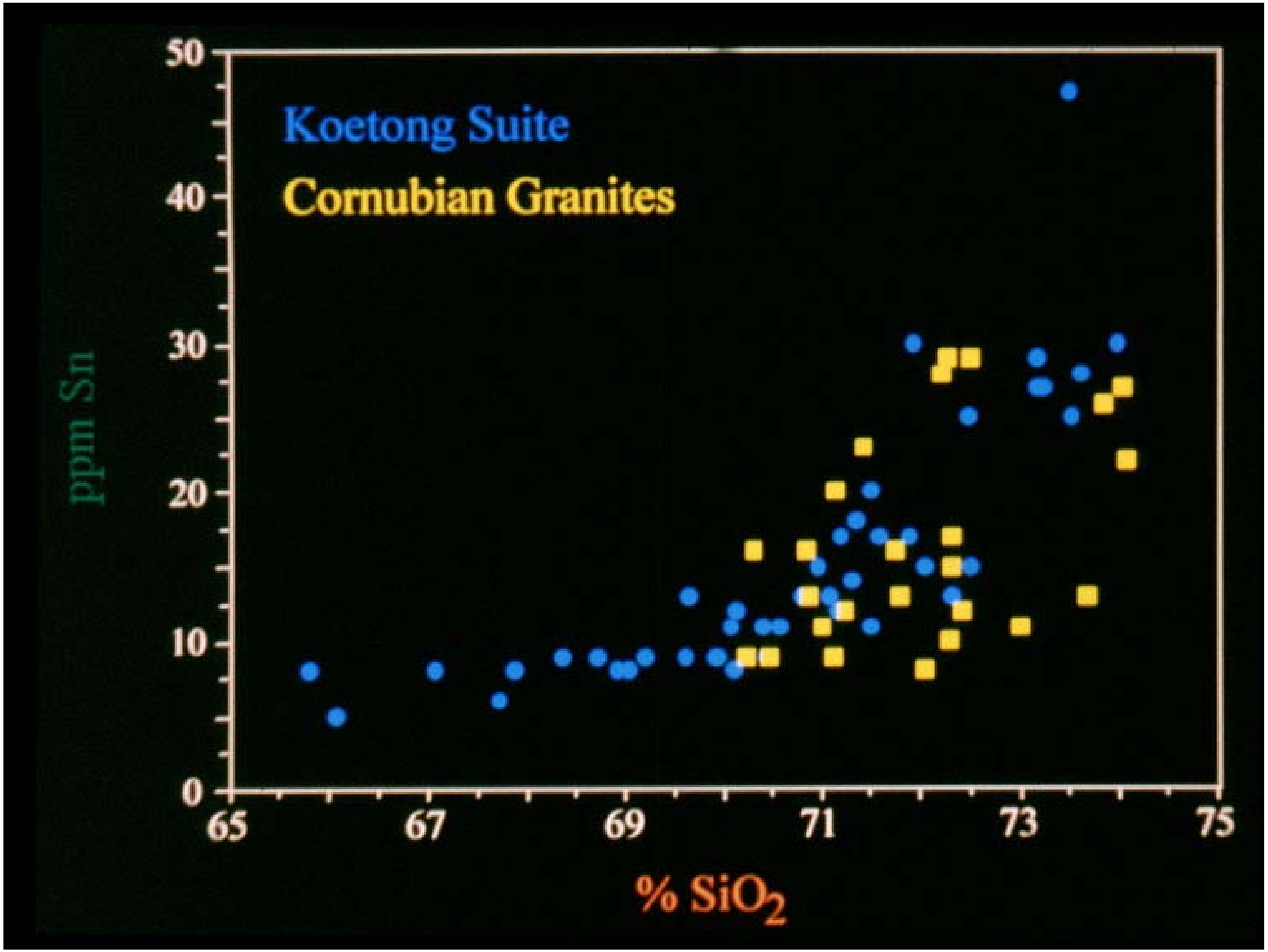


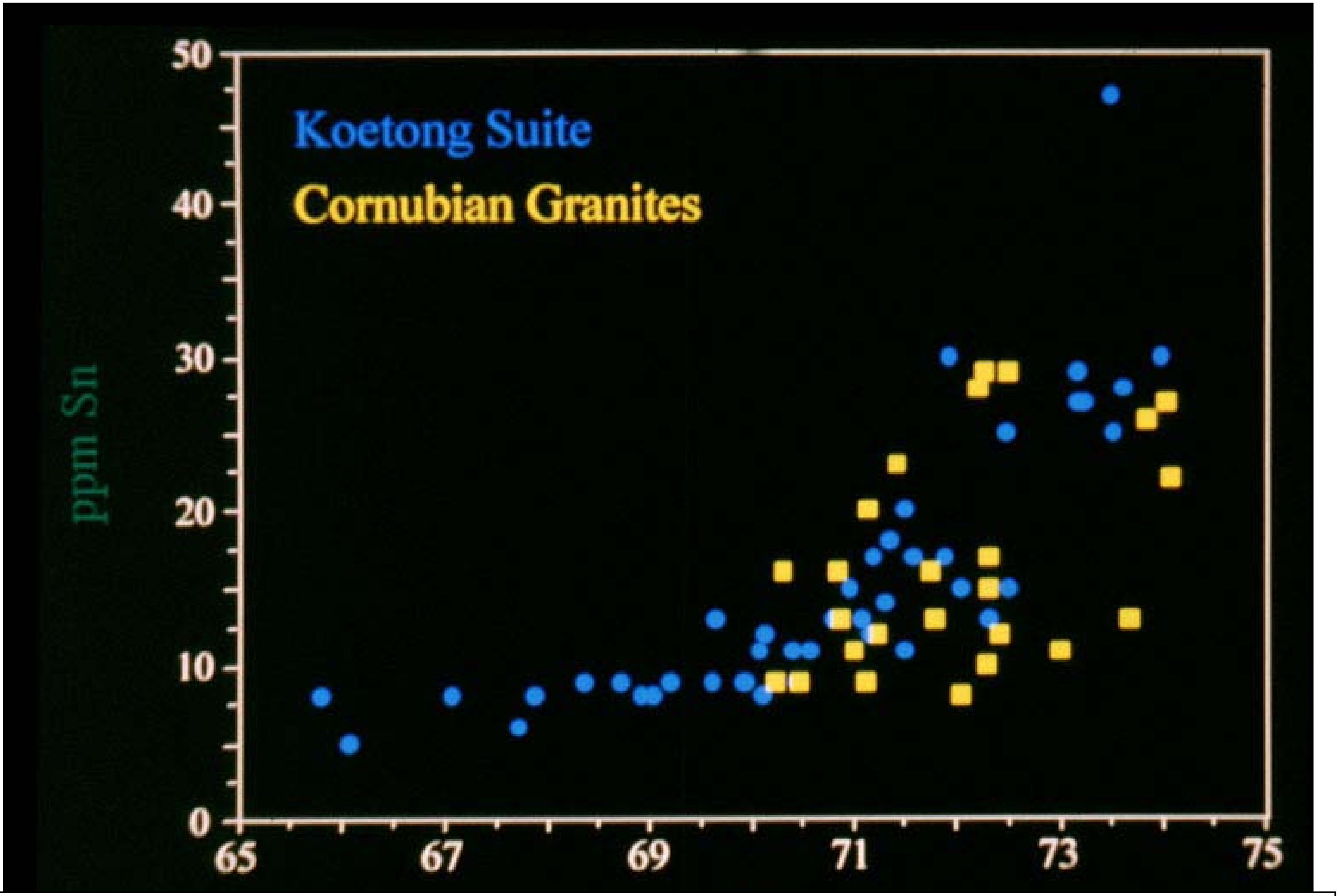
This figure shows the general similarity in the compositions of the Cornubian granites and the Koetong Suite for Rb. This is significant for understanding the origin of the felsic tin granites such as those of Cornubia, for which more mafic rocks are generally not seen, as they are in the Koetong Suite.


ppm Ba
600
400
200
0
65
67
69
71
73
75
% SiO2
Koetong Suite
Cornubian Granites



A comparison of Ba contents in the Koetong Suite and the Cornubian granites, again showing the effects of feldspar fractionation.


Koetong Suite
Cornubian Granites
ppm Sn
0
10
20
30
40
50
65
67
69
71
73
75
% SiO_2



This figure shows how the relatively high Sn comments of the Cornubian granites can be obtained by the fractional crystallisation of a melt containing less than 10 ppm of that element.

P_2O_5 ABUNDANCE IN HIGH-SILICA MELTS

- Phosphorus has a low to very low abundance in Al-undersaturated to weakly saturated high-silica melts and the content can be used as a crude geothermometer.
- P is progressively more soluble in Al-oversaturated melts where it forms a complex with Al:

$Si_2O_4 = AlPO_4$ (berlinite replacement)

- Hence P_2O_5 contents increase strongly during the fractional crystallisation of such melts, as for example in the “tin granites”.
- This has a dramatic effect on the accessory minerals that form and the behaviour of many trace elements during fractionation. For example, this is responsible for many of the unusual trace element characteristics of the “tin granites”, e.g. decreasing Th and LREE in the evolving melts.

PRODUCTION OF THE “TIN GRANITES”

PROCESSES CAN BE GROUPED INTO THREE STAGES:

1. Partial melting of “fertile” sedimentary rock (Q + Or + Ab + H_2O)
2. Separation of the melt from its residue or “restite”
3. Extended fractional crystallisation of that partial melt

The melt that separates from its partial melting residue before undergoing fractional crystallisation:

- will contain Q ~ ab ~ or (the Tuttle & Bowen composition)
- will probably not be water-saturated (~2-3% H_2O)
- will contain a small amount of excess Al_2O_3 (0.7 – 1.0%)
- will not have extreme abundances of any trace elements

These properties are mainly based on the occurrence of such rocks

DEVELOPMENT OF STRONG AL OVERSATURATION

An S-type Tuttle & Bowen low-temperature partial melt forms in equilibrium with restite minerals such as cordierite and sillimanite.

Based on observed rocks, these melts contain ~ 0.7 to 1.0% excess Al_2O_3.

Such a melt evolves dominantly by the precipitation of quartz and feldspars.

Such a mixture of minerals is just saturated with Al_2O_3:

SiO_2 $K_2O.Al_2O_3.6SiO_2$ $Na_2O.Al_2O_3.6SiO_2$ $CaO.Al_2O_3.2SiO_2$

with mol. Al_2O_3 = sum mol. ($K_2O + Na_2O + CaO$)

Hence the removal of 80% of a melt as crystals would increase the Al-oversaturation by a factor of 5. Hence an initial 0.75% excess would produce 3.75% normative C.

This is a slight oversimplification because there would be a small amount of Al-oversaturated biotite also precipitating. On the other hand, fractionation may remove more than 80% of the melt as crystals.

H_2O contents of melts also increase with fractionation and David London has shown that the solubility of excess Al_2O_3 increases with increasing H_2O.The observed maximum normative C in fractionated granites is ~ 4%.

“TIN GRANITES”: ARE THEY MAGMATIC OR METASOMATIC?

A magmatic origin is strongly favoured by the correspondence of composition with the Tuttle & Bowen minimum.

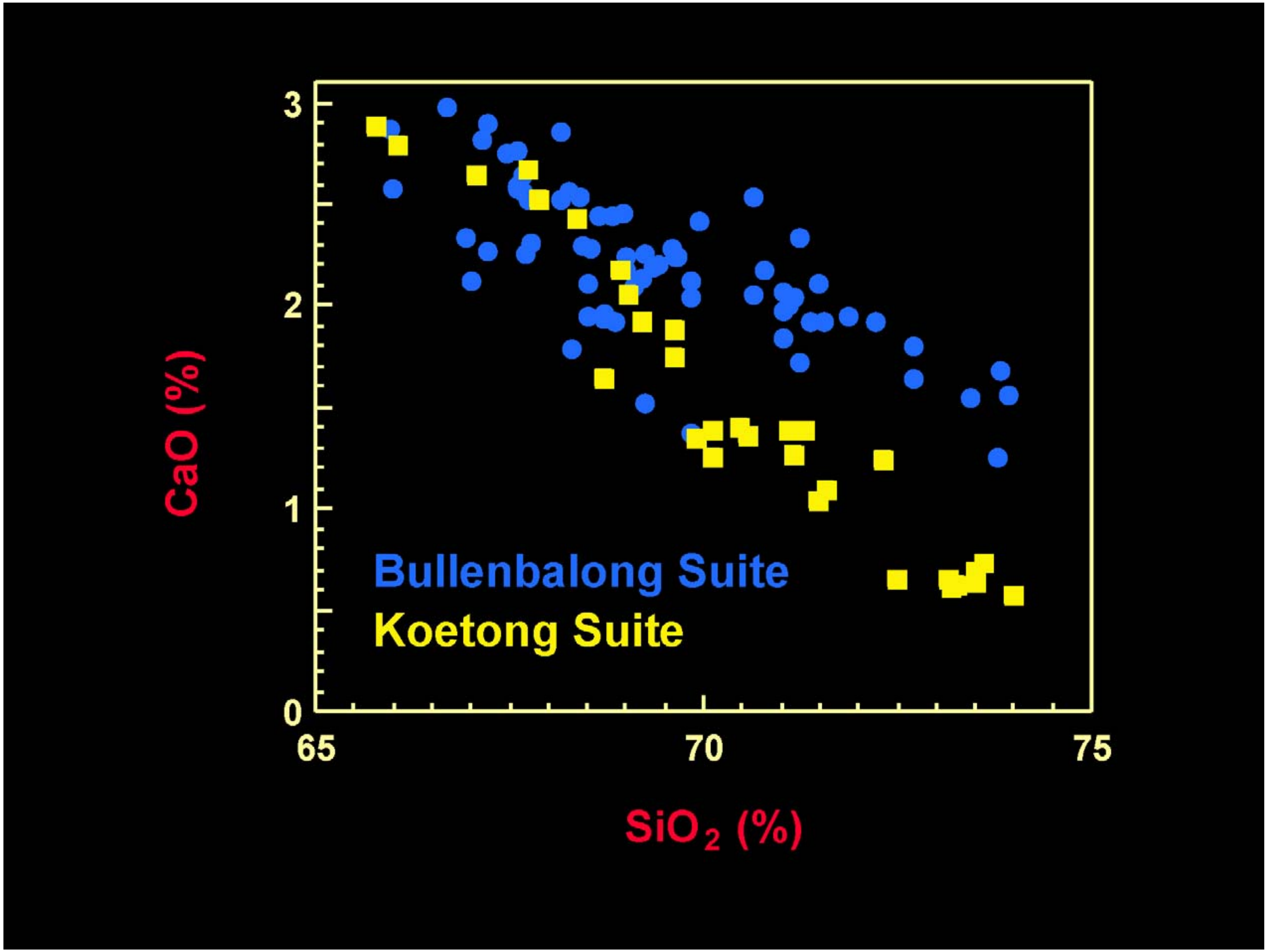
But there have been problems with such an origin:

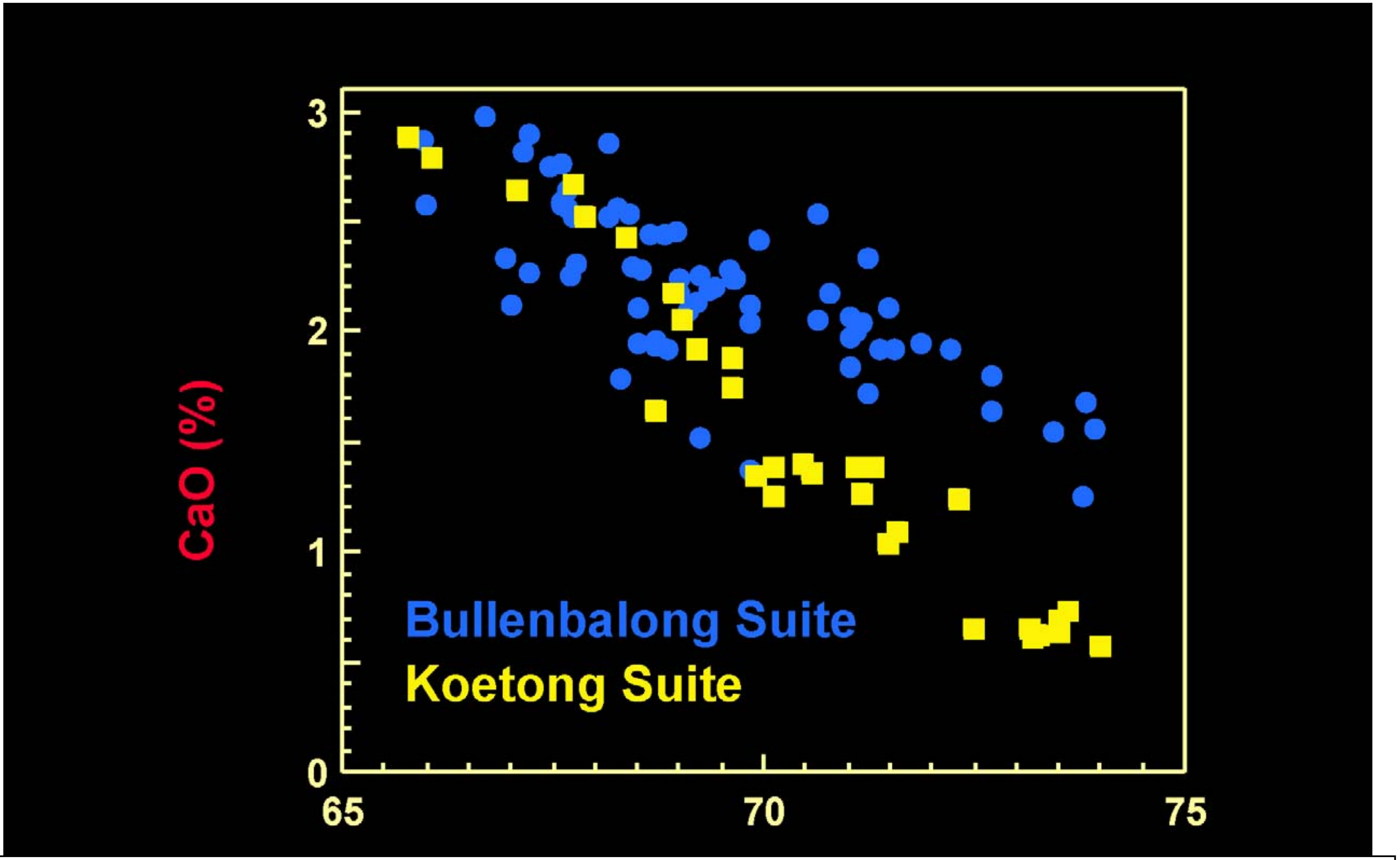
- Very strong alteration of feldspars, etc
- Extreme trace element abundances
- Strongly oversaturated in Al or peraluminous
- Volcanic equivalents were not known until relatively recently

So the magmatic origin has been questioned. Note also that some of the compositional effects of feldspar removal by fractional crystallisation might be achieved also by feldspar removal through hydrothermal alteration.

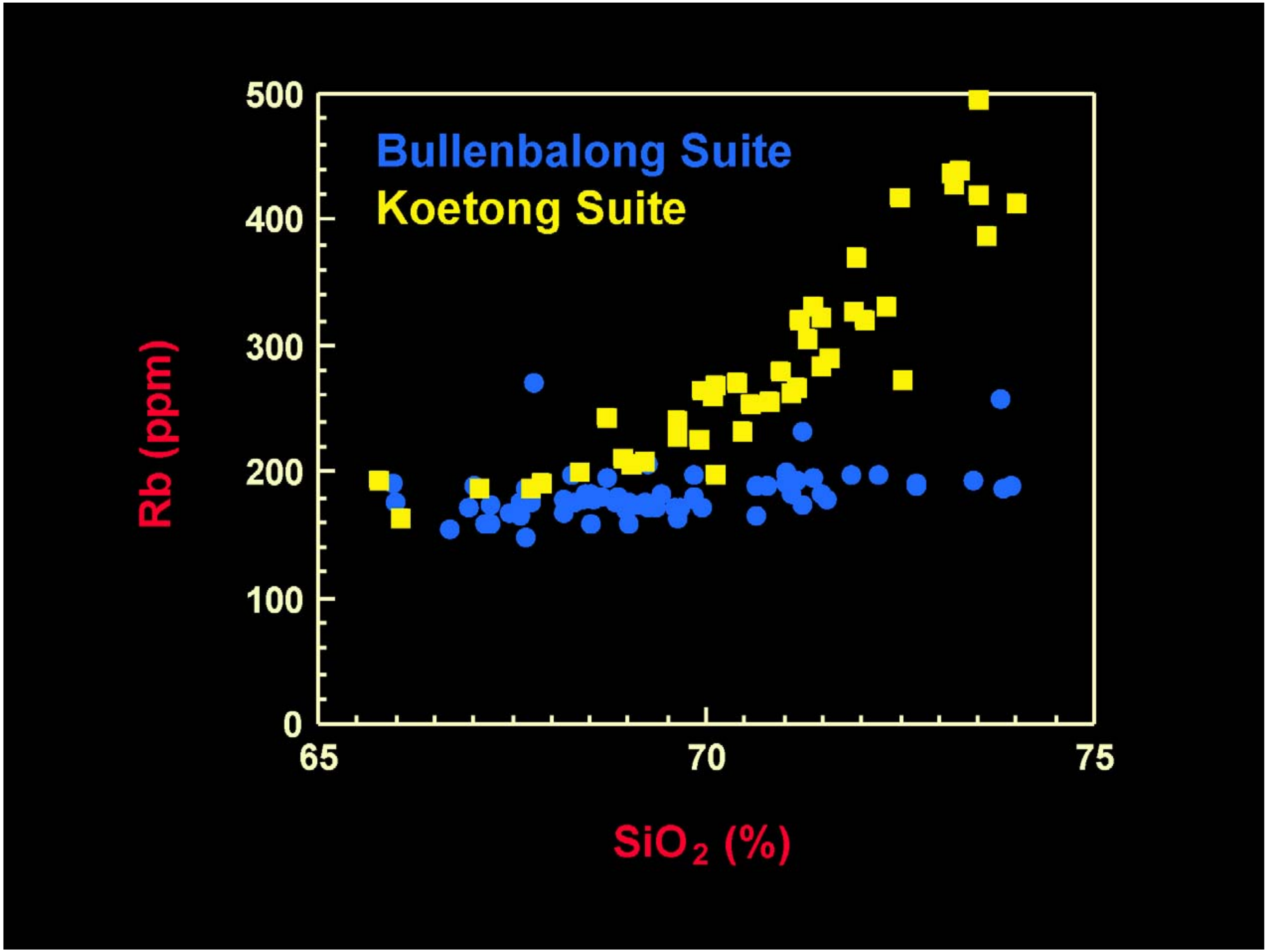
In response to the above four points the magmatist would now argue:

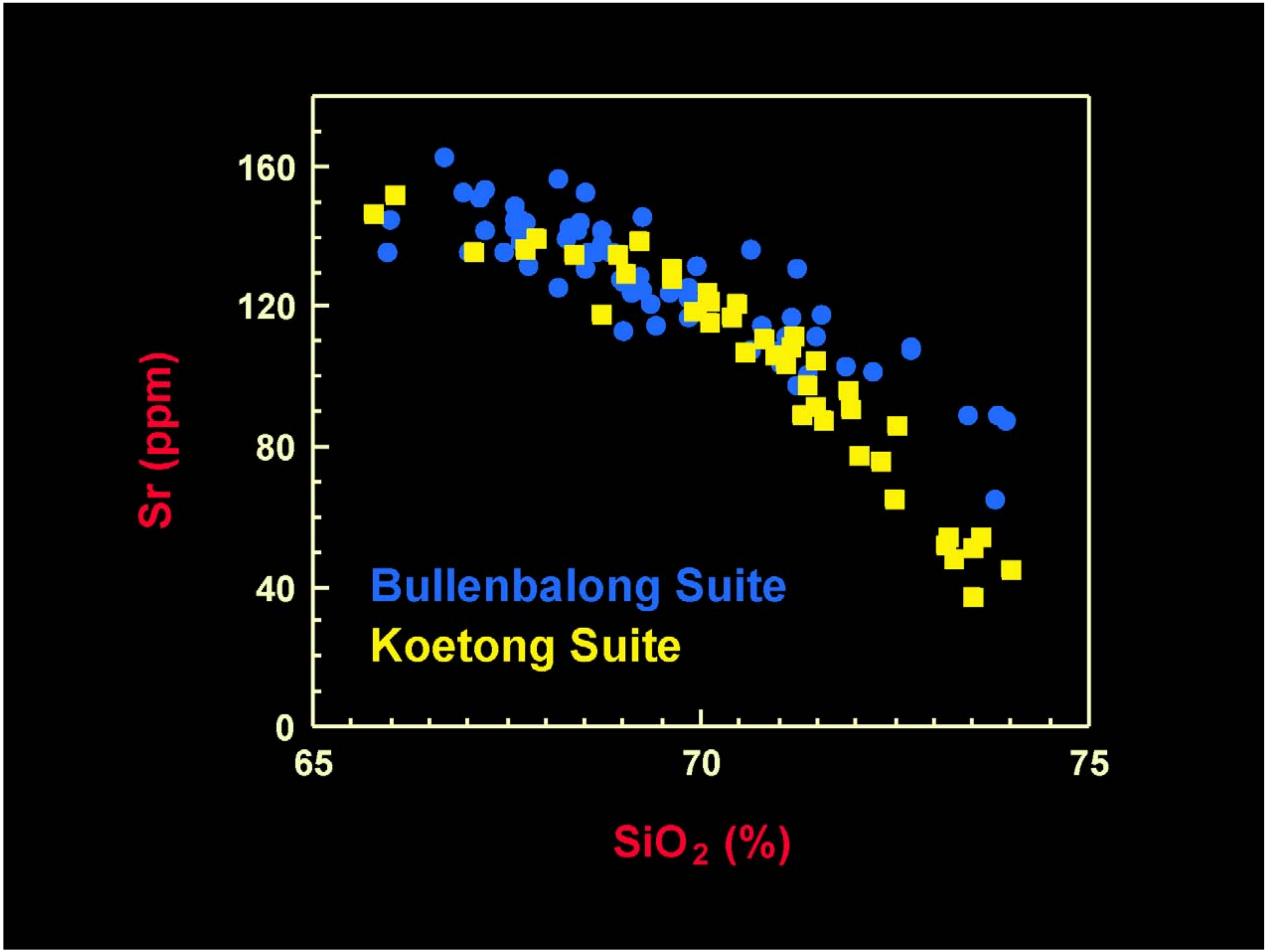
- Feldspar alteration would result from concentration of H_2O during FC
- Trace element abundances can be accounted for by FC
- FC can also lead to increasing Al oversaturation, in more H_2O-rich melts
- Volcanic equivalents are now known, e.g. the glassy Macusani Volcanics
- A magmatic origin is also indicated by the abundances of P in feldspars

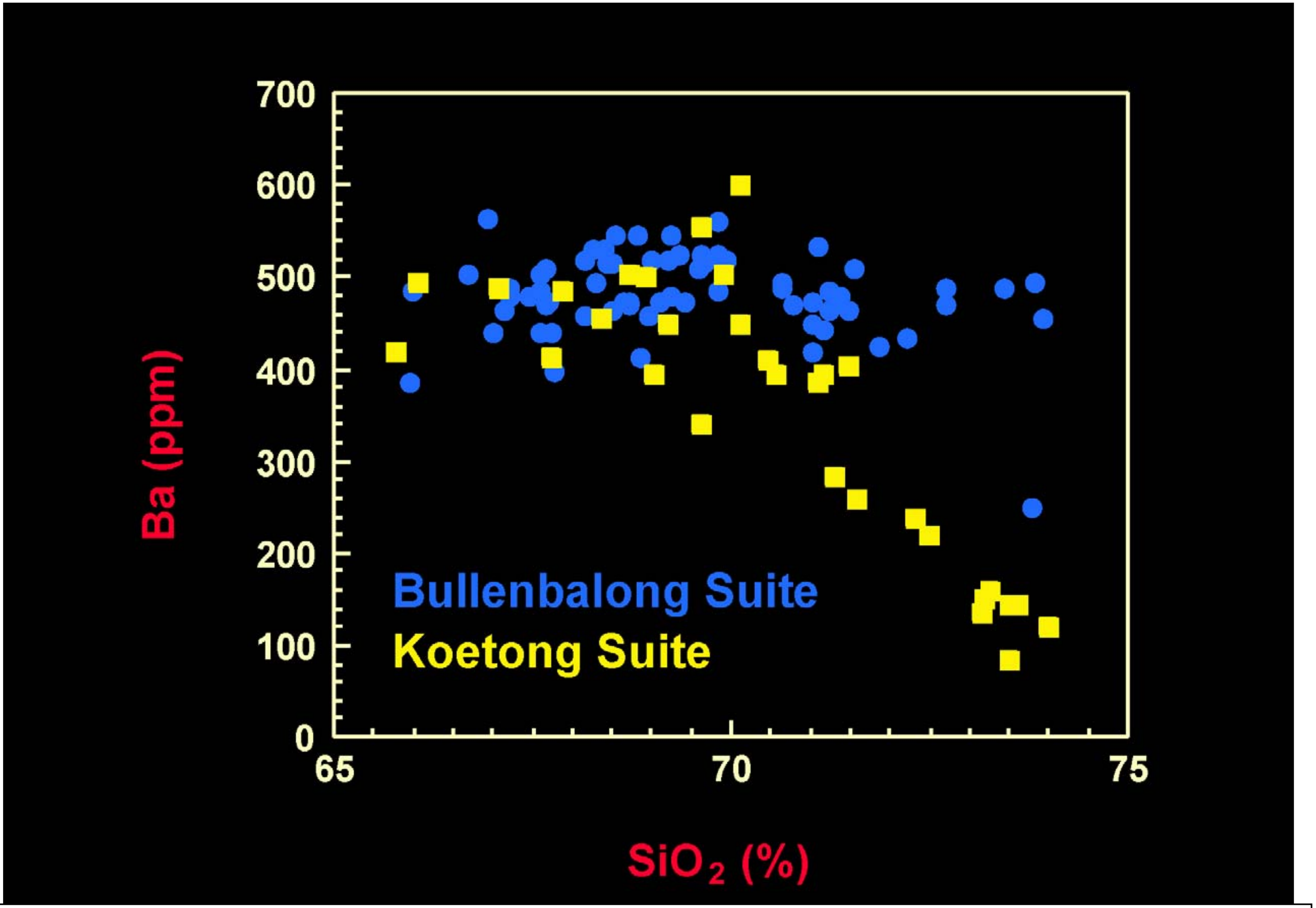

3
2
1
0
65
70
75
CaO (%)
SiO₂ (%)
Bullenbalong Suite
Koetong Suite



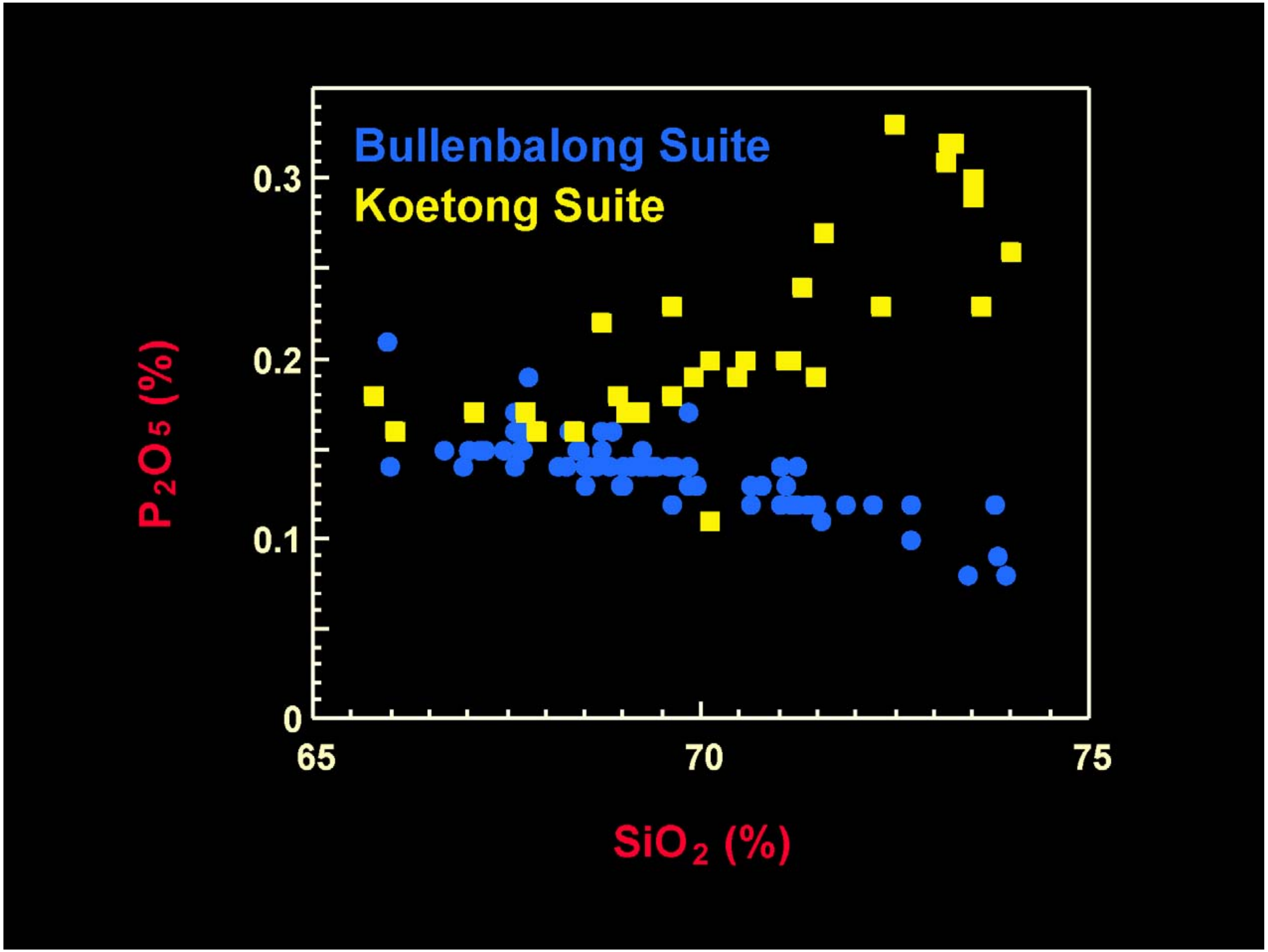
This and the next 8 figures shows the contrast between the Koetong Suite, where the more felsic compositions were produced by fractional crystallisation, and the Bullenbalong Suite, where they did not. In the latter case, the compositional evolution occurred through the removal of a felsic melt containing ~ 74% SiO_2 from its mafic restite.

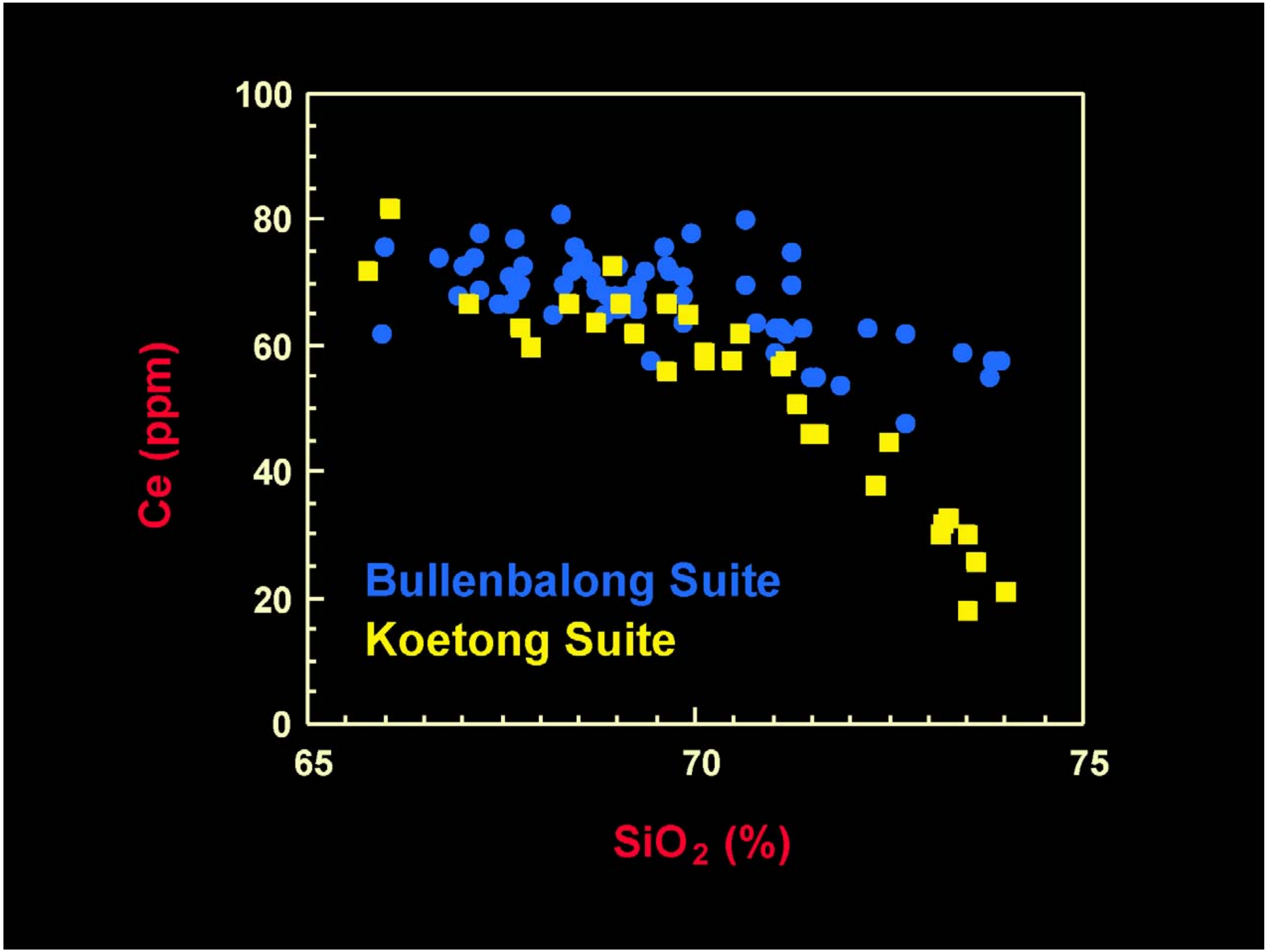

Bullenbalong Suite
Koetong Suite
Rb (ppm)
0
100
200
300
400
500
65
70
75
SiO2 (%)

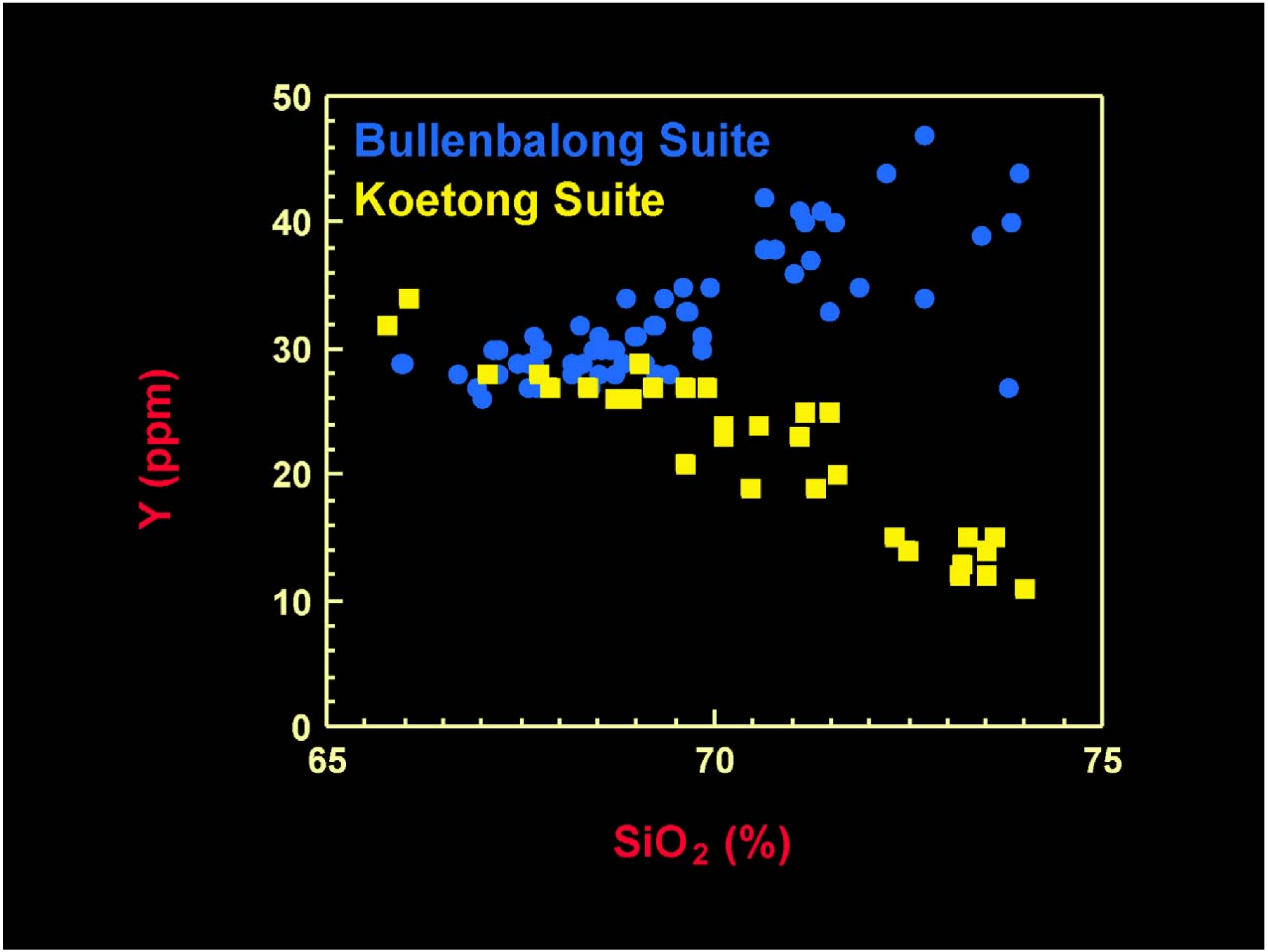

Sr (ppm)
160
120
80
40
0
65
70
75
SiO2 (%)
Bullenbalong Suite
Koetong Suite

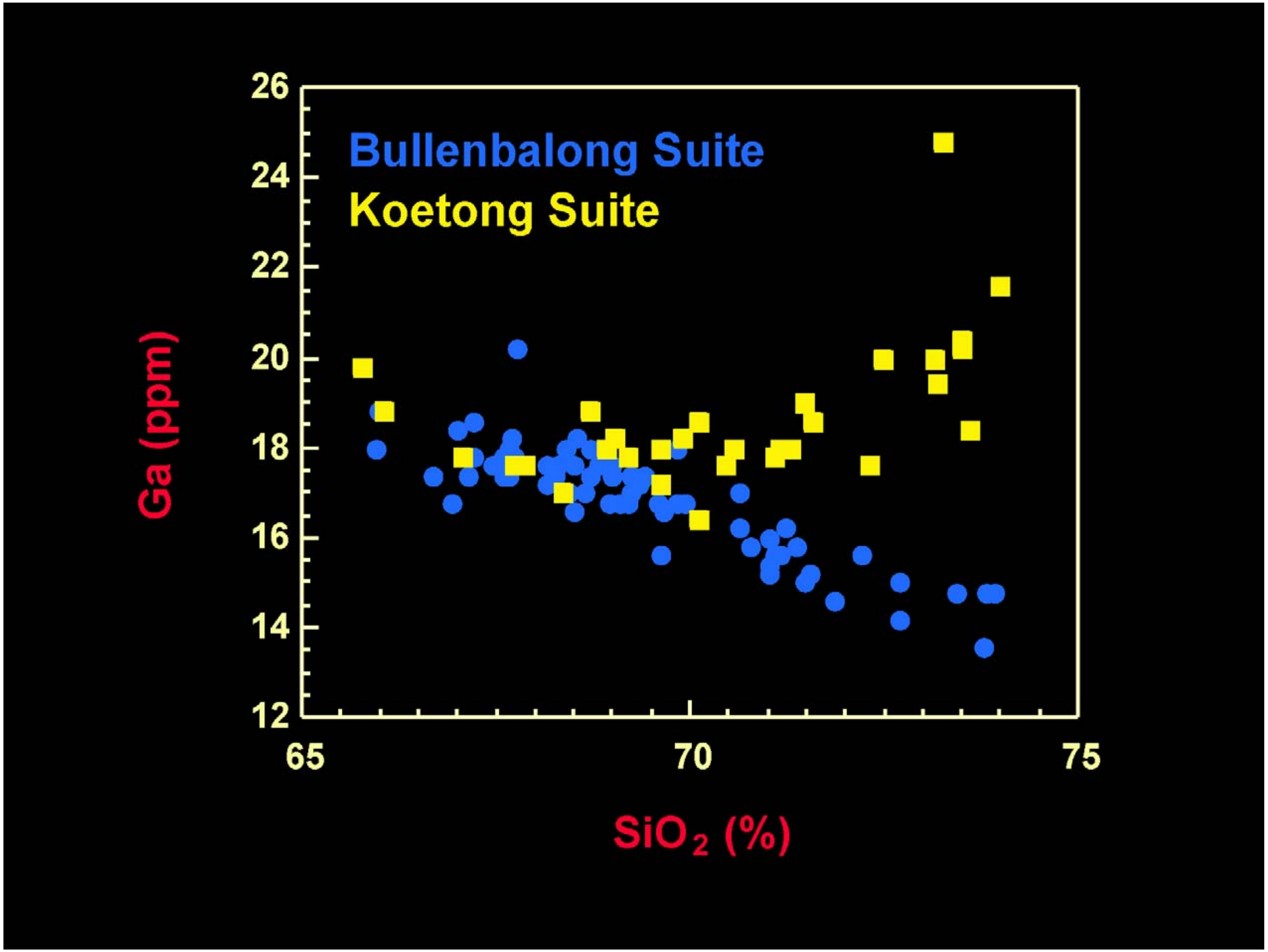


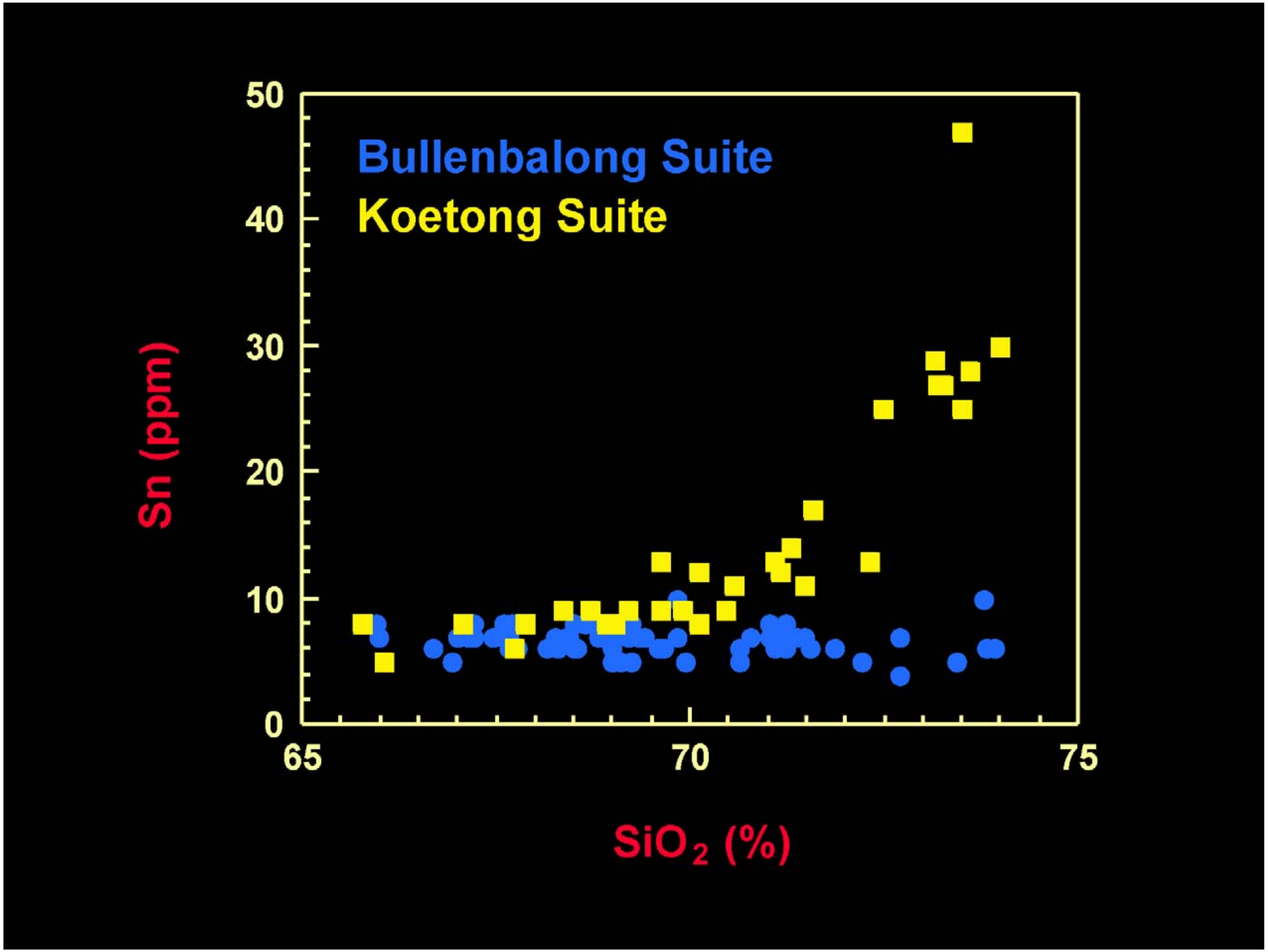
For one sample of Bullenbalong, there was a small degree of fractional crystallisation, reflected here in a low Ba content, and on a previous figure in a higher Rb content.


Bullenbalong Suite
Koetong Suite
0.3
0.2
0.1
0
65
70
75
P_2O_5 (%)
SiO_2 (%)


100
80
60
40
20
0
Ce (ppm)
65
70
75
SiO₂ (%)
Bullenbalong Suite
Koetong Suite


Bullenbalong Suite
Koetong Suite
Y (ppm)
SiO$_2$ (%)
0
10
20
30
40
50
65
70
75


Bullenbalong Suite
Koetong Suite
Ga (ppm)
SiO₂ (%)
26
24
22
20
18
16
14
12
65
70
75

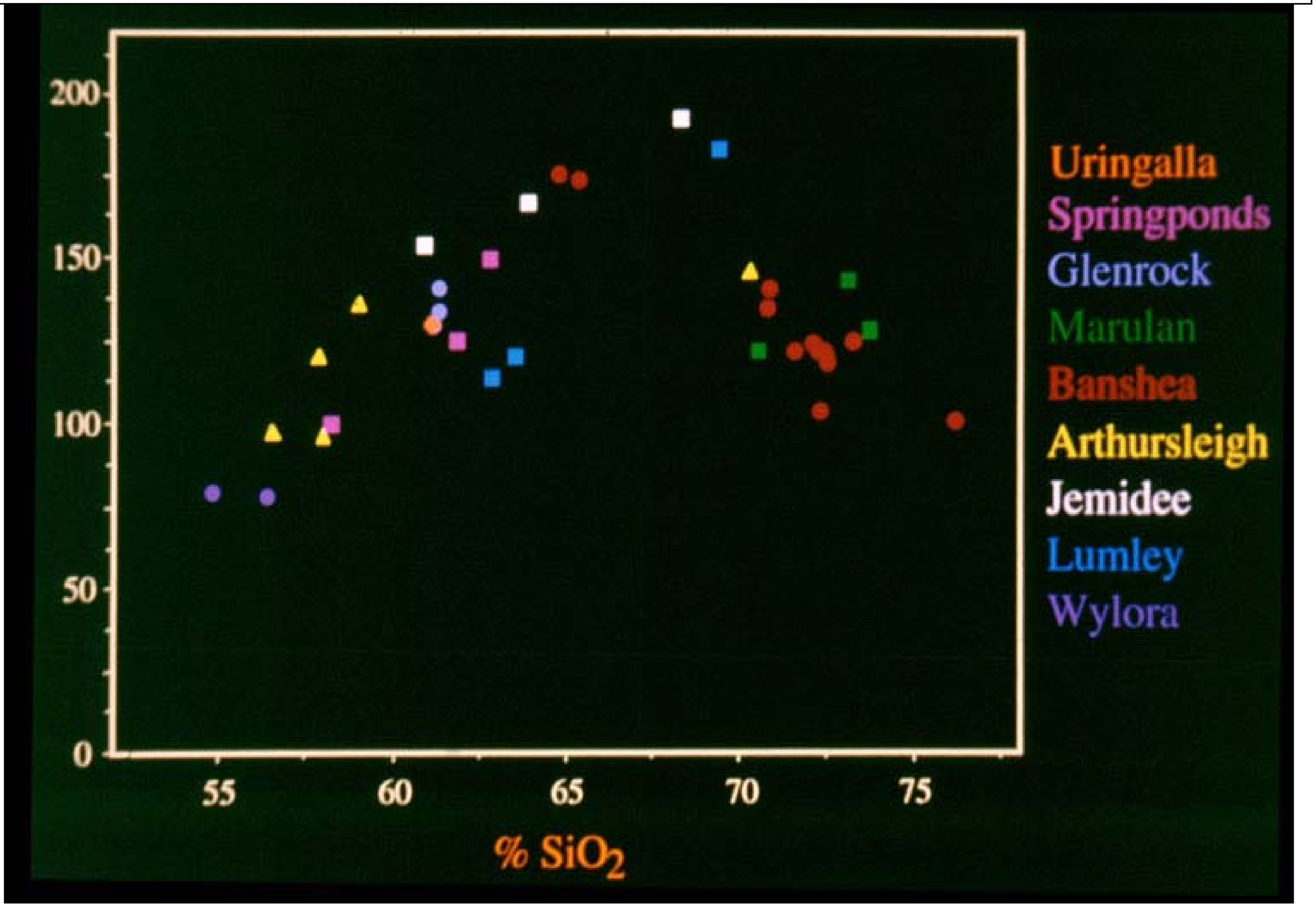

Bullenbalong Suite
Koetong Suite
Sn (ppm)
SiO₂ (%)
0
10
20
30
40
50
65
70
75

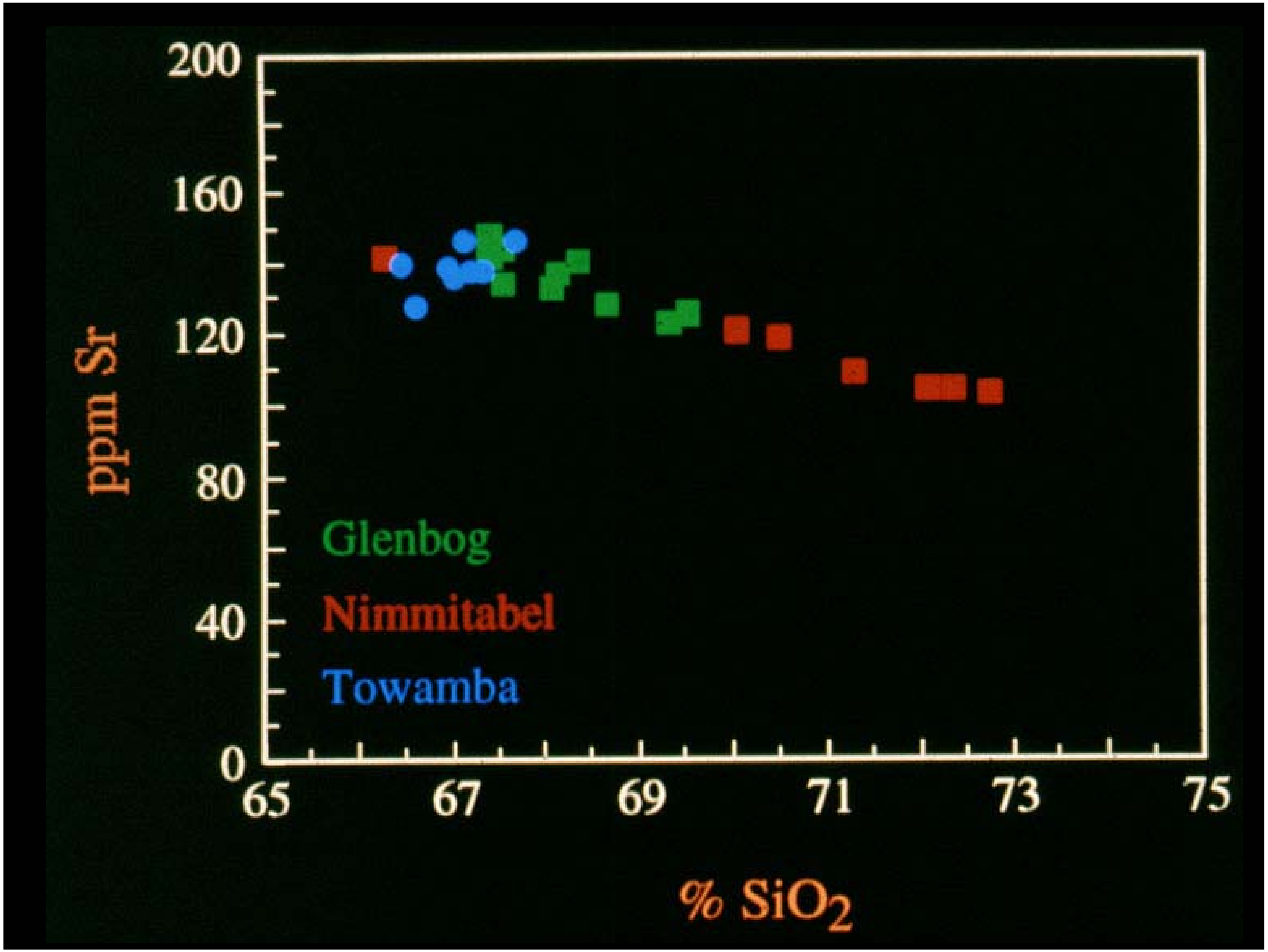
4. VARYING DEGREES OF PARTIAL MELTING

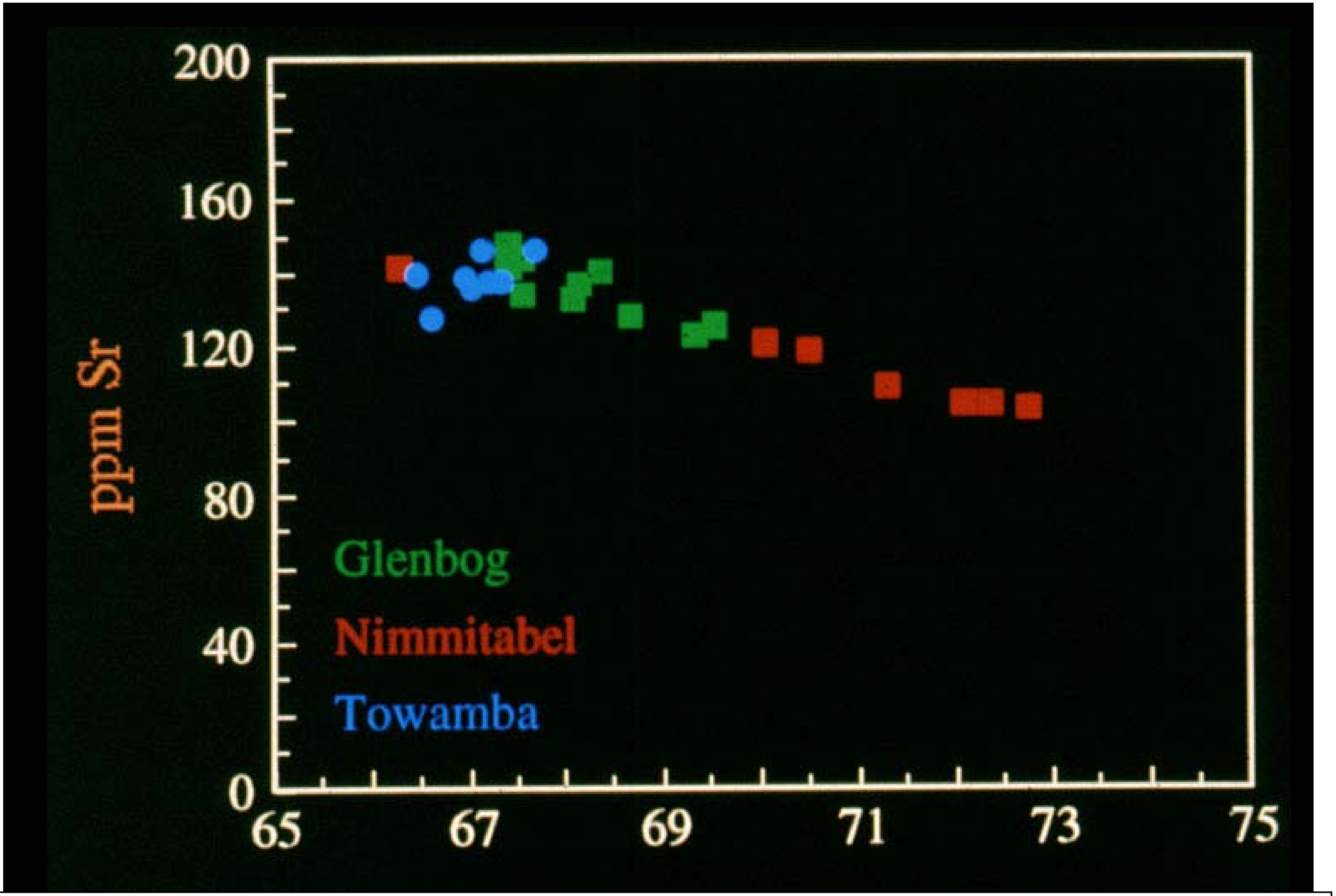
Beyond the point where progressive melting of a granite source rock leads to the removal of one of the components of that melt (Q + ab + or), the temperature of melting will rise and the compositions of the melt will change as the fraction of melt increases. This is a potential mechanism for the generation of variation within rock suites that probably has not received the attention that it merits. It is approximately the reverse of the process of fractional crystallisation for cases in which extreme enrichments or depletions of trace elements have not been produced by that other process. It is possible that variations within the high-temperature granites of the Marulan Suite of the LFB (Carr *et al.*, 1992) were produced in way, but there would not seem to be any other possible cases in the LFB. It has not been favoured as a general mechanism for any of those other granites partly because of their distinctive patterns of linear compositional variation, in contrast to Marulan. But in particular, the fact that the variation within single plutons parallels that of groups of plutons within a suite, would imply that this mechanism can only have operated if every detail of compositional variation within plutons corresponded to different fractions of melt that had been generated by varying degrees of melting. This process seems to be better suited to producing suites that comprise plutons of different but individually relatively uniform compositions, particularly tonalitic ones such as Marulan.

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.

This figure illustrates the limited range of composition of each pluton of the Marulan Suite, relative to the whole suite.

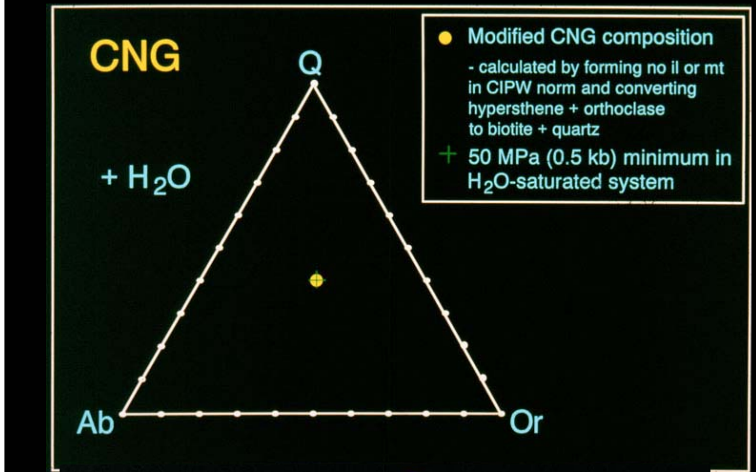


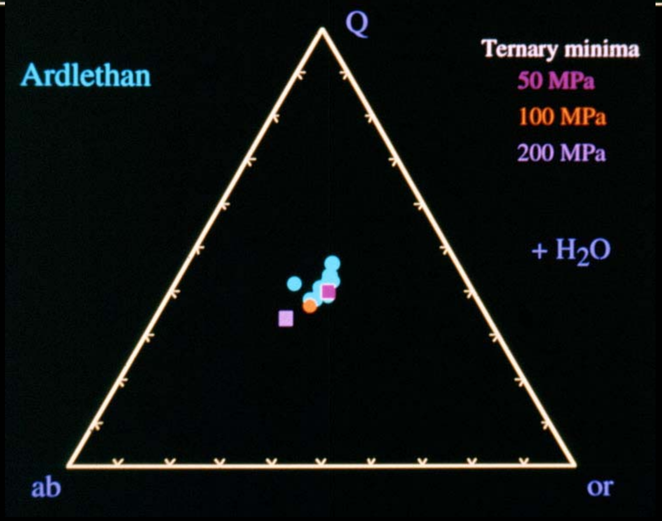

200
160
120
80
40
0
ppm Sr
65
67
69
71
73
75
% SiO_2
Glenbog
Nimmitabel
Towamba



This figure shows that the trends within individual plutons of the Glenbog Suite are parallel to that of the whole suite.

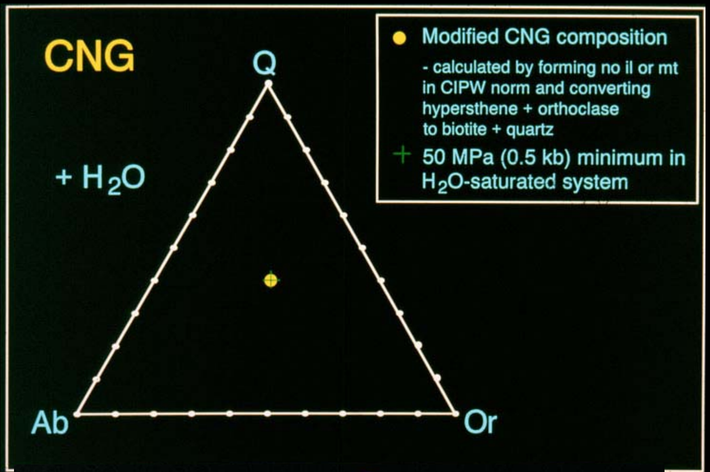
5. HYDROTHERMAL ALTERATION

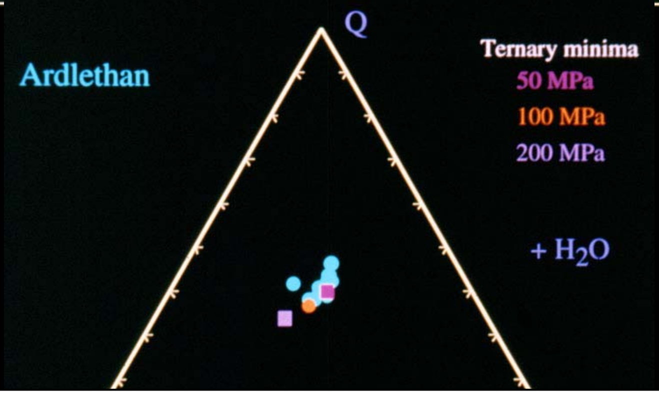




Subsolidus hydrothermal alteration may alter the composition of a granite as feldspars are replaced by sheet silicates with the loss of those elements that cannot be accommodated in the latter, principally Na, Ca and Sr, while K and Rb could be added from circulating solutions. The primary evidence for alteration is generally petrographic; however chemical data generally show that its effects are overrated. Many rocks in which there are clear petrographic signs of alteration plot in a very tight field or array on chemical variation diagrams, which would not be expected if their compositions were in part the result of low temperature alteration. Also, for most felsic granites of this type, the compositions are generally very close to the minimum-temperature compositions for hydrous melts in equilibrium with quartz and feldspars (Tuttle & Bowen 1958), shown on the left for the Cornubian granites for which metasomatism has frequently been invoked. The Ardlethan Granite is petrographically strongly altered, but it can be seen that there is still a dominant high-temperature magmatic signature.

5. HYDROTHERMAL ALTERATION



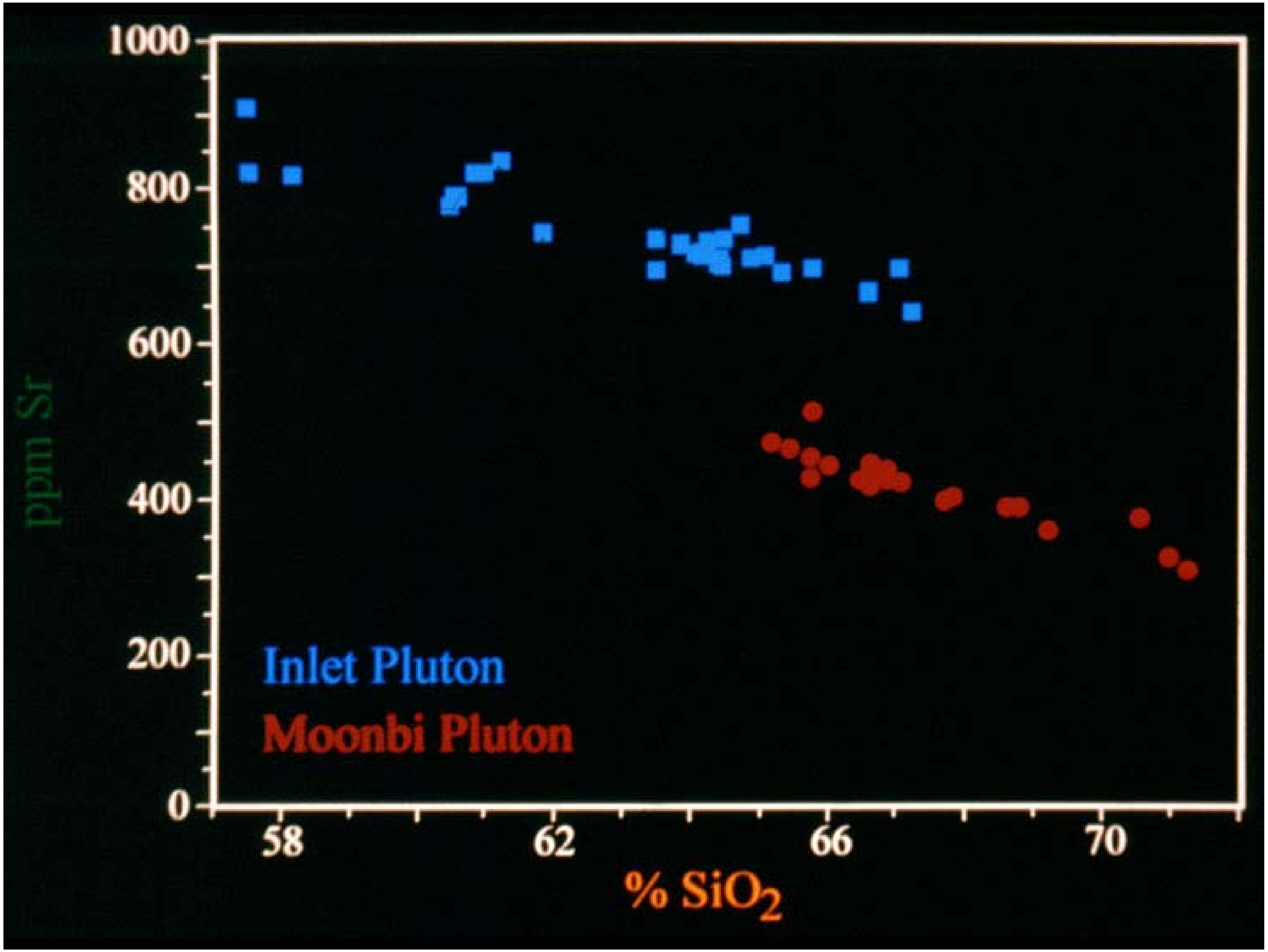


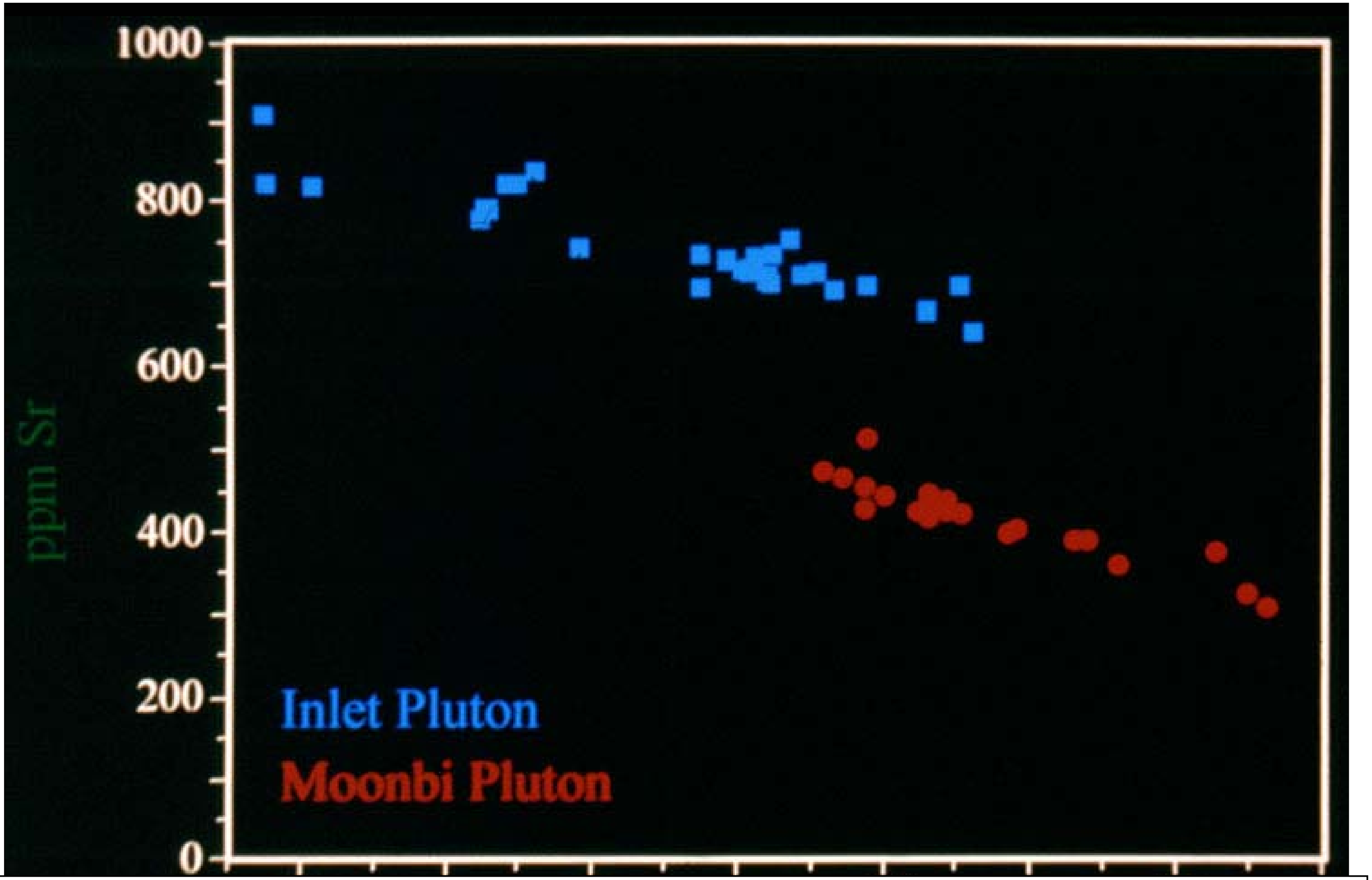
Subsolidus hydrothermal alteration may alter the composition of a granite as feldspars are replaced by sheet silicates with the loss of those elements that cannot be accommodated in the latter, principally Na, Ca and Sr, while K and Rb could be added from circulating solutions. The primary evidence for alteration is generally petrographic; however chemical data generally show that its effects are overrated. Many rocks in which there are clear petrographic signs of alteration plot in a very tight field or array on chemical variation diagrams, which would not be expected if their compositions were in part the result of low temperature alteration. Also, for most felsic granites of this type, the compositions are generally very close to the minimum-temperature compositions for hydrous melts in equilibrium with quartz and feldspars (Tuttle & Bowen 1958), shown on the left for the Cornubian granites for which metasomatism has frequently been invoked. The Ardlethan

Tuttle, O.F. & Bowen, N.L. (1958). Origin of granite in the light of experimental studies in the system $NaAlS_cO_8$-$KAlSi_3O_8$-SiO_2-H_2O. *The Geological Society of America Memoir* **74**.

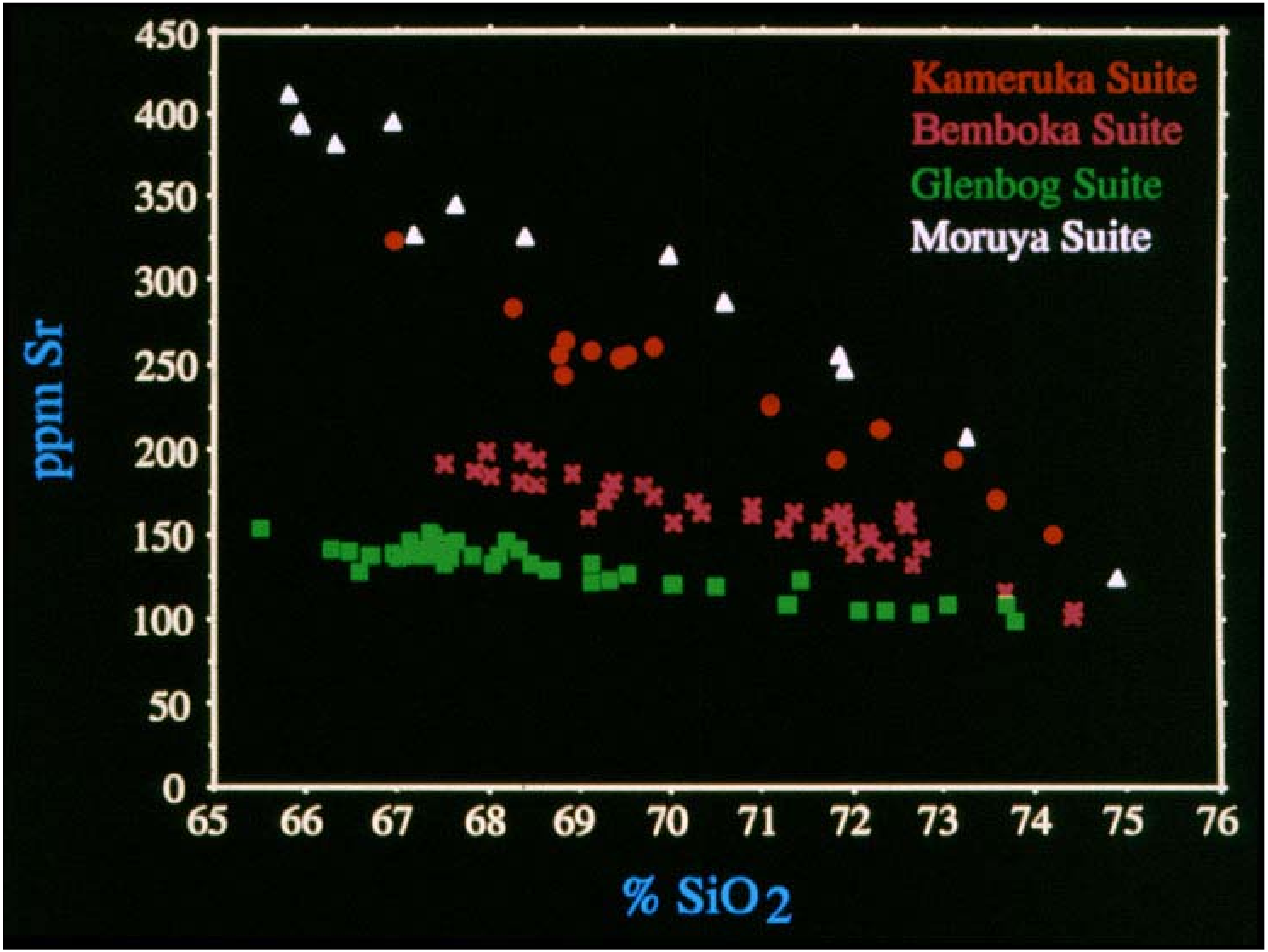
6. HETEROGENEOUS SOURCE ROCKS

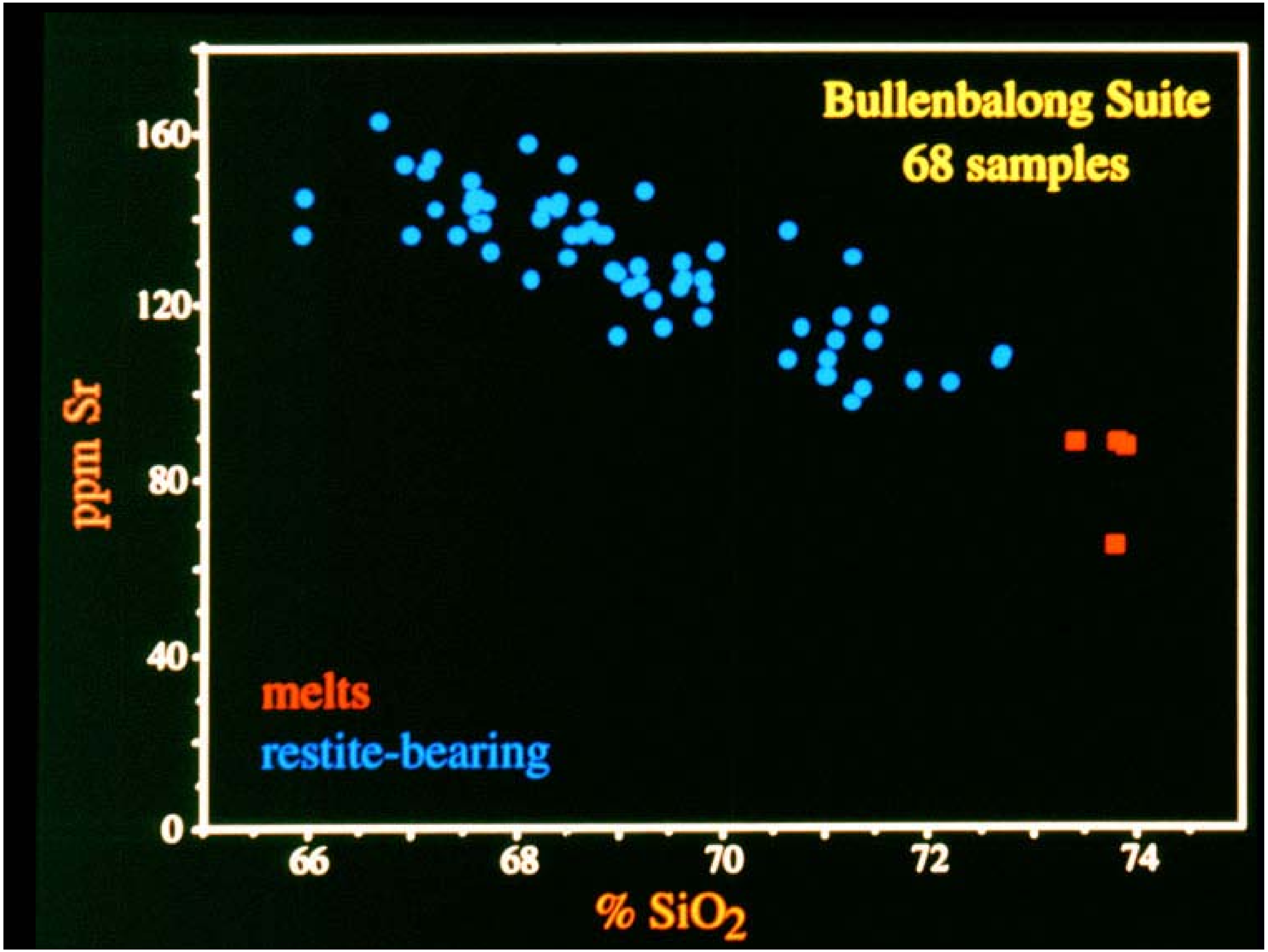
Suites of I-type granites in the LFB often show a remarkable compositional coherence, e.g. Sr in the Glenbog Suite shows extremely regular variation throughout 12 plutons that occur over a distance of more than 250 km. While homogeneity in a single pluton could be ascribed to thorough mixing at an early stage, for the Glenbog Suite this implies a relatively homogeneous distribution of Sr in the source rocks that must have contributed separately to the different plutons. The capacity to recognise suites depends on the internal variations within their two source materials being small relative to the overall differences between them. A corollary of the very precise suite definitions that can be made in many cases in southeastern Australia, is that either the source materials were very homogeneous, or were mixed thoroughly at an early stage in the production of the suite, that latter situation being unlikely when a suite comprises several dispersed plutons. Because sedimentary source rocks are more heterogeneous than those of I-type granites, S-type suites individually show more scatter in element concentrations about the dominant trend for a suite. Also, when the more mafic members of S-type suites have compositions close to those of their source rocks, it is possible that they might show variations inherited from those source materials.

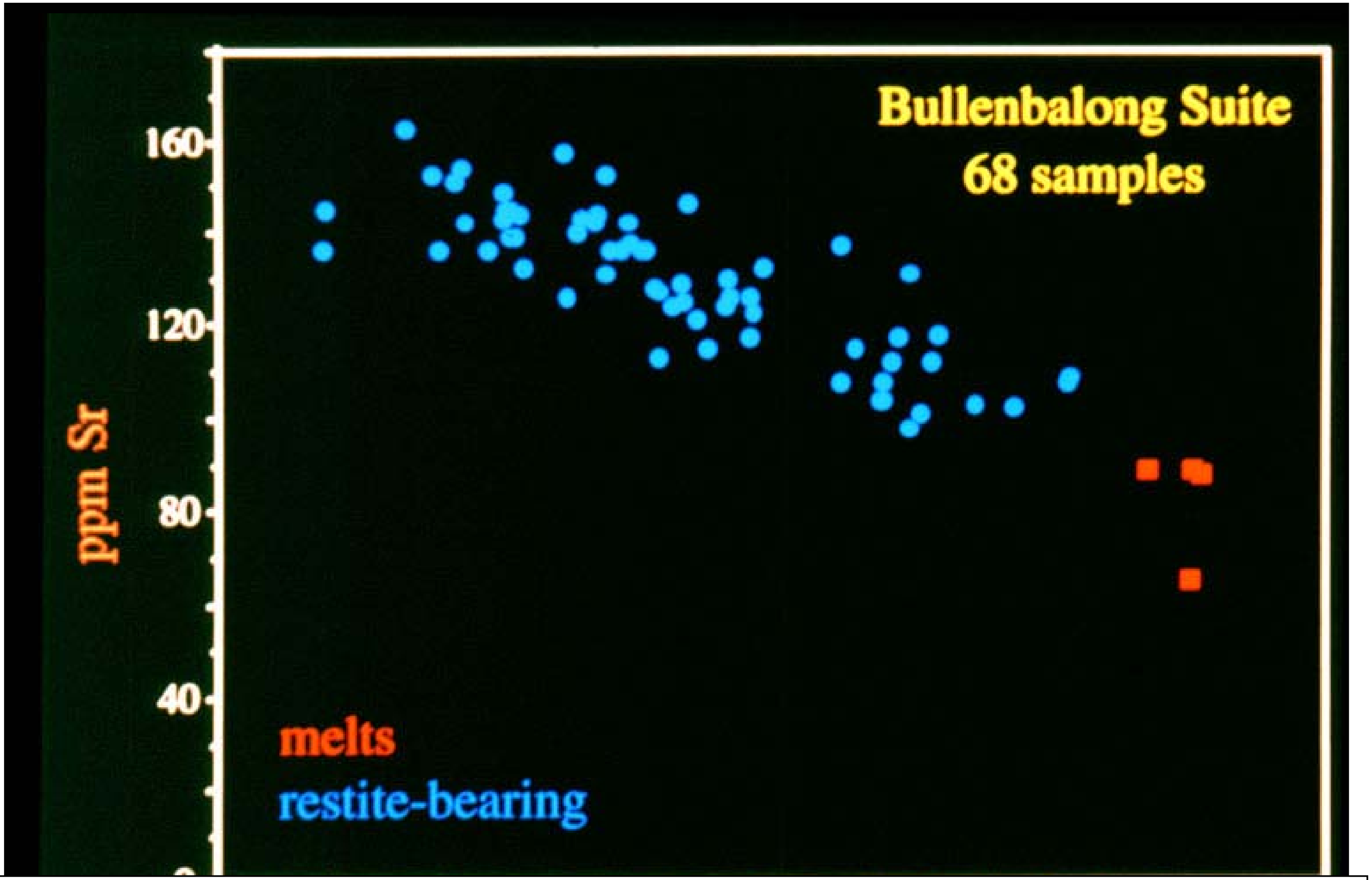

1000
800
600
400
200
0
ppm Sr
58
62
66
70
% SiO2
Inlet Pluton
Moonbi Pluton



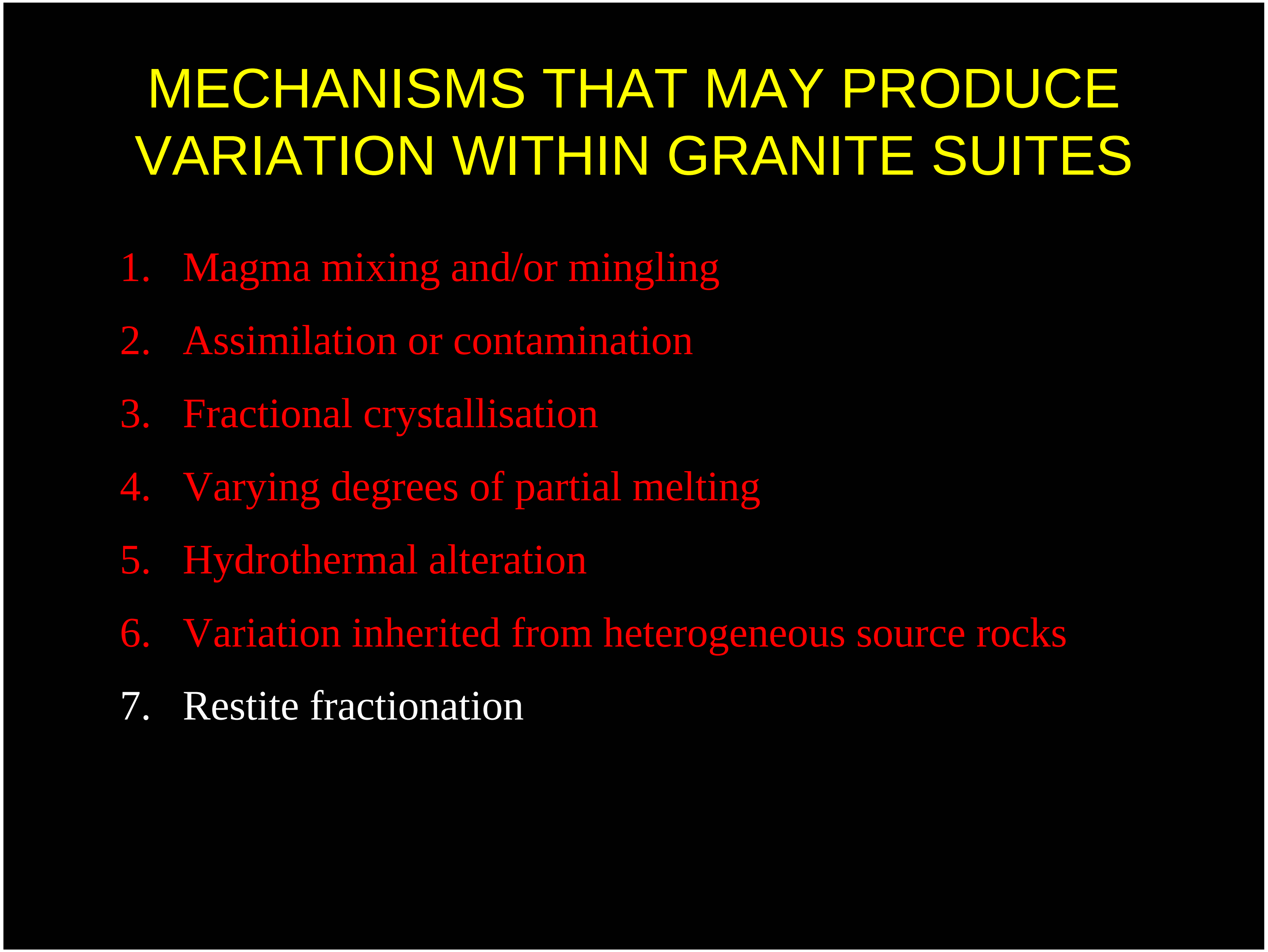
The rather high correlations between elements in this and the following figure for I-type granite suites could only have been produced if the source materials for each suite were not only distinctive, but also rather uniform in composition.


Kameruka Suite
Bemboka Suite
Glenbog Suite
Moruya Suite
ppm Sr
450
400
350
300
250
200
150
100
50
0
65
66
67
68
69
70
71
72
73
74
75
76
% SiO_2


Bullenbalong Suite
68 samples
ppm Sr
160
120
80
40
0
66
68
70
72
74
% SiO2
melts
restite-bearing



In contrast to the previous two figures, the S-type granites of the Bullenbalong Suite, while they generally define good trends, do show a much greater degree of scatter about that trend. This is to be expected for granites that were derived from relatively heterogeneous sedimentary rocks.



MECHANISMS THAT MAY PRODUCE VARIATION WITHIN GRANITE SUITES

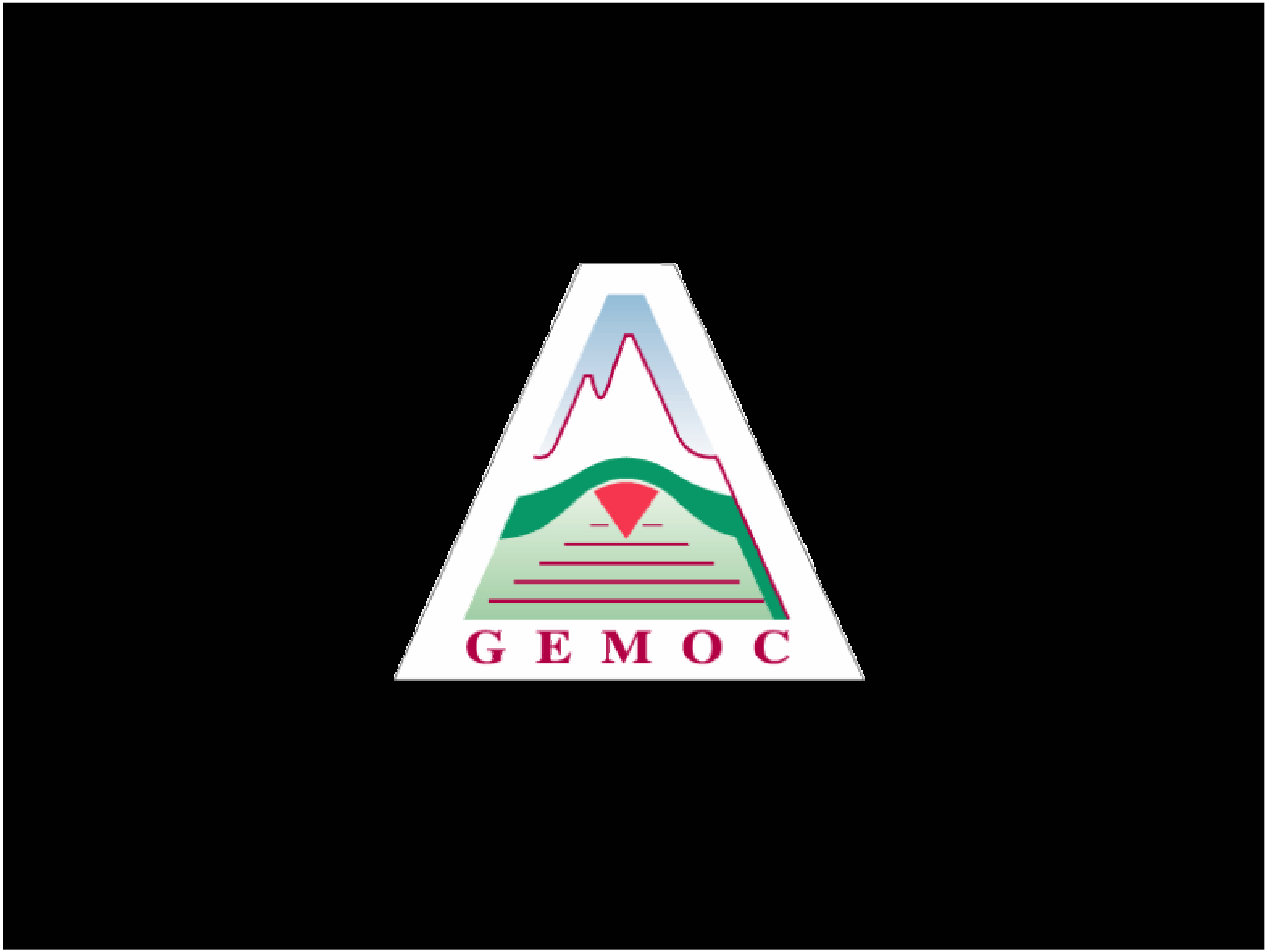
1. Magma mixing and/or mingling
2. Assimilation or contamination
3. Fractional crystallisation
4. Varying degrees of partial melting
5. Hydrothermal alteration
6. Variation inherited from heterogeneous source rocks
7. Restite fractionation

MECHANISMS THAT MAY PRODUCE VARIATION WITHIN GRANITE SUITES

1. Magma mixing and/or mingling
2. Assimilation or contamination
3. Fractional crystallisation
4. Varying degrees of partial melting
5. Hydrothermal alteration
6. Variation inherited from heterogeneous source rocks
7. Restite fractionation

The various mechanisms that have been proposed to account for the variations within granite suites are listed in this slide. Mechanisms 5 and 6, both forms of crystal fractionation, are regarded as the dominant processes. Nos 1 and 2 are also important. Nos 3, 4 and 7 may be locally significant but cannot be invoked to account for large scale compositional variations.

Chappell, B.W. 1996. Compositional variation within granite suites of the Lachlan Fold Belt: its causes and implications for the physical state of granite magma. *Transactions of the Royal Society of Edinburgh: Earth Sciences* **87**, 159-170.


GEMOC