TOWARDS A UNIFIED MODEL OF GRANITE PETROGENESIS

Bruce W. Chappell
GEMOC, Macquarie University, NSW 2010

Modern granite studies date from the observation by Tuttle & Bowen (1958) that the compositions of the most felsic granites correspond closely with those of hydrous melts produced in equilibrium with quartz and feldspars in the laboratory. This resolved the controversy about whether or not granites are igneous rocks firmly in favour of the magmatic view. These experiments do not tell us whether such haplogranites result from the fractional crystallisation of a more mafic melt, as Bowen (1949) believed, or of partial melting of appropriate material to produce primary granite magmas, which Bowen (1947) conceded could occur. There is now enough evidence to show that haplogranites can form in either way, with uncertainty about the relative amounts and the mechanism of formation in certain cases. However, primary felsic granite magmas, the products of partial melting, are overall the much more abundant type.

Although they are clearly magmatic, details of the origin of the less felsic granites are controversial. Many processes have been proposed to account for the details of formation of such granites and the generation of compositional variation within granite suites. All of these processes probably operate, and can be firmly established in particular examples. The question is on what scale and how frequently a particular process operated. Mechanisms that have been determined in one or a few cases should not necessarily be regarded as general processes. Neither should those processes established in small areas be regarded as necessarily applying to granite bodies of batholithic dimensions.

The key to the resolution of many of these problems has been the observation that granites of very similar bulk compositions have formed over a wide range of magmatic temperatures. *High-temperature granites* were produced under conditions where zircon was soluble when the more mafic rocks were produced, and were defined on that basis by Chappell *et al*. (1998). These rocks formed from complete melts, fractional crystallisation was an important process in their evolution, and they include cumulate rocks. Zircon was saturated in the *low-temperature granites*, even when they have bulk compositions ~ 60% SiO_2, the magmas could never have been completely molten, and the rocks evolved principally by the removal of entrained crystals of restite. Low-temperature granites formed when the source rocks contained sufficient of the quartz, albite, K-feldspar and H_2O components for enough melt to be produced for a magma, that is a fluid comprising melt and crystals, to form at temperatures near 800°C. High-temperature granites generally result from the partial melting of source rocks in which at least one of those components was depleted before the melt could separate from its source materials, with the result that melting continued to higher temperatures. If there is insufficient of these low melting components to produce an extractable melt or magma even at higher temperatures, then the source rock is infertile. Each of those cases will now be considered.

Insufficient minimum-temperature melt forms because the source rocks are deficient in:

1. **Quartz**. Melting continues to higher temperatures with the incorporation of more albite and K-feldspar components in the melt. This leads to the production of quartz monzonites, monzodiorites, etc., as with rocks of the Boggy Plain Supersuite.
2. **Albite**. This is the least common case, but S-type granites that were derived from heavily weathered source rocks may approach this situation. Such pelitic rocks contain low amounts of albite, and perhaps quartz, and may be infertile in terms of producing a granite magma.

3. **K-feldspar**. Continued melting in the absence of K-feldspar produces melts of tonalitic composition. This is a common situation in production of the large continental margin batholiths such as those of the Cordillera, and in the Clarence River Supersuite, which comprise relatively low-K rocks derived from source rocks sharing that character.
4. **H_2O**. In this case, the low H_2O-contents leads to melting of the other three components at higher temperatures, producing the A-type granites. The higher temperatures are shown by the high Zr contents and consequent higher zircon saturation temperatures of these rocks. Partitioning of other distinctive trace elements, such as the REE, Y and Ga, into the melt, also occurs at these higher temperatures.

Most granites suites evolve by the removal of crystals from a melt, that is by crystal fractionation. This may be either fractional crystallisation in which the crystals were precipitated from the melt (mainly high-temperature), or restite crystal fractionation where the crystals had been entrained in the melt (low-temperature). Both mechanisms are important, and their operation in a particular case is determined by the composition and hence the physical properties of the melt, which is largely determined by the temperature of partial melting, which in turn is largely a function of the source composition. It is those source rock compositions that basically determine not only the composition of a melt or magma, but also the physical nature of the magmatic response of source rocks to heating, or the fraction of melt in the migma or magma, and the manner in which it fractionates. This dependence on source compositions of both the physical and chemical properties of magmas, and their evolution, provides a unifying basis for further developing our understanding of the origins of granites.

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TOWARDS A UNIFIED THEORY OF GRANITE PETROGENESIS


Bowerman's Nose, Dartmoor Granite

Bruce
Chappell

GEMOC

THE CONTRIBUTION OF TUTTLE & BOWEN (1958)

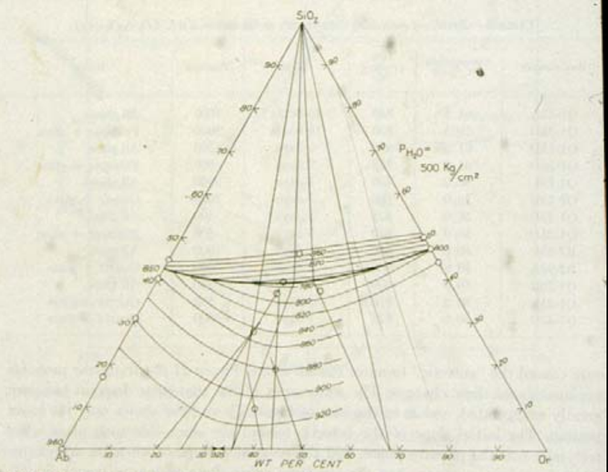


FIGURE 22.—*The 500 kg/cm² isobaric equilibrium diagram for the system $NaAlSi_3O_8$–$KAlSi_3O_8$–SiO_2–H_2O projected onto the anhydrous base of the $NaAlSi_3O_8$–$KAlSi_3O_8$–SiO_2–H_2O tetrahedron*

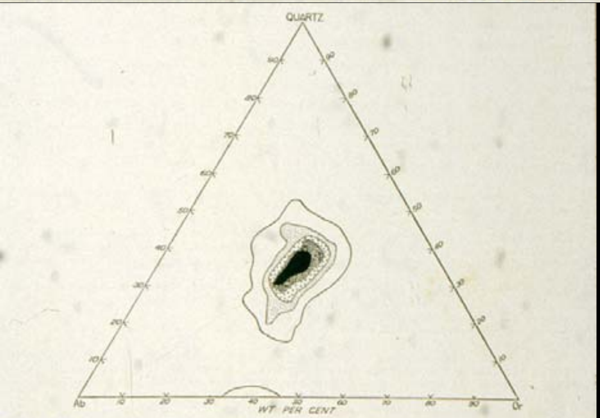


FIGURE 42.—*Contour diagram illustrating the distribution of normative albite, orthoclase, and quartz in all (571) the analyzed plutonic rocks in Washington's Tables that carry 80 per cent or more normative Ab + Or + Q*

Modern granite studies started with the observations of Tuttle & Bowen (1958) that:

1. Hydrous silicate melts that occur at the lowest temperatures contain close to equal proportions of Q, Ab and Or components, and

2. The most felsic granites containing more than 80% Q + Ab + Or components, have compositions that are very close to those lowest T melts.

This resolved the arguments over whether granites are metamorphic or igneous rocks, firmly in favour of the magmatic* view.

These experiments are consistent with the felsic rocks forming as the end products of fractional crystallisation of mafic rocks, as Bowen believed, or as primary felsic melts, formed during partial melting, as is now widely thought to be the case.

*magma = hot natural fluid, may be melt plus crystals, not necessarily melt alone (Scrope, 1862)

THE CONTRIBUTION OF TUTTLE & BOWEN (1958)

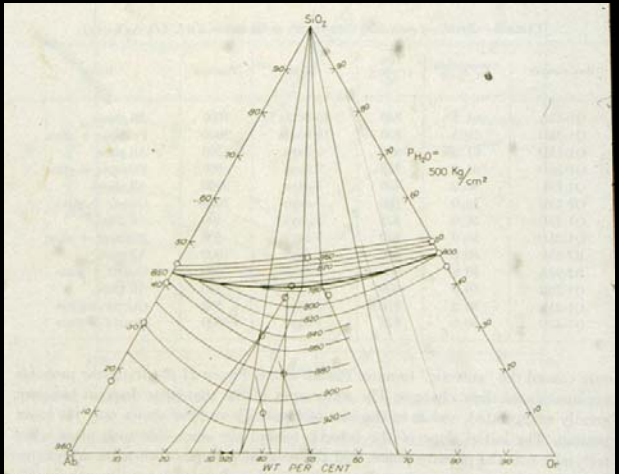
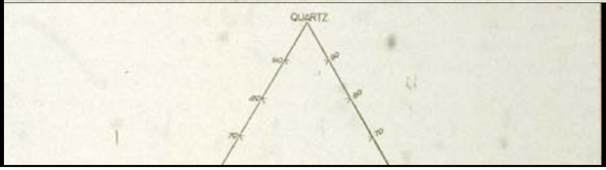


FIGURE 22.—The 500 kg/cm² isobaric equilibrium diagram for the system $NaAlSi_3O_8$-$KAlSi_3O_8$-SiO_2-H_2O projected onto the anhydrous base of the $NaAlSi_3O_8$-$KAlSi_3O_8$-SiO_2-H_2O tetrahedron



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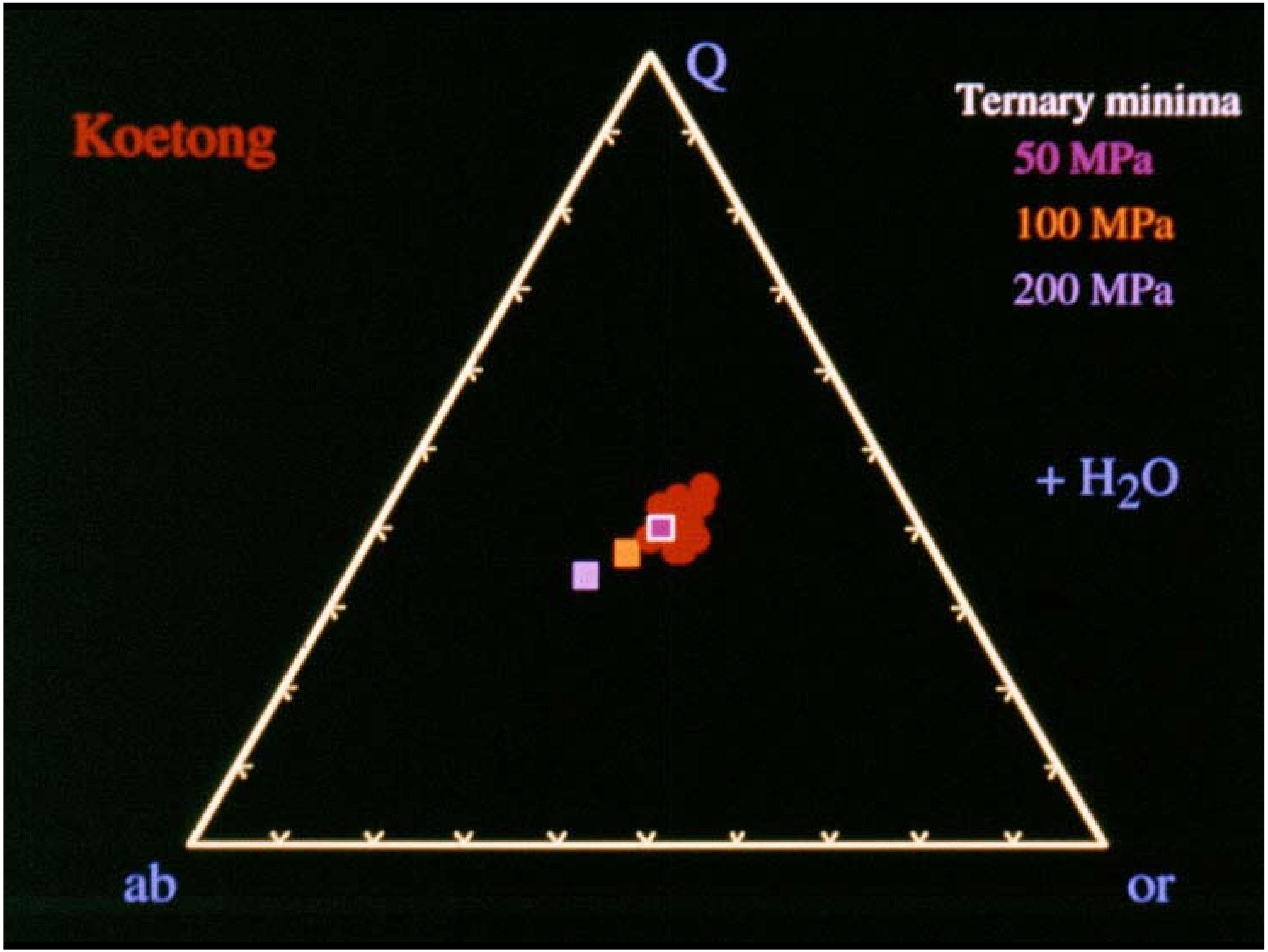
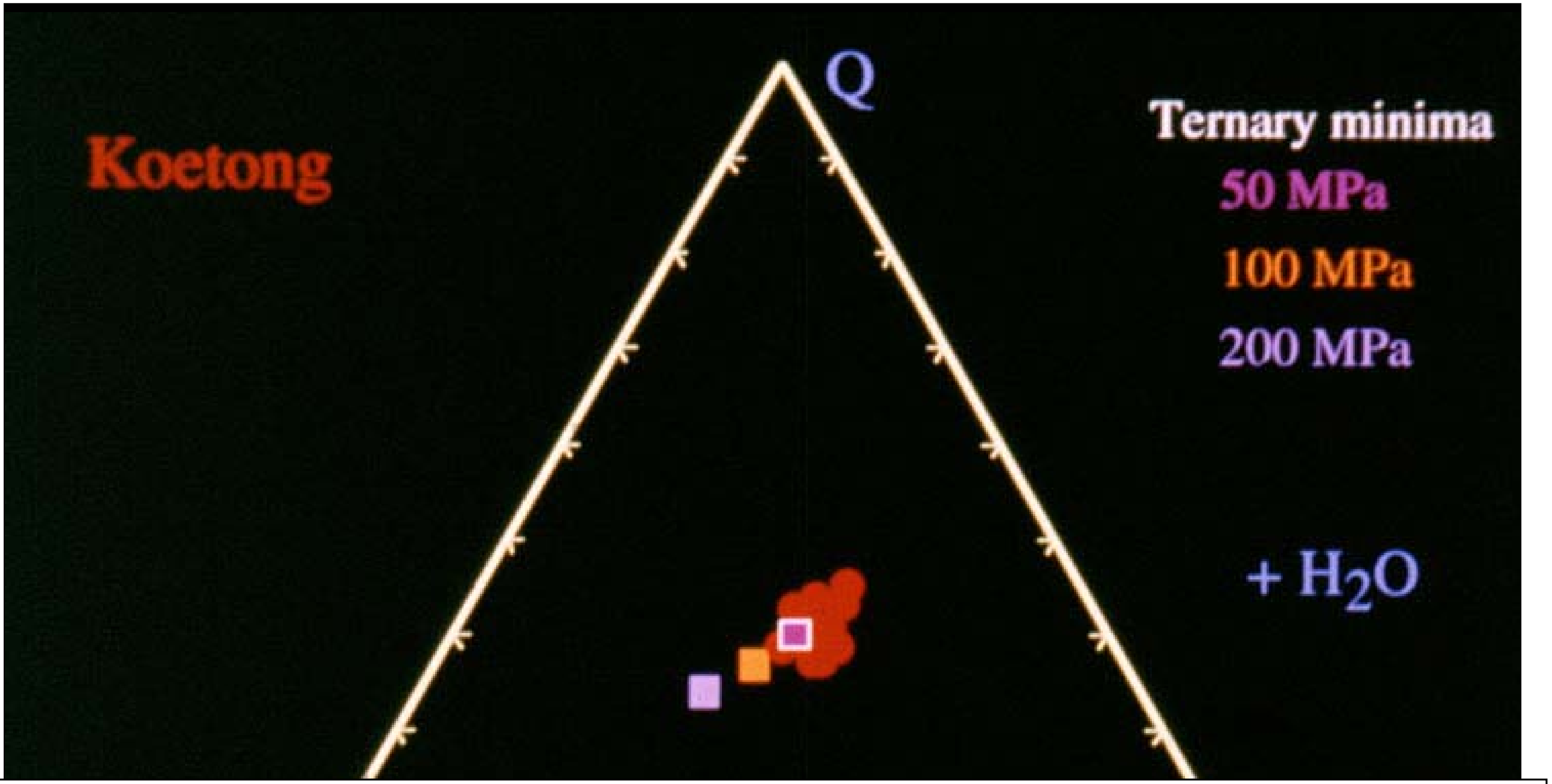
Scrope (1862) quoted by Shand (1950)

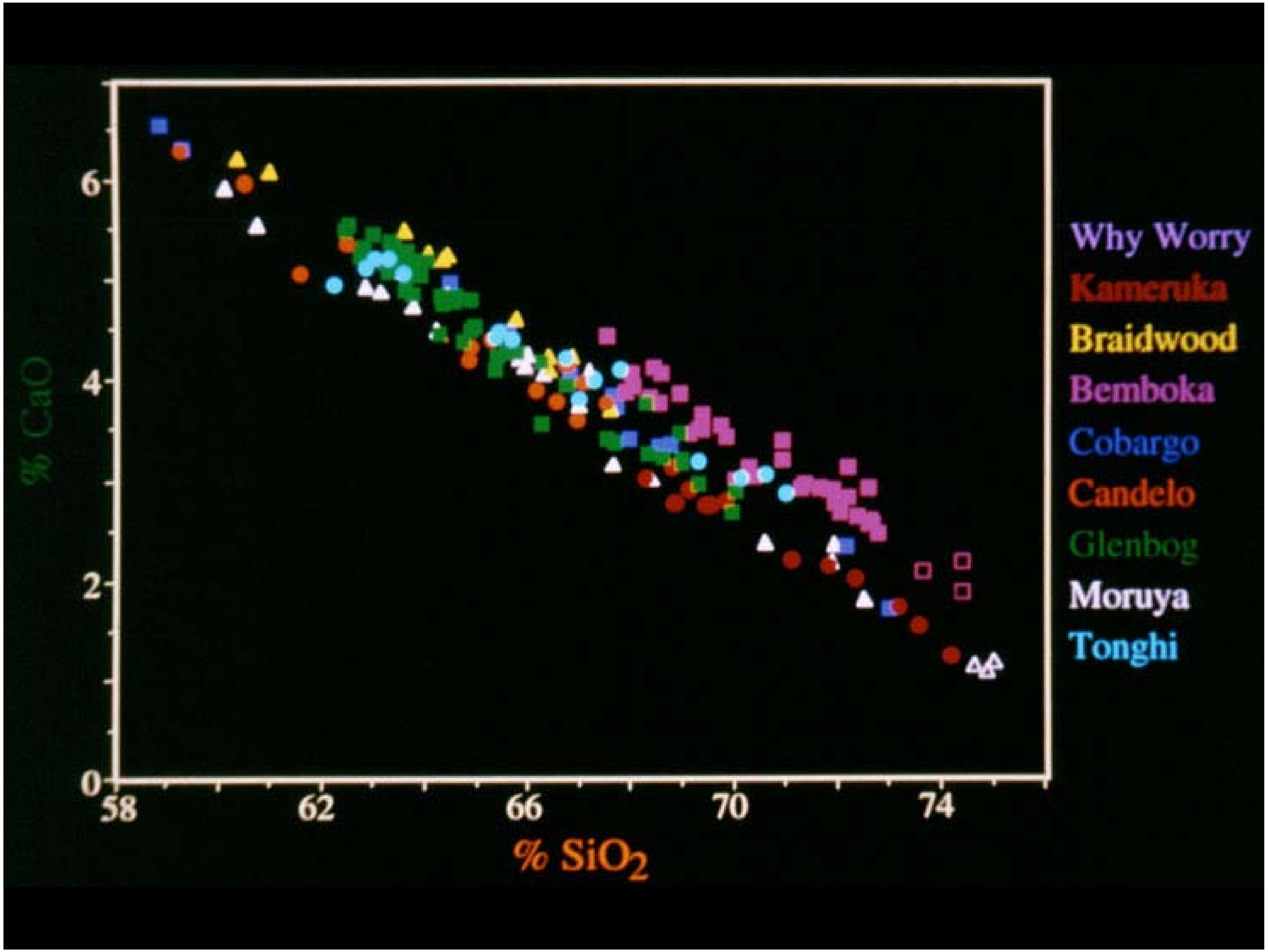
Shand, S.J. 1950. *Eruptive rocks* (4th ed.). Murby, London.


Koetong
Q
ab
or
Ternary minima
50 MPa
100 MPa
200 MPa
+ H_2O



The most fractionated granites of the S-type Koetong Suite illustrate the convergence between the compositions of felsic granites and of the experimentally determined minimum-temperature melts determined by Tuttle & Bowen (1958).

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**.


% CaO
0
2
4
6
58
62
66
70
74
% SiO_2
Why Worry
Kameruka
Braidwood
Bemboka
Cobargo
Candelo
Glenbog
Moruya
Tonghi

ORIGINS OF THE LESS FELSIC GRANITES

There is far less agreement about details of the origins of the less felsic granites, such as those shown in the previous slide.

Although they are clearly magmatic, details of the origin of the less felsic granites are controversial. Many processes have been proposed to account for the details of formation of such granites and the generation of compositional variation within granite suites. All of these processes probably operate, and can be firmly established in particular examples. The question is on what scale and how frequently a particular process operated. Mechanisms that have been determined in one or a few cases should not necessarily be regarded as general processes. Neither should those processes established in small areas be regarded as necessarily applying to granite bodies of batholithic dimensions.

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

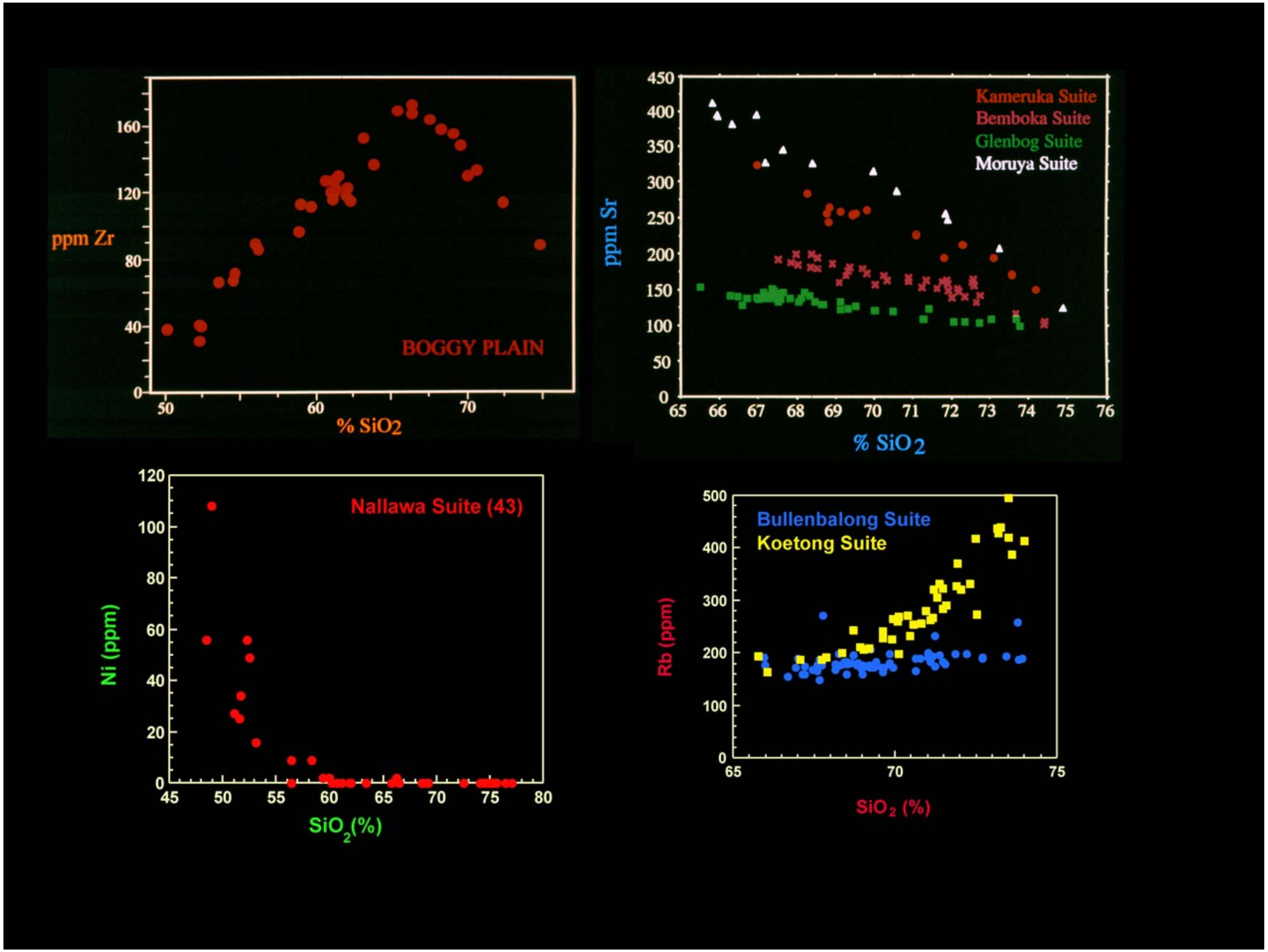
THE DOMINANT MECHANISMS

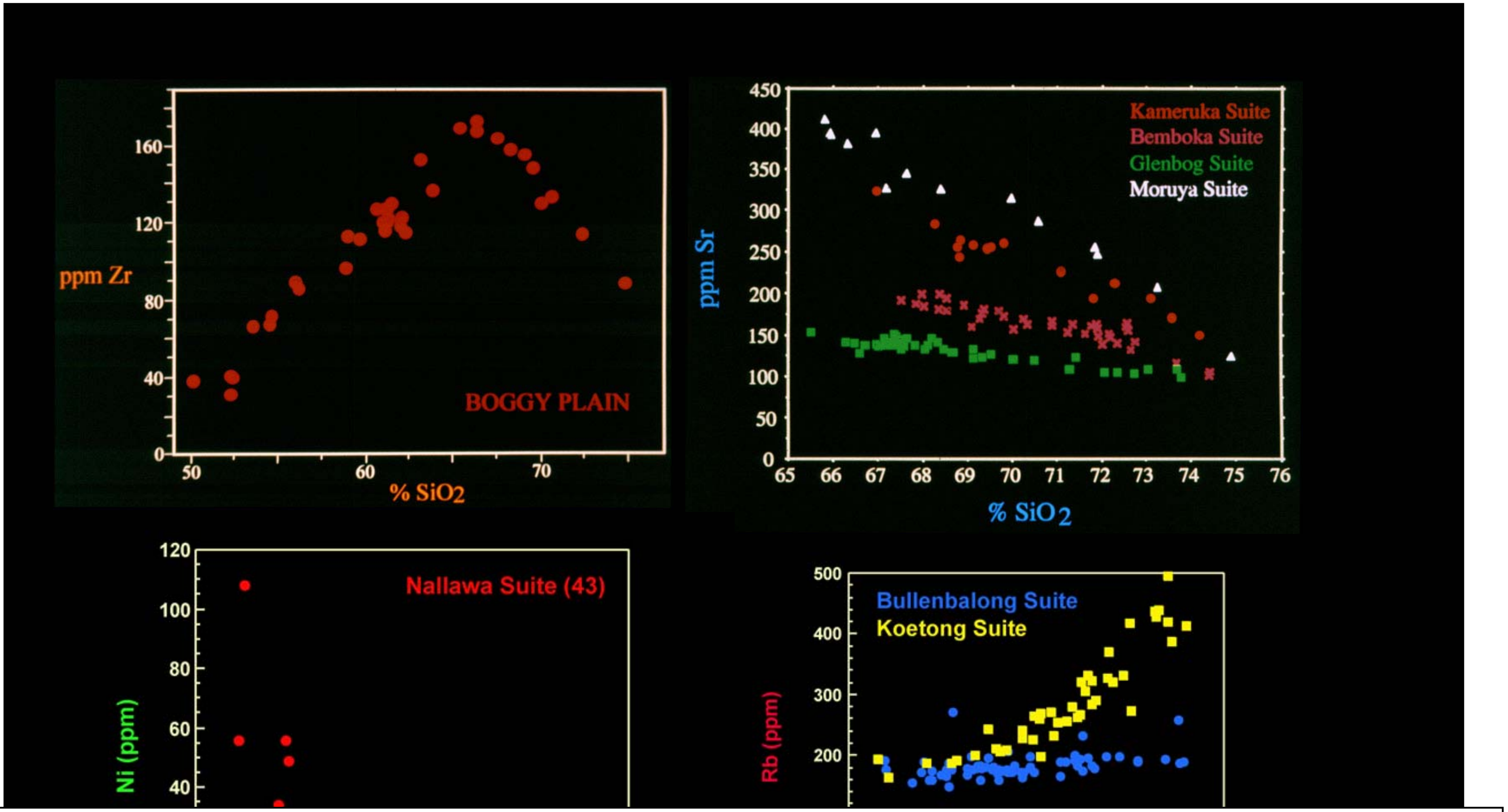
Of the possible mechanisms shown in the previous slide, the two mechanisms of crystal fractionation must be regarded as the dominant processes.

Fractional crystallisation is the classic process in which the precipitation and removal of crystals from a largely or completely molten magma leads to a series of more evolved compositions. This takes place among the high-temperature granites and in the late stages of evolution of the low-temperature granites. It is characterised by curved trends on element variation diagrams. It is an important process in the concentration of metals, and H_2O, at the magmatic stage and is more likely to lad to mineralisation.

The process of restite crystal fractionation leads to changes in composition through the removal of entrained crystals residual from partial melting of the source. It is characteristic of the low-temperature granites, that is most I-types and all S-types, and may be followed by low-temperature fractional crystallisation.

Some examples of the distinctive patterns of compositional variation associated with these two processes are seen in the next slides.

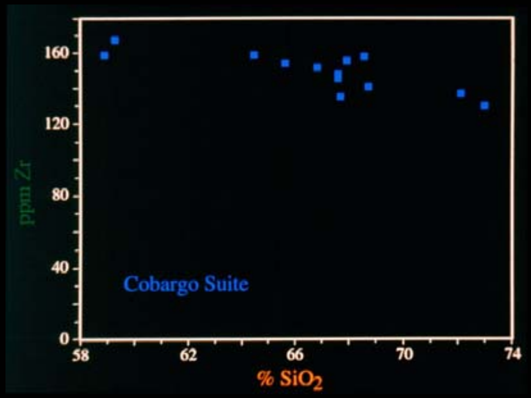

ppm Zr
160
120
80
40
0
50
60
70
% SiO2
BOGGY PLAIN
450
400
350
300
250
200
150
100
50
0
ppm Sr
65
66
67
68
69
70
71
72
73
74
75
76
% SiO2
Kameruka Suite
Bemboka Suite
Glenbog Suite
Moruya Suite
120
100
80
60
40
20
0
Ni (ppm)
45
50
55
60
65
70
75
80
SiO2(%)
Nallawa Suite (43)
500
400
300
200
100
0
Rb (ppm)
65
70
75
SiO2 (%)
Bullenbalong Suite
Koetong Suite

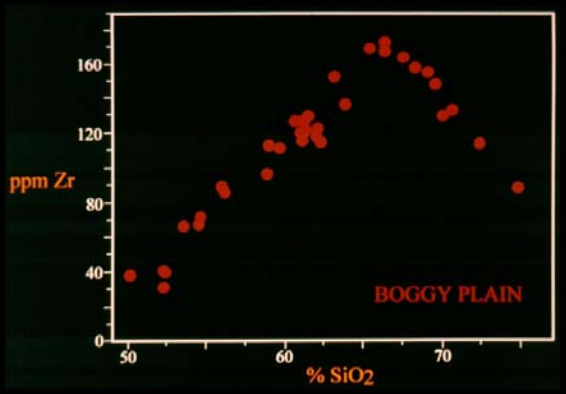


Variation in the Bemboka Suite is dominated by restite separation, with the three most felsic samples being further modified by fractional crystallisation of the primary melt.

For the Koetong Suite, it is thought that below about 69% SiO_2, the compositions evolved by restite separation, and by fractional crystallisation at higher SiO_2 values. For the Bullenbalong Suite, one sample at the felsic end was modiified by fractional crystallisation.

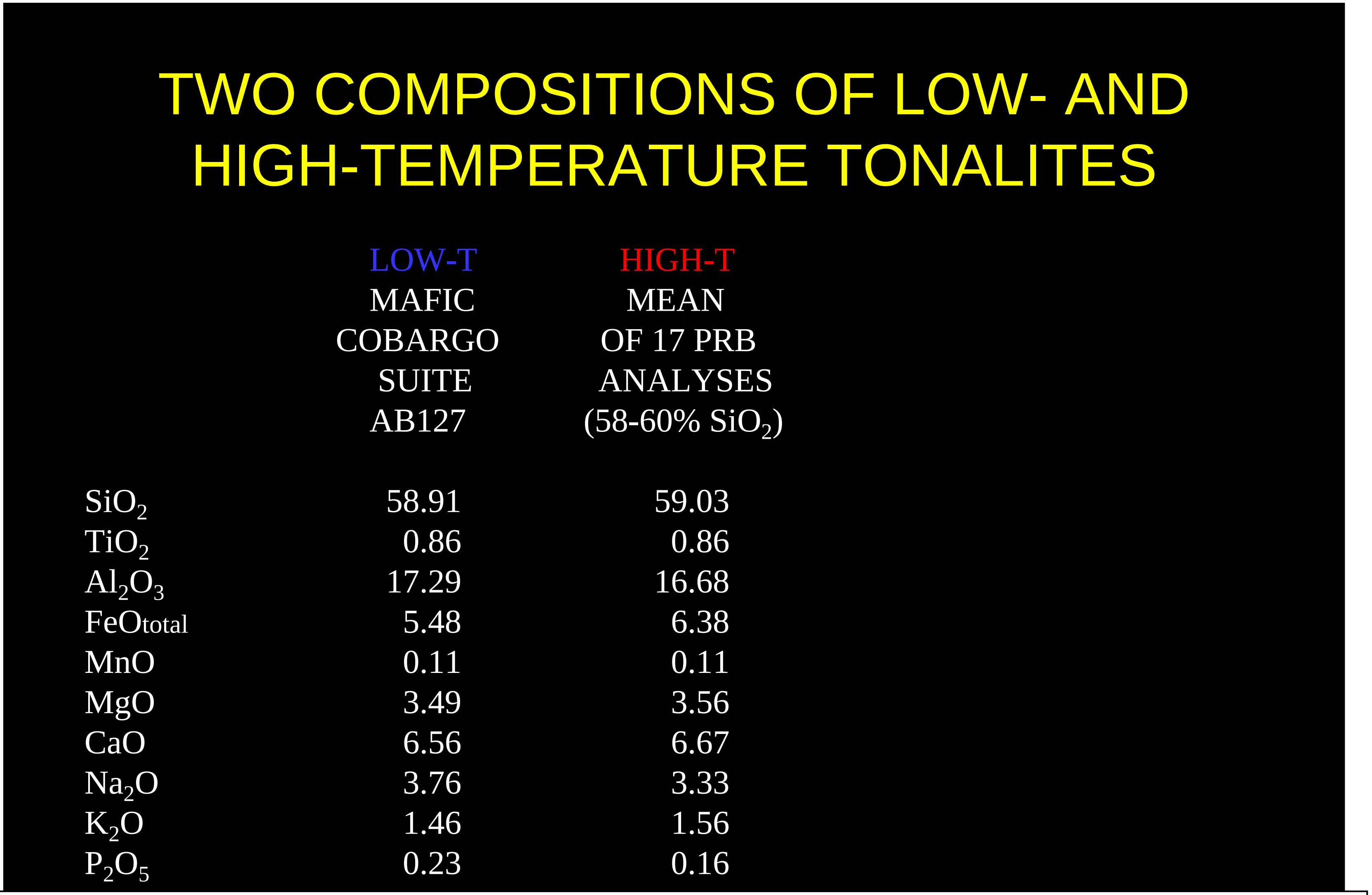
LOW- AND HIGH-TEMPERATURE GRANITES





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

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



TWO COMPOSITIONS OF LOW- AND HIGH-TEMPERATURE TONALITES

	LOW-T MAFIC COBARGO SUITE AB127	HIGH-T MEAN OF 17 PRB ANALYSES (58-60% SiO_2)
SiO_2	58.91	59.03
TiO_2	0.86	0.86
Al_2O_3	17.29	16.68
FeO_{total}	5.48	6.38
MnO	0.11	0.11
MgO	3.49	3.56
CaO	6.56	6.67
Na_2O	3.76	3.33
K_2O	1.46	1.56
P_2O_5	0.23	0.16

The analysis of a low-temperature tonalite is from the Cobargo Suite of the Bega Batholith.

The composition of the high-temperature tonalite is an average of 17 analyses from the Peninsular Ranges Batholith of Southern and Baja California.

WHY ARE THERE LOW- AND HIGH-T GRANITES?

Why do granites form at varying temperatures, particularly when we consider that this is not a function of the composition of a particular granite? For example, tonalites of the Cobargo Suite apparently formed at temperatures ~ 800°C and are “low-temperature”, while Cordilleran-like tonalites formed at temperatures in excess of 1000°C and are “high-temperature”. Yet both types can have very similar major element compositions, as shown in the previous slide, and hence similar temperatures for the start of melting (solidus) and crystallisation (liquidus). The two types cannot be discriminated using major elements.

The answer, as with so many things related to granites, lies in the source rock compositions. A granite will be low-temperature in nature if there are sufficient low-temperature melt components in the source region to form an extractable magma at low magmatic temperatures. If there are insufficient of those components, then melting must continue to higher temperatures, if a granite magma is to be produced.

SOURCE ROCKS WITH ENOUGH Q, Ab, Or, H_2O TO FORM AN EXTRACTABLE LOW-T MAGMA

If the source rocks contain sufficient Q, Ab, Or and H_2O for the amount of melt to reach the critical melt fraction (~35%) before any of the first three components are depleted, then a low-T magma will be produced. This may be extracted from the source as a melt, but more probably *en masse* as a mixture of crystals and melt that may later fractionate to produce a range of rock compositions.

The low-temperature granites that result may be I- or S-type, depending on the source materials, and comprise monzogranites (adamellites) through granodiorites or quartz monzonites (low-K or high-K sources), to tonalites and quartz monzodiorites. The more mafic rocks have that property because of the presence of entrained restite and will have compositional features that reflect their source rock compositions. Examples are the tonalites at Jindabyne and Moruya-Cobargo, which reflect lower-K source rocks, the monzogranites of the Moonbi Supersuite from higher-K sources, and the distinctive S-type granodiorites and tonalites that have compositions that reflect a prior weathering event (lower Ca and Na).

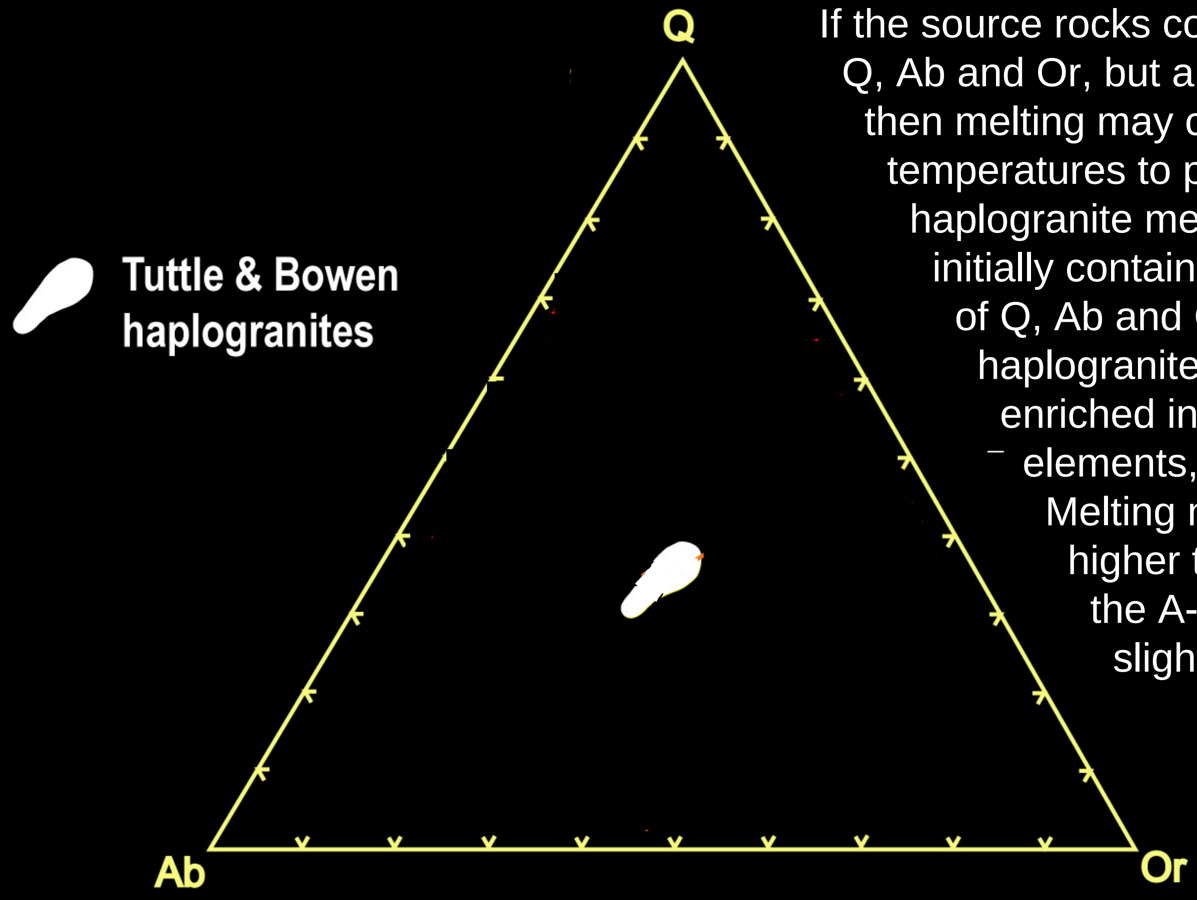
SOURCE ROCKS WITHOUT ENOUGH Q, Ab, Or, H_2O TO FORM AN EXTRACTABLE LOW-T MAGMA

There are four obvious simple or end-member cases for which the source rocks would not form an extractable low-temperature melt because of a critical deficiency in one component. These are:

	high-T product
1. Source rocks deficient in H_2O (free or combined)	A-types
2. Source rocks deficient in SiO_2 (quartz)	monzonites
3. Source rocks deficient in K (K-feldspar and/or biotite)	tonalites
4. Source rocks deficient in Na (albite)	infertile

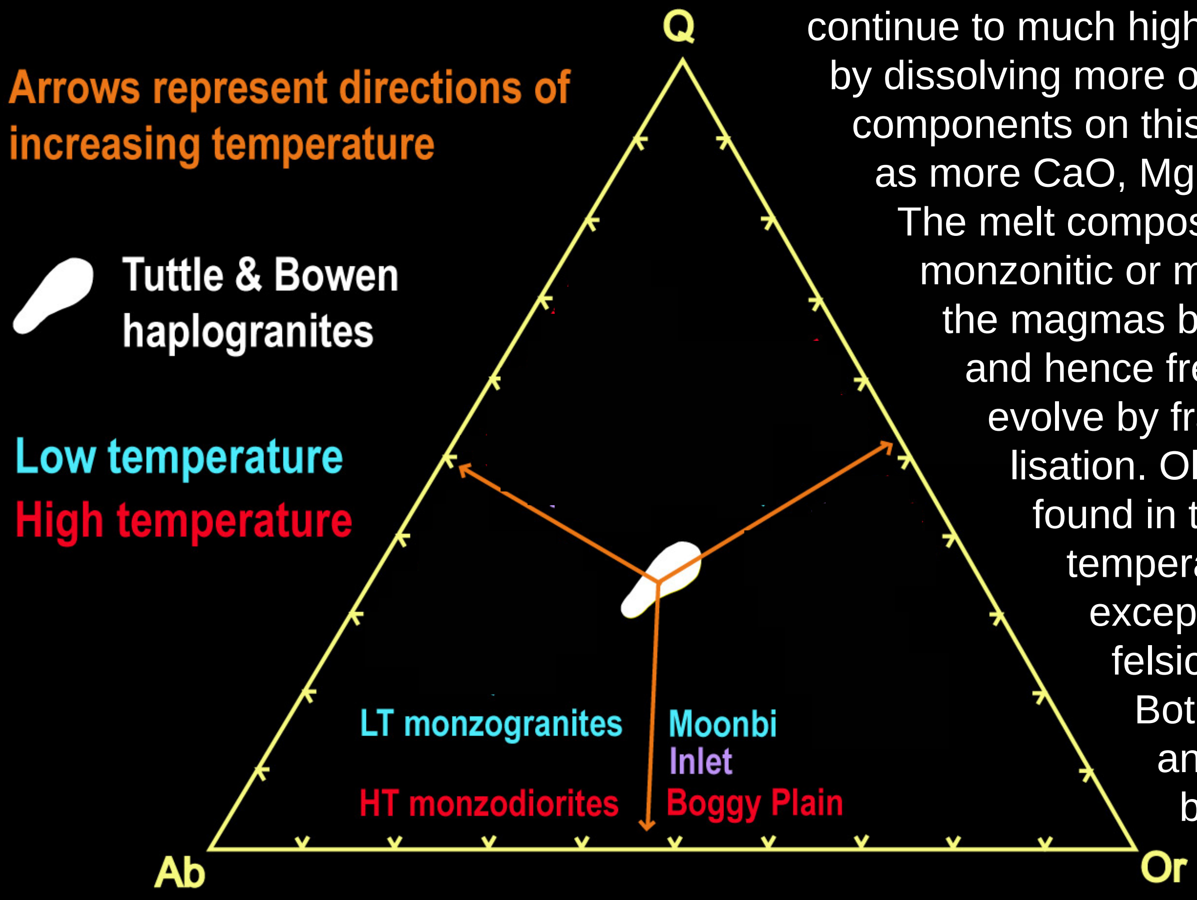
Each of these will now be discussed.

SOURCE COMPOSITIONS DEFICIENT IN H_2O ONLY



If the source rocks contain sufficient Q, Ab and Or, but are deficient in H2O, then melting may continue to higher temperatures to produce an A-type haplogranite melt. Such a melt will initially contain similar proportions of Q, Ab and Or to the low-temp. haplogranites, but will be enriched in certain trace elements, e.g. Zr, Ga, Y. Melting may continue to higher temperatures when the A-type melts become slightly less felsic.

SOURCE ROCK COMPOSITIONS CRITICALLY DEFICIENT IN QUARTZ



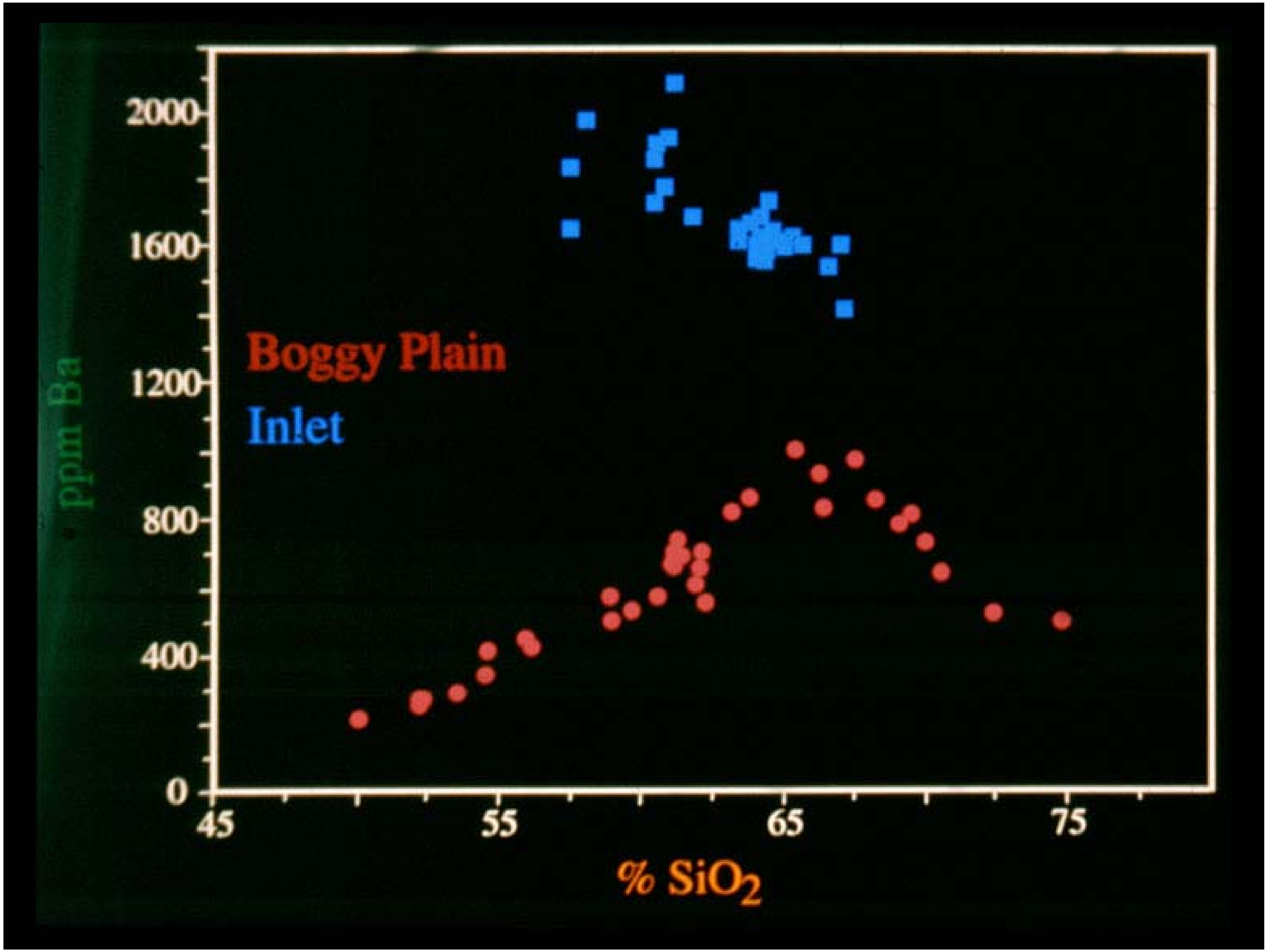
Arrows represent directions of increasing temperature

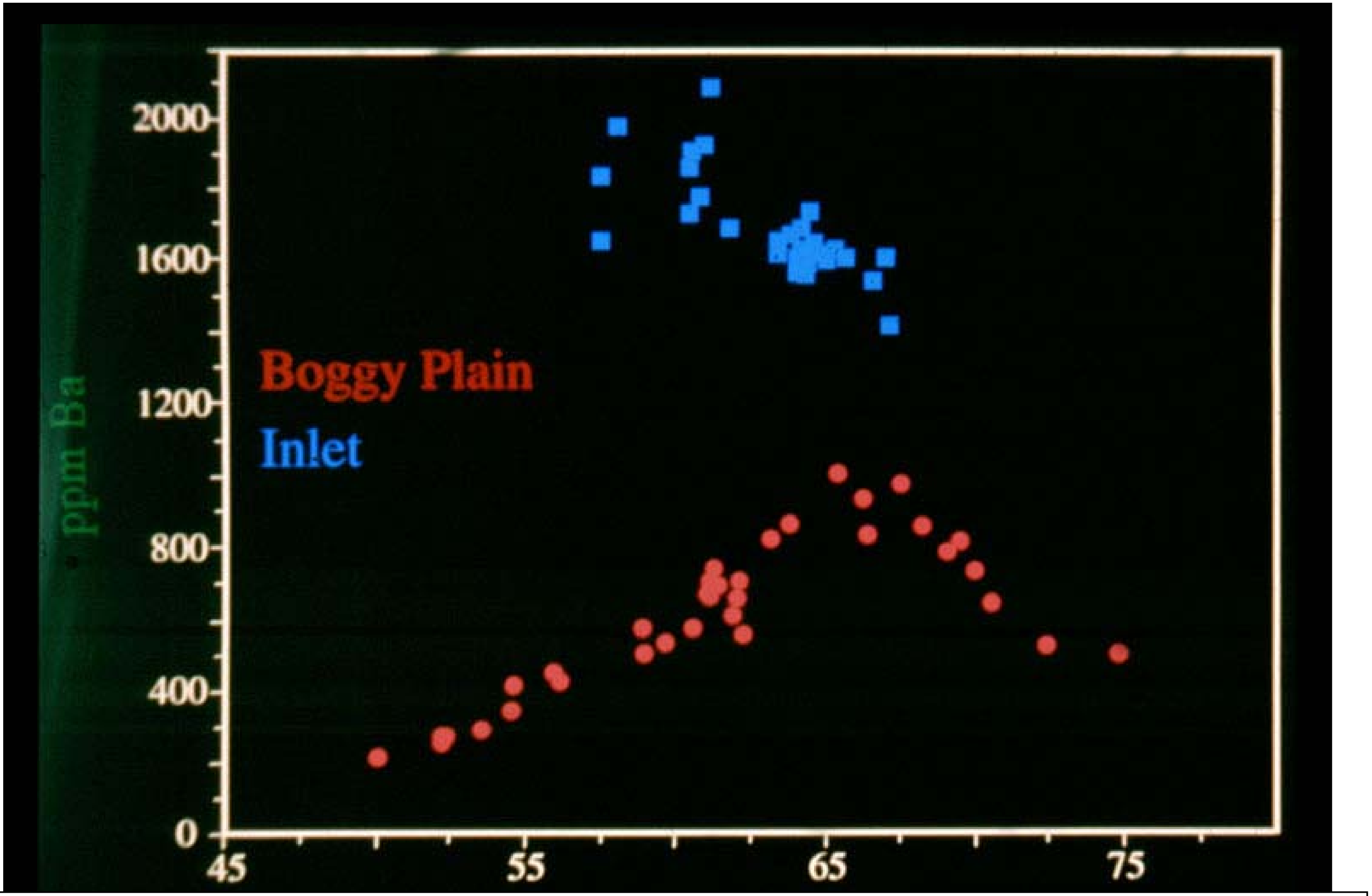
Tuttle & Bowen haplogranites

Low temperature

High temperature

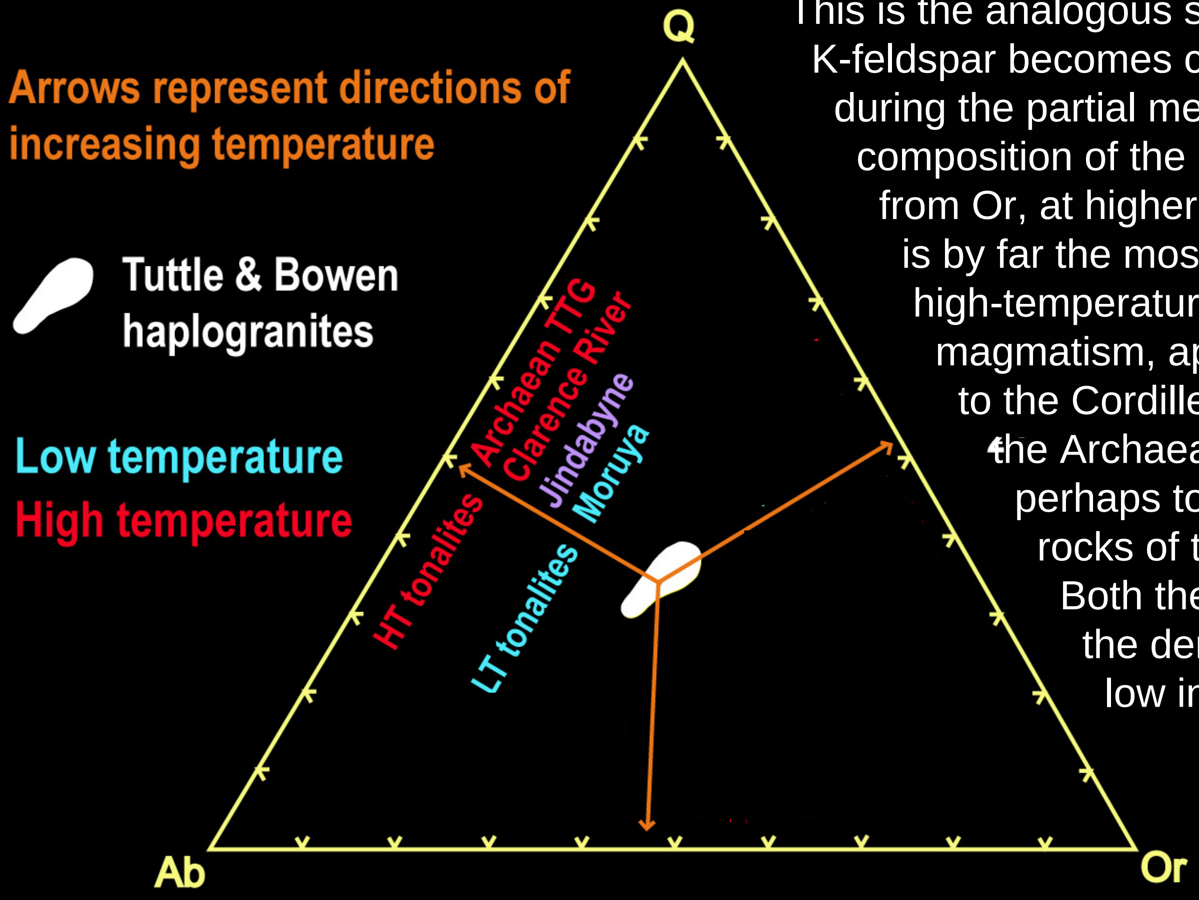
If the source rocks are critically deficient in the quartz component then melting will continue to much higher temperatures by dissolving more of the Ab and Or components on this diagram, as well as more CaO, MgO and FeO, etc. The melt compositions will be monzonitic or monzodioritic and the magmas being less viscous and hence free of restite, will evolve by fractional crystallisation. Old zircon will not be found in these high-temperature granites, except as xenocrysts in felsic fractionated melt. Both the source rocks and the granites are broadly monzonitic.


ppm Ba
2000
1600
1200
800
400
0
45
55
65
75
% SiO_2
Boggy Plain
Inlet



This figure illustrates the differences between the Zr variation in the low-temperature Inlet Suite and the high-temperature Boggy Plain Suite. In addition to the inflection in Zr abundances for Boggy Plain, note also its much greater range in SiO_2 contents.

SOURCE COMPOSITIONS CRITICALLY DEFICIENT IN K-FELDSPAR COMPONENT



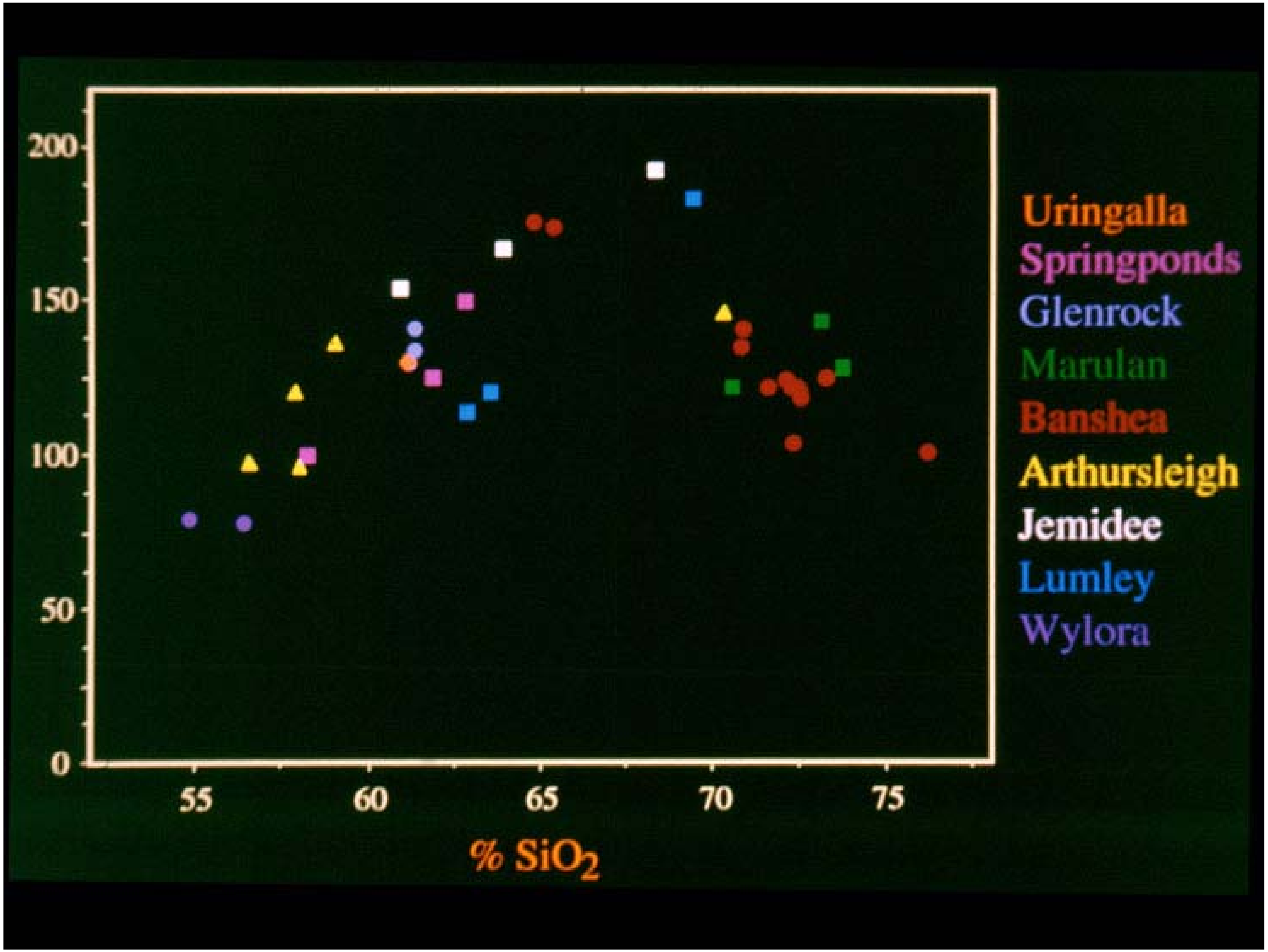
Arrows represent directions of increasing temperature

Tuttle & Bowen haplogranites

Low temperature

High temperature

This is the analogous situation in which K-feldspar becomes critically depleted during the partial melting event. The composition of the melt moves away from Or, at higher temperatures. This is by far the most common case of high-temperature granite magmatism, applying as it does to the Cordilleran-like tonalites, the Archaean TTG’s, and perhaps to some plutonic rocks of the island arcs. Both the source rocks and the derived granites are low in K.


200
150
100
50
0
55
60
65
70
75
% SiO_2
Uringalla
Springponds
Glenrock
Marulan
Banshea
Arthursleigh
Jemidee
Lumley
Wylora

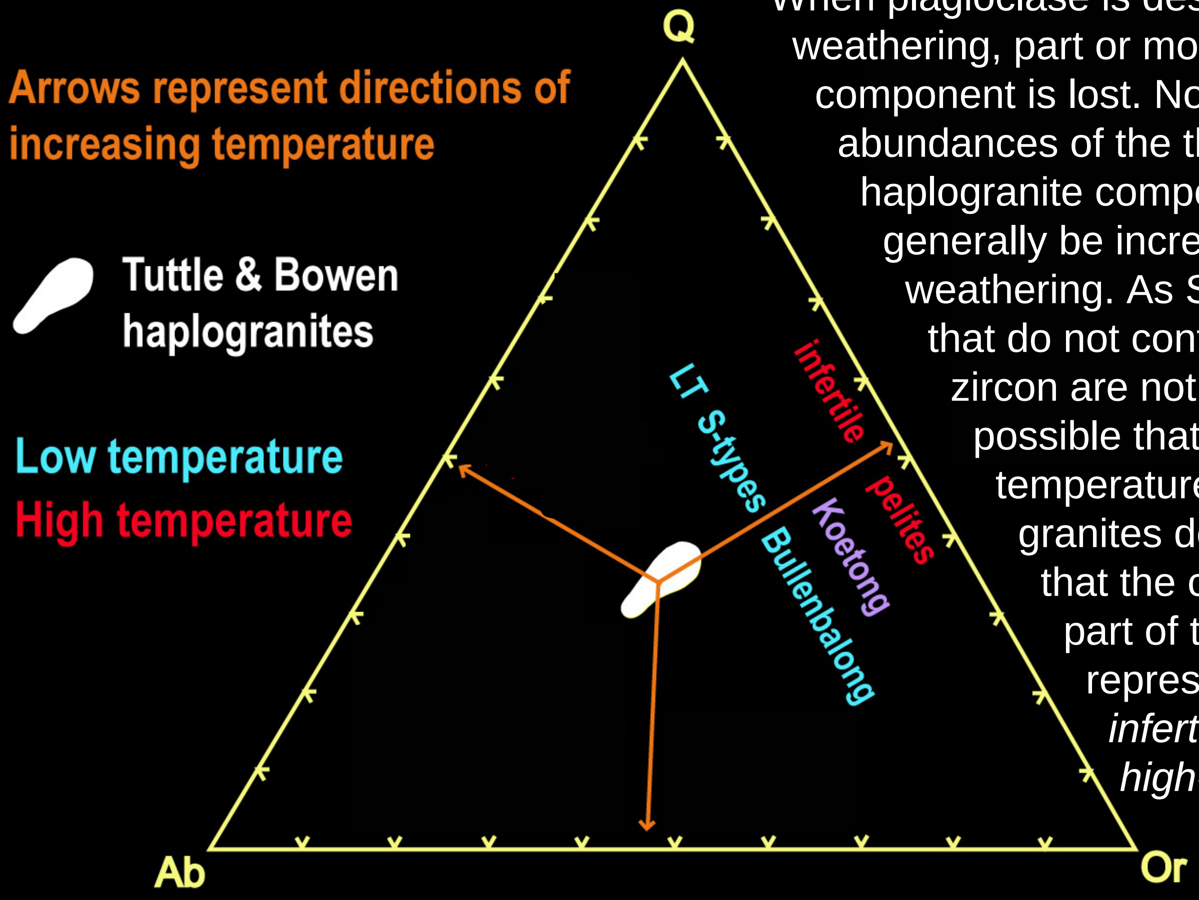
COMPOSITIONAL VARIATION WITHIN HIGH-TEMPERATURE TONALITE SUITES

The Marulan Batholith illustrates an important feature of high-temperature tonalite suites. That is, in contrast to the higher-K suites, the amount of variation within individual plutons is restricted, and any within-suite variation is largely provided by variations between different plutons. Zoned tonalite plutons are rare and fractional crystallisation, at least at the level at which the rocks are seen, does not seem to be a significant process.

In contrast, plutons of the higher-K high-temperature suites are almost invariably zoned. Wyborn *et al*. (2001) have suggested that this is because such suites contain more of the low-melting components (because of the higher K content), so that during crystallisation, those components cannot be completely retained between the cumulus minerals so that some of that melt is displaced back into the main body of melt. During the crystallisation of tonalites, that melt is retained within the minerals and hence captured within the solidification zone, so that the remaining melt does not change in composition. It may be because the higher-K magmas have a greater propensity to fractionate, rather than any geochemical association between various elements, that results in those magmas being more commonly associated with significant mineralisation.

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.

SOURCE COMPOSITIONS CRITICALLY DEFICIENT IN THE ALBITE COMPONENT



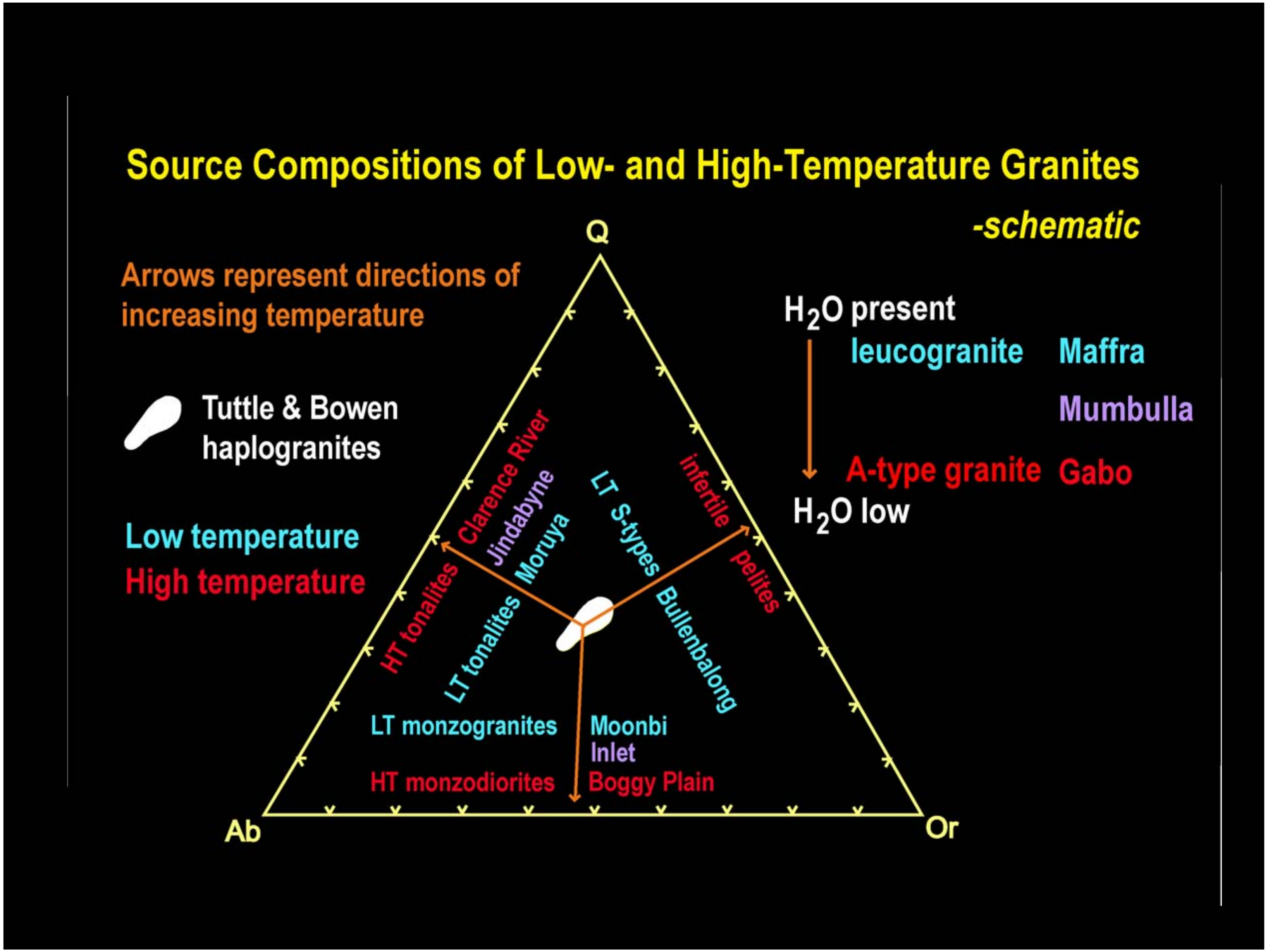
Arrows represent directions of increasing temperature

Tuttle & Bowen haplogranites

Low temperature

High temperature

When plagioclase is destroyed during weathering, part or most of the Ab component is lost. Note that the abundances of the three other haplogranite components would generally be increased by weathering. As S-type granites that do not contain inherited zircon are not known, it is possible that high-temperature S-type granites do not exist, so that the corresponding part of this figure is represented by *infertile pelites* and *high-K leucosomes*.



Source Compositions of Low- and High-Temperature Granites

-schematic

Arrows represent directions of increasing temperature

Tuttle & Bowen haplogranites

Low temperature

High temperature

H_2O present

leucogranite Maffra

Mumbulla

A-type granite Gabo

H_2O low

SOME IMPLICATIONS FOR METALLOGENESIS

High-temperature granites are much more likely to be related to mineralisation, for the following reasons:

1. During the partial melting process, at higher temperatures, the solubility of trace metals in the melt will be greater than at lower temperatures.
2. High-temperature suites are more likely* to undergo fractional crystallisation, which may increase the abundances of rare elements in the evolving melt.
3. H_2O contents of the melts will also increase with such fractionation, so that mineralising fluids are more likely to be released (cf. low-temperature suites as discussed by White (2001).
4. High-temperature magmas are also largely molten magmas and because of both the higher temperatures and that larger fraction of melt, would introduce more heat into the country rocks.

* Particularly those that are monzonitic rather than tonalitic

White, A.J.R. 2001. Water, restite and granite mineralisation. Australian Journal of Earth Sciences 48, 551-555.

A UNIFIED MODEL OF GRANITE GENESIS

Most granites formed from processes initiated by heating and partial melting of the crust. Both the physical and chemical properties of the granite magmas that formed in a particular case were largely determined by the compositions of their source rocks. Although granites show a great diversity in their compositions and in details of their evolution, those features mostly relate back to the compositions of their source rocks, which are the unifying element in granite genesis.

To a significant degree, the physical and compositional evolution of a granite magma has been predetermined by the chemical composition of the source rocks. Each source responds to heating in a manner that is a physicochemical expression of that composition. This applies most precisely if the source rocks behave as a closed system but it is still relevant in systems that are open for some components (e.g. H_2O), or to any mixed sources.

Individual samples of granites may have evolved in a large variety of ways. But it is important to distinguish between the processes that can occur commonly and on a large scale, and those that do not. Crystal fractionation, either of entrained or previously precipitated crystals, appears to be the dominant mechanism in that regard. A mechanism involving varying degrees of partial melting may also be significant for some granites, but its role is at present not quantified.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