FROM TUTTLE AND BOWEN ONWARDS

Bruce W. Chappell
GEMOC, Macquarie University, NSW 2010

Publication of the Tuttle & Bowen (1958) memoir resolved the intense debate about whether granites are magmatic or metasomatic in origin, firmly in favour of the magmatic view. This marked the beginning of modern granite studies. Tuttle & Bowen showed that the most felsic granites have remarkably uniform major element compositions which match very closely those of hydrous silicate melts that in the laboratory exist in equilibrium with quartz, K-feldspar and Na-plagioclase at the lowest possible temperatures.

The experiments of Tuttle & Bowen (1958) showed that the felsic granites, at least, form by processes that involve equilibrium between melt and crystals at high temperature – they are magmatic or igneous rocks. Bowen (1949) himself held the view that granites are the end products of fractional crystallisation of basalt, but he conceded that his data were equally consistent with an origin by "selective fusion of appropriate material", what we now generally call *partial melting*. Undoubtedly, felsic granites of both types do exist. However, it is now widely thought that felsic granites are more generally either primary partial melts, or products derived from such primary melts, for various reasons, First, studies of high-grade metamorphic rocks and granulite inclusions show that the crust may be heated to temperatures sufficient to cause melting of appropriate source materials. Also, partial melting of crustal rocks can be observed directly in deep exposed crust in the form of migmatites, although the "leucosome" compositions may not closely match those of granites. Second, at least in more continental regions, granites dominate over mafic rocks in most plutonic terranes. Third, trace elements are not strongly fractionated in many felsic granites, suggesting that the granites represent primary, or close to primary, compositions. Finally, petrogenetic considerations for the "low-temperature" granite suites imply that the melt phase of the magma involved in their production existed at low magmatic temperatures and had a felsic composition. Worldwide, the low-temperature granites dominate over the high-temperature type. There are some minor granites that were probably derived by the fractional crystallisation of basalt, but more frequently the granites that evolved through that process, at high temperatures, were derived from melts that were initially less mafic than basalt or higher in K.

The studies of Tuttle & Bowen initially led to a widely-held view that all granites were derived from sedimentary source rocks. This was codified in the "granite series" of Read (1957), in which all granites are related in their origin from sedimentary rocks and in which a series of granites can be identified that develop through time at progressively higher levels in the crust - all granites are "S-type". That view was questioned when early isotopic data showed that granites may have primitive isotopic compositions, and by the realization that hornblende-bearing granites cannot have been derived from source rocks that contained a component of weathered material.

Chemical weathering destroys minerals that are unstable at the Earth's surface and converts them into clay minerals, with other elements being carried away in solution. Ca and Na are removed from mantle-derived rocks by weathering and a proportion is unavailable for subsequent granite-forming processes. Carbonates and clay-rich rocks are infertile in this context, as are quartz-rich rocks, and cannot undergo partial melting; greywackes, containing quartz, feldspars and a clay component (depleted in Na and Ca), may form S-type granites. Such granites are distinct from the I-type granites in which the source rocks had not been modified by weathering, as noted by Chappell & White (1974, 1992). Developments in the I- and S-type subdivision over twenty five years were discussed by Chappell & White (2001). The principal developments have been the recognition of magnetite- and ilmenite-series granites (Ishihara, 1977), infracrustal and supracrustal source rocks (Chappell & White, 1984), application of the concept to volcanic rocks (Owen & Wyborn, 1979) and to fractionated granites (Chappell, 1999), and the recognition of high- and low-temperature granites (Chappell *et al.*, 1998, 2000).

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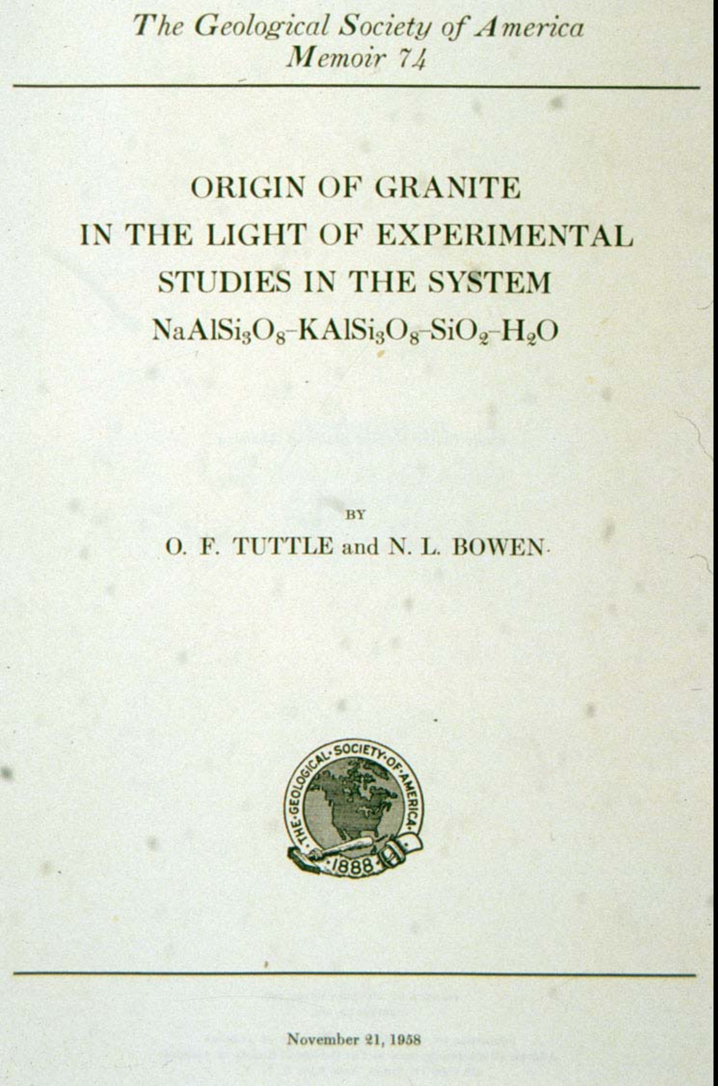

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Memoir 74

ORIGIN OF GRANITE
IN THE LIGHT OF EXPERIMENTAL
STUDIES IN THE SYSTEM
$NaAlSi_3O_8$-$KAlSi_3O_8$-SiO_2-H_2O

BY
O. F. TUTTLE and N. L. BOWEN

1888

November 21, 1958

INTRODUCTION

FROM
TUTTLE & BOWEN
ONWARDS

Bruce Chappell

GEMOC

THE BEGINNING OF MODERN GRANITE STUDIES

The observation by James Hutton in 1785 of the intrusive nature of granite dykes in Glen Tilt, Scotland, showed that granites are plutonic rocks and were not formed as deposits from a primeval ocean, as the Neptunists had proposed. Over time an intense debate developed over the origin of these plutonic rocks, about whether granites have an origin that is igneous (magmatic) or metasomatic (produced by granitisation). This “granite controversy” was largely, although not entirely, fueled by concerns over how large bodies of igneous rock could be intruded as magmas into the crust – the so-called “room problem”.

Publication of the Tuttle & Bowen memoir in 1958 resolved these arguments firmly in favour of the magmatic view, and marked the beginning of modern granite studies. Tuttle & Bowen showed that the most felsic granites have remarkably uniform major element compositions which match very closely those of hydrous silicate melts that in the laboratory exist in equilibrium with quartz, K-feldspar and Na-plagioclase at the lowest possible temperatures.

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The observation by James Hutton in 1785 of the intrusive nature of granite dykes in Glen Tilt, Scotland, showed that granites are plutonic rocks and were not formed as deposits from a primeval ocean, as the Neptunists had proposed. Over time an intense debate developed over the origin of these plutonic rocks, about whether granites have an origin that is igneous (magmatic) or metasomatic (produced by granitisation). This “granite controversy” was largely, although not entirely, fueled by concerns over how large bodies of igneous rock could be intruded as magmas into the crust – the so-called “room problem”.

The full reference to the Tuttle & Bowen Memoir is:

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**.

This is the most significant single contribution to our understanding of the origin of granites. It established, beyond doubt, the magmatic origin of granites and brought the granite controversy of the early to mid-20th century, and ideas of granitisation as a significant mechanism for the origin of these rocks, to an abrupt end.

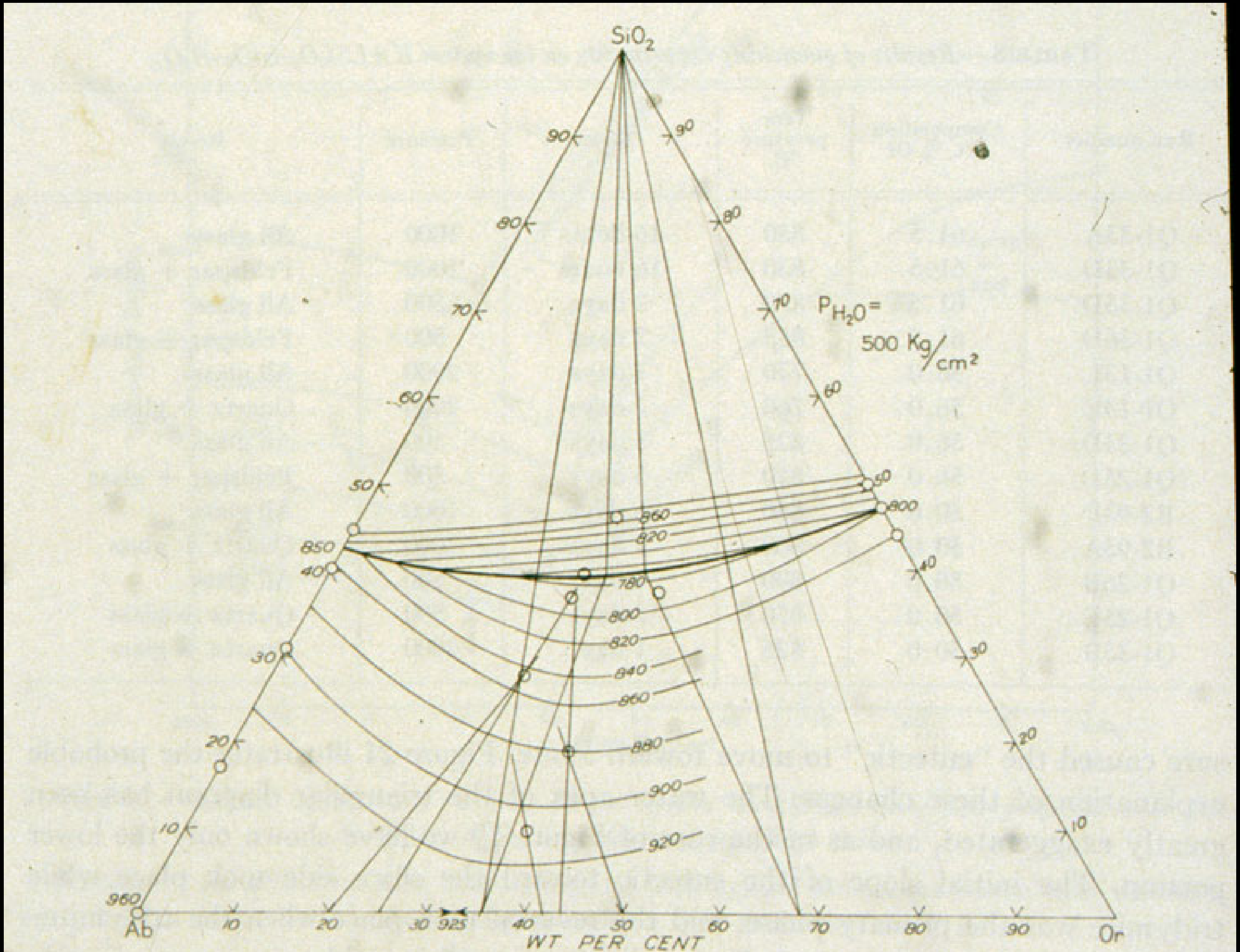


FIGURE 22.—*The 500 kg/cm² isobaric equilibrium diagram for the system $NaAlSi_3O_8$–$KAlSi_3O_8$–SiO_2–H_2O projected onto the anhydrous base of the $NaAlSi_3O_8$–$KAlSi_3O_8$–SiO_2–H_2O tetrahedron*

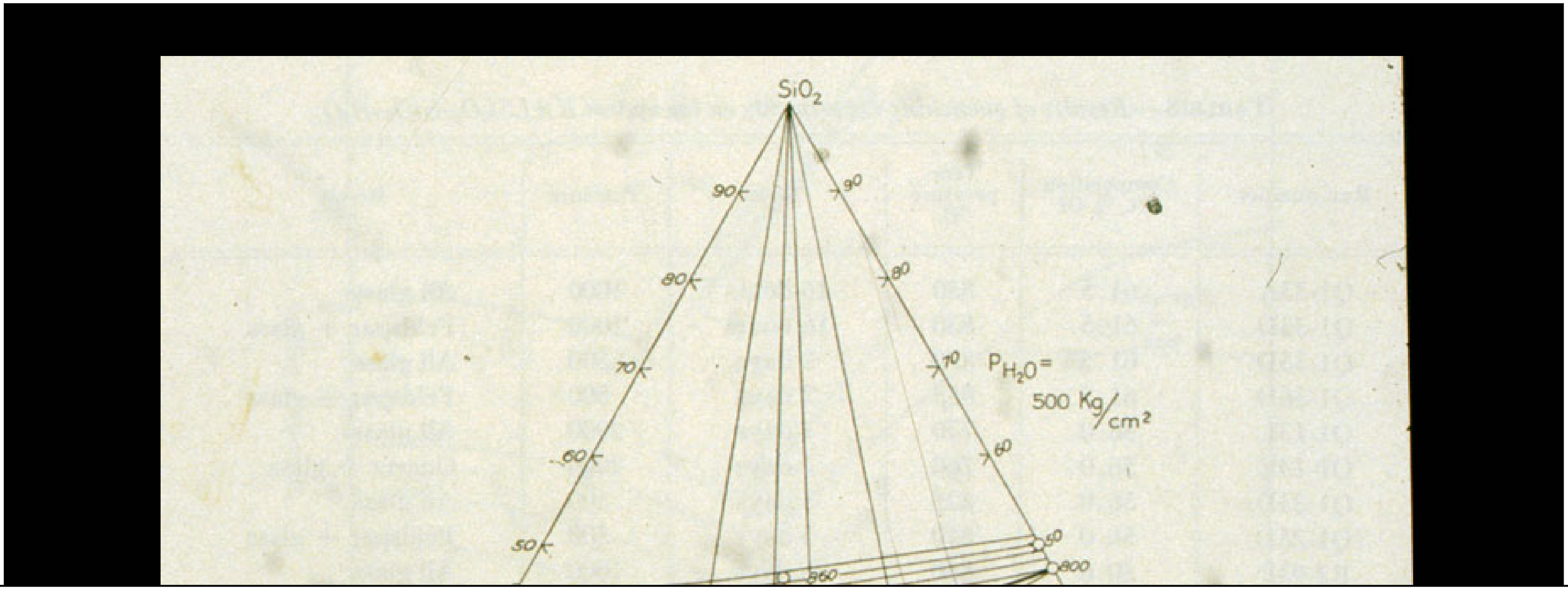


Figure is from p. 54 of Tuttle & Bowen (1958).

In this figure, the crystallisation temperatures in the four-component system, including H_2O, are projected on to the anhydrous face of the tetrahedron. The lines indicating temperatures are isothermal lines on the liquidus surface.

Any felsic melt comprising dominantly these components will cool to meet a liquidus surface and will then fractionate and change composition in a direction of lower temperature, so that melts of all initial compositions would eventually reach the central part of this diagram.

Conversely, any solid source material comprising these components, will initially produce a melt of the central composition, only moving away when one of the components became depleted, with rising temperature.

Of particular interest is the very steep temperature gradient on the quartz side of the minimum, meaning that partial melting would not dissolve significant amounts of quartz excess to the requirements of a minimum temperature melt.

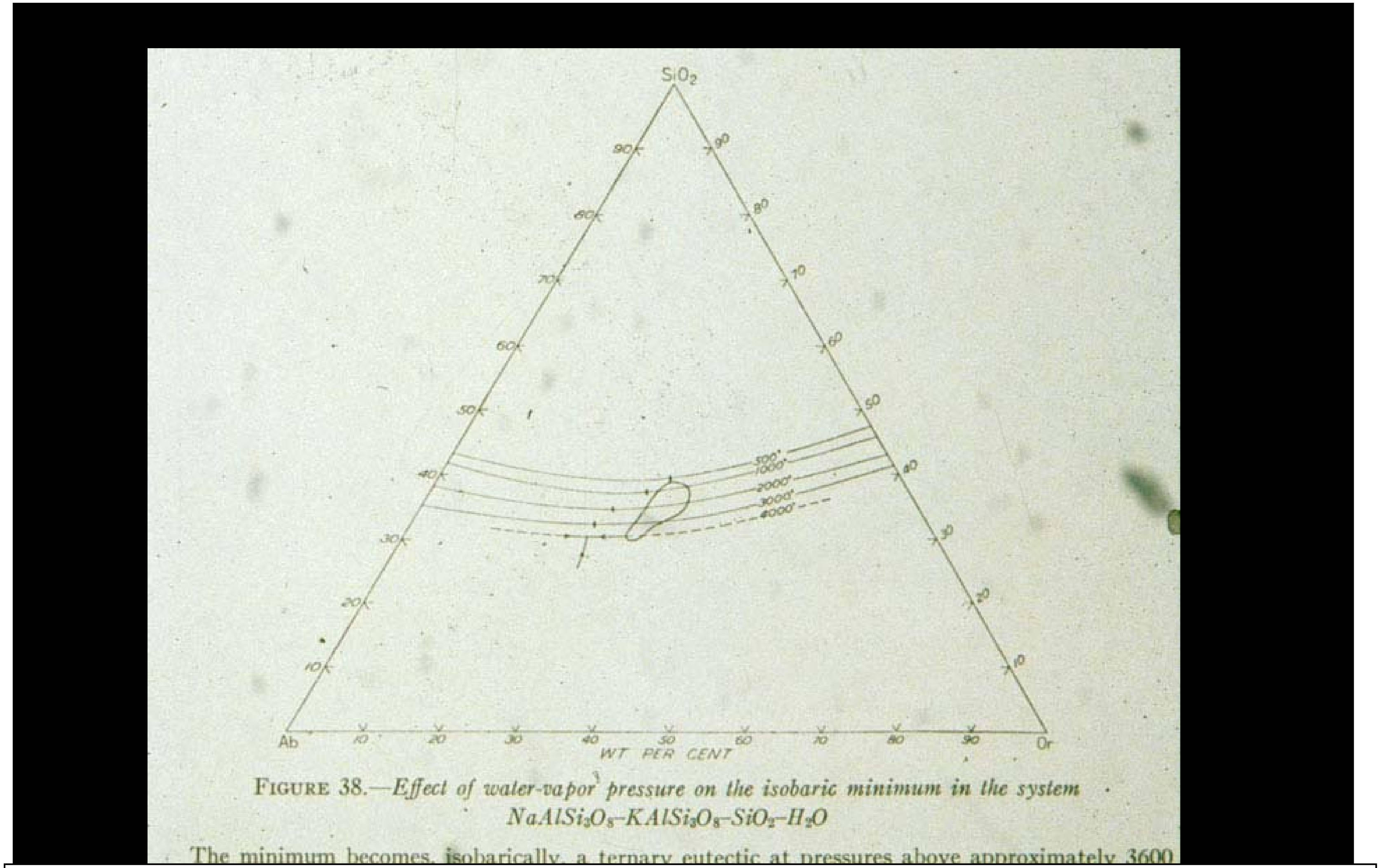


FIGURE 38.—*Effect of water-vapor pressure on the isobaric minimum in the system* $NaAlSi_3O_8–KAlSi_3O_8–SiO_2–H_2O$

The minimum becomes, isobarically, a ternary eutectic at pressures above approximately 3600

Figure is from p. 75 of Tuttle & Bowen (1958)

The outline of the maximum occurrence of compositions of natural rocks that is shown in this figure, is from the next figure in this sequence.

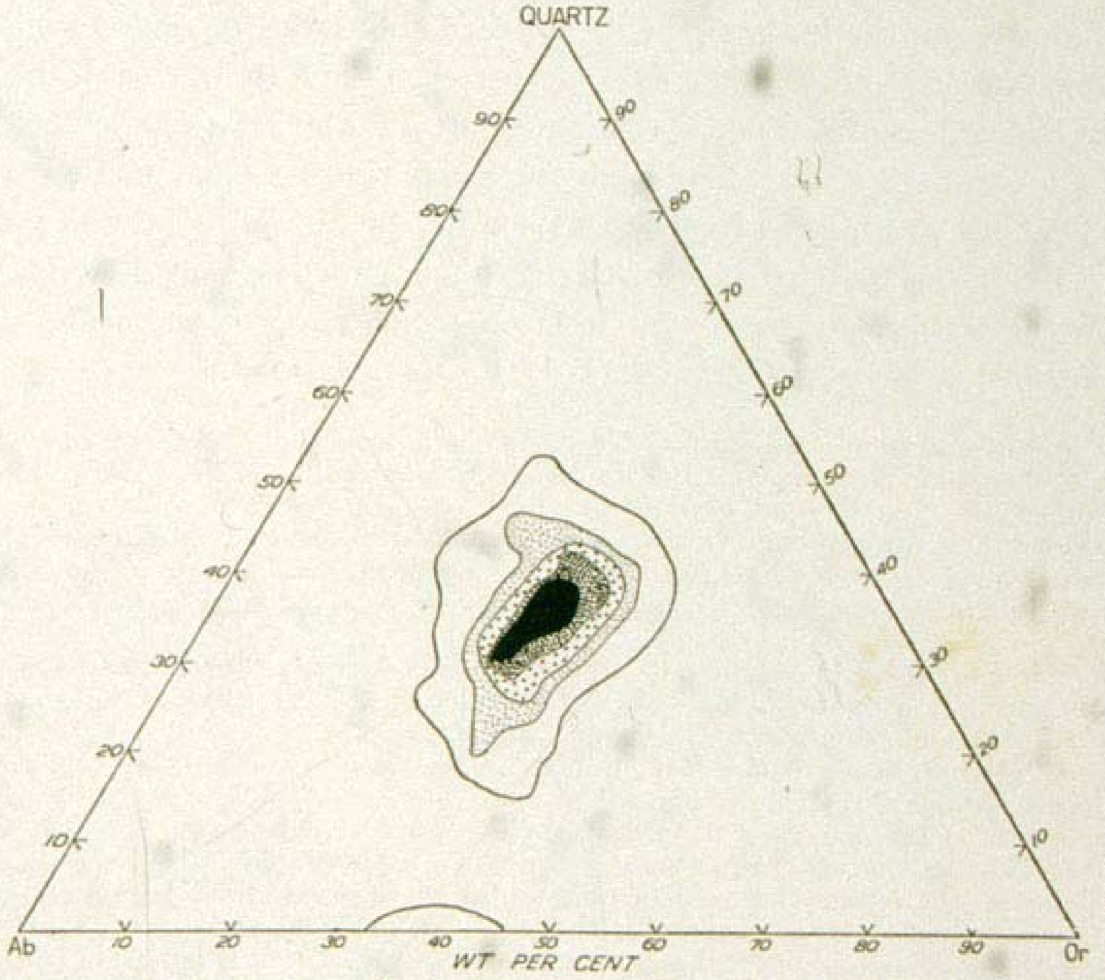


FIGURE 42.—*Contour diagram illustrating the distribution of normative albite, orthoclase, and quartz in all (571) the analyzed plutonic rocks in Washington's Tables that carry 80 per cent or more normative Ab + Or + Q*

Figure is from p. 79 of Tuttle & Bowen (1958).

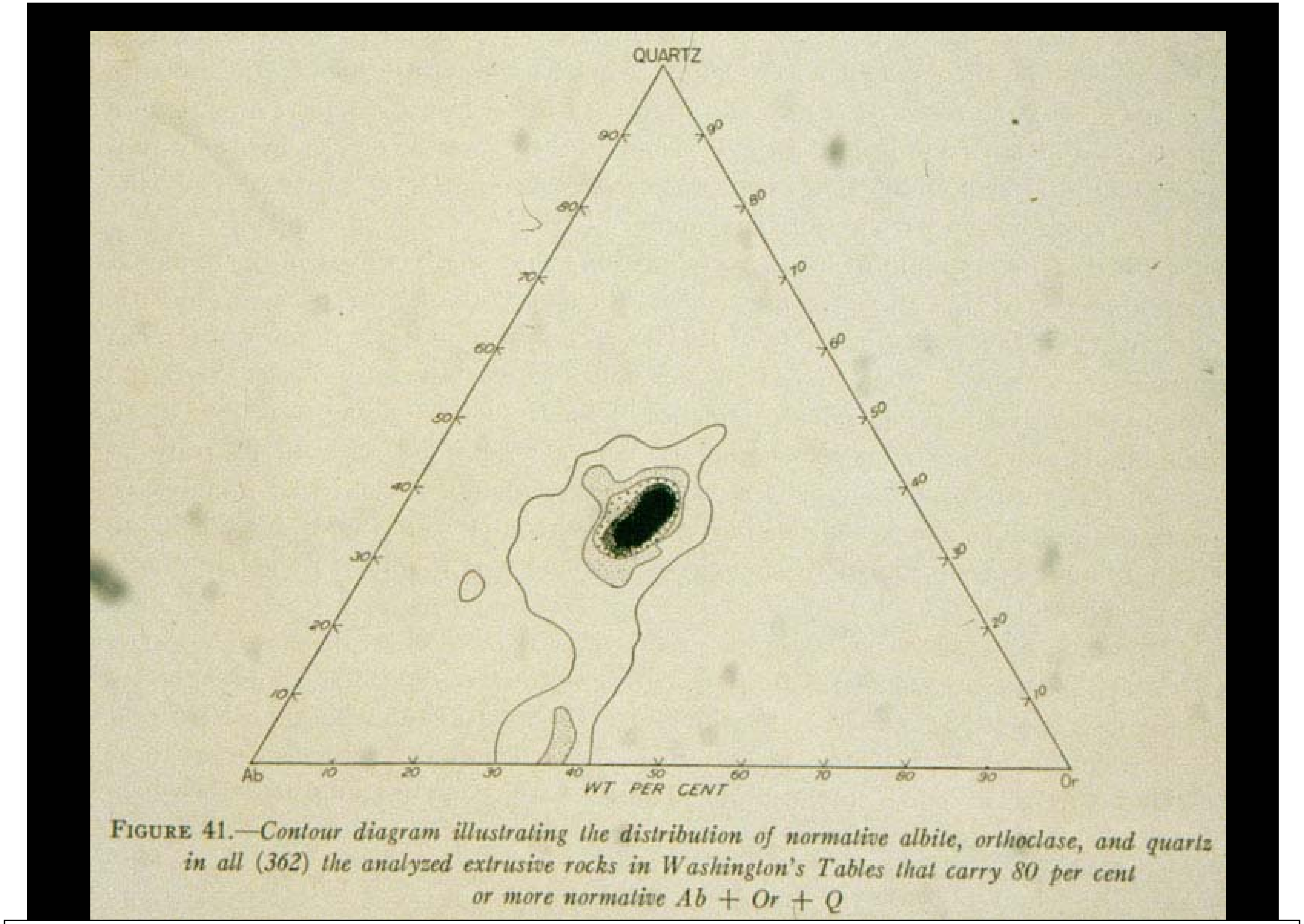


Figure 41.—*Contour diagram illustrating the distribution of normative albite, orthoclase, and quartz in all (362) the analyzed extrusive rocks in Washington's Tables that carry 80 per cent or more normative Ab + Or + Q*

Figure is from p. 78 of Tuttle & Bowen (1958).

GRANITES AS PRODUCTS OF PARTIAL MELTS

The experiments of Tuttle & Bowen (1958) showed that the felsic granites, at least, form by processes that involve equilibrium between melt and crystals at high temperature – they are magmatic or igneous rocks.

Bowen (1949) himself held the view that granites are the end products of fractional crystallisation of basalt, but he conceded that his data were equally consistent with an origin by “selective fusion of appropriate material”, now generally called *partial melting*.

Undoubtedly, felsic granites of both types do exist. However, it is now widely thought that felsic granites are more generally either primary partial melts, or products derived from such primary melts, for the following reasons:

- Direct observation of partial melting in the crust
- Dominance of granites over mafic rocks in most plutonic terranes
- Trace elements are not strongly fractionated in many felsic granites
- Petrogenetic considerations for the “low-temperature” granite suites

There are some minor granites that could have been derived by the fractional crystallisation of basalt, but more frequently the fractionated granites were derived by that process operating on melts that were less mafic than basalt.

What is this mechanism of *fractional crystallisation*?

Bowen, N.L. (1949). The granite problem and the method of multiple prejudices. In: Gilluly, J. (ed.) *Origin of granite*, The Geological Society of America Memoir **28**, 79-90.

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.

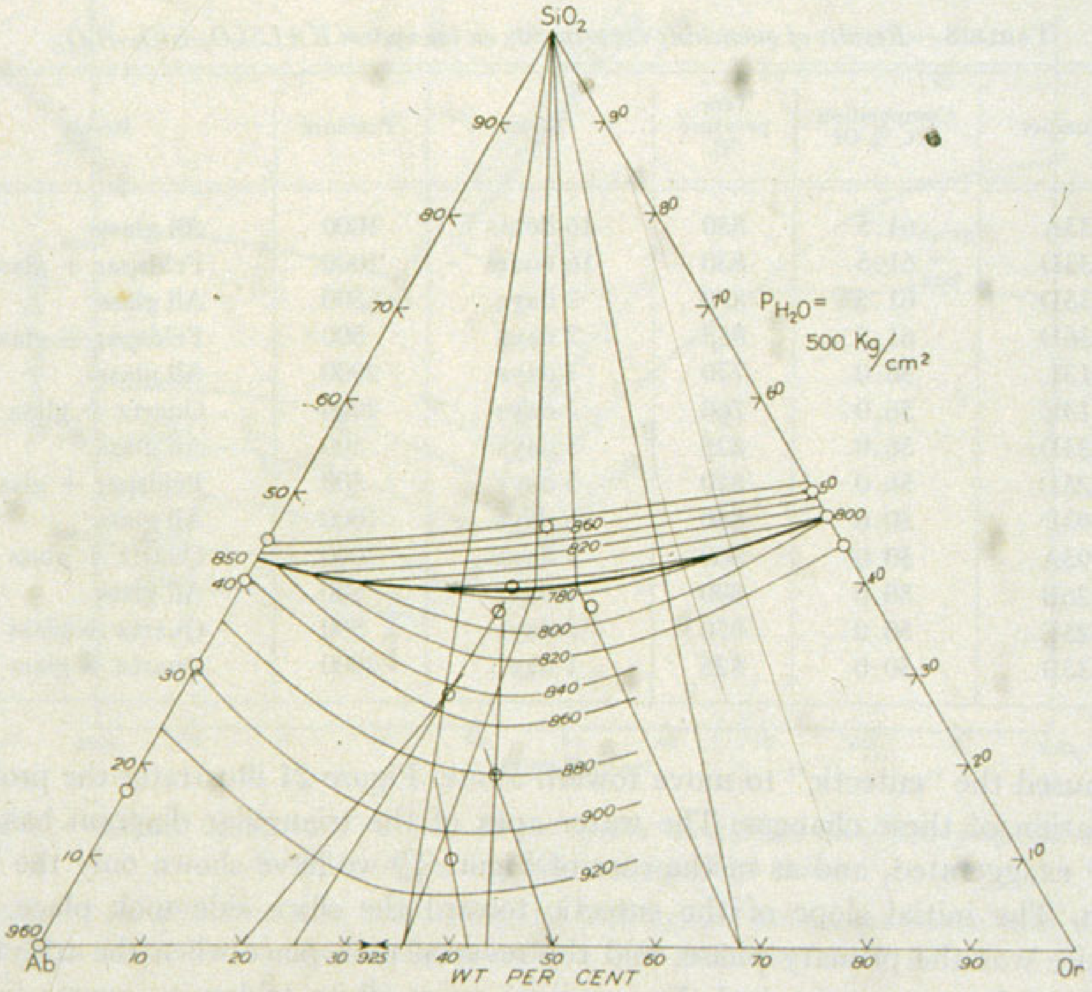
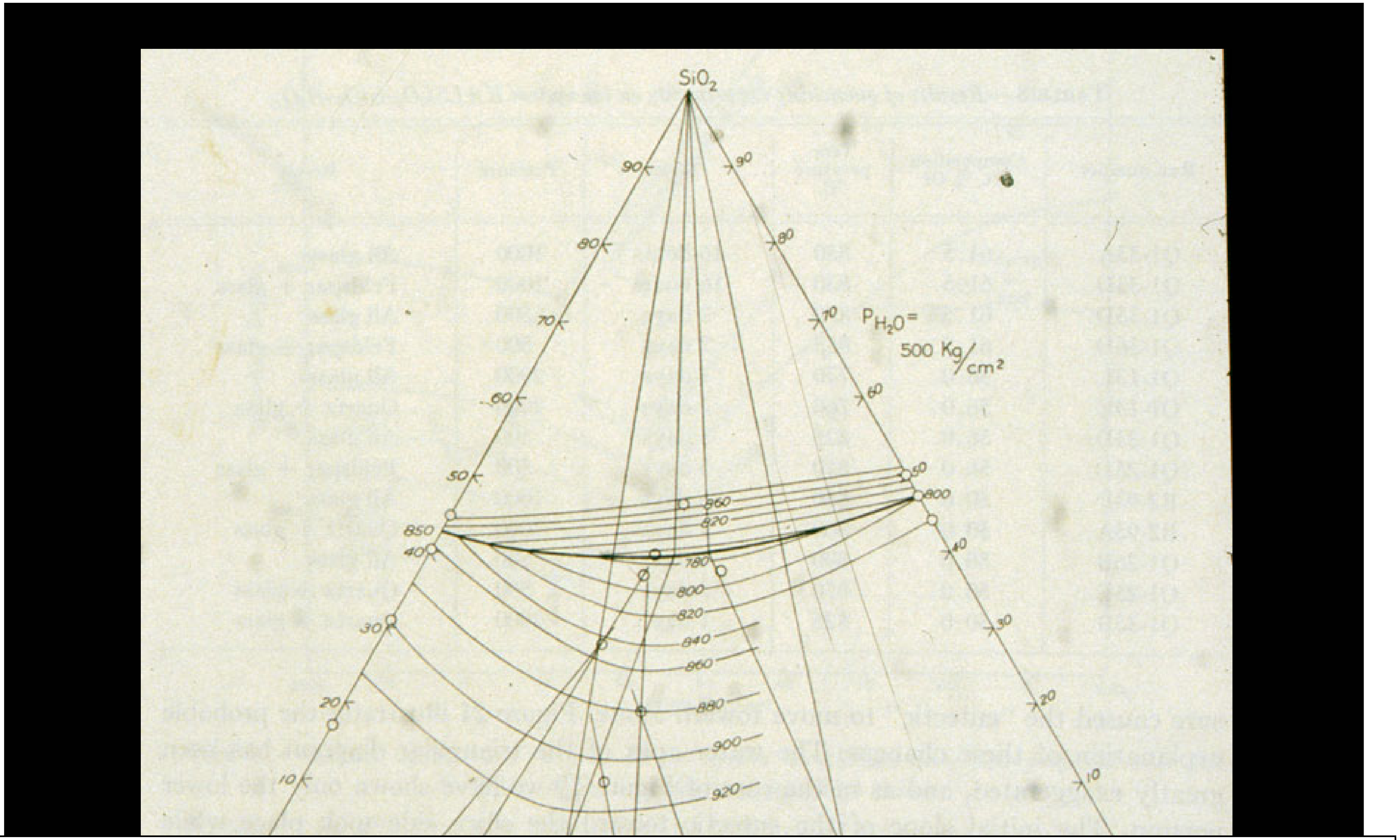
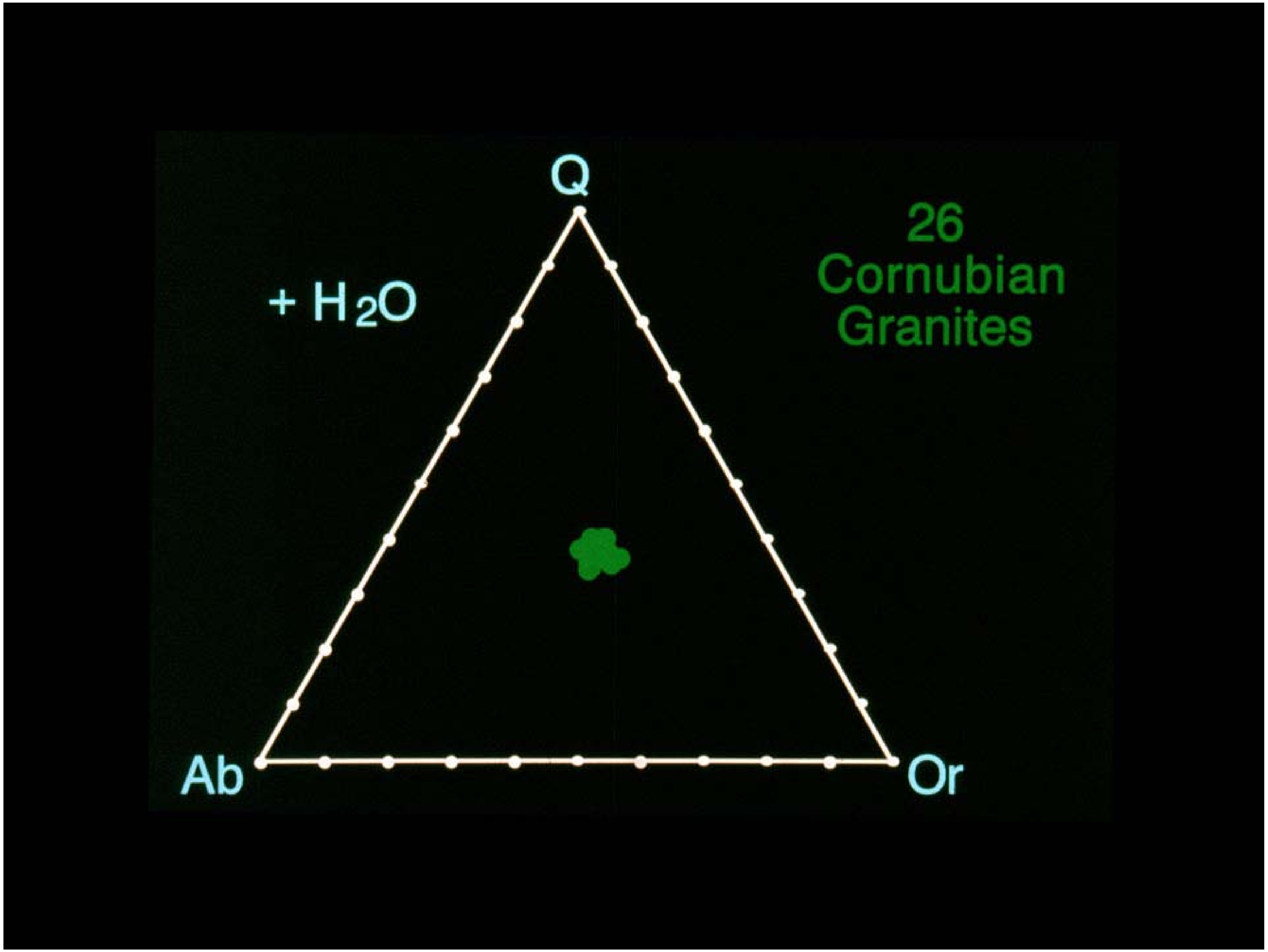


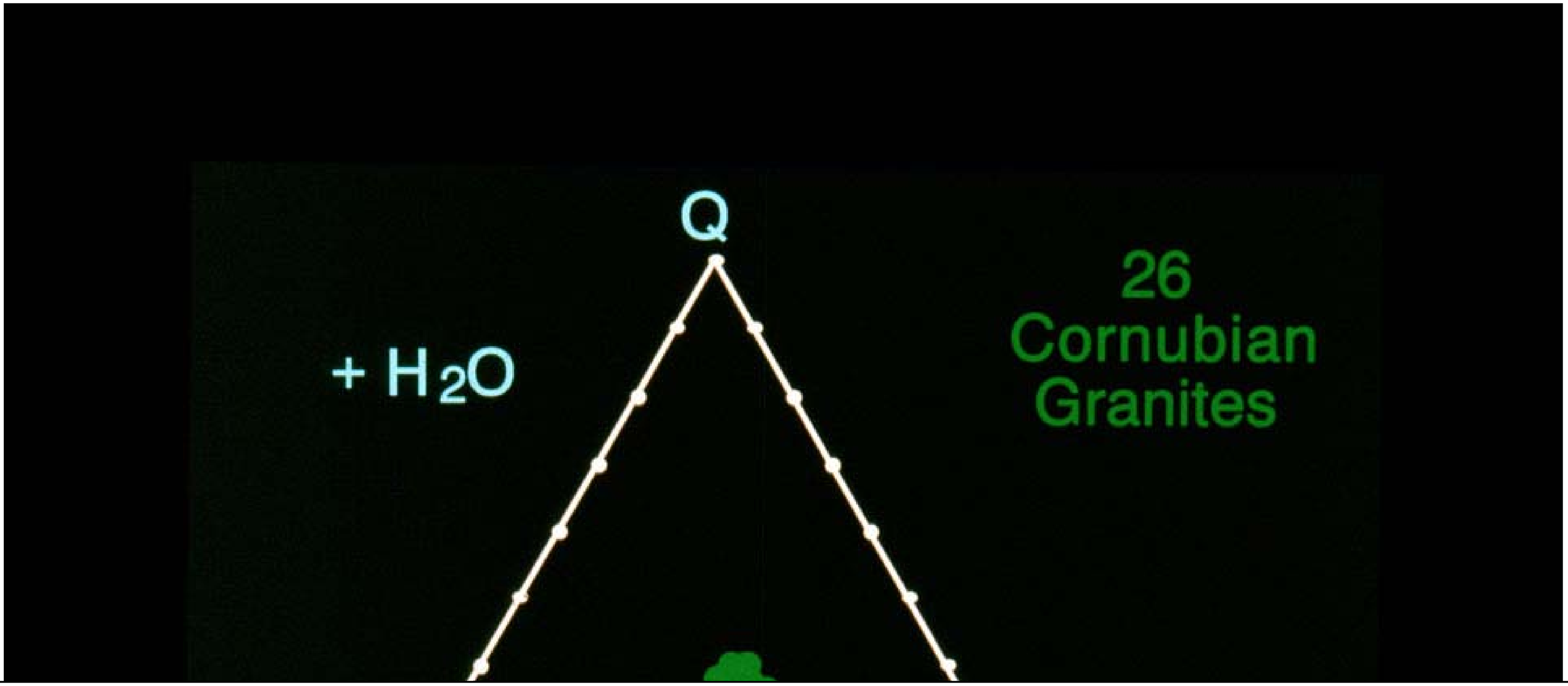
FIGURE 22.—*The 500 kg/cm² isobaric equilibrium diagram for the system $NaAlSi_3O_8$–$KAlSi_3O_8$–SiO_2–H_2O projected onto the anhydrous base of the $NaAlSi_3O_8$–$KAlSi_3O_8$–SiO_2–H_2O tetrahedron*



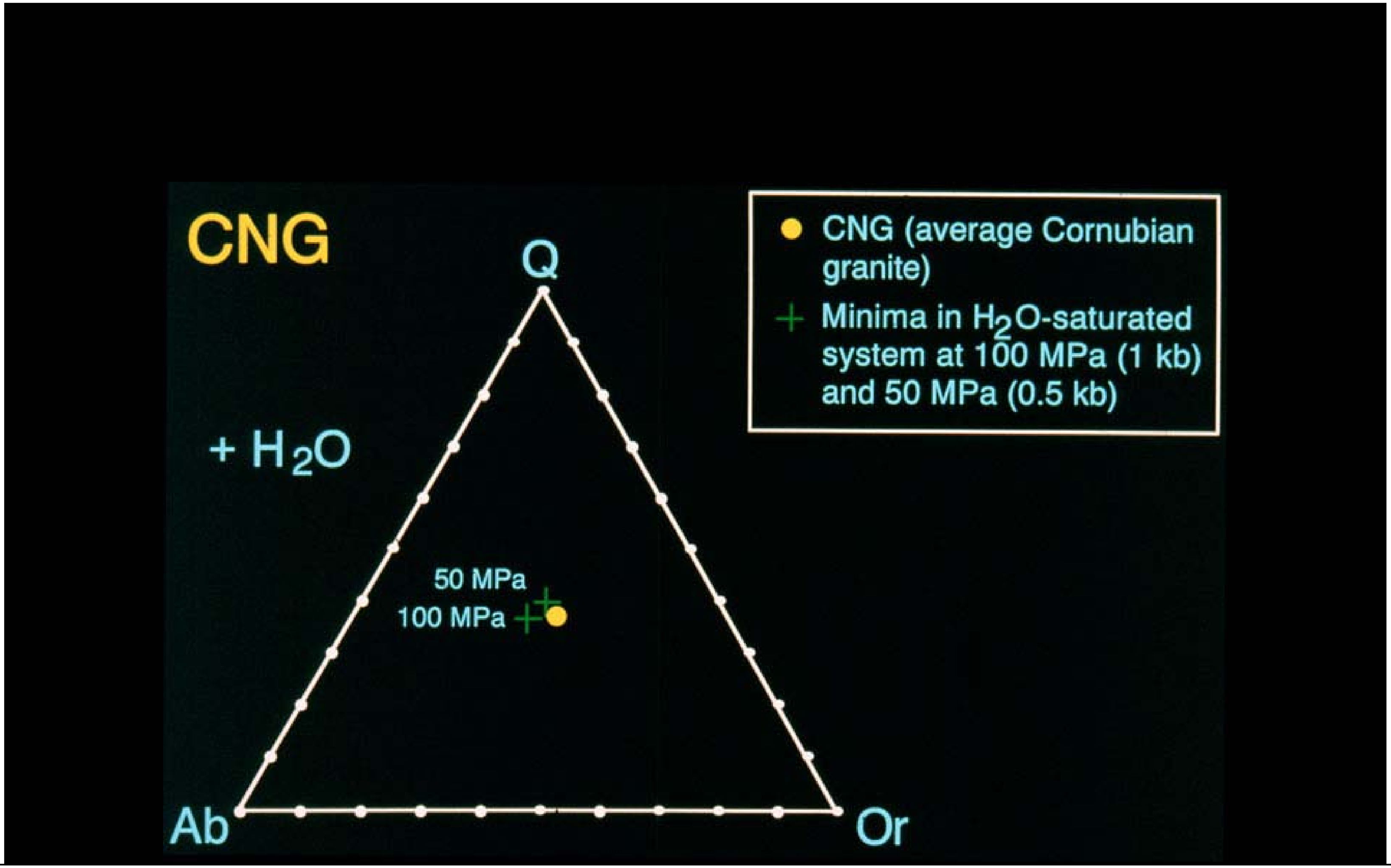
This diagram is shown again to stress the point that compositions in the low-temperature minimum can arise either by the fractional crystallisation of melt, or partial melting of earlier rocks, with compositions lying anywhere in the diagram, as Bowen (1949) pointed out.

Figure is from p. 54 of Tuttle & Bowen (1958).

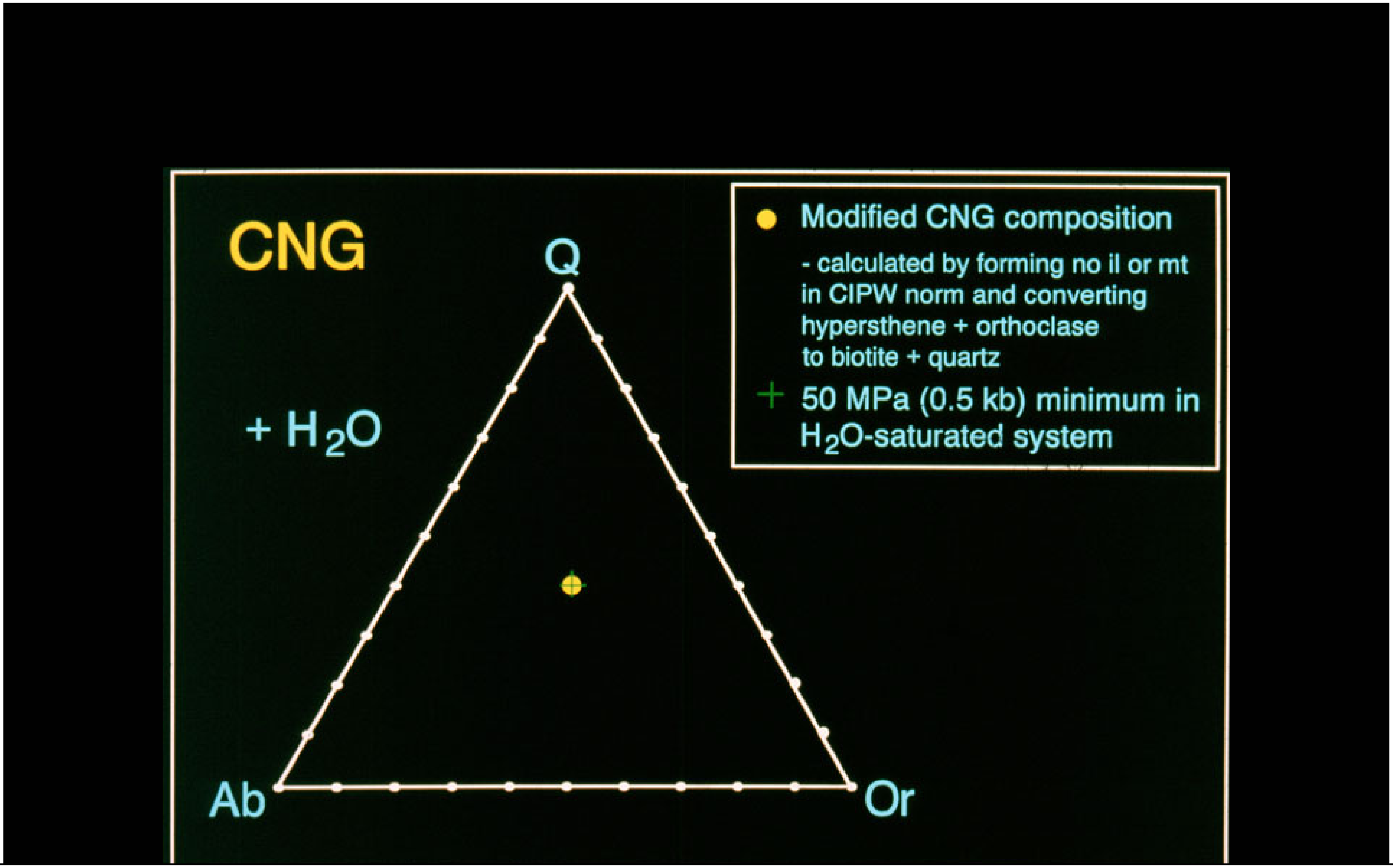

Q
+ H_2O
26 Cornubian Granites
Ab
Or



This is a plot of 26 granites of the Cornubian Batholith of SW England, analysed by the author, on a Q-ab-or diagram. All of the Cornubian granites are very felsic and can be plotted on this figure. It has long been suggested that metasomatism was a very important process in the formation of these particular granites, an idea that was partly based on the fairly extensive alteration of the rocks seen in then section, and more broadly on the difficulties of producing these strongly fractionated rocks by magmatic processes. The concentration of these points in a small part of the diagram suggests that metasomatism was not an important process, particularly when it is realised that it is a part of the diagram close to the low-temperature minimum identified by Tuttle & Bowen (1958).



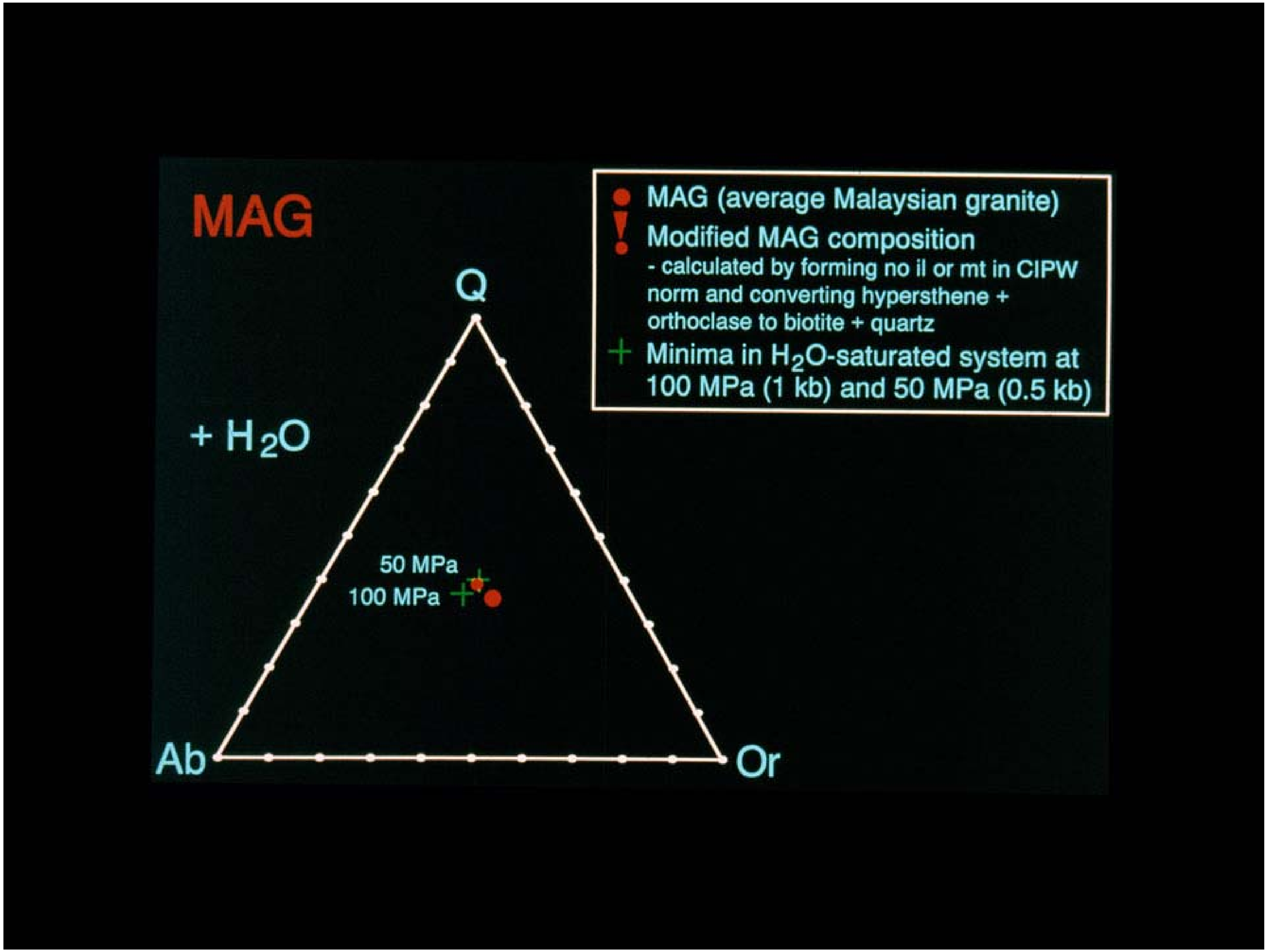
The position of the average of the 26 Cornubian granites is shown relative to the position of the thermal minima in the Q-Ab-Or-H_2O system at 500 and 100 MPa (0.5 and 1.0 kb). These pressures correspond to H_2O-saturation at depths of about 1.5 and 3 km.



● Modified CNG composition
- calculated by forming no il or mt in CIPW norm and converting hypersthene + orthoclase to biotite + quartz

+ 50 MPa (0.5 kb) minimum in H_2O-saturated system

Correction for the presence of crystals of biotite in these rocks brings the average composition precisely to coincidence with the minimum of Tuttle & Bowen at 50 MPa. This exactness of the fit must be partly fortuitous, but the magmatic origin of these rocks is clear. On the scale at which they were sampled, the rocks behaved as closed systems as far as metasomatism was concerned.



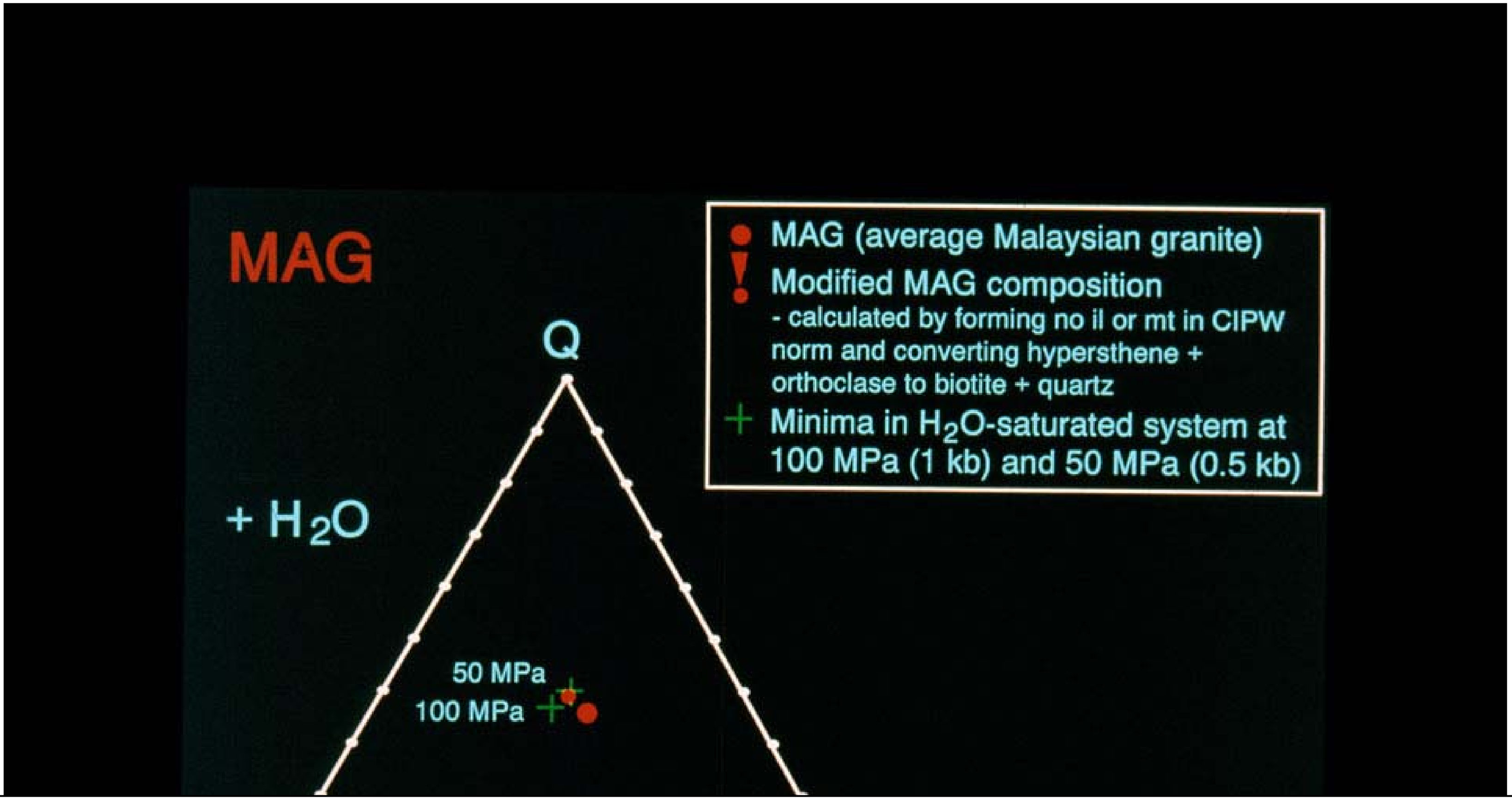
MAG

+ H_2O

● MAG (average Malaysian granite)

! Modified MAG composition
- calculated by forming no il or mt in CIPW norm and converting hypersthene + orthoclase to biotite + quartz

+ Minima in H_2O-saturated system at 100 MPa (1 kb) and 50 MPa (0.5 kb)



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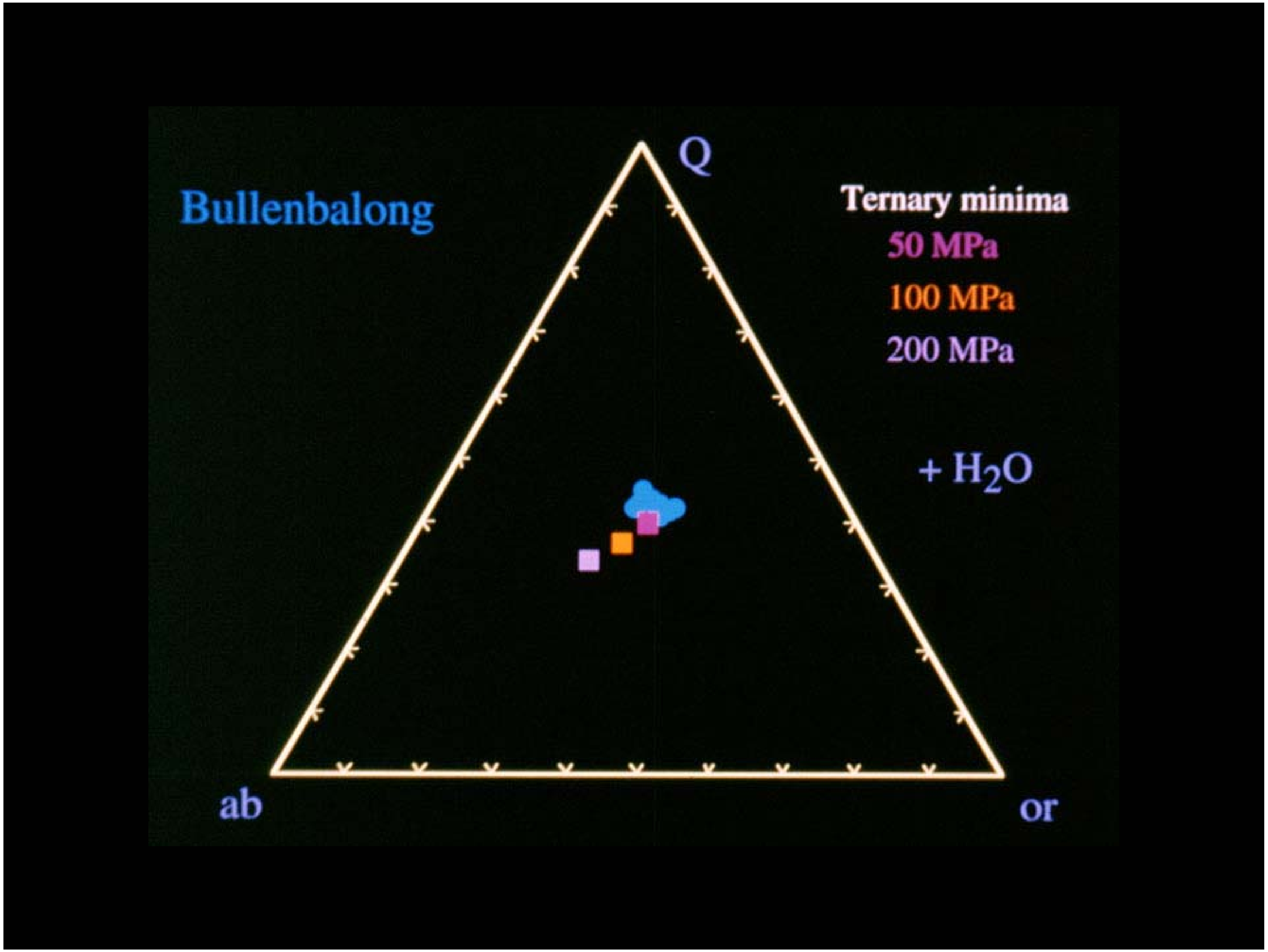
Tuttle & Bowen plot for analysed “tin granites” of the Main Range of the Malaysian Peninsular and Penang Island, from the PhD thesis of T.C. Liew (ANU, 1983). There is a close similarity with the Cornubian granites shown earlier. There is a significant difference for these rocks, however, as we will see later. They are cumulative rocks, in which crystals of quartz, feldspars and accessory minerals that were precipitated at the Tuttle & Bowen minimum were then concentrated relative to the melt, to produce these rocks.



Bullenbalong

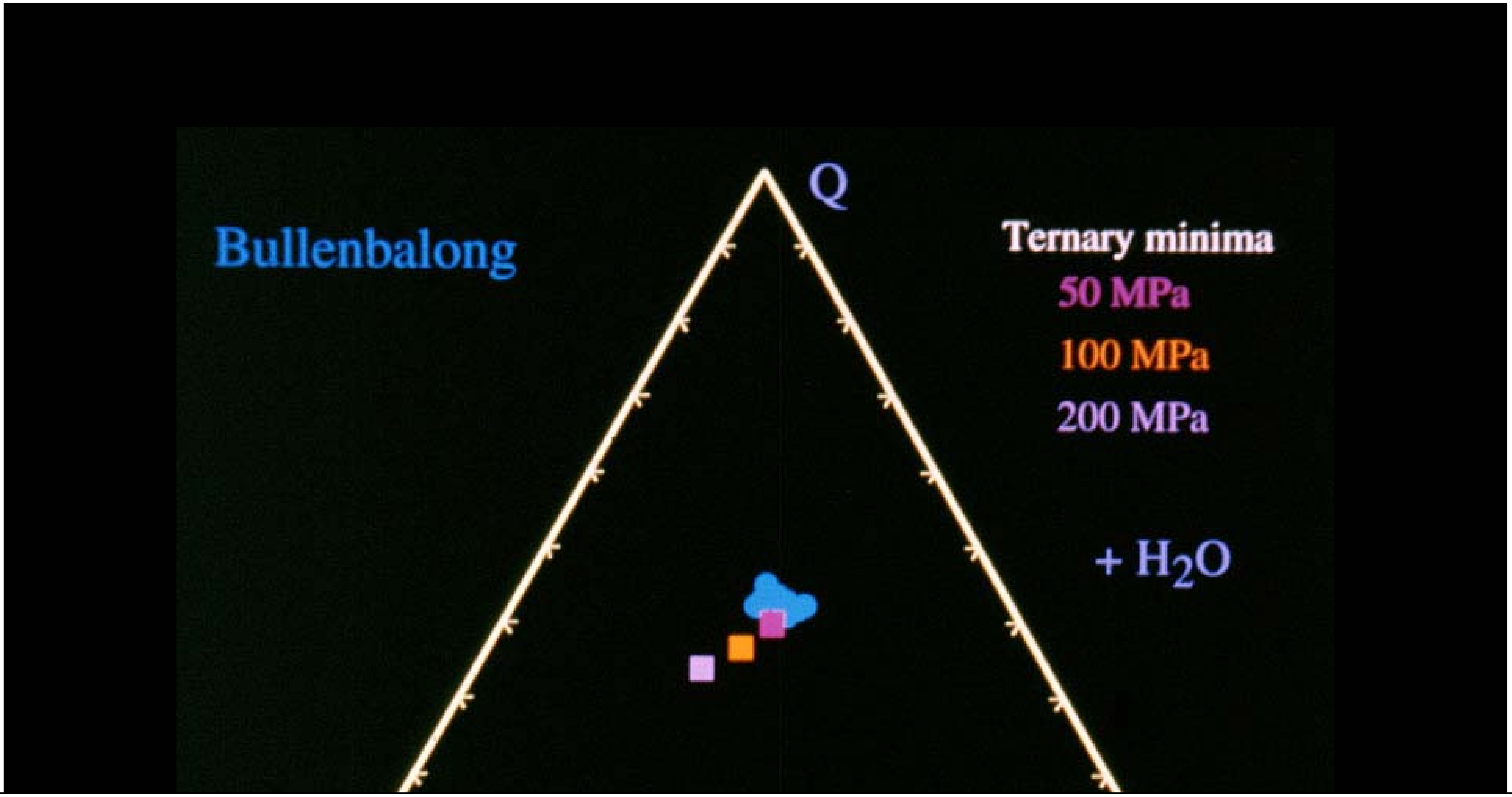
Ternary minima

50 MPa

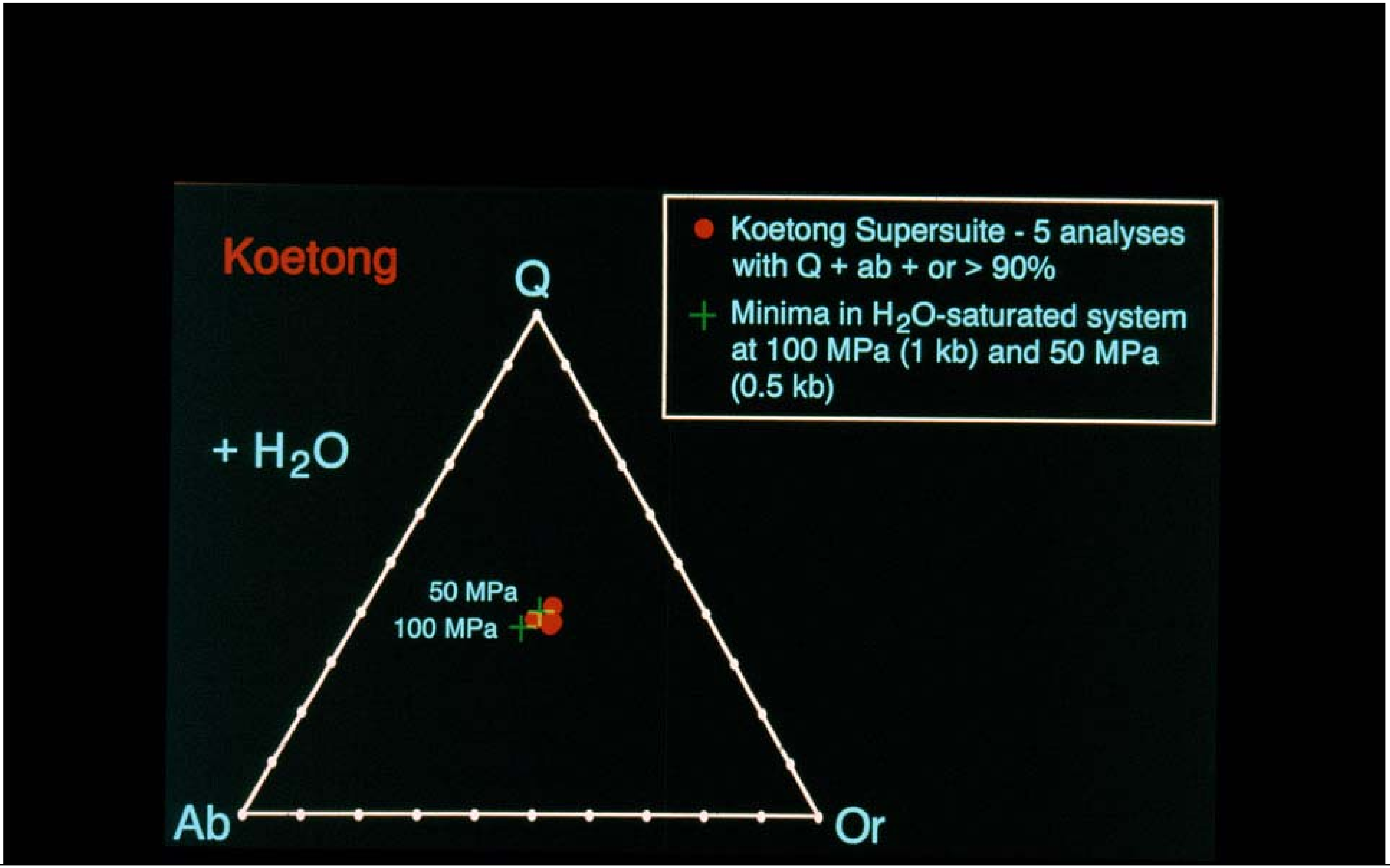
100 MPa

200 MPa

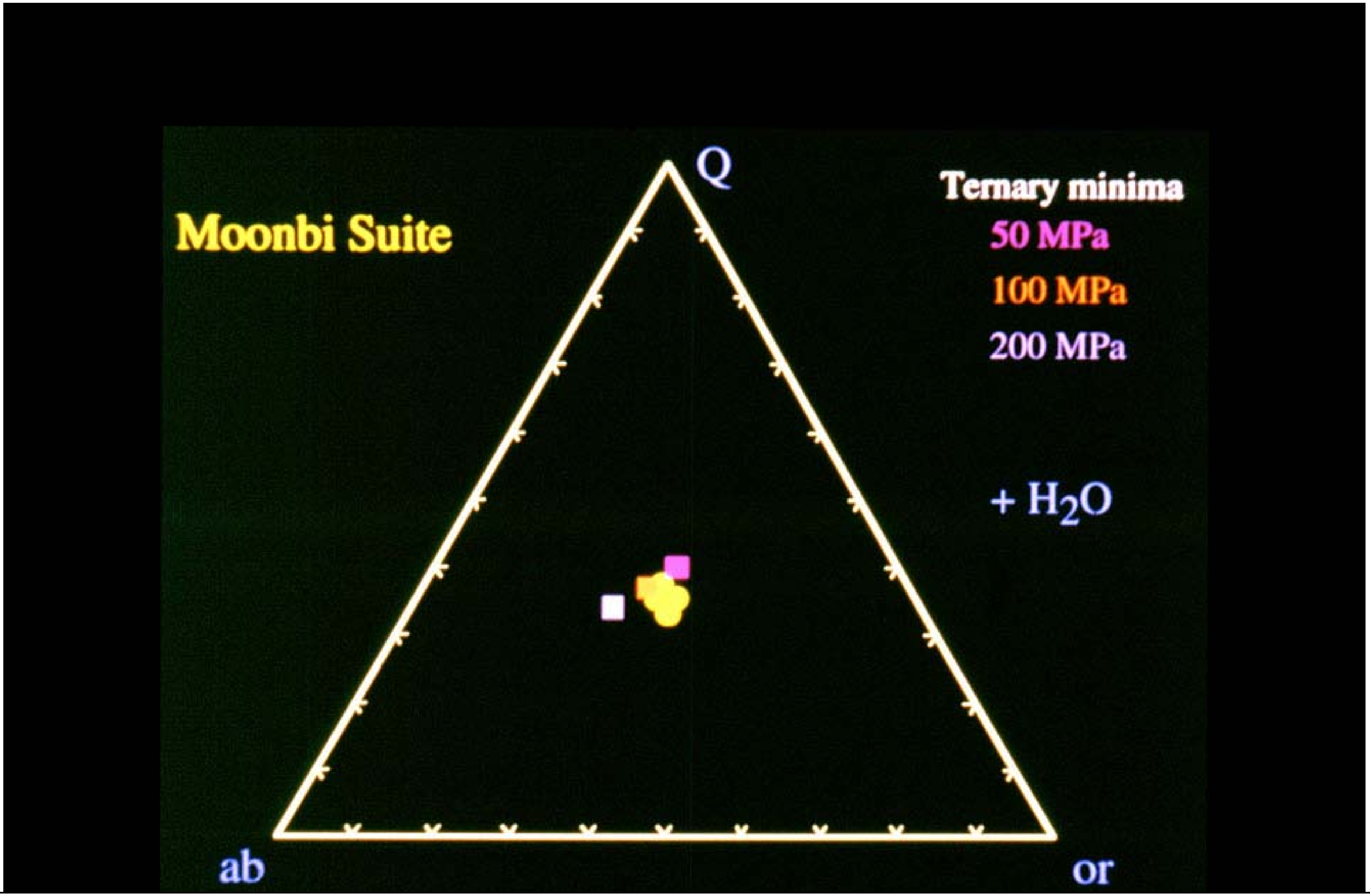
+ H_2O



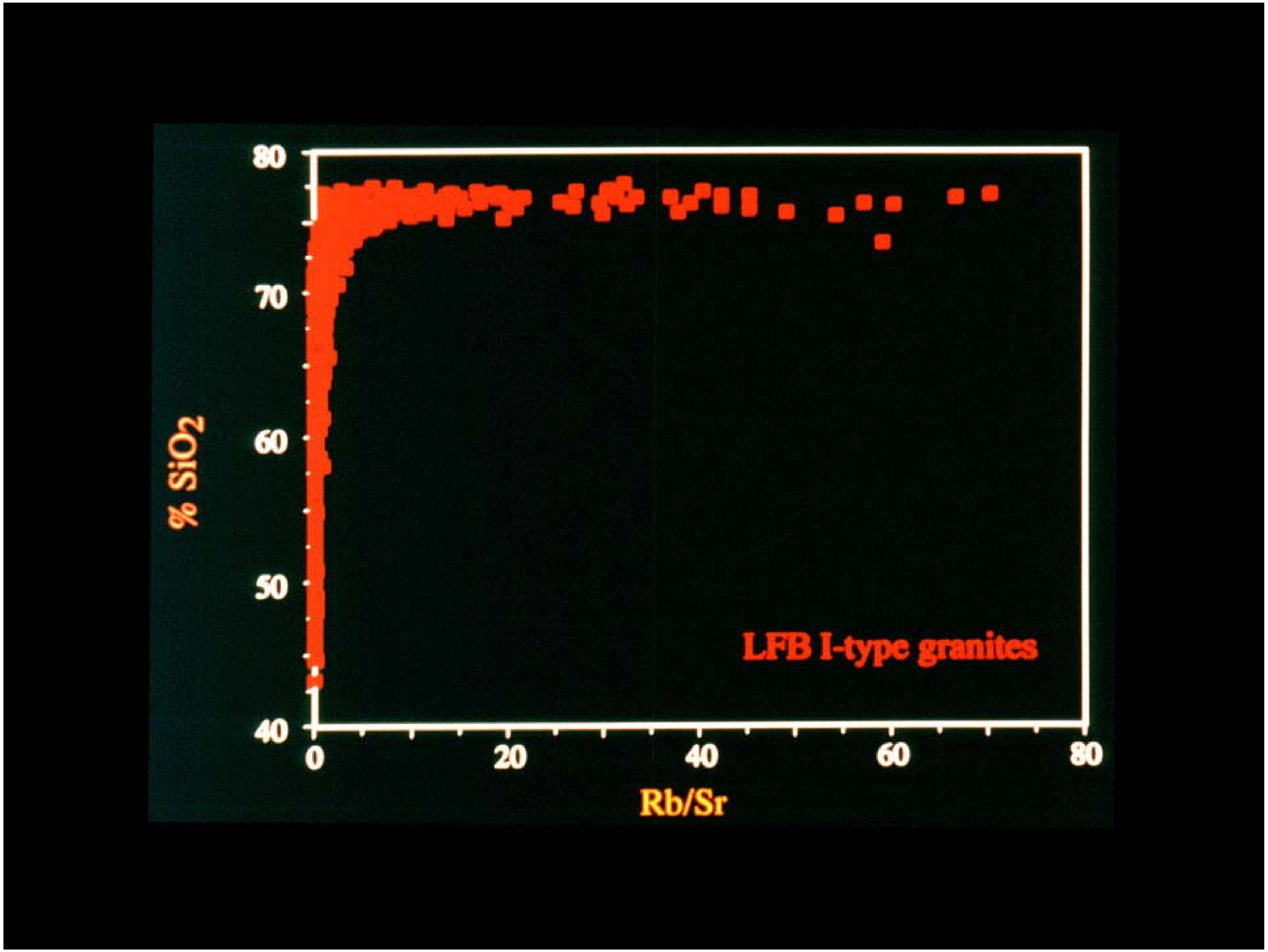
Tuttle & Bowen plot of the most felsic granites of the Bullenbalong Suite, the most extensively developed suite of S-type granites of the Lachlan Fold Belt. In this case the rocks are interpreted as partial melts but there clearly has either been some modification of melts that would have formed at pressures ~ 500 Mpa (~15 km) by fractionation at low pressures, or else the partial melting continued slightly above the minimum-temperature composition after depletion of Ab from the source materials.

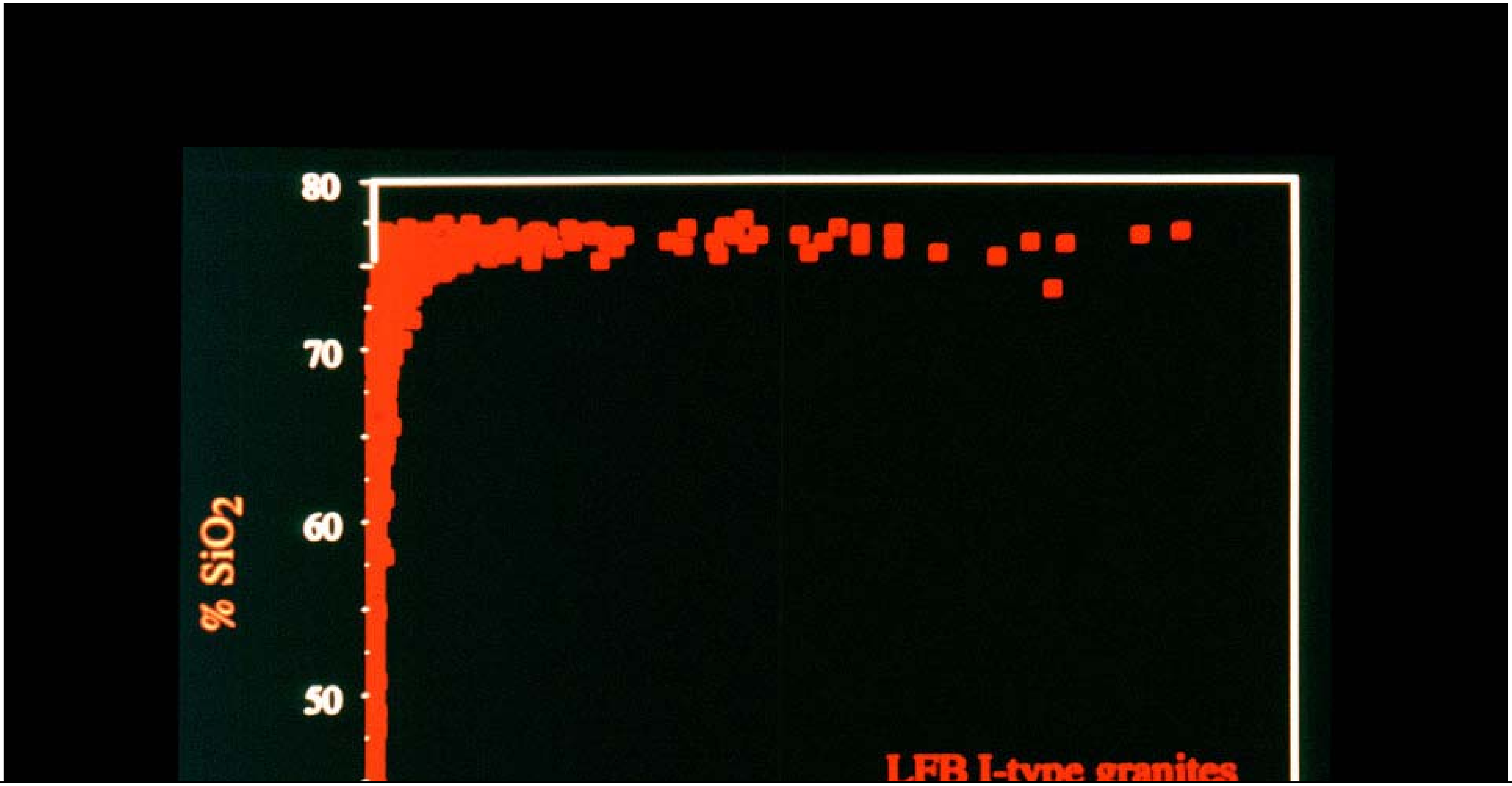


Tuttle & Bowen plot of the most felsic granites of the S-type Koetong Supersuite of the Wagga Batholith. In this case, on the basis of trace element abundances, the rocks are interpreted as products of fractional crystallisation from an melt initially containing about 70% SiO_2.

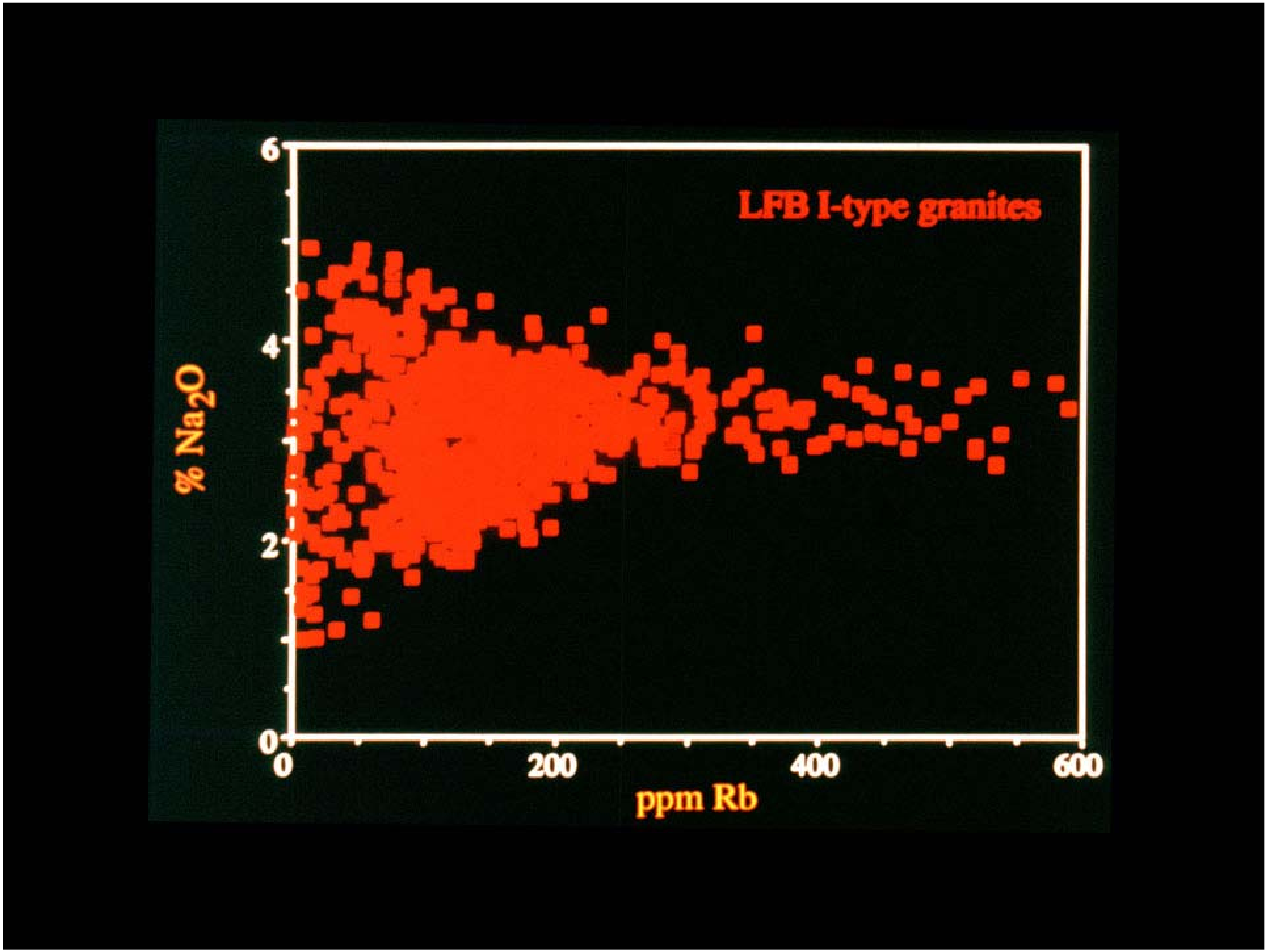


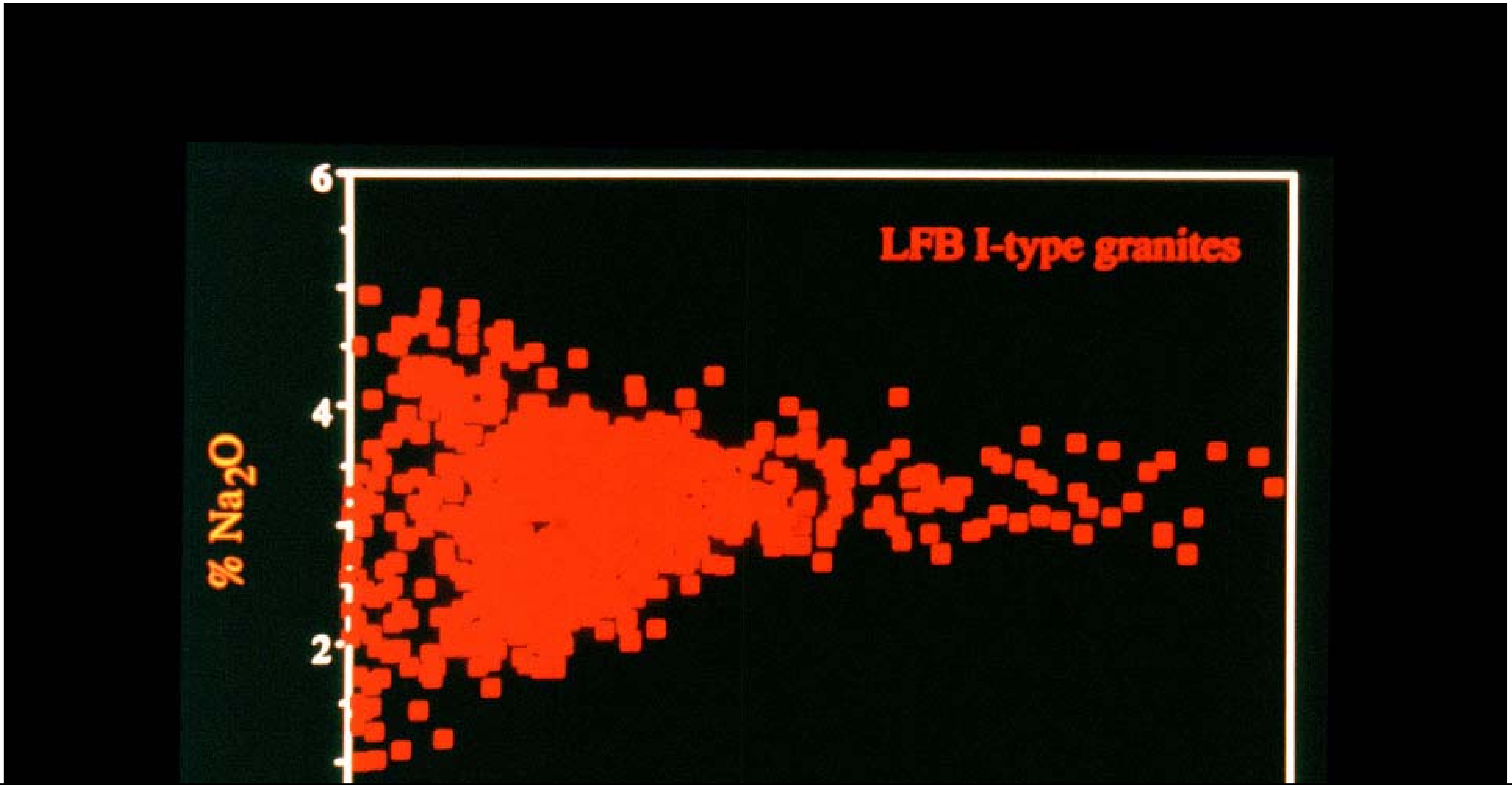
Tuttle & Bowen plot of felsic granites of the I-type Moonbi Suite of the southern end of the New England Batholith. These are again interpreted as partial melts rather than products of extended fractional crystallisation from more mafic magmas.


80
70
60
50
40
% SiO_2
0
20
40
60
80
Rb/Sr
LFB I-type granites



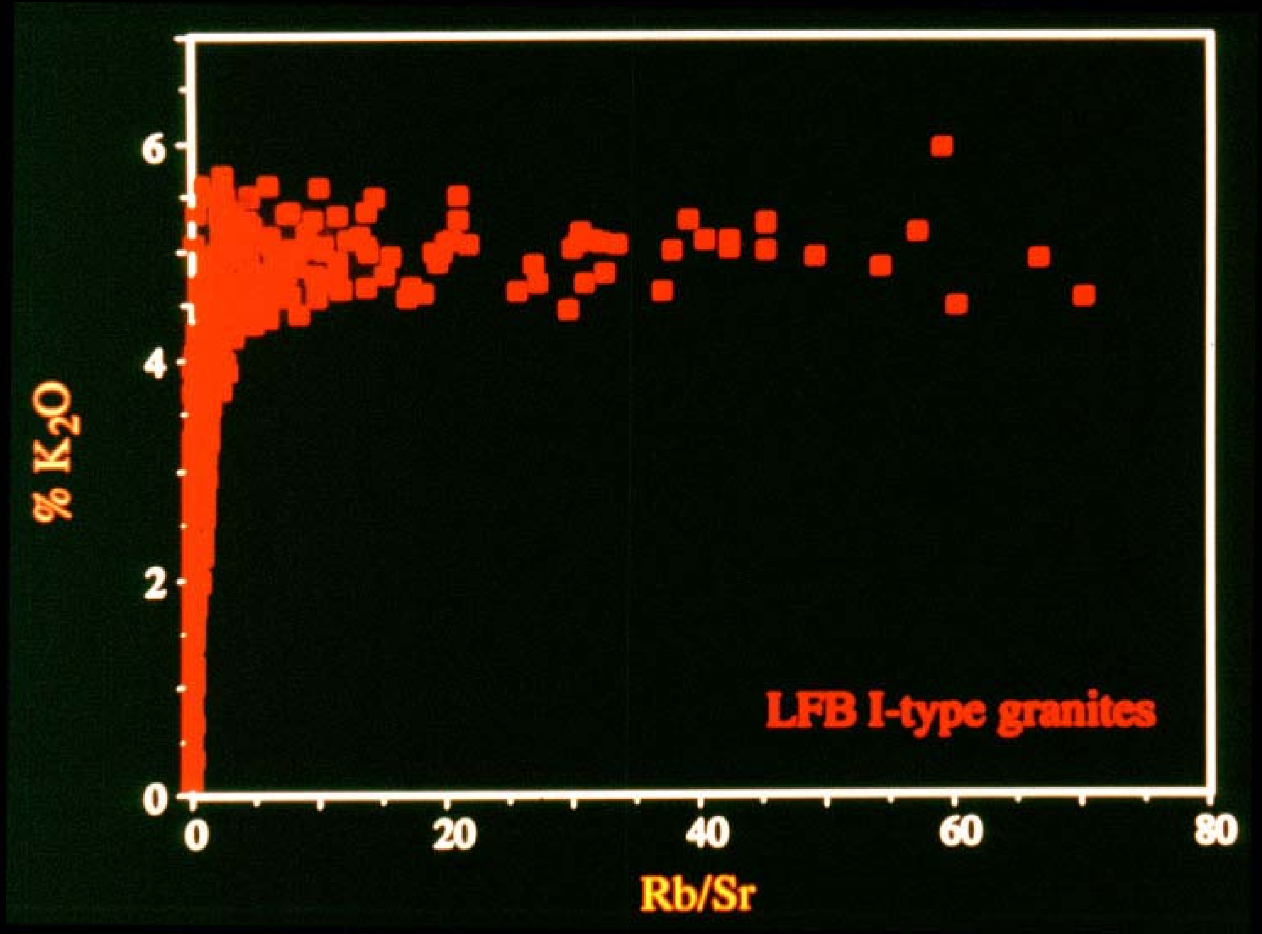
Rb increases and Sr decreases as granite compositions become more felsic, for whatever reason. This is also the case if fractional crystallisation occurs at or near the Tuttle & Bowen minimum. This slide shows that in more felsic and possibly more fractionated granites, the abundance of SiO_2 has a limited maximum value. This corresponds to the rapid increase in temperature of melts plotted on the Tuttle & Bowen diagram, moving away from the minimum temperatures towards quartz. This plot includes 1302 I-type granites from the LFB, of which only 19 (1.45%) have SiO_2 contents greater than 75%, with a maximum of 77.69%.


LFB I-type granites
% Na2O
6
4
2
0
0
200
400
600
ppm Rb



The abundance of Rb increases up to about 250 ppm from more mafic to more felsic granites, and increases beyond 250 ppm with fractional crystallisation. This diagram shows that the abundance of Na_2O converges on a value of about 3.2 ± 0.5% in felsic and fractionated rocks.

This diagram applies to all felsic granites, irrespective of whether their distinctive compositions result from partial melting in equilibrium with quartz and feldspars, or the fractional crystallisation of quartz and feldspars.


6
4
2
0
% K_2O
0
20
40
60
80
Rb/Sr
LFB I-type granites

The concentrations of K_2O in felsic and fractionated granites converge on a value of 5.0 ± 0.5%.. This is greater than the value of 3.2% for Na2O in the previous slide, despite the Tuttle & Bowen minima having subequal amounts of Ab and Or, because the values plotted on these two slides are wt% and the molecular weight of K_2O (94.10) is likewise greater than Na_2O (61.98).

The last three slides show again that felsic granites have restricted compositions.

READ’S GRANITE SERIES

For about a decade, the contribution of Tuttle & Bowen (1958) consolidated to the view that there are “granites and granites” (Read, 1948), that all granites are related in a series from deep-level early-formed granites associated with high grade metamorphic rocks and migmatites, progressively through to high-level intrusive plutons. The *granite series* of Read (1957) expressed this as a sequence of granite types that evolved both in time and space:

4. Plutons
3. Allochthonous granites
2. Parauthochthonous granites, e.g. Cooma
1. Authochthonous granites, with migmatites and metamorphic rocks

Read’s series had two errors. It implied that all granites formed from sedimentary source rocks and it did not recognise the existence of cogenetic volcanic rocks.

The view that most granites were derived by the partial melting of sedimentary source rocks was challenged both by the discovery that large granites may be isotopically primitive (Hurley *et al*., 1965) and the realisation that hornblende-bearing granites cannot be derived from source rocks that contain a weathered component (e.g. Chappell, 1966).

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The view that most granites were derived by the partial melting of sedimentary source

References:
Chappell, B.W. 1966. Petrogenesis of the granites at Moonbi, New South Wales. PhD thesis, Australian National University, Canberra (unpublished).
Hurley, P.M., Bateman, P.C., Fairbairn, H.W. & Pinson, W.H. Jr. 1965. Investigation of initial ^{87}Sr/^{86}Sr ratios in the Sierra Nevada Plutonic Province. *Bulletin of the Geological Society of America* **76**, 165-174.
Read, H.H. 1948. Granites and granites. *The Geological Society of America Memoir* **28**, 1-19.
Read, H.H. 1957. *The Granite Controversy*. Thomas Murby & Co, London.

THE ELEMENTS NOT CONSIDERED BY TUTTLE & BOWEN

Tuttle & Bowen were principally concerned with the *felsic* granites, those with compositions dominated by only a few of the elements, namely H O Na Al Si and K. By doing that, they were able to make the single greatest contribution to our understanding of rocks of the granite family. But many of those rocks also contain other elements, e.g. Ca and Fe, in significant abundances. Also, many less abundant trace elements can vary widely in amount in these rocks and some may be concentrated as granite systems evolve, to form deposits of economic importance. We must now consider some of those other elements.

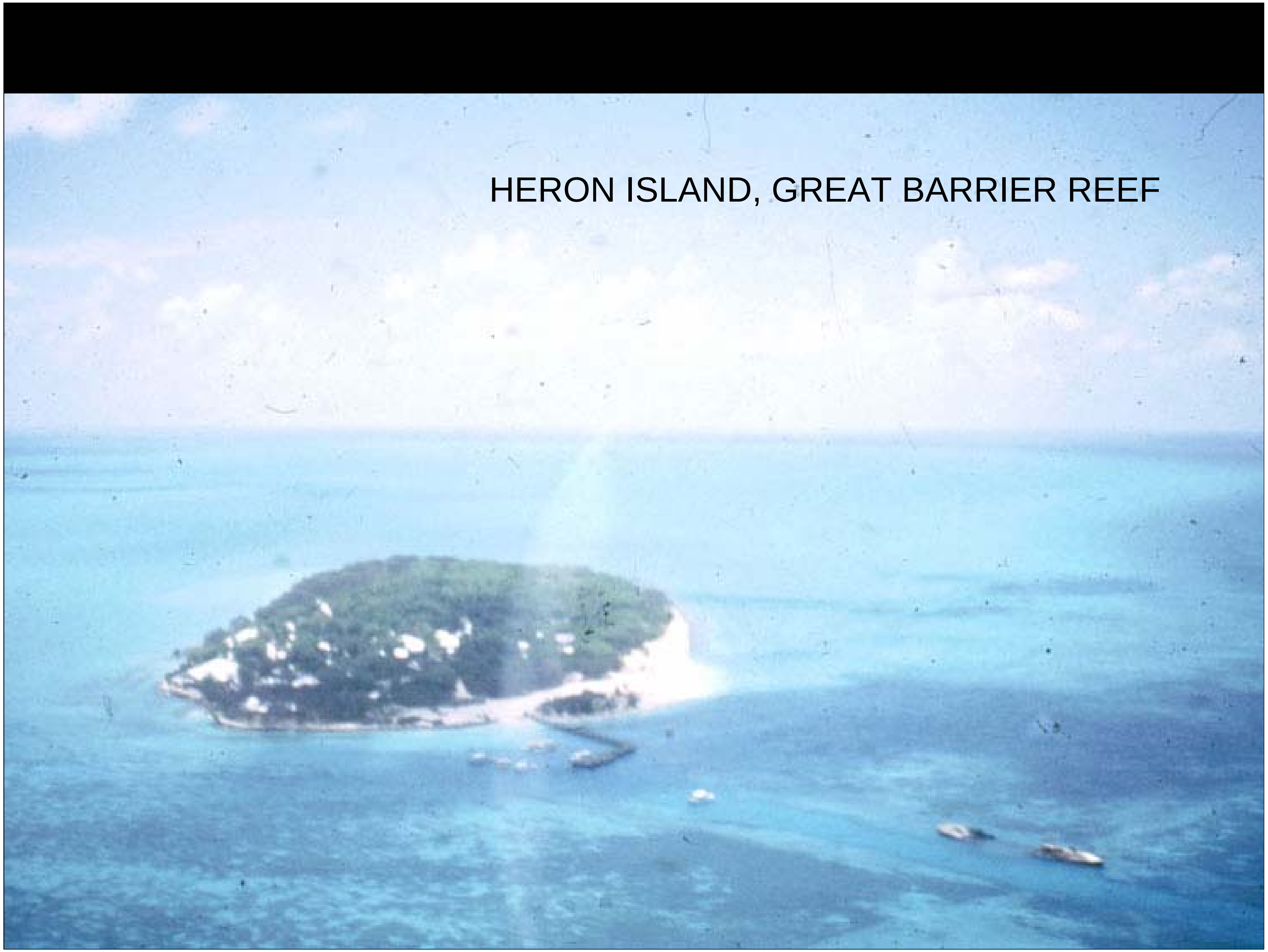
The term *fractionation* is frequently used to refer to processes by which the abundances of elements are changed, for example in the purification of a compound in the laboratory. It can be applied to the natural processes that change the chemical compositions of various components of the Earth, including 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. We will now consider an important example.

THE EFFECTS OF WEATHERING ON LATER GRANITE COMPOSITIONS

The process of weathering at the Earth’s surface produces the strongest fractionation of the elements in this planet, at least since the core separated from the mantle. This process results from the fact that most minerals that had formed earlier at high temperatures become unstable and new minerals are produced, dominated by members of the clay mineral group.

This fractionation occurs because the elements Na Ca and Sr cannot be accommodated to any extent in the clay minerals and are removed to the oceans, and later in part to other sedimentary rocks. Since Na is an essential component for partial melting of the crust and hence of all granites, the weathering event can have a profound effect on the nature of any granites that might subsequently form, and may even determine if they do form. Likewise, Ca and Sr and important major and trace constituents of the less felsic granites.

The effects of this fractionation are shown in the following slide, in which a Ca + Sr-rich mass sits in a Na-rich solution.

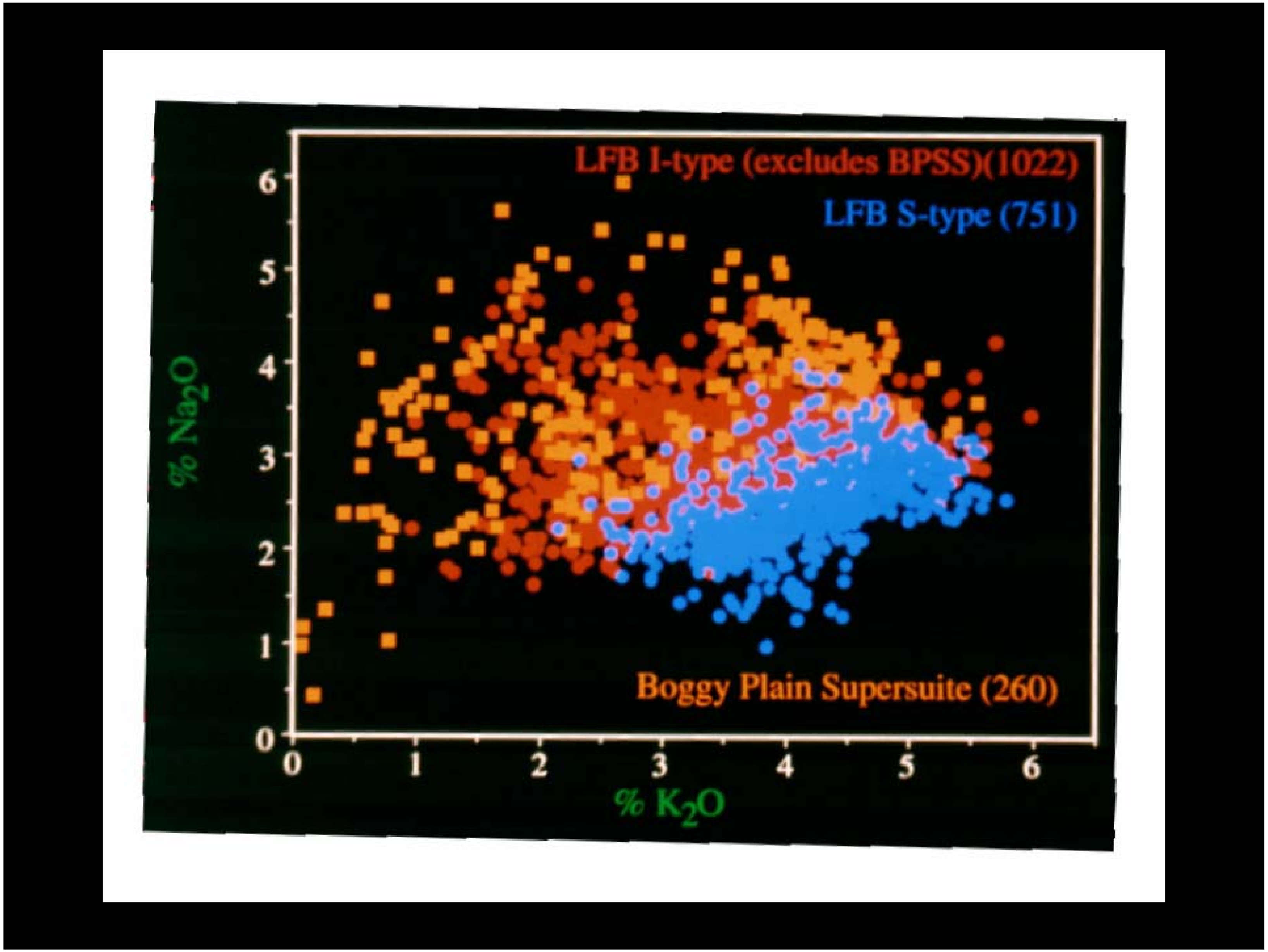


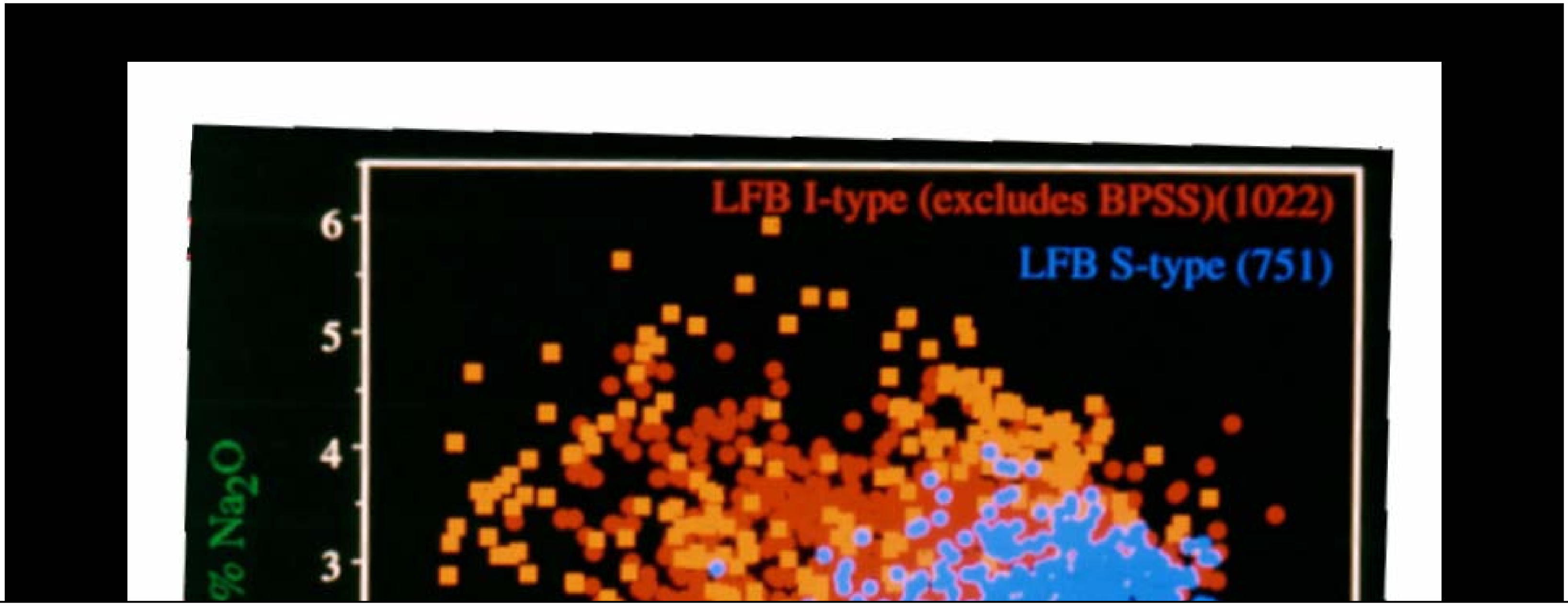
HERON ISLAND, GREAT BARRIER REEF

HERON ISLAND, GREAT BARRIER REEF

SOME NOTES ON CHEMICAL WEATHERING

Chemical weathering destroys minerals that are unstable at the Earth’s surface and converts them into clay minerals, with other elements being carried away in solution. This process of chemical fractionation produces four principal groups of rocks (Goldschmidt’s terminology), the resistates (quartz-rich or sandstones), the precipitates (clay-rich or shales), the carbonates (limestone and lesser dolomite) and the evaporates (evaporites and sea water). This slide makes the point that Ca and Na are removed from mantle-derived rocks by weathering and a proportion is unavailable for subsequent granite-forming processes. Carbonates and clay-rich rocks cannot undergo partial melting; greywackes, containing quartz, feldspars and a clay component (depleted in Na and Ca), may form S-type granites.


LFB I-type (excludes BPSS)(1022)
LFB S-type (751)
Boggy Plain Supersuite (260)
% Na$_2$O
% K$_2$O
0
1
2
3
4
5
6
0
1
2
3
4
5
6



This slide illustrates that the S-type granites of the LFB are restricted to higher K contents and have lower abundances of Na, reflecting prior weathering of their source materials. The high-temperature (Boggy Plain) and low-temperature I-type granites, that will be considered later, are distinguished from each other on this plot.

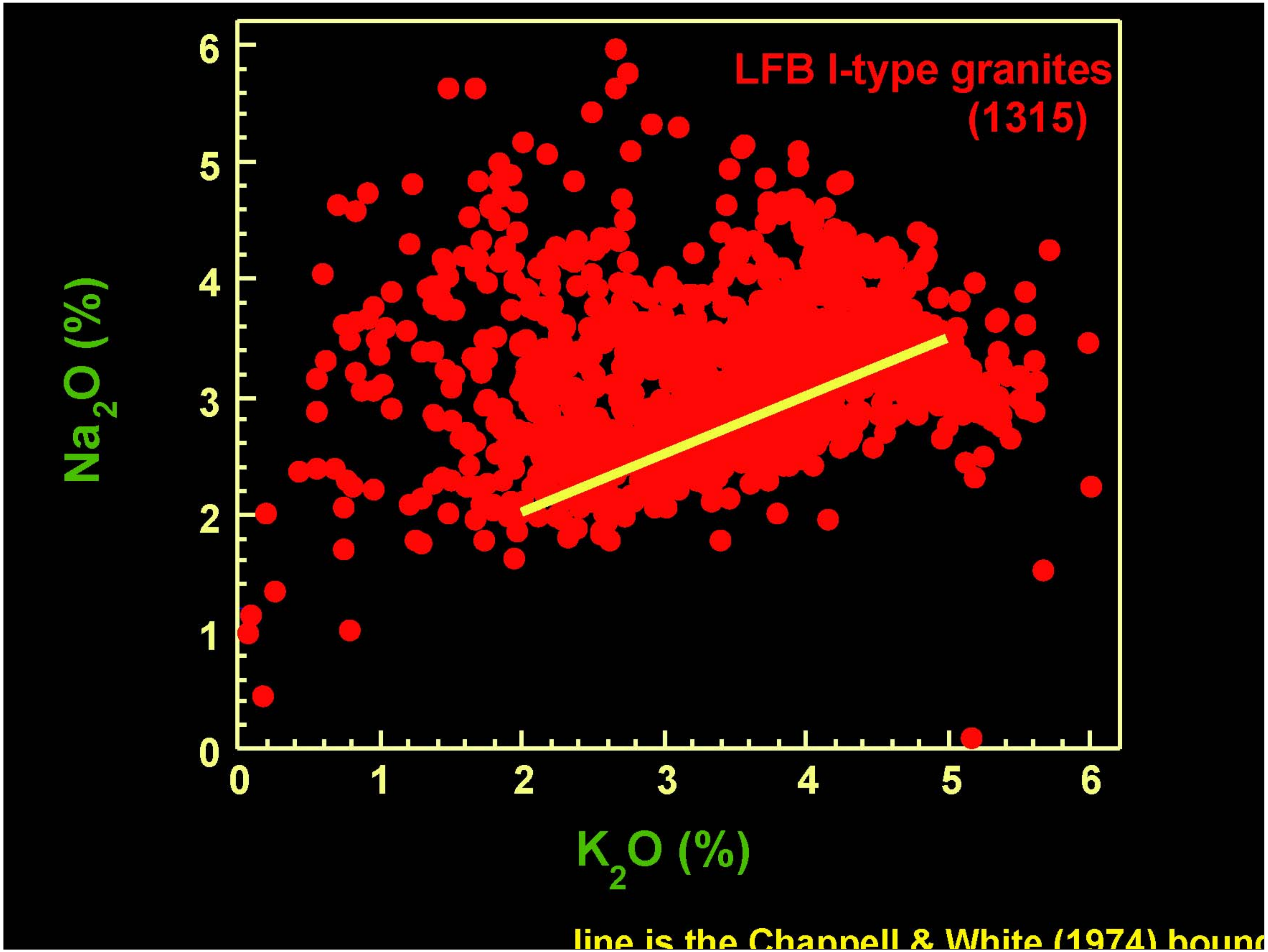
The I- and S-type granite references:

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

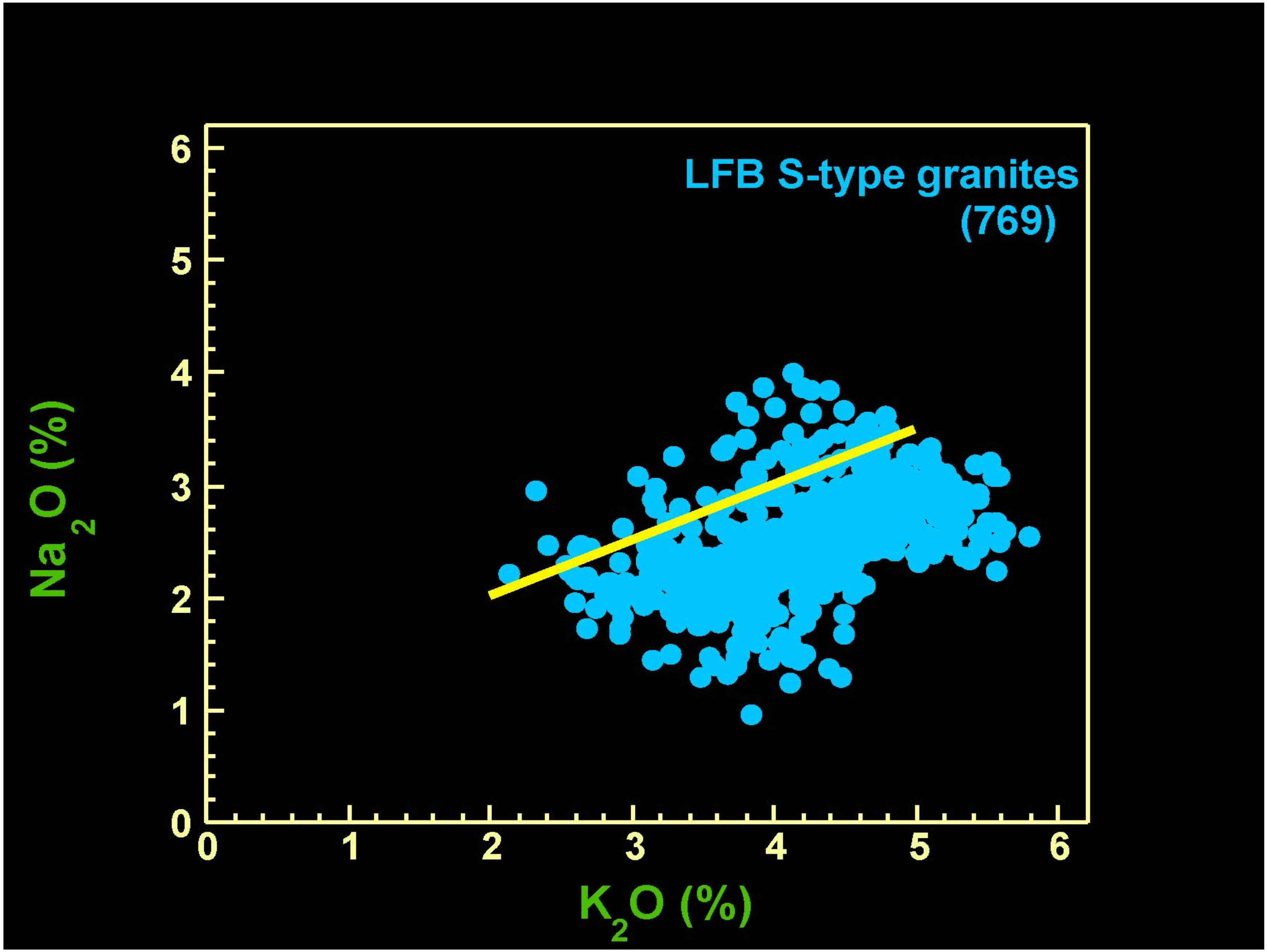
Chappell, B.W. & White, A.J.R. 1984. I- and S-type granites in the Lachlan Fold Belt, southeastern Australia. *In* Xu Keqin & Tu Guangchi (eds), *Geology of Granites and Their Metallogenic Relations*, pp. 87-101. Science Press, Beijing.

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

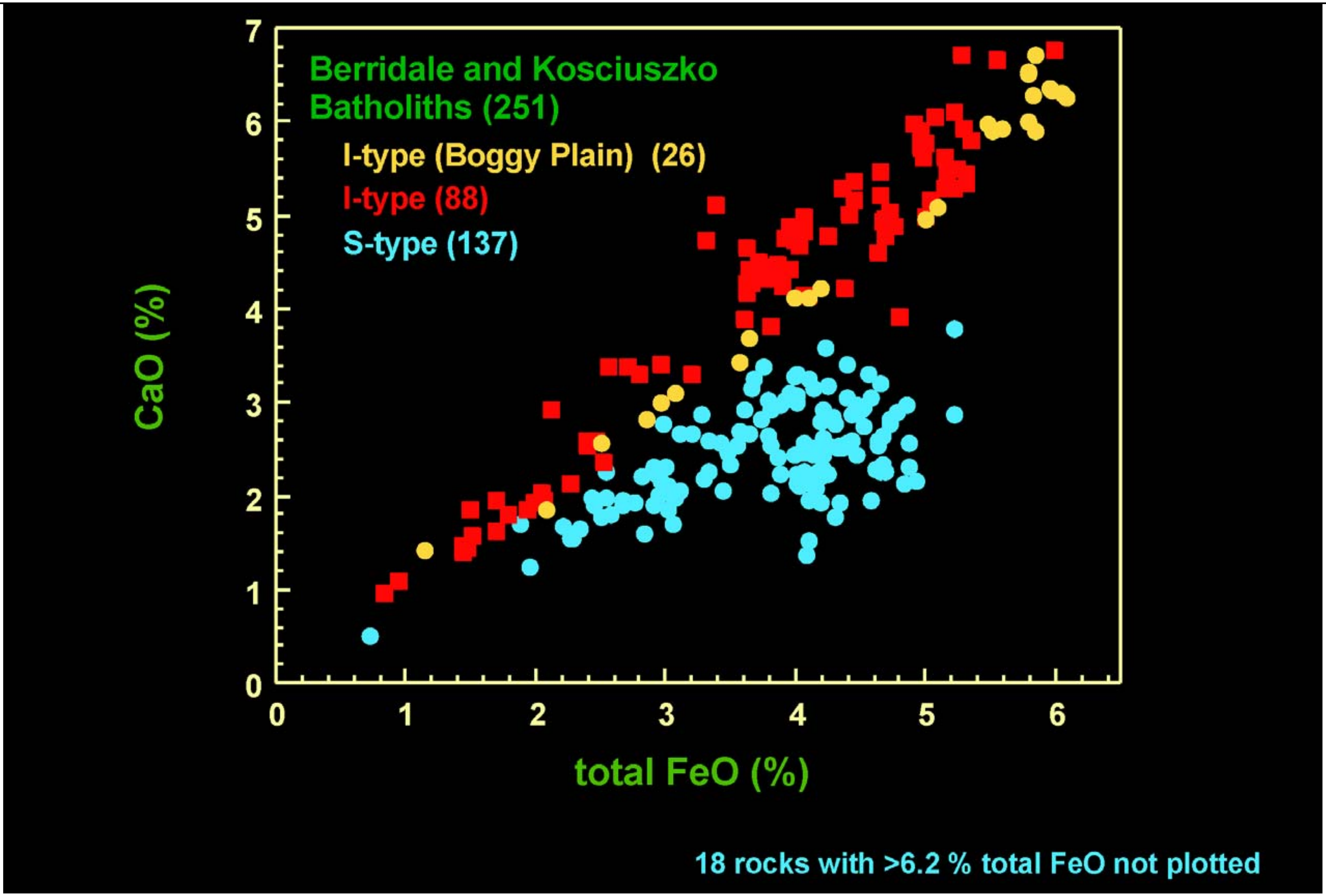
Chappell, B.W. & White, A.J.R. 2001. Two contrasting granite types: 25 years later. *Australian Journal of Earth Sciences* **48**, 489-499.

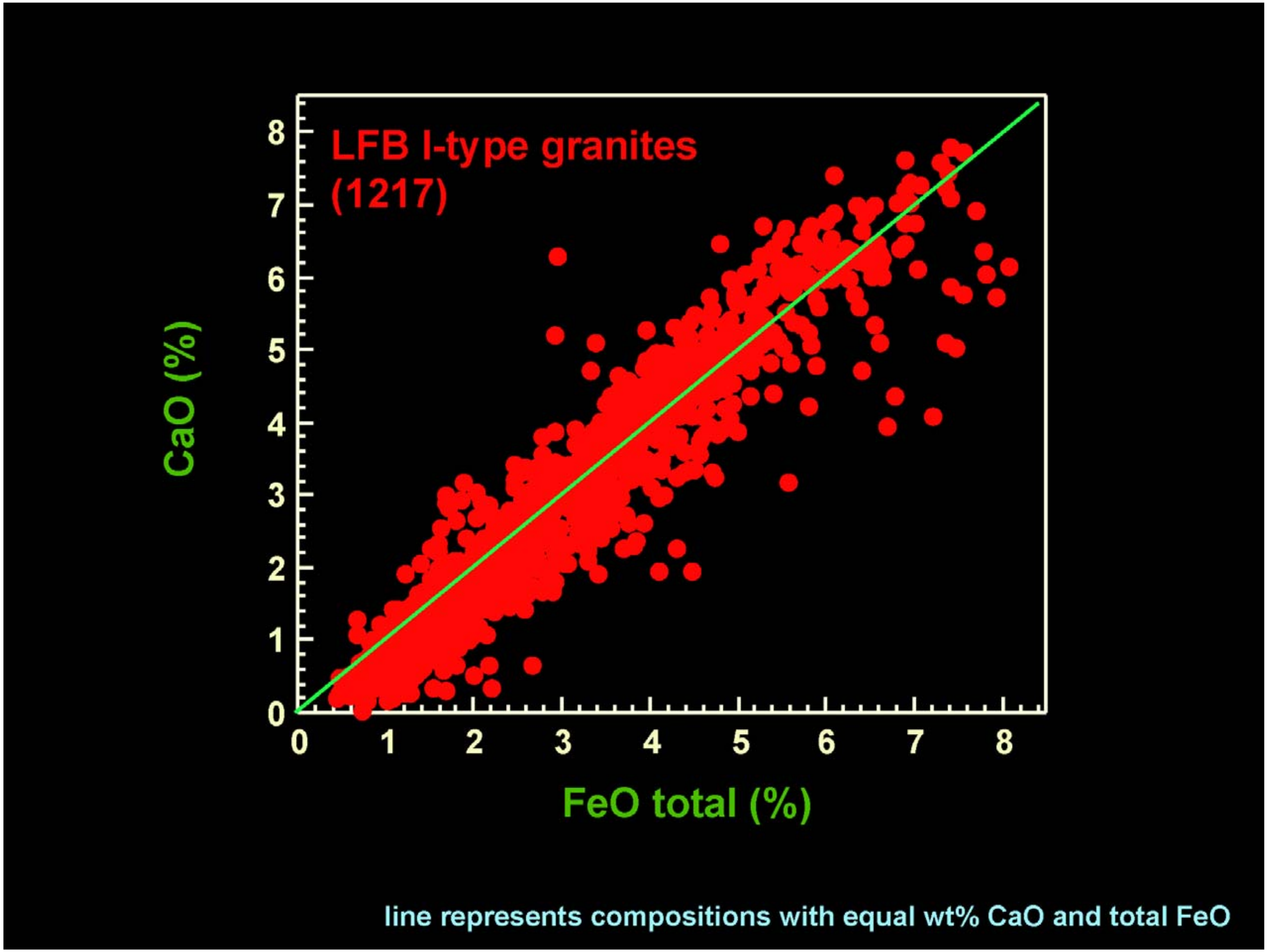


line is the Chappell & White (1974) boun

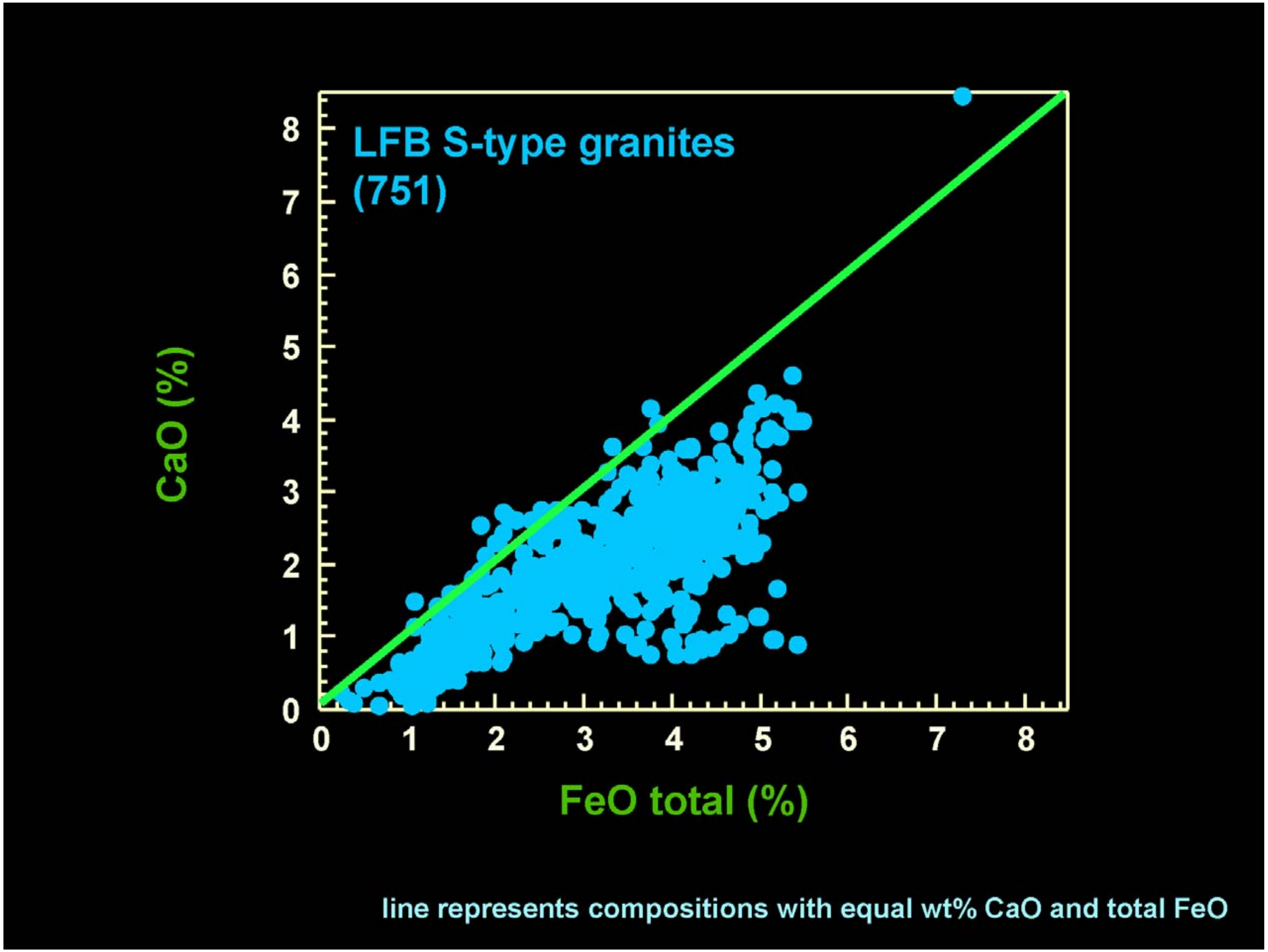

LFB S-type granites
(769)
Na_2O (%)
K_2O (%)
0
1
2
3
4
5
6
0
1
2
3
4
5
6

These are all of the data (except for the most Fe-rich samples) now available for the region in which the I- and S-type granite subdivision was first recognised.





line represents compositions with equal wt% CaO and total FeO


LFB S-type granites
(751)
CaO (%)
FeO total (%)
0
1
2
3
4
5
6
7
8
line represents compositions with equal wt% CaO and total FeO

Al SATURATION AND THE TERMS METALUMINOUS AND PERALUMINOUS

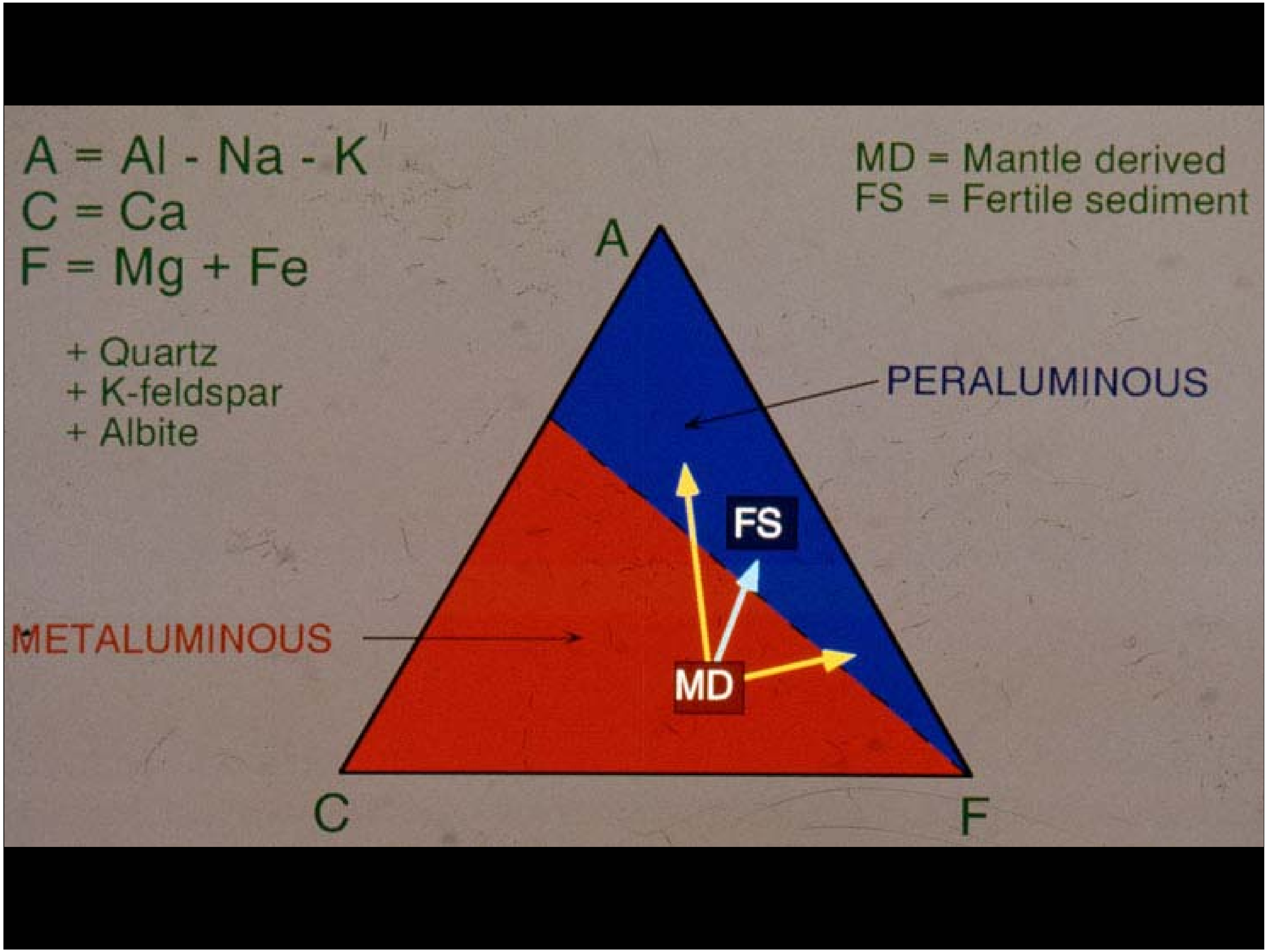
The concept of silica-saturation is easily understood. Silica (quartz) occurs in igneous rocks with bulk compositions that are saturated in silica.

Al-saturation is less straightforward. A rock is just saturated in Al when there is sufficient of that element present to just incorporate all of the Na Ca and K of that rock in feldspars. If there is less Al, it is undersaturated and another Ca-bearing mineral such as clinopyroxene or hornblende must form. If the rock is oversaturated in Al, then an Al-bearing mineral in addition to feldspars, such as muscovite, or an aluminosilicate, or cordierite, must occur.

Shand proposed the useful terms *metaluminous* and *peraluminous* to refer to rocks that are respectively under- and oversaturated in Al.

When the elements in a rock are recast as hypothetical minerals in a CIPW norm, metaluminous rocks contain normative diopside (di) and peraluminous rocks contain normative corundum (C). These normative minerals will correspond to the presence of specific Al-poor or Al-rich minerals in the rock.

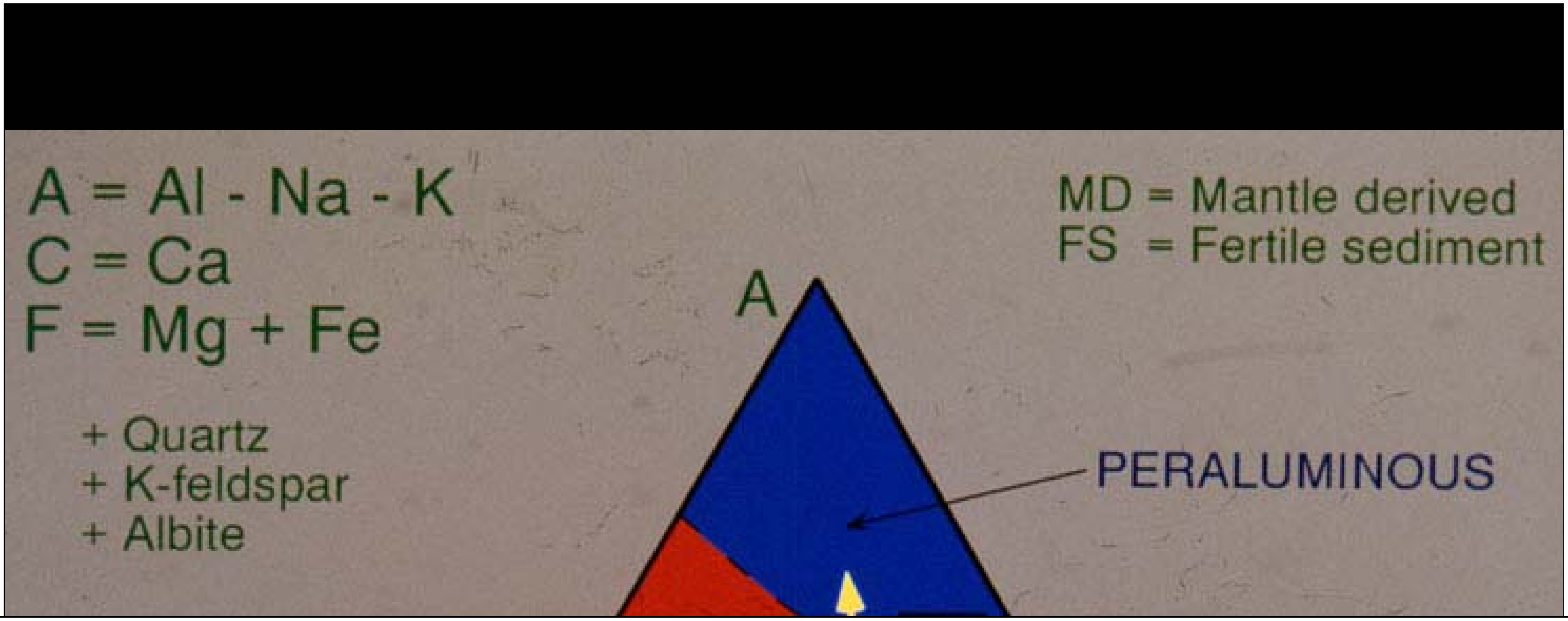
Zen (1986) introduced the term *aluminium saturation index* (ASI) as a measure of the degree of Al saturation. At a value of ASI = 1, a rock is just saturated while metaluminous rocks have ASI < 1 and peraluminous rocks have ASI > 1 (see notes).



A = Al - Na - K
C = Ca
F = Mg + Fe

+ Quartz
+ K-feldspar
+ Albite

MD = Mantle derived
FS = Fertile sediment

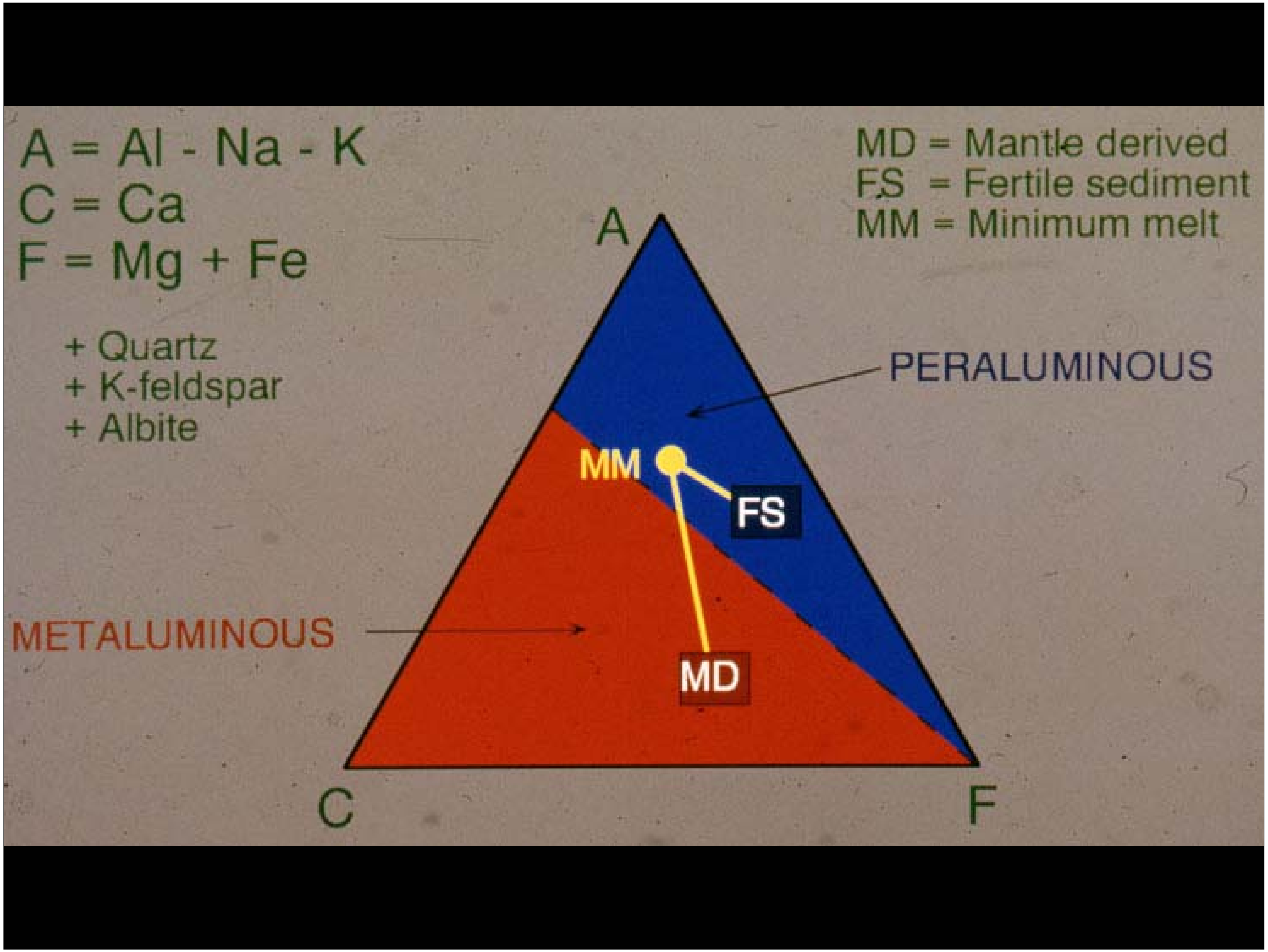


A = Al - Na - K
C = Ca
F = Mg + Fe

+ Quartz
+ K-feldspar
+ Albite

MD = Mantle derived
FS = Fertile sediment

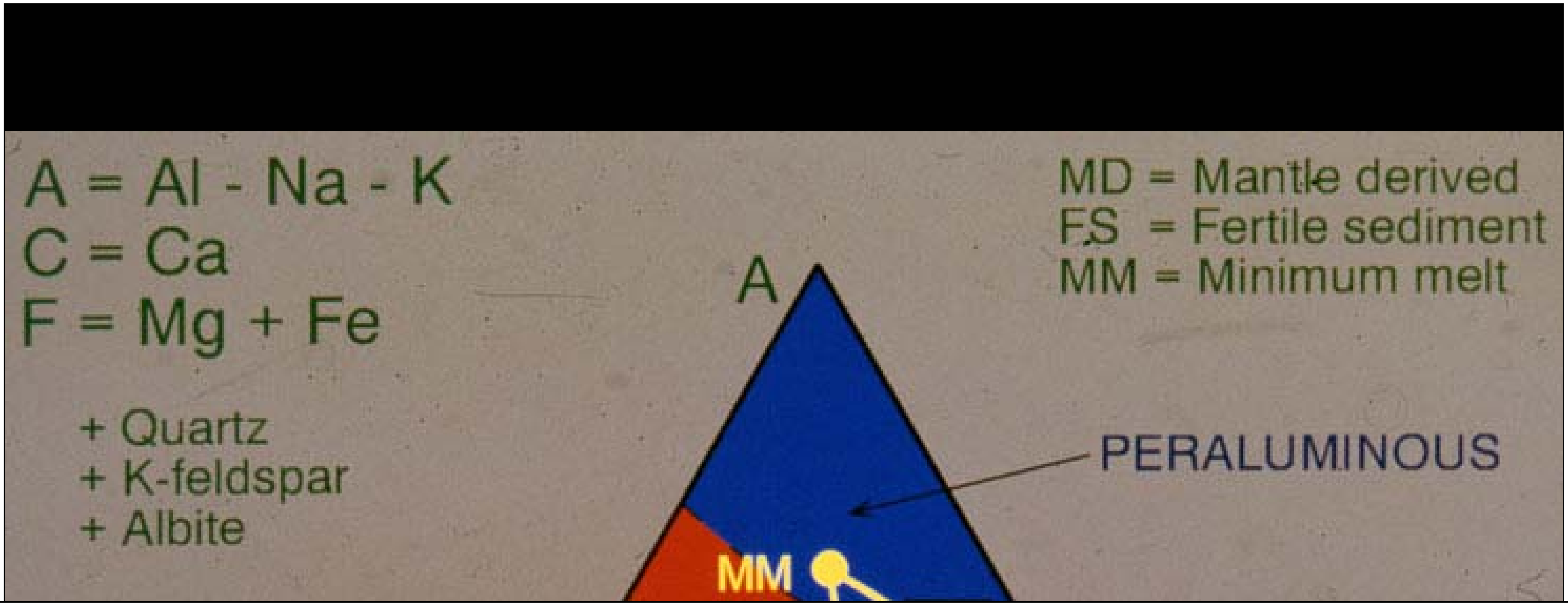
This is an ACF diagram slightly modified to plot the three components in atomic proportions. Rock compositions in the red field are metaluminous, those in the blue are peraluminous. Mantle-derived materials are always metaluminous and will plot near the point MDC (mantle-derived crust). When MDC is weathered, then the loss of Ca will produce a vector away from C and the loss of Na one towards A. Depending on the degree of weathering, this may move the bulk composition into the peraluminous field, to a point such as that represented by FS. This is how peraluminous granite source rocks are produced. If the weathering is more intense and too much feldspar is destroyed to provide Na for partial melting (K will be present in clay minerals), then the rock is infertile in terms of partial melting.



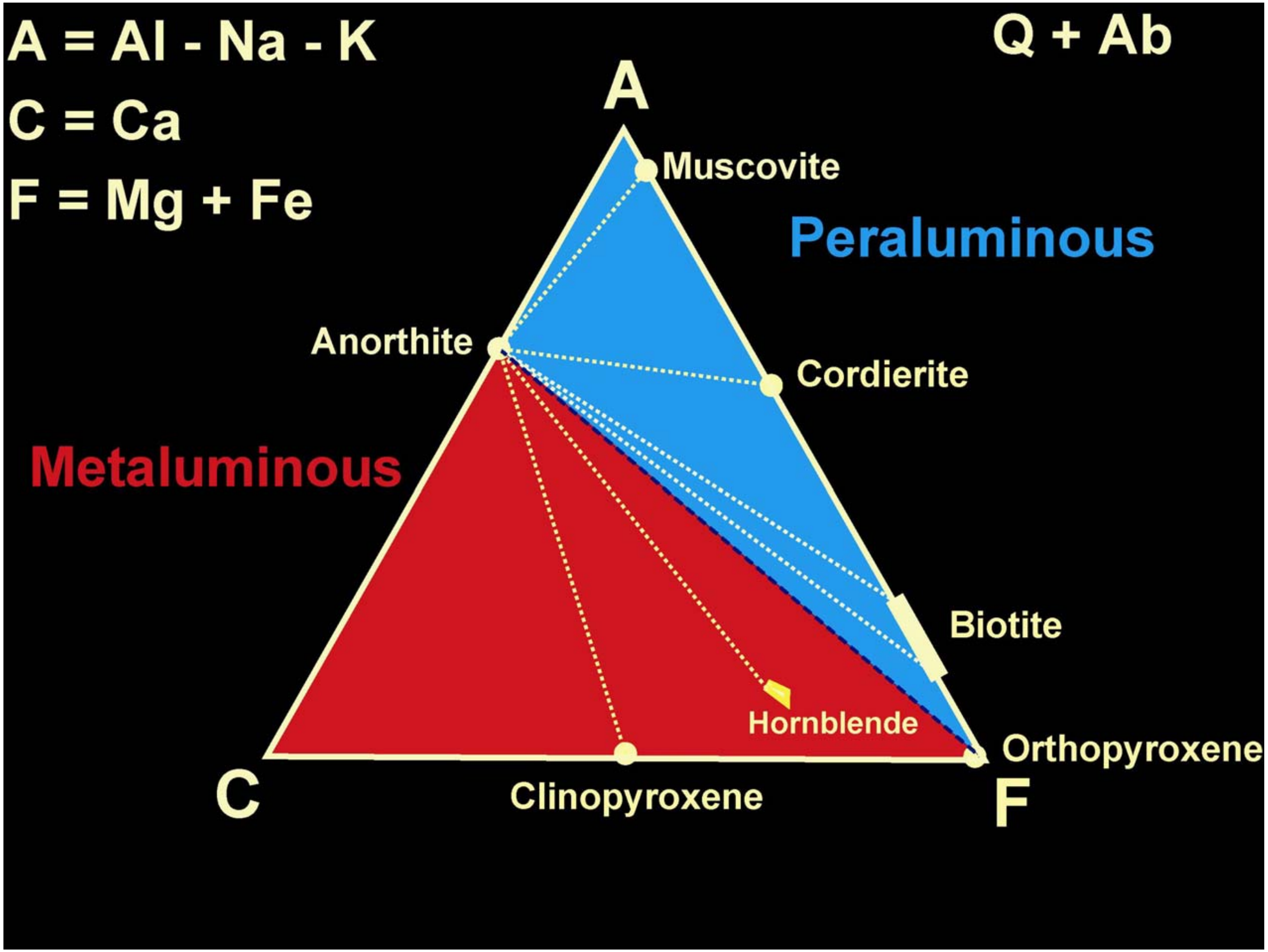
A = Al - Na - K
C = Ca
F = Mg + Fe

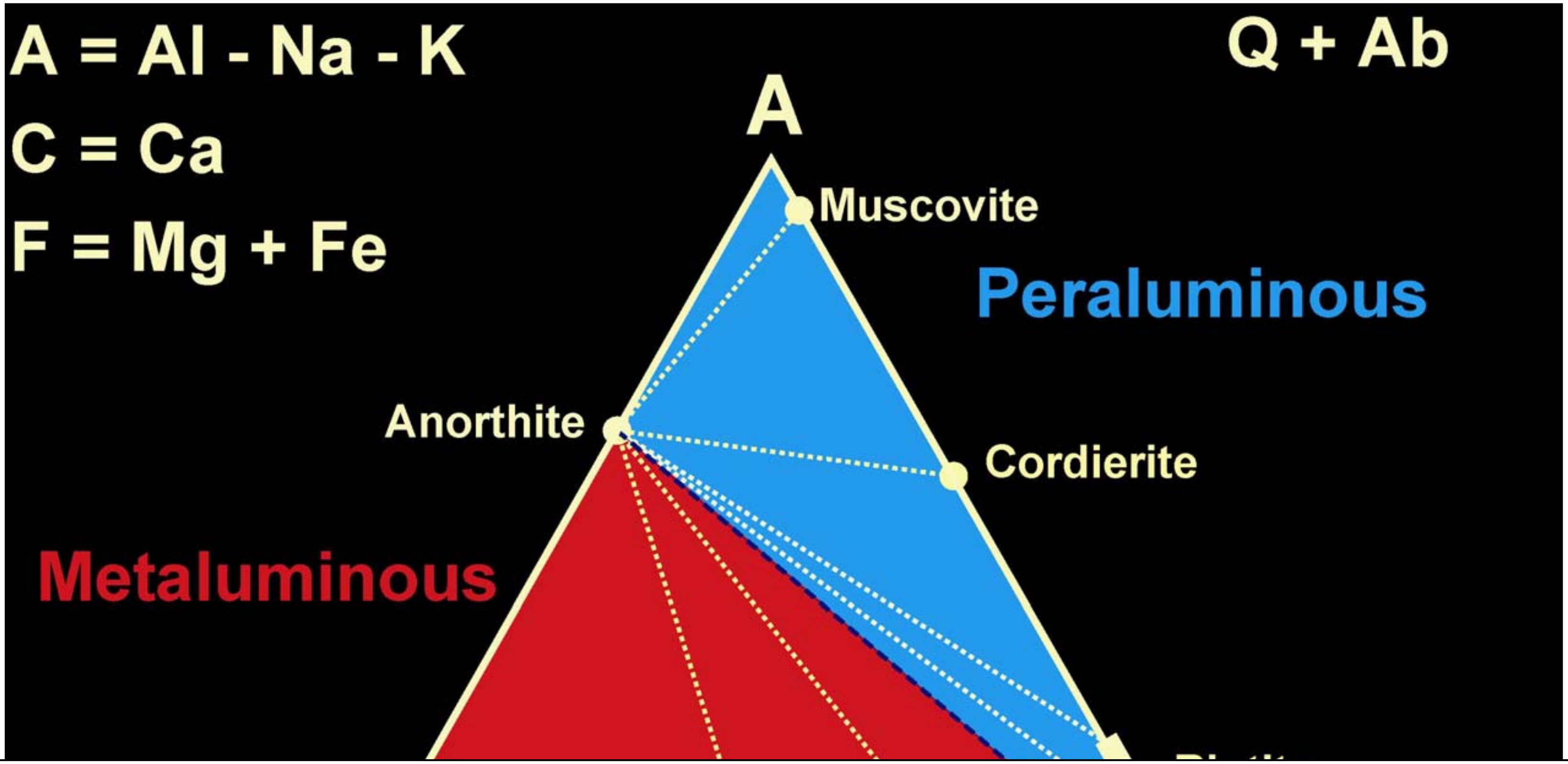
+ Quartz
+ K-feldspar
+ Albite

MD = Mantle derived
FS = Fertile sediment
MM = Minimum melt

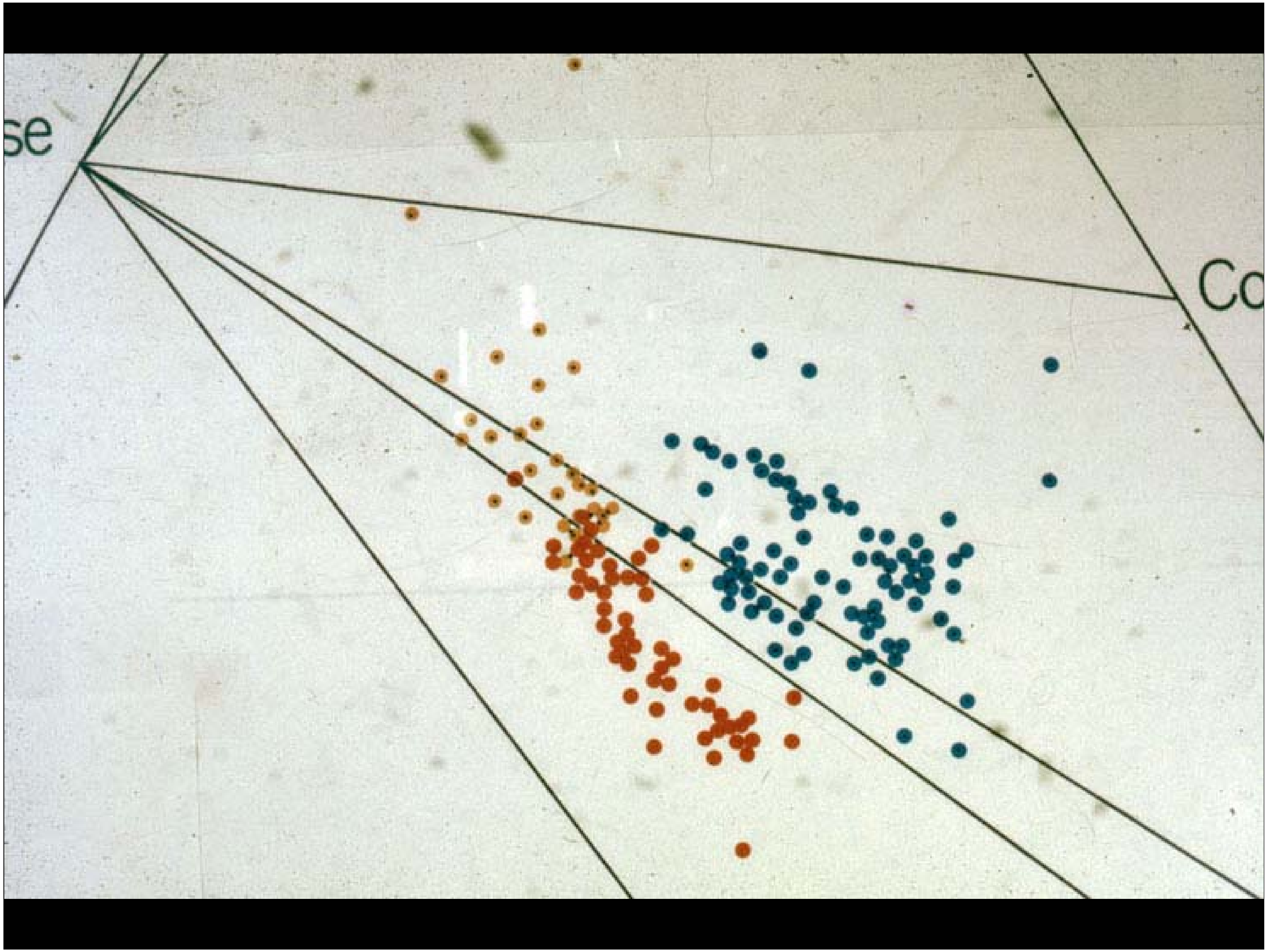


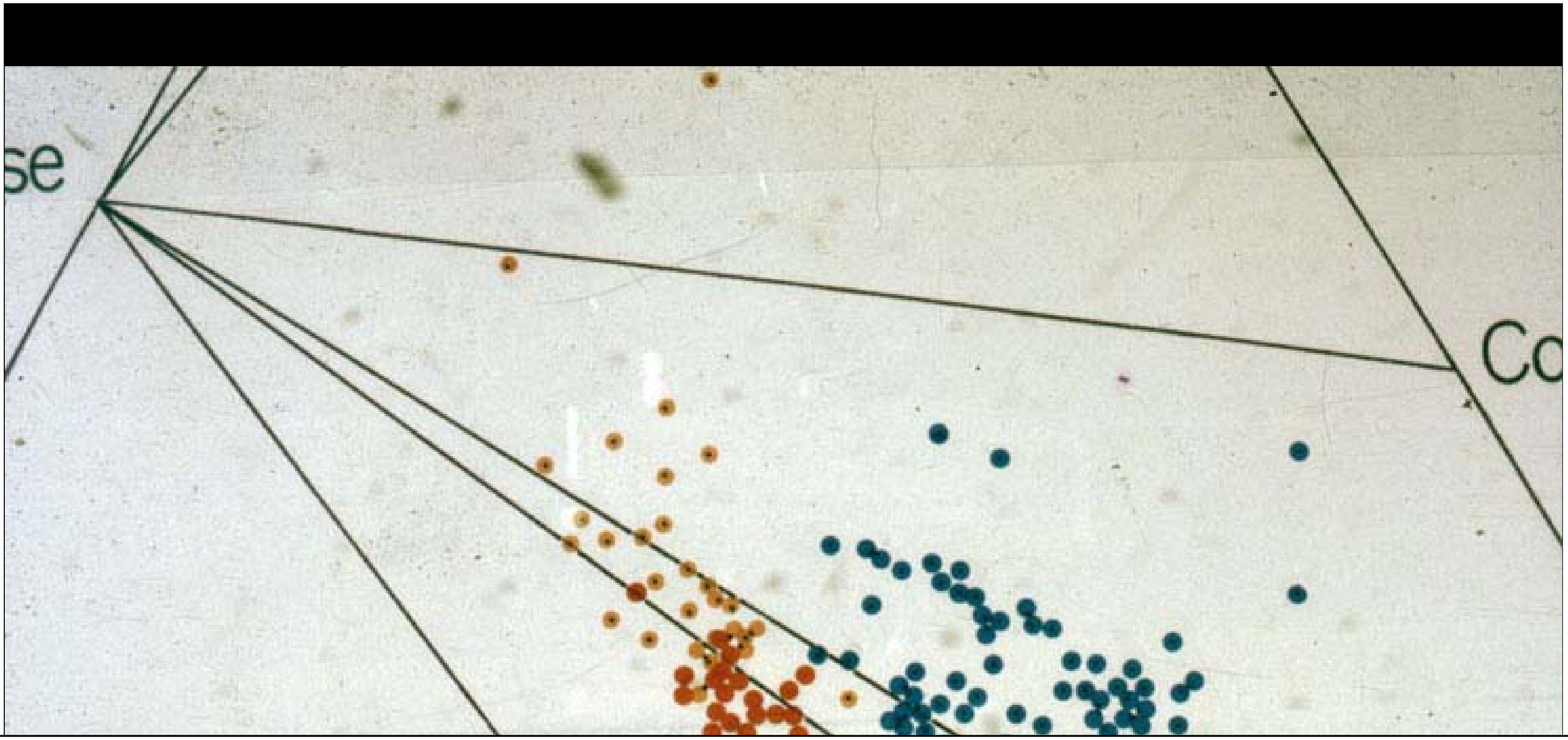
Irrespective of the mechanism that produces variation within suites of granites, the compositions will lie in a general way between those of the source materials (MD and FS) and low temperature melts (MM). This diagram shows that S-type granites will always be peraluminous, whereas I-types can be either peraluminous or metaluminous depending on whether a given rock has incorporated more of the source components or of low-temperature melt components. It should be stressed that this argument is virtually independent of the details of petrogenesis. For example, the metaluminous character of a more mafic I-type granite could be the result of magma mingling between more dominant mantle material and a partial melt of the crust, or a high degree of partial melting of mafic source rocks, or the incorporation of greater amounts of mafic source materials initially present either as a melt (fractional crystallisation), or as solids (restite).


A = Al - Na - K
C = Ca
F = Mg + Fe
Q + Ab
A
Muscovite
Peraluminous
Anorthite
Cordierite
Metaluminous
Biotite
Hornblende
Orthopyroxene
C
Clinopyroxene
F

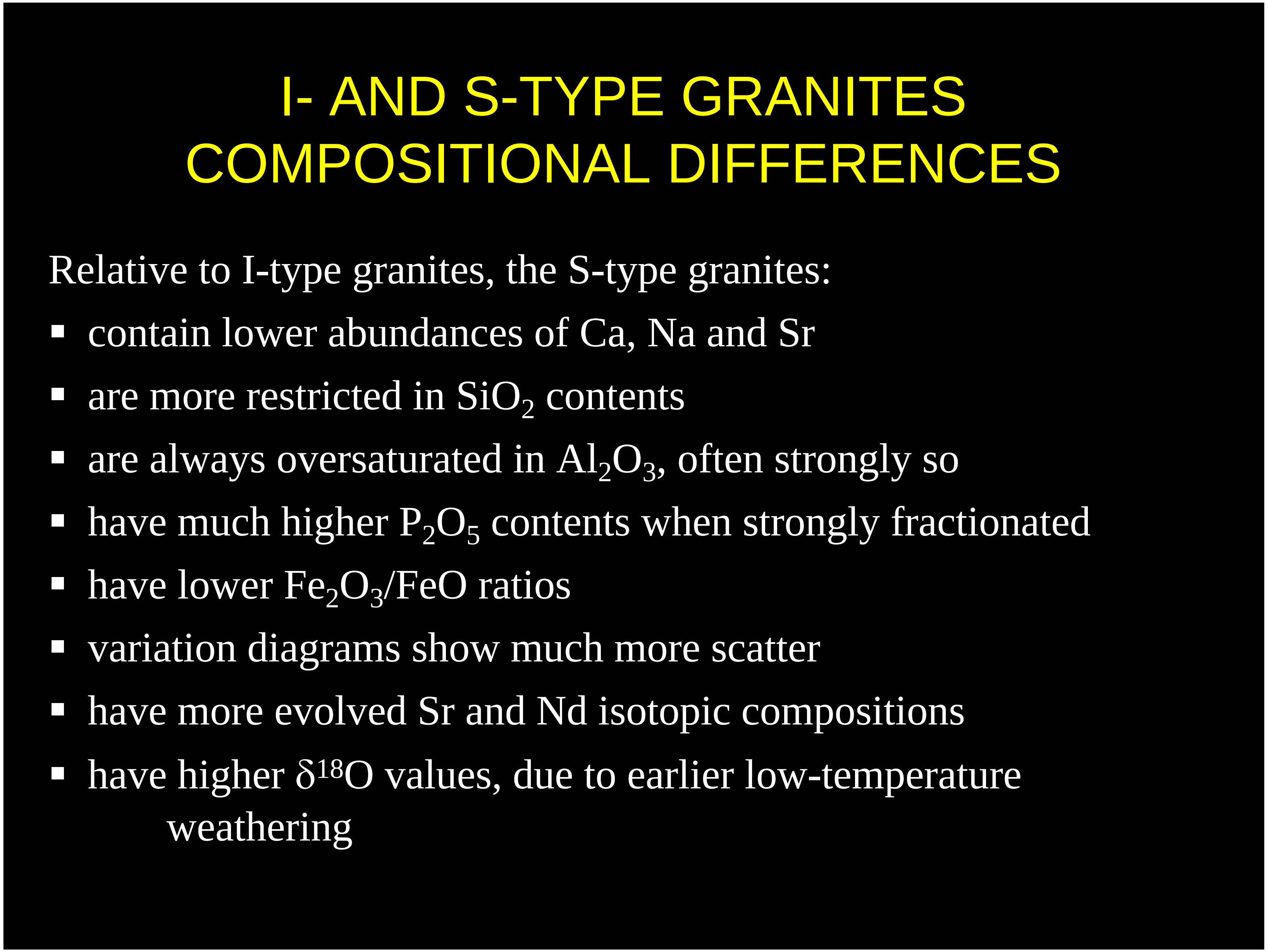


This is an ACF diagram for the mineral facies that includes amphibolite facies and hornblende hornfels facies and granitic rocks. The minerals present in a particular granite will include quartz, plagioclase (Ab + An), plus any two adjacent minerals in the sequence muscovite-cordierite-biotite-hornblende, the assemblage for a particular rock being determined by the point at which it plots in the figure. In the case of biotite, the Al-rich and Al-poor compositions can be regarded as two minerals in solid solution, so that a rock plotting in the area bounded by biotite and anorthite should contain only biotite (e.g. the Dalgety Granodiorite of the Berridale Batholith for most samples).


se
Co



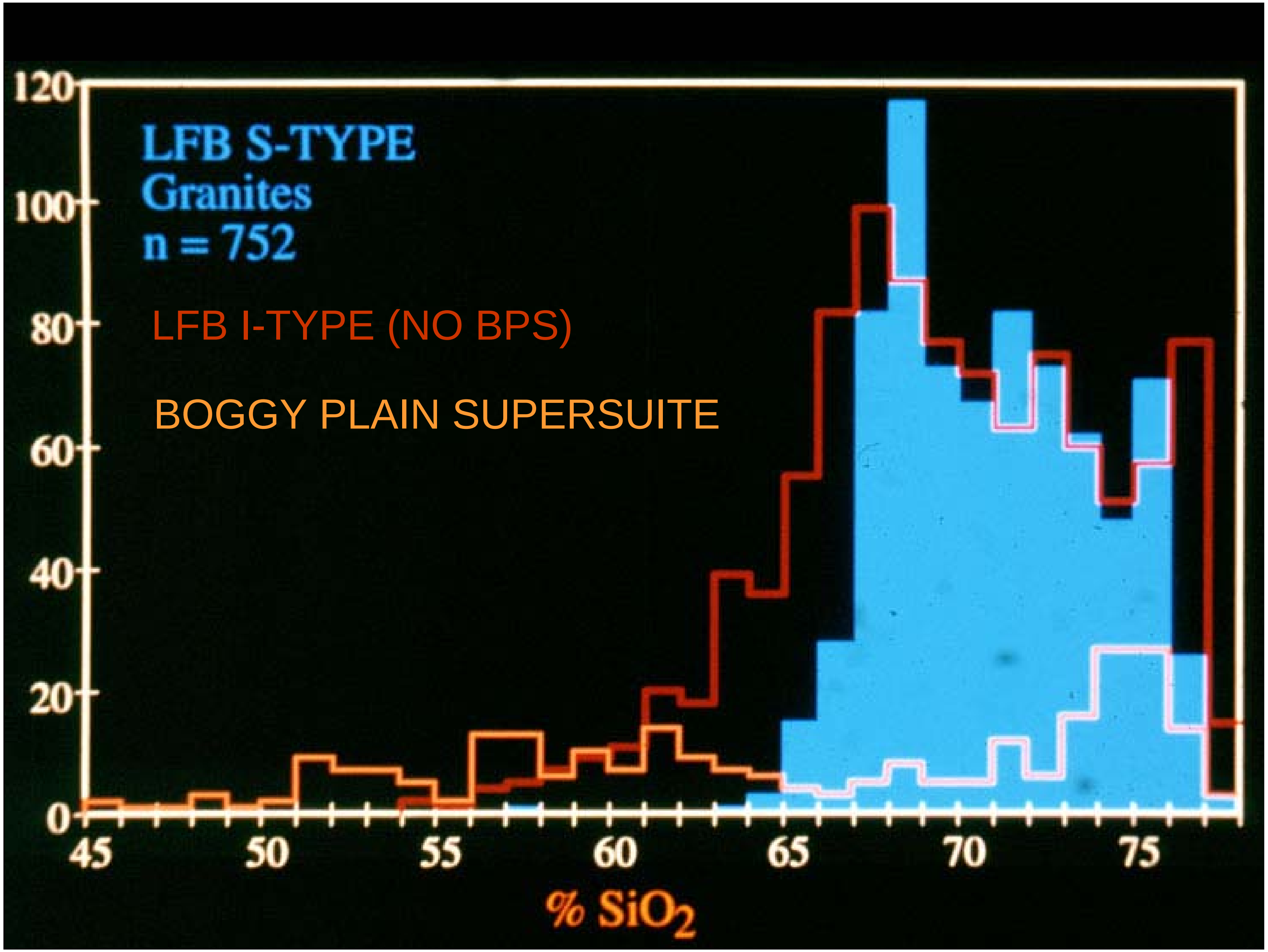
This slide was originally prepared for a talk at the Sydney IGC in 1976. Data are from the Berridale and Kosciuszko Batholiths. Red points hornblende-bearing I-type granites, such as rocks of the Jindabyne Suite. The yellow points are hornblende-free I-type granites, such as the Buckleys Lake Monzogranite. The Blue points represent the S-type granites - those lying above the anorthite to Al-rich biotite join would be mainly from the cordierite, or altered cordierite granodiorites of the Bullenbalong Supersuite. The S-type points below that join would be mainly from the Dalgety Suite, which is generally free of cordierite.

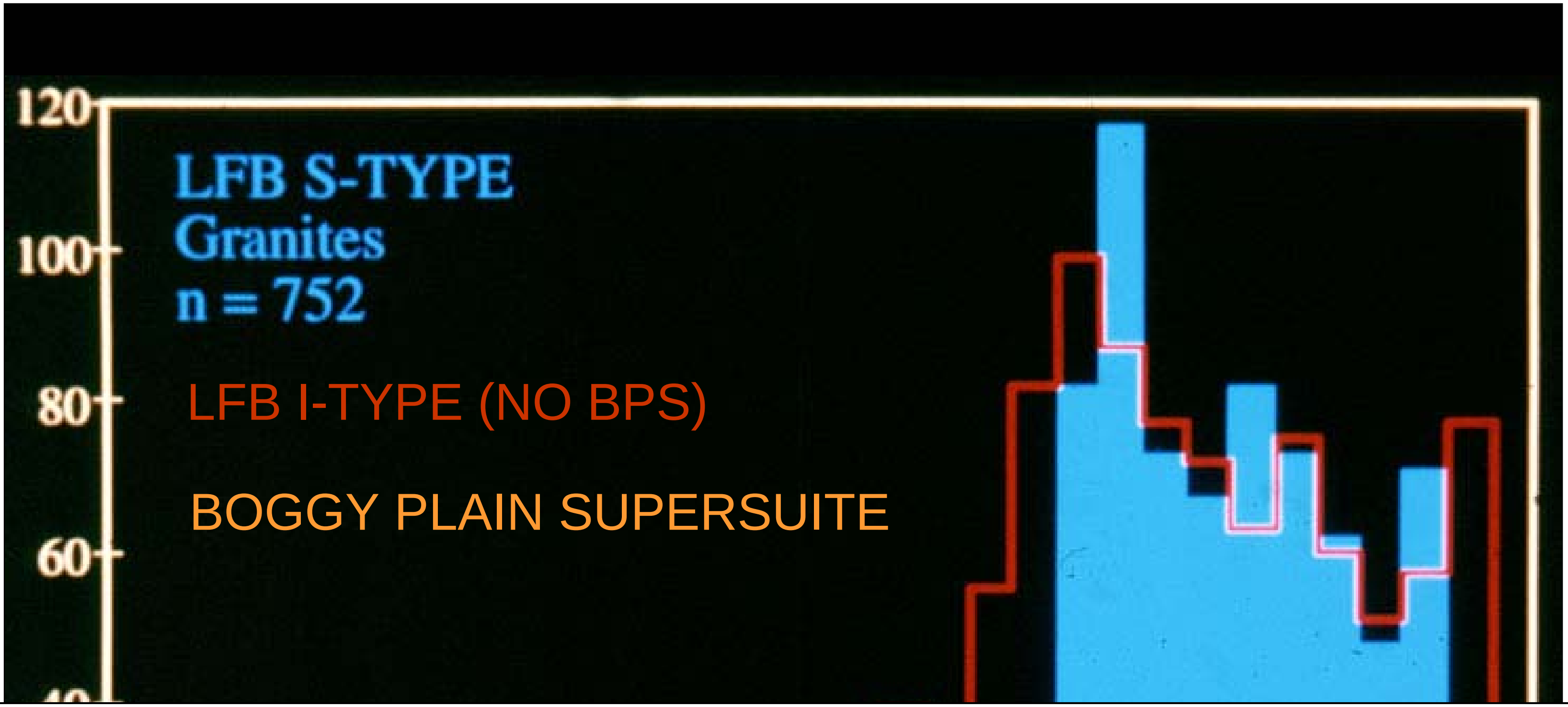


I- AND S-TYPE GRANITES COMPOSITIONAL DIFFERENCES

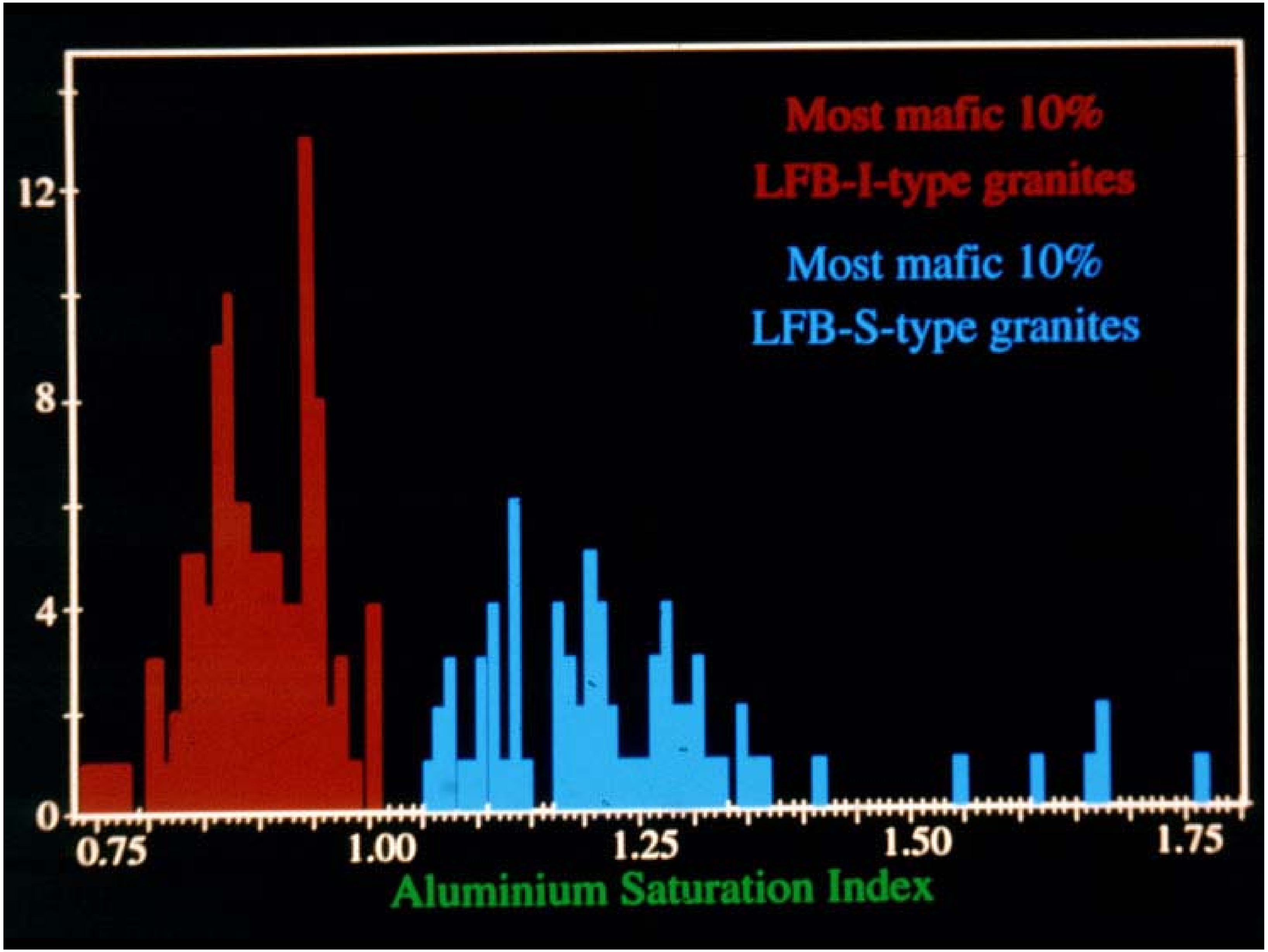
Relative to I-type granites, the S-type granites:

- contain lower abundances of Ca, Na and Sr
- are more restricted in SiO_2 contents
- are always oversaturated in Al_2O_3, often strongly so
- have much higher P_2O_5 contents when strongly fractionated
- have lower Fe_2O_3/FeO ratios
- variation diagrams show much more scatter
- have more evolved Sr and Nd isotopic compositions
- have higher $\delta^{18}O$ values, due to earlier low-temperature weathering

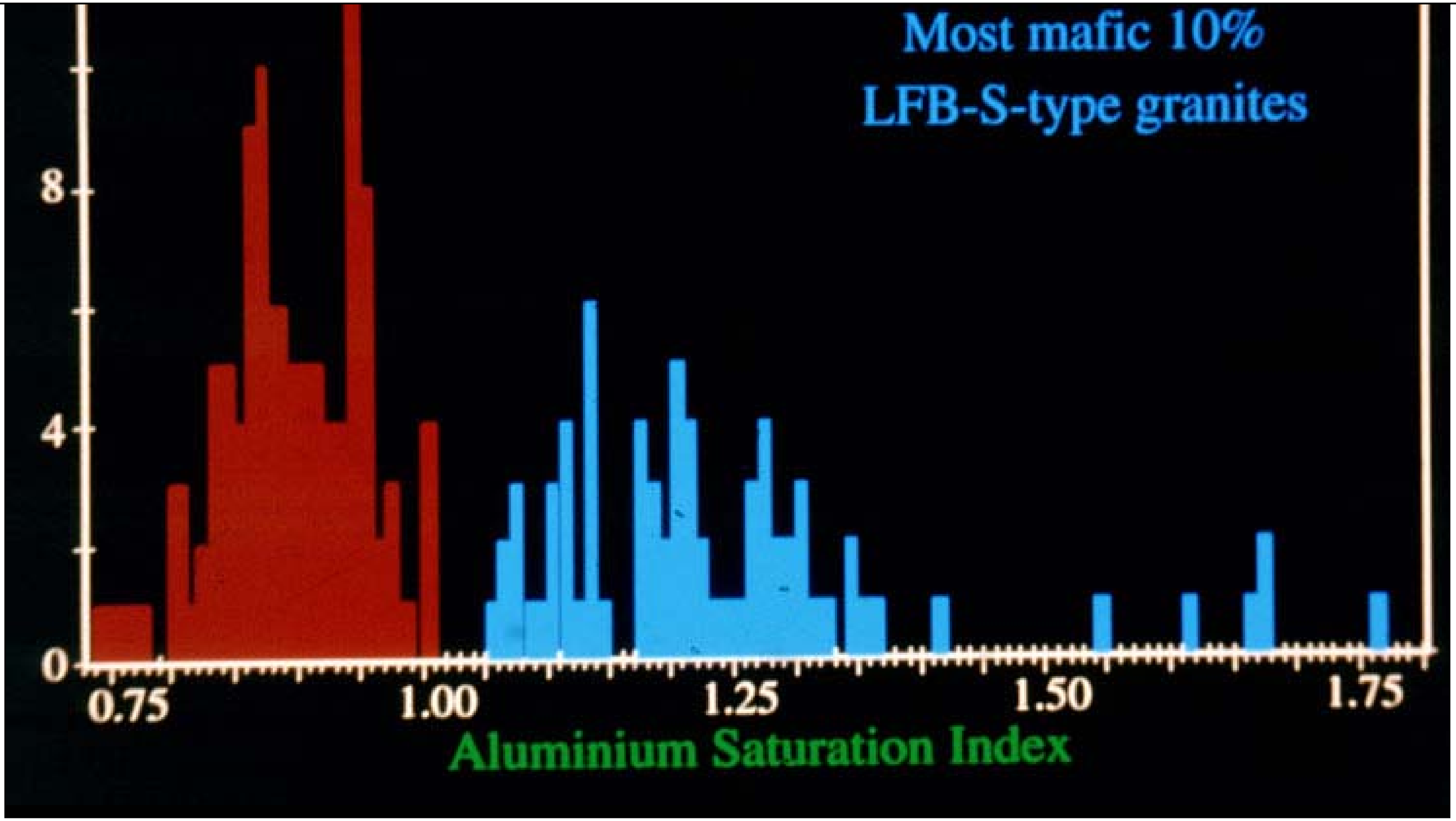

LFB S-TYPE
Granites
n = 752
LFB I-TYPE (NO BPS)
BOGGY PLAIN SUPERSUITE
0
20
40
60
80
100
120
45
50
55
60
65
70
75
% SiO_2

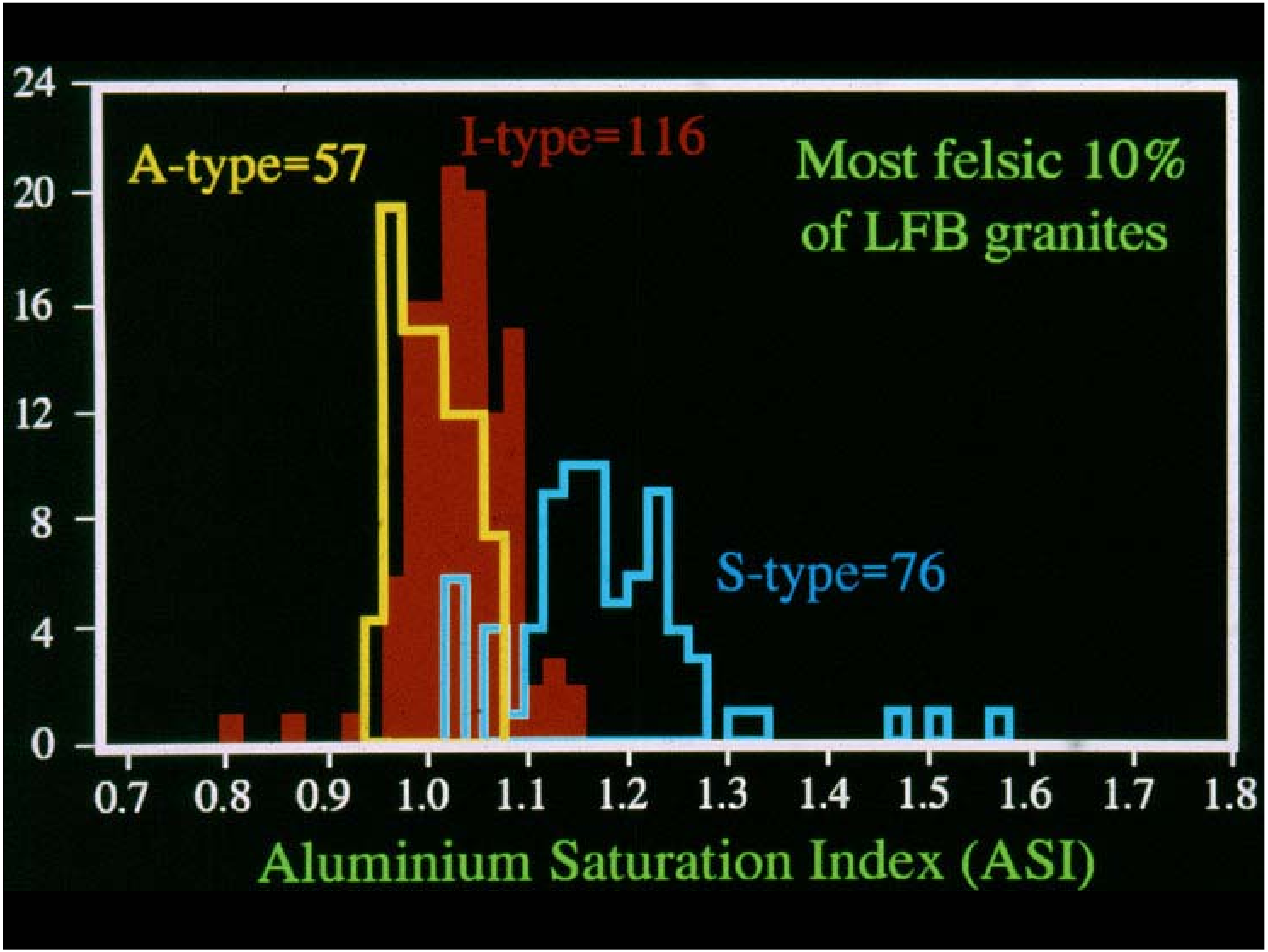


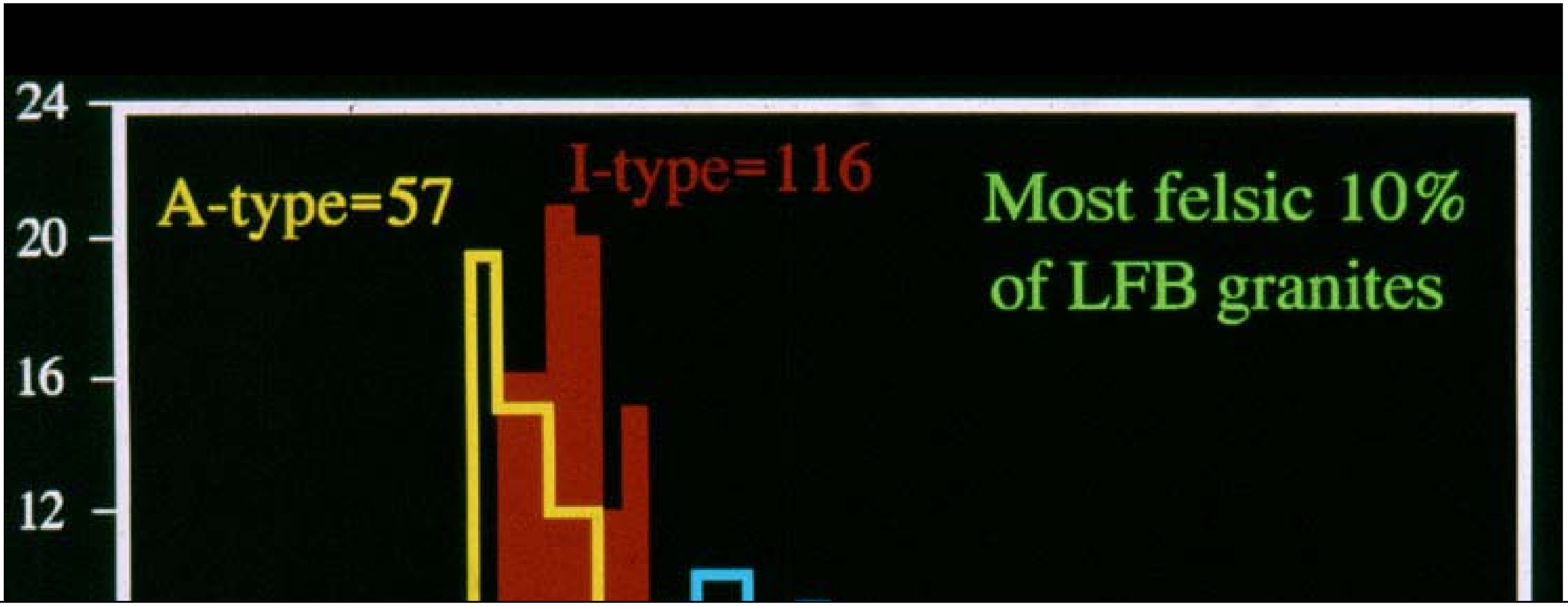
S-type granites of the LFB have a relatively restricted range of SiO_2 contents. Of 752 analysed samples only one contains less than 63% SiO_2 and that is an unusual rock that contains abundant garnet and occurs as cumulative layers in a relatively felsic granite. The most mafic S-type granites typically contain abundant quartz, plagioclase, biotite and cordierite. I-type granite compositions extend to much lower SiO_2 contents, with those of the Boggy Plain Supersuite outlined in orange on this figure, and others in red. The S-type granites with the lowest SiO_2 contents are more mafic than I-type granites of similar SiO_2 contents. They are dark-coloured rocks with up to 30% biotite and abundant cordierite, but they also contain abundant quartz, up to 40%..


Most mafic 10%
LFB-I-type granites
Most mafic 10%
LFB-S-type granites
12
8
4
0
0.75
1.00
1.25
1.50
1.75
Aluminium Saturation Index

This slide shows that there is no overlap in the degree of Al-saturation between the most mafic I- and S-type granites of the LFB. This can be used to argue that the two types are not compositionally transitional. It is argued that this separation is seen because these are the granites whose compositions are closest to those of their distinctive source rocks.

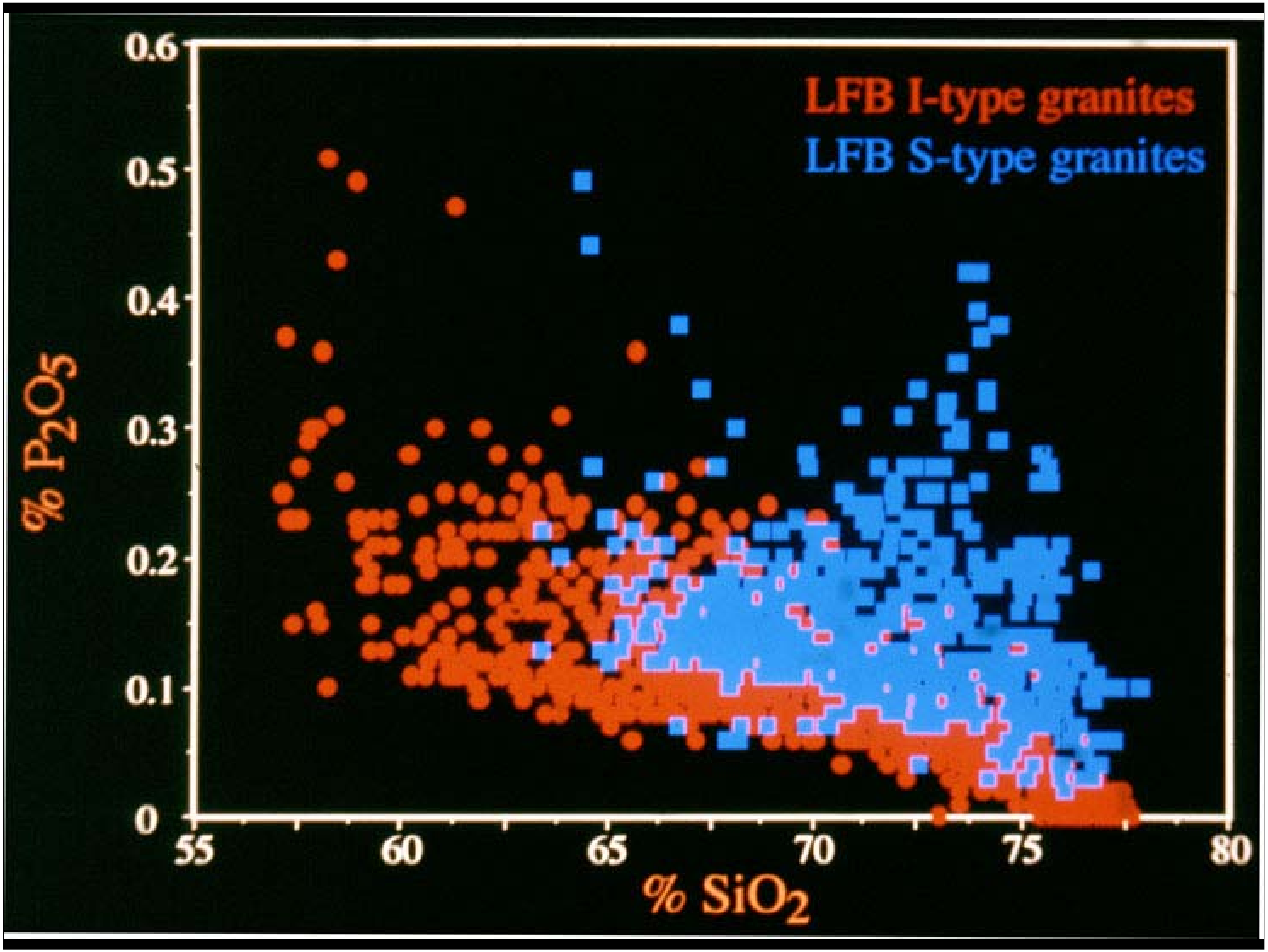



A-type=57
I-type=116
Most felsic 10%
of LFB granites
S-type=76
0
4
8
12
16
20
24
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
Aluminium Saturation Index (ASI)



This figure shows that at more felsic compositions the degrees of Al-saturation of I- and S-type granites converge and there is some overlap. It also shows that the majority of the most felsic I-type granites are peraluminous, as recognised by Chappell & White in 1974 when the boundary between the two types was made at an ASI value (as it is now termed) of 1.1. It is possible that the melts from which these felsic granites crystallised did have a distinct break in ASI, but a slight redistribution of the alkali elements during cooling caused the boundary to be degraded. For further comments on that and other aspects of Al-saturation in the felsic granites, see the following reference:

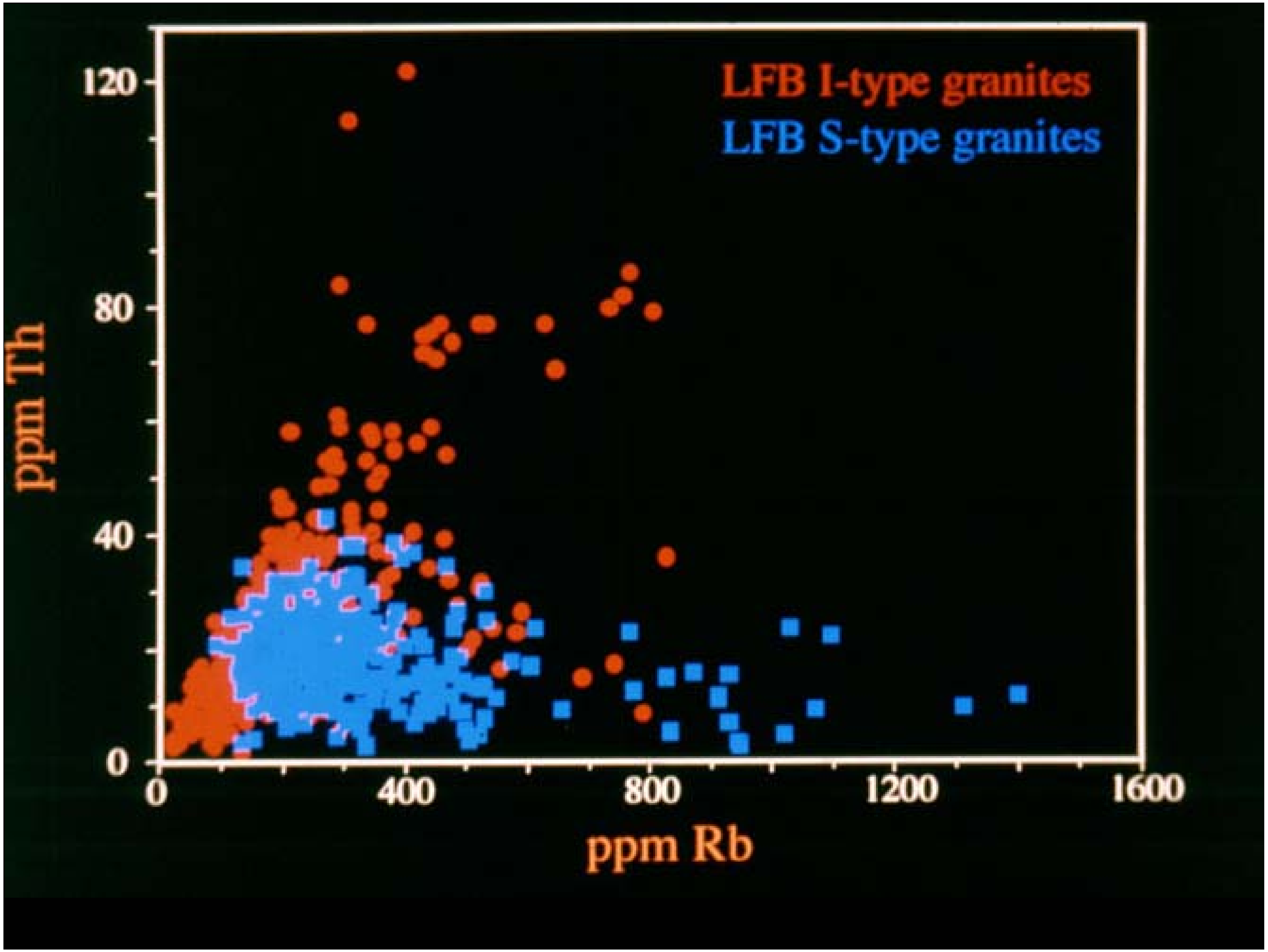
Chappell, B.W. 1999. Aluminium saturation in I- and S-type granites and the characterization of fractionated haplogranites. *Lithos* **46**, 535-551.

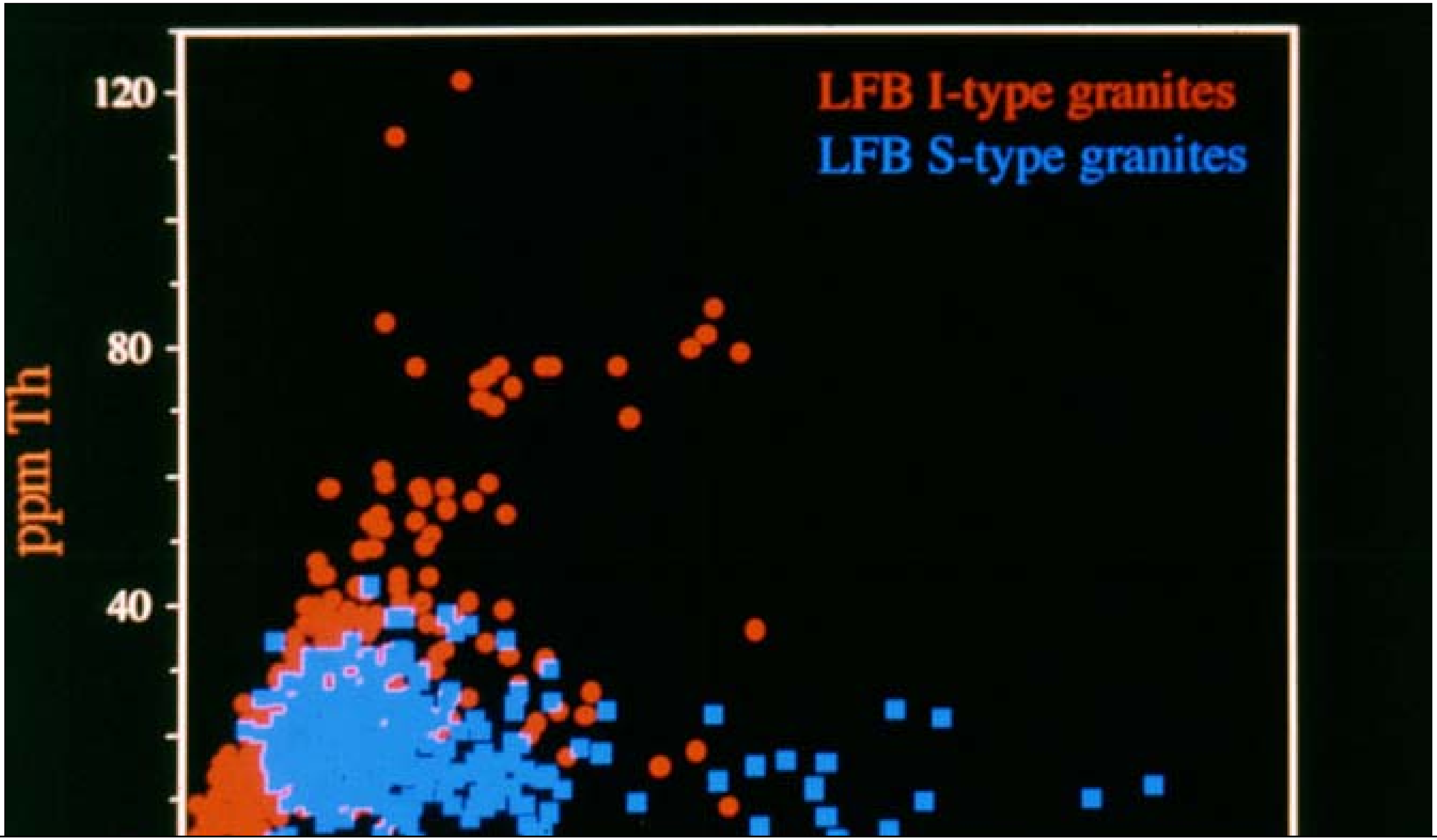

LFB I-type granites
LFB S-type granites
% P$_2$O$_5$
0.6
0.5
0.4
0.3
0.2
0.1
0
55
60
65
70
75
80
% SiO$_2$

P_2O_5 ABUNDANCE IN HIGH-SILICA MELTS

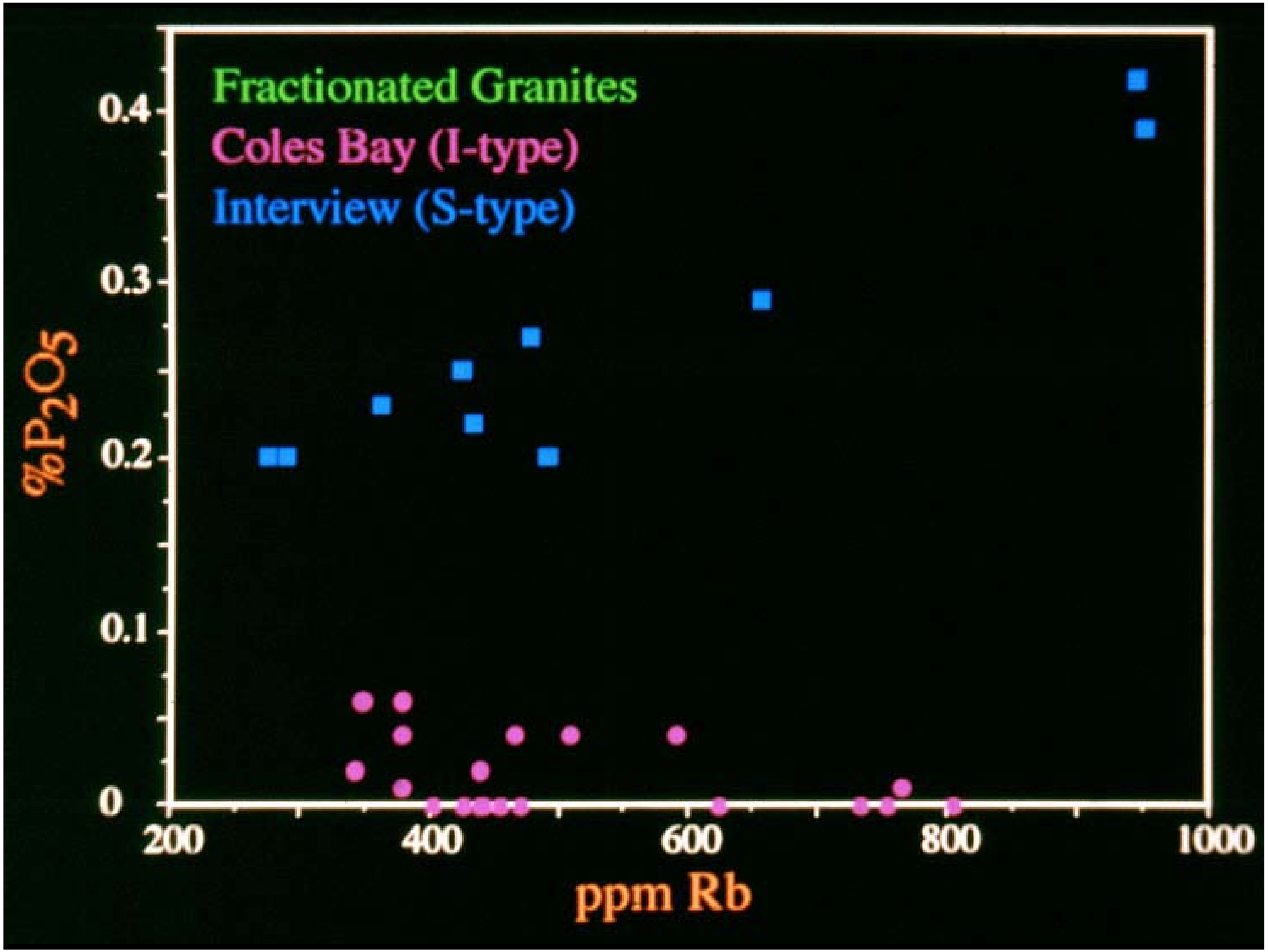
- Phosphorus has a low to very low abundance in metaluminous to weakly peraluminous high-silica melts and the content can be used as a crude geothermometer.
- P is progressively more soluble in more strongly Al-oversaturated melts where it forms a complex with Al:

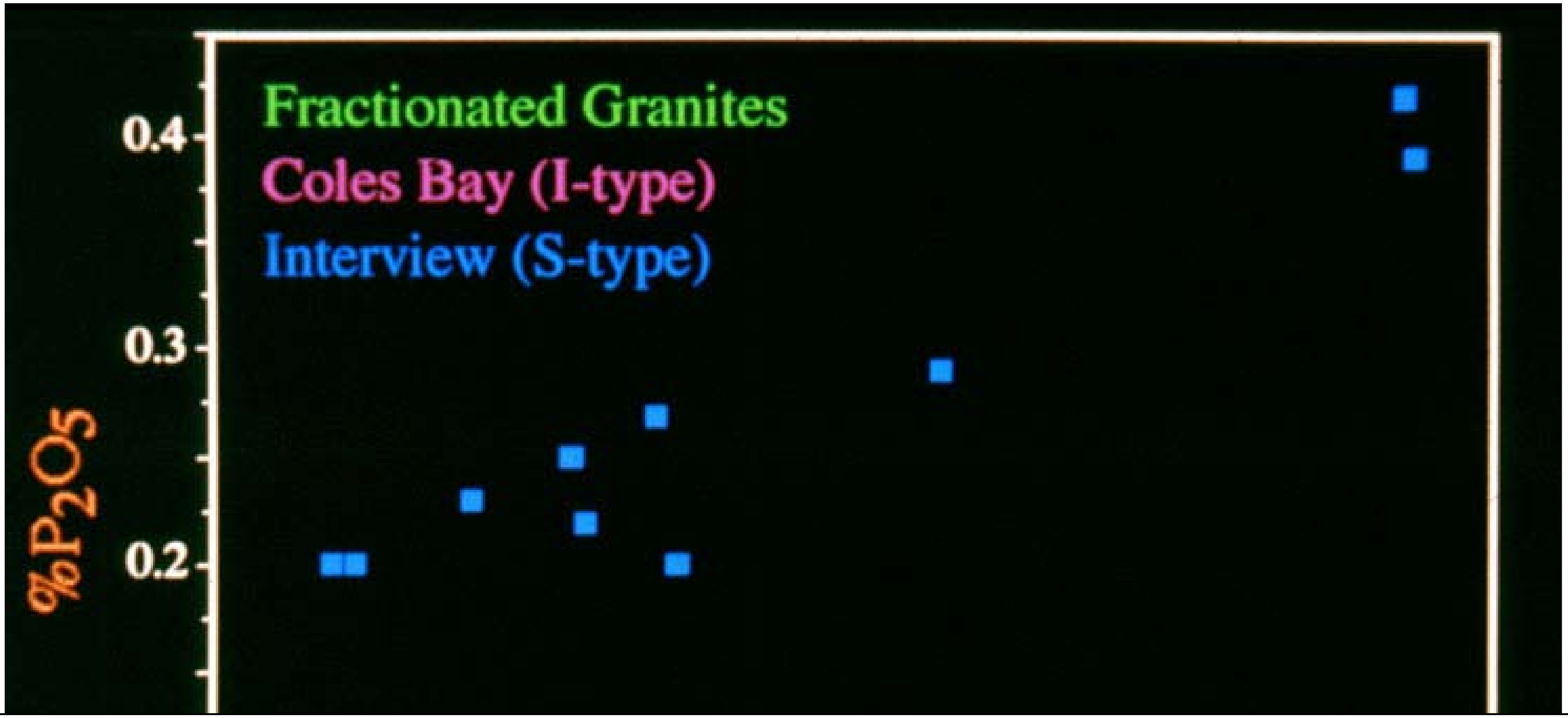
  $Si_2O_4 = AlPO_4$ (berlinite substitution)
- This has a dramatic effect on the accessory minerals that form and the behaviour of many trace elements during fractionation. This leads to many distinctive differences between felsic and more fractionated I- and S-type granites


LFB I-type granites
LFB S-type granites
ppm Th
120
80
40
0
ppm Rb
0
400
800
1200
1600



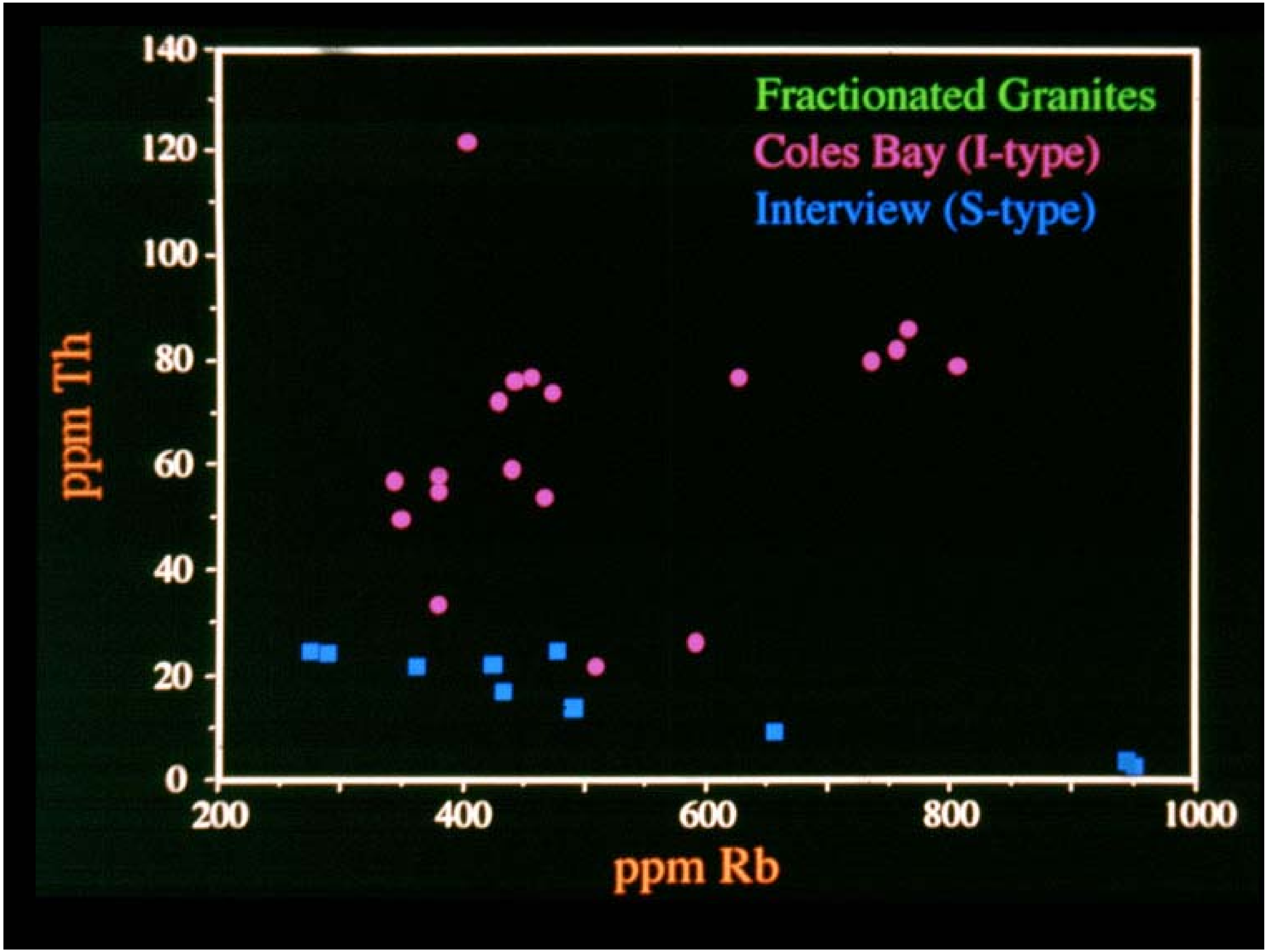
This figure shows the dramatic difference between the Th abundances of strongly evolved I- and S-type granites. Ir results from the presence of significant amounts of P in the S-type melts, so that monazite precipitates and is removed, carrying Th and the rare earth elements with it. This behaviour means that fractionated S-type granites have a distinctive radiometric signature (high U and low Th).

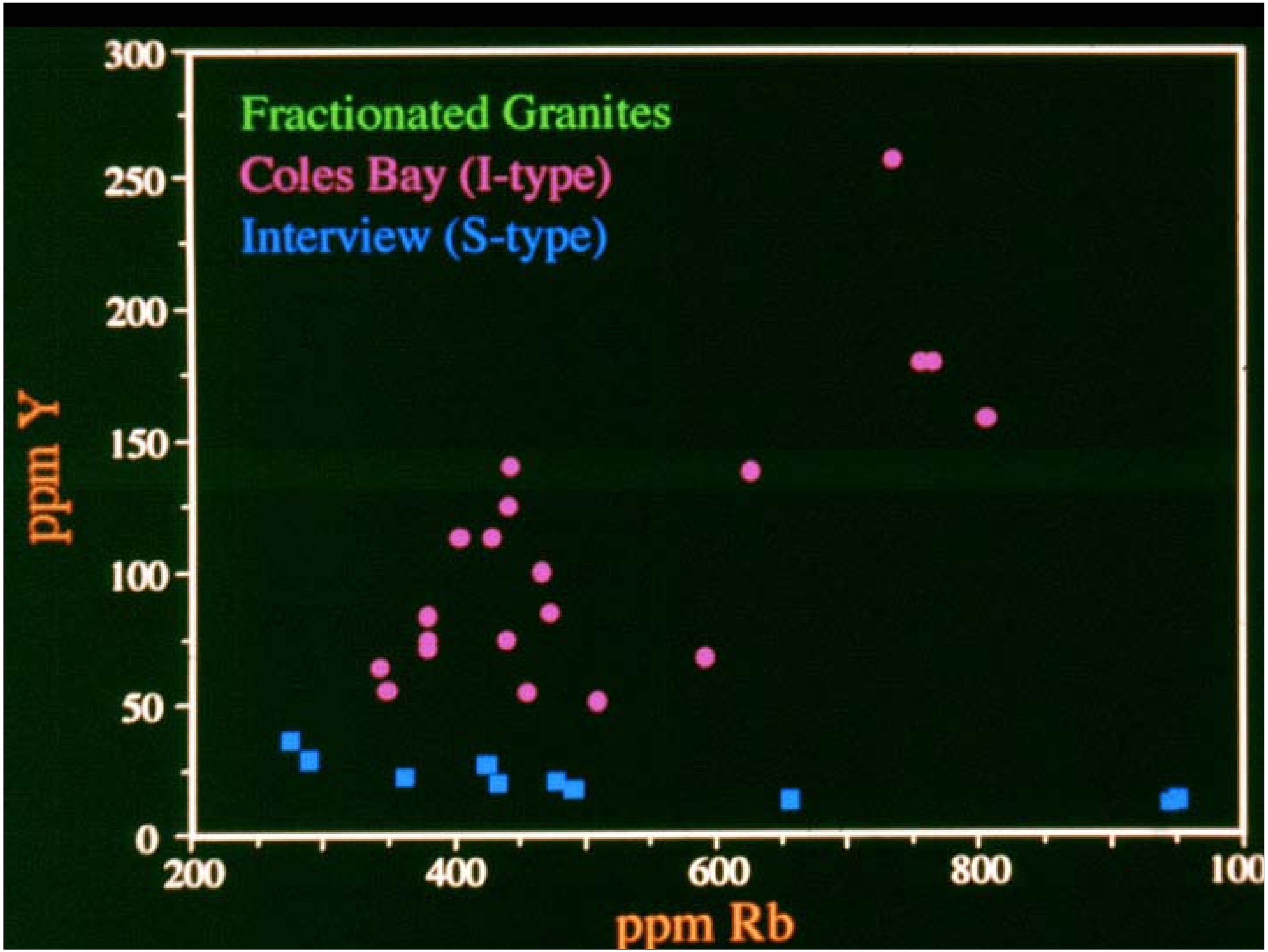

Fractionated Granites
Coles Bay (I-type)
Interview (S-type)
0.4
0.3
0.2
0.1
0
%P2O5
200
400
600
800
1000
ppm Rb



This is a specific example contrasting the behaviour of P between strongly fractionated I- and S-type suites. The Coles Bay Suite occurs on the Freycinet Peninsula of eastern Tasmania, and the Interview Suite on the Tasmanian west coast. For more discussion of this and the next two diagrams, refer to:

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

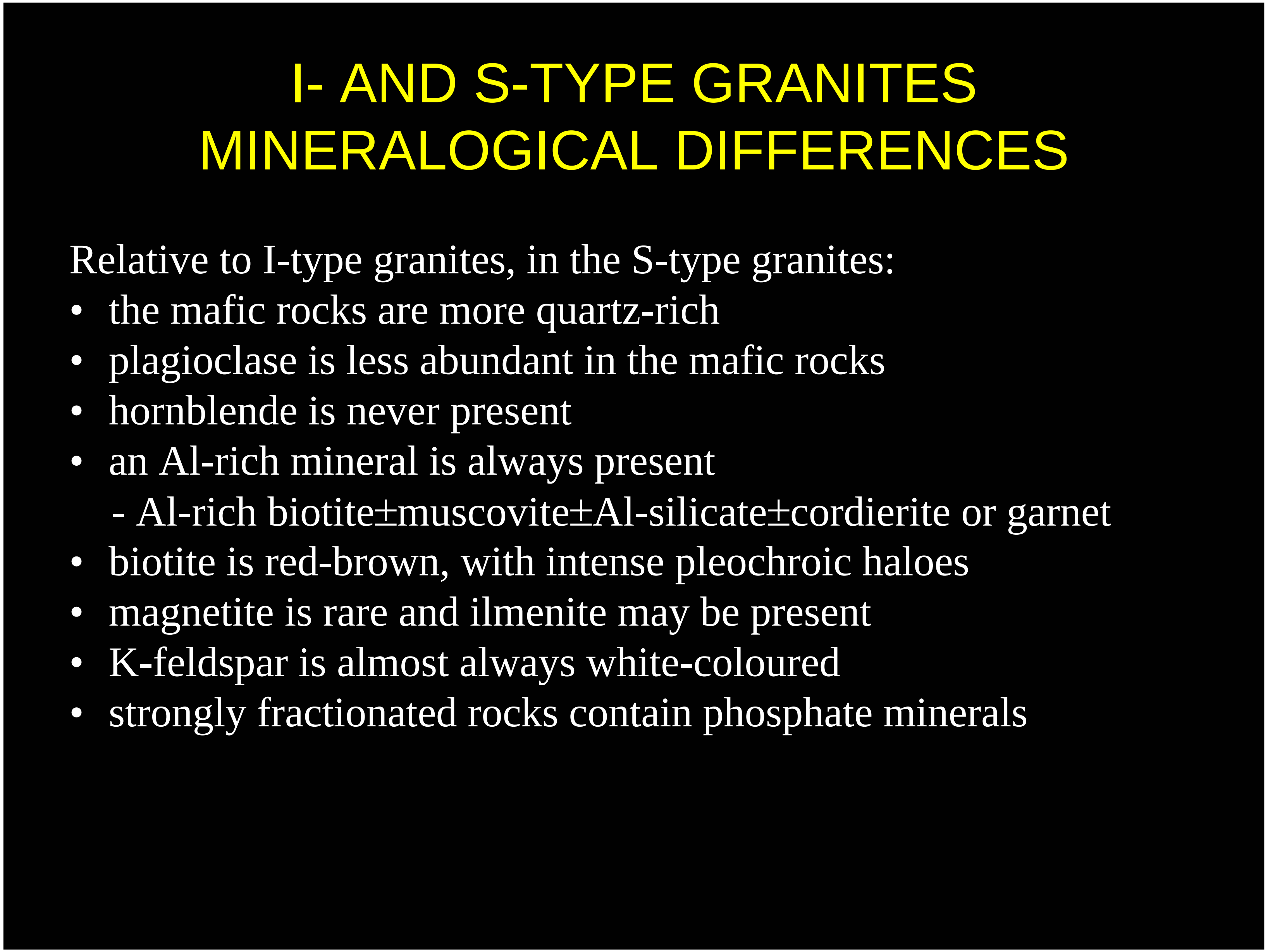

Fractionated Granites
Coles Bay (I-type)
Interview (S-type)
ppm Th
ppm Rb
0
20
40
60
80
100
120
140
200
400
600
800
1000


Fractionated Granites
Coles Bay (I-type)
Interview (S-type)
ppm Y
300
250
200
150
100
50
0
200
400
600
800
100
ppm Rb

I- AND S-TYPE GRANITES COMPOSITIONAL DIFFERENCES

Relative to I-type granites, the S-type granites:

- contain lower abundances of Ca, Na and Sr
- are more restricted in SiO_2 contents
- are always oversaturated in Al_2O_3, often strongly so
- have much higher P_2O_5 contents when strongly fractionated
- have lower Fe_2O_3/FeO ratios
- variation diagrams show much more scatter
- have more evolved Sr and Nd isotopic compositions
- have higher $\delta^{18}O$ values, due to earlier low temperature weathering



I- AND S-TYPE GRANITES
MINERALOGICAL DIFFERENCES

Relative to I-type granites, in the S-type granites:

- the mafic rocks are more quartz-rich
- plagioclase is less abundant in the mafic rocks
- hornblende is never present
- an Al-rich mineral is always present
  - Al-rich biotite±muscovite±Al-silicate±cordierite or garnet
- biotite is red-brown, with intense pleochroic haloes
- magnetite is rare and ilmenite may be present
- K-feldspar is almost always white-coloured
- strongly fractionated rocks contain phosphate minerals


GEMOC