Assessing the Metallogenic Potential of Proterozoic Granite Suites from First Principles

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Proterozoic Granites in Australia crop out over at least 145 000 km^2 (Table 1). To assess their metallogenic potential, a systematic study was undertaken of all granites as well as the composition of rocks within five kilometres of the granite boundaries (Budd et al., 2001). For the granites, data on the field characteristics (presence of alteration, miarolitic cavities, presence or absence of pegmatites, etc) as well as the mineralogical, major and trace element compositions of the granites were compiled. Individual granite plutons were then aggregated into suites and Supersuites on a province basis. Data were also assembled on the mineralogical composition of the host rocks, specifically the presence of reactive minerals such as carbonate, carbon, feldspar, magnetite and hematite. A GIS was constructed of all data, and simple proximity analysis was used to intersect the granite plutons as well as 5 km buffers around each pluton with known mineral deposits and occurrences. The commodities and ore deposit types were recorded around each pluton. Each occurrence was checked to ensure its age was ≤ the age of the related intrusion.

On the basis of similarities between Suites/Supersuites of different provinces, nine granite associations were identified based on their chemical characteristics, pressure/temperature conditions in their source region and their associated metallogeny. Due to insufficient data, 8.3% of exposed Australian Proterozoic granites could not be classified (Table 1). The differences between each Association and its related metallogeny is believed to be controlled by first order differences in temperature and pressure conditions in their source regions. Second order changes that also influenced metallogeny, are imposed by interaction with their host rocks.

<table>
<tr><th>No.</th><th>Granite Association</th><th>Area (km^2)</th><th>% of Area</th><th>Granite type (%)</th><th>Temp (% of Area)</th><th>Pressure (% of Area)</th><th>Metallogeny</th></tr>
<tr><td>1</td><td>Forsayth</td><td>3529</td><td>2.4</td><td rowspan="2">S-Type (2.9%)</td><td>Low (2.4%)</td><td rowspan="4">Moderate (81.8%)</td><td>Barren</td></tr>
<tr><td>2</td><td>Allia</td><td>659</td><td>0.5</td><td>High (0.5%)</td><td>Sn ± Ta, W, Au</td></tr>
<tr><td>3</td><td>Kalkadoon</td><td>25673</td><td>17.7</td><td rowspan="7">I-Type (88.8%)</td><td rowspan="2">Low (31.0%)</td><td>Barren</td></tr>
<tr><td>4</td><td>Nicholson</td><td>19312</td><td>13.3</td><td>Minor Vein Sn, W, Cu</td></tr>
<tr><td>5</td><td>Sybella</td><td>8935</td><td>6.1</td><td rowspan="3">High (54.1%)</td><td>Low (6.2%)</td><td>Barren</td></tr>
<tr><td>6</td><td>Cullen</td><td>44126</td><td>30.4</td><td rowspan="2">Moderate (as above)</td><td>Au ± Sn, W, U, Cu, Bi</td></tr>
<tr><td>7</td><td>Hiltaba</td><td>25480</td><td>17.6</td><td>Cu + Au ± Ag, U</td></tr>
<tr><td>8</td><td>Maramungee</td><td>1845</td><td>1.3</td><td rowspan="2">Low (3.7%)</td><td rowspan="2">High (3.7%)</td><td>Barren</td></tr>
<tr><td>9</td><td>Sally Downs</td><td>3566</td><td>2.4</td><td>Minor Vein Au</td></tr>
<tr><td>10</td><td>Unclassified</td><td>12004</td><td>8.3</td><td>? (8.3%)</td><td>? (8.3%)</td><td>? (8.3%)</td><td>?</td></tr>
<tr><td></td><td>Total</td><td>145129</td><td></td><td>100.0</td><td>100.0</td><td>100.0</td><td></td></tr>
</table>

Table 1: Granite Associations of the Australian Proterozoic and their exposed area, granite types, estimated pressure and temperature conditions at their source at the time of melting, and their associated metallogeny.

Australian Proterozoic granites: their ages and the age and composition of their sources

Australian Proterozoic igneous rocks are distinctly bimodal in composition: there are no significant intermediate suites. An analysis of the ages of Australian Proterozoic igneous rocks, shows most were emplaced between 1880-1450 Ma (Figure 1A). As the ages used are U-Pb zircon age determinations, the majority in Figure 1 are felsic in composition. Each of the major I-type Associations dominates over a different time interval, and with decreasing age, there is a wider spread in age of each association (Figure 1A). There are no discrete continent wide metallogenic-events. Instead there is a spread of ages when conditions in the lower crust were optimal for the generation of each of these granite Associations.

Figure 1B plots the ages of these igneous rocks against their Sm-Nd model ages. As the greater majority of the samples plot to the right of the line linking equivalent U-Pb zircon and Sm-Nd model ages it is argued that most igneous rocks were not direct derivatives from the mantle. Rather, the majority are inferred to have been derived from lower crustal sources with varying crustal residence times. It is also noted that bulk of these sources were formed between 2500-2000 Ma when there is very little record of igneous activity in Australia.

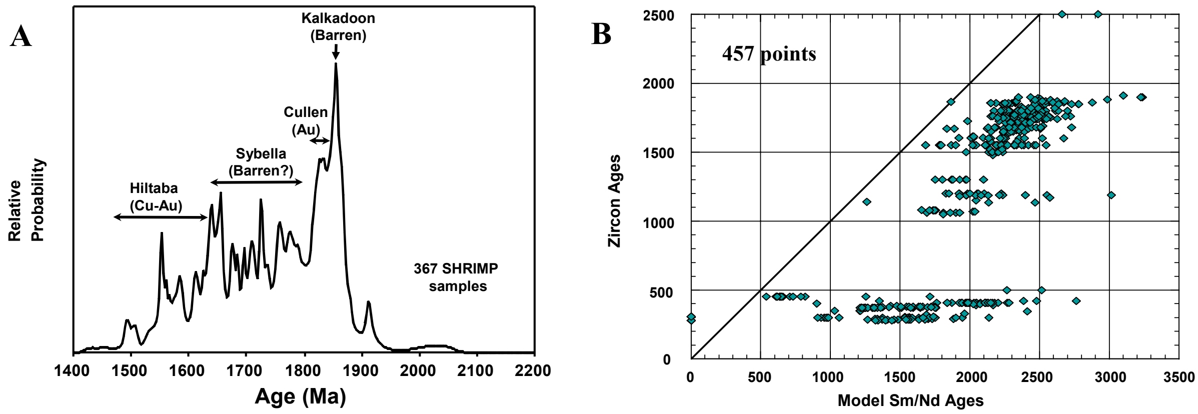

Figure 1: A. Relative probability plot of 367 Shrimp U-Pb zircon age determinations of Australian Proterozoic Granitic Rocks. The approximate ages of 4 of the major Proterozoic I-type granite associations and their Metallogeny (Table 1). B: Plot of Zircon ages Proterozoic and Palaeozoic granitic rocks and their Sm-Nd model ages. The line draw is for equivalent zircon and Sm-Nd model ages. (Data are from the Geoscience Australia OZCHRON database).

Where there were sufficient data (Table 1), 88.8% of outcropping Proterozoic granites are I-type and 2.3% are S-types (Chappell & White ,1974). The two S-type Associations (Table 1) were identified by ASI>1.1 at < 72 wt % SiO_2 and usually the presence of garnet, or cordierite and/or muscovite. The seven I-types Associations (Table 1) were characterised by biotite ± hornblende.

First order influences on the Metallogeny: the Pressure and Temperature of the source

1) Pressures in the source region at the time of melting

By analysis of multi-element normalised abundance diagrams (Figure 2), it is possible to identify the minerals that are in equilibrium with granitic melts in their source regions and hence estimate the pressure at which melting took place. Granites melts that form at pressures lower than 1.0 GPa are plagioclase stable in the source region (Wyllie & Wolf, 1993). Such granites are identified by multi-element normalised abundance diagrams which are Sr-depleted, Y non-depleted (Wyborn et al., 1992). These patterns dominates 87.9 % of Proterozoic Granites (Figures 2A & 2B) and indicate that the great majority of Australian Proterozoic granites resulted from crustal geothermal gradients that are greater than 30°/km (Figure 3), well above the accepted steady state crustal geothermal gradient of 15°/km (Lachenbruch & Sass, 1978). Such high geothermal gradients are characteristic of extensional regimes and/or areas of substantial mafic intrusions.

It is possible to further subdivide those granites that have plagioclase-stable source regions into moderate and low pressure. Patiňo Douce (1997) suggested that crystallisation of plagioclase + orthopyroxene during very low pressure (P ≤ 0.4 GPa) and high temperature (>900°C) incongruent melting of tonalite and granodiorite produces major and trace element characteristics similar to A-type granites (e.g., low Al, Ca., Mg, Sr and Eu contents, and high Ga/Al and K/Na ratios). On mutli-element plots, these are indicated by extreme depletions in Sr, P, Ti and strong enrichments in La, Ce, Nd, and

Y (Figure 2B). These patterns are typical of the Sybella Association which comprise 6.1 % of the area of exposed Proterozoic Granites (Table 1).

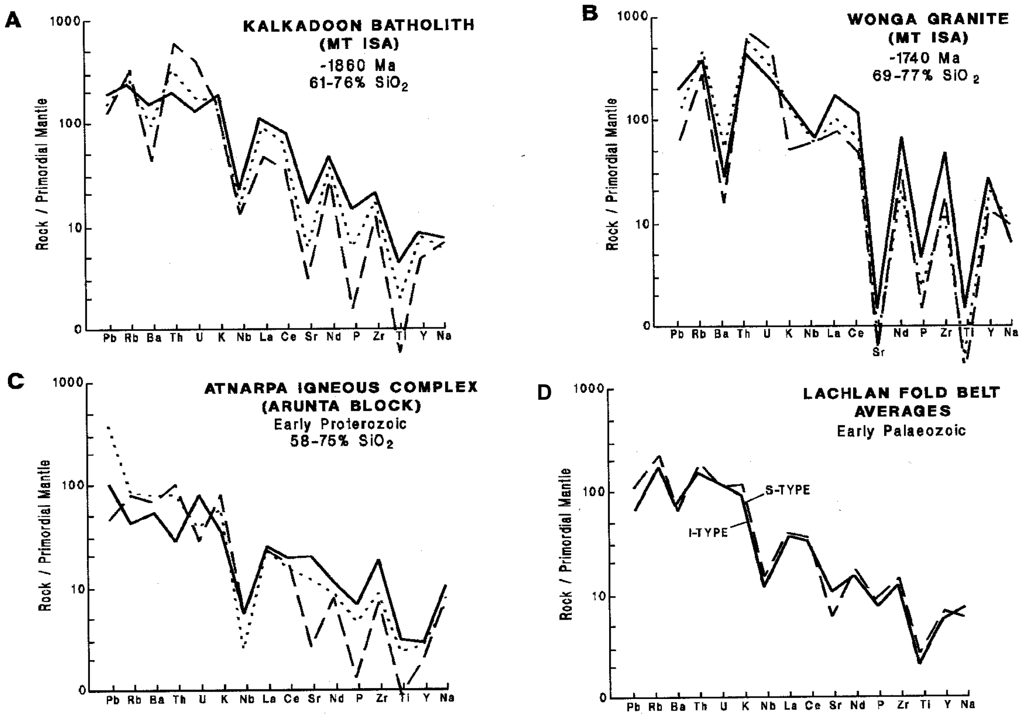

Figure 2: Multi-element primordial-mantle-normalised abundance diagrams for representative Australian granites. Normalising values are from Sun and McDonough (1989). In A,B, and C, the solid line is the lowest SiO_2 content, the dotted line is an intermediate SiO_2 content and the dashed line the most felsic SiO_2 content. In D, the solid line is the average I-type granite and the dashed line is an average S-type from the Lachlan Fold Belt.

In contrast, the presence of a garnet residue in the source region is taken to indicate pressures > 0.85 – 1.0 GPa and depths > ~30 kms (Wyllie & Wolf, 1993; Patiño Douce & Beard, 1995). Melts that are formed in equilibrium with garnet have a characteristic Y-depleted, Sr non-depleted pattern in rocks with < 70 wt. % SiO_2 (Wyborn et al., 1992). These patterns are characteristic of the Maramungee and Sally Downs Associations (Figure 1C), which comprise only 3.7% of exposed Australian Proterozoic granites. The Maramungee Association consists predominantly of Na-rich trondjhemites, whilst the Sally Downs Association is I-(granodioritic) type (Chappell and Stephens, 1988). These two associations indicate lower crustal geothermal gradients which are can occur in compressional terrains, (e.g. subduction or collision zones), but are not exclusive to them.

2) Temperatures in the source regions at the time of melting

Chappell et al (1998) developed the concept of High- and Low-Temperature granites. High-Temperature granites crystallise from a magma that was completely or largely molten. In contrast, Low-Temperature Granites contain a significant proportion of crystals (or restite) from the source region. The dominant reaction forming Low Temperature granites is the minimum melt breakdown of quartz + K-feldspar + albite + H_2O in the source region. If sufficient melt is generated by this process, then minerals such as plagioclase, hornblende and biotite will be entrained as restite in the melt. On Harker variation diagrams, Low-Temperature granites are characterised by linearly increasing trends with increasing SiO_2 for elements that are concentrated in the minimum melt (K_2O, Na_2O, Rb, and U). In contrast, elements that are concentrated in the restite have linearly decreasing trends with increasing SiO_2. In the field, Low-Temperature granites are distinguished by large, uniform unzoned plutons that grade subtly from granite (Sensu Stricto) to monzogranites to granodiorites to rare tonalites. Comagmatic volcanics tend to be crystal-rich and compositionally difficult to distinguish from their plutonic equivalents. The Kalkadoon and Sally Downs Associations are both Low-Temperature granites: the former distinguished by its Sr-depleted, Y-non depleted character, the later its Sr-non depleted, Y-depleted character.

If the temperature in the source region increases further, more minerals breakdown to produce High-Temperature granites. Of particular importance in the production of granitic melts are the dehydration reactions of muscovite, biotite and hornblende (Johannes & Holtz, 1996). Harker variation diagrams for High-Temperature granites are more variable. Elements that are incompatible in the melt such as Rb, and U, show exponentially increasing trends with increasing SiO_2, whilst elements that are captured into the melt early show exponentially decreasing trends with increasing SiO_2. As noted by Chappell et al (1998), elements such as Ba and Zr that are incompatible in the melt initially, but later enter crystallising phases, increase initially and then decrease with increasing SiO_2. In the field, high temperature granites are variable and comprise zoned plutons, weakly zoned mozogranites to granodiorites, and homogenous leucogranites. Pegmatites, greisens and aplites are common later phases. Where they can be distinguished, volcanics are compositionally distinct from their comagmatic plutonic equivalents.

Three Proterozoic Granite Associations are regarded as High-Temperature granites: the Cullen, Hiltaba and Sybella Associations. The Cullen Association is spatially associated with Au ± Sn, W, U, Bi, Cu mineralisation. It occurs in two age ranges: firstly from ~1840-1800 Ma in the Pine Creek, Tennant Creek, and Tanami regions and secondly at around 625 Ma in the Telfer area. The Hiltaba Association is spatially associated with Au, Cu ± U, LREE. It ranges in age from about 1640 to 1480 Ma and occurs in the Gawler, Cloncurry, western Arunta, Olary and possibly thewestern Georgetown regions. Compositionally the Hiltaba Association is distinguished from the Cullen Association by higher, CaO, Na_2O, U Y, Zr, La, Ce and Nb contents. The Hiltaba Association granites are oxidised to strongly oxidised (Champion & Heinemann plot of 1994) and are characterised by extensive alteration zones, both within the granite and the country rock, with either very high Na_2O/K_2O or K_2O/Na_2O. In contrast, the Cullen Association is only moderately oxidised and related alteration is more subtle. The Cullen Association is believed to have formed by breakdown of biotite in the source region at temperatures <900° whilst the Hiltaba Association is thought to have formed by breakdown of amphibole in the source region at temperatures >1000°C.

Metallogenically, the high-temperature Sybella Association is enigmatic. It is clearly fractionated but is only spatially associated with small vein Sn and W deposits. In some regions (e.g. in the southern Tennant Creek area) the granites have imparted a strong alteration overprint on the country rock and there is evidence of a late fluid phase emanating from the granites. Also Rb contents and Rb/Sr increase exponentially with increasing SiO_2 contents. These factors are usually taken to indicate fractionation and hence mineral potential. In particular, I-(granodioritic) intrusions that are spatially related to mineralisation show these trends of exponentially increasing Rb, U and Rb/Sr with increasing SiO_2. From the Sybella Association data, however, the converse is not true, i.e., not all granites with similar trends or field evidence of late magmatic fluids are mineralised.

3) A summary Petrogenetic Grid for Australian Proterozoic Granites and its Metallogenic Implications

From the data above, a simple petrogenetic Grid can be developed (Figure 3) showing the interpreted PT conditions operating in the sources of the major Australian I-type granite Associations. This is only an approximation of the actual PT conditions of the source region as factors such as H_2O, CO_2, F, and B contents and Fe/Mg ratio of hornblende and biotite can influence the relative positions of the curves (Johannes & Holtz, 1996). Although an approximation, this petrogenetic Grid suggests that all Australian Proterozoic Granites result from elevated crustal geothermal gradients, with the Sybella Association requiring extremely high gradients of >60°km. Only the moderate pressure Cullen and Hiltaba Associations are spatially coupled with significant mineralisation however: both occur in the field of High-Temperature granites and require breakdown of biotite and/or amphibole in the source region.

Such elevated geothermal gradients required to generate the metallogenically important granites cannot be produced by models of conduction of heat from the mantle or from the influence of large mafic intrusions. A plausible way to achieve these unusually high geothermal gradients in the Australian Proterozoic is to consider radiogenic heat production as a major contributor (McLaren et al., in press). Australian Proterozoic granites are more enriched in K, Th, U than almost any other time period with the exception of some late Archaean granites. Independent validation of how relatively high these high K, Th and U contents are comes from present day heat flow measurements in areas of exposed Proterozoic outcrops. These average 85 mWm^{-2} with values locally in excess of 100 mWm^{-2} (Sandiford and Hand, 1998 based on Cull, 1982), which is significantly in excess of the global Proterozoic average of ~50mWm^{-2} (McLaren et al., in press).

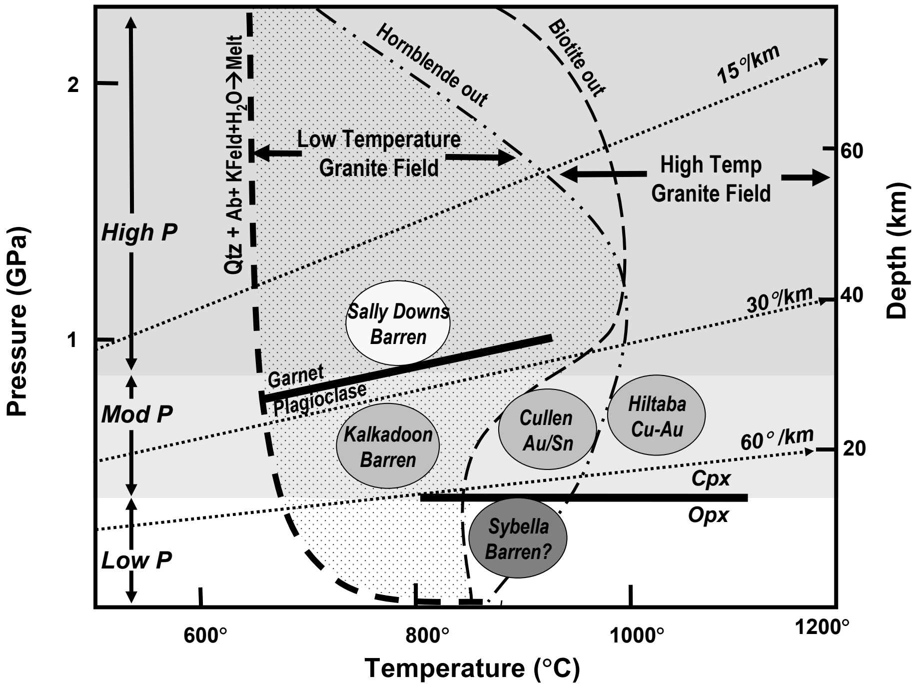

Figure 3. A petrogenetic Grid for Australian Proterozoic Granite Associations. Source for the data are 1) qtz (quartz) Ab (albite) KFeld (K-Feldspar) + H_2O → melt: Johannes & Holtz (1996); 2) cpx (clinopyroxene) →opx (orthopyroxene) boundary: Patiño Douce (1997); 3) garnet →plagioclase boundary: Wyllie & Wolf (1993); 4) biotite out curve: Vielzeuf & Montel (1994); 5) hornblende out curve: Wyllie & Wolf (1993). The stippled area is the area of generation of Low-Temperature granites. Also plotted are geothermal gradients of 15°, 30° and 60°/km: the 15°/km gradient is the standard continental geotherm of Lachenbruch & Sass (1978).

2. Second Order Influence of host rock compositions on Metallogeny

The Redox state of any granite suite imparts an important control on types of metal it can transport. Ishihara (1977) noted that magnetite series granites were associated with porphyry Cu-Mo deposits, whilst the ilmenite series were related to greisen-type Sn-W deposits. It is accepted that Redox of the source region exerts the primary control on the redox of the derived magma.

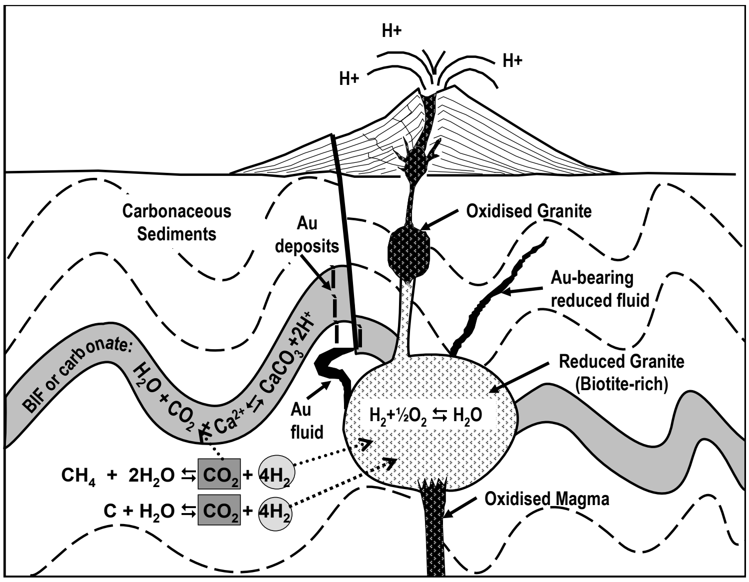

Figure 4: Cartoon expressing observed control of carbon-rich country rock on the redox state of the magma. It is proposed that H^+ diffused into the magma caused the magma to reduce as it crystallises

However, consistently throughout the Proterozoic there are non-magnetic I-type suites associated with Au occurrences which plot in the reduced field on the Champion & Heinemann Plot (1994). Where these reduced I-types occur, carbon usually present in the local country rocks.

It is suggested that the commonly observed reduction of magnetite-bearing suites can result from the infusion of H_2 from carbonaceous country rocks into the magma. In some regions, shallow plutons revert back to an oxidised state, due either to the H_2 ceasing to be able to pass into the magma chamber or because H_2 has diffused back into the atmosphere (Czamanske & Wones, 1973). Where the Cullen and Hiltaba Association granites become more reduced, usually as a result of intrusion into carbonaceous rocks, the related deposits become Au-dominant: Cu is very minor.

3. Can we turn the results of this Proterozoic study into a predictive tool for assessing granite related metallogeny globally?

Australian Proterozoic granites associated with mineralisation are all High-Temperature granites that are Sr-depleted, Y non-depleted and relatively enriched in K, Th and U. Although granites of the early to middle Palaeozoic Lachlan Fold Belt are also dominated by Sr-depleted, Y non-depleted granites, they are not as enriched in K, Th and U as their Proterozoic counterparts (Figure 1D). In Australia, Proterozoic granites have the highest abundances of K, Th and U, particularly when compared with early Archaean and post-late Palaeozoic granites. Further, where mineralisation is spatially associated with Proterozoic granites it nearly always occurs external to the granites, in contrast to porphyry-style deposits which are located within or very close to the igneous rocks. Igneous rocks associated with porphyry-style deposits are also more intermediate in composition, being dominated by andesite, diorites, and tonalites. There are no porphyry deposits in the Australian Proterozoic. Hutchinson (1981) also noted that porphyry deposits are not common in the Proterozoic globally. It is suggested that this absence relates to the rarity of intermediate igneous rocks, which is a function of the high crustal geothermal gradients of the Proterozoic.

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Assessing the Metallogenic Potential of Proterozoic Granite Suites from First Principles

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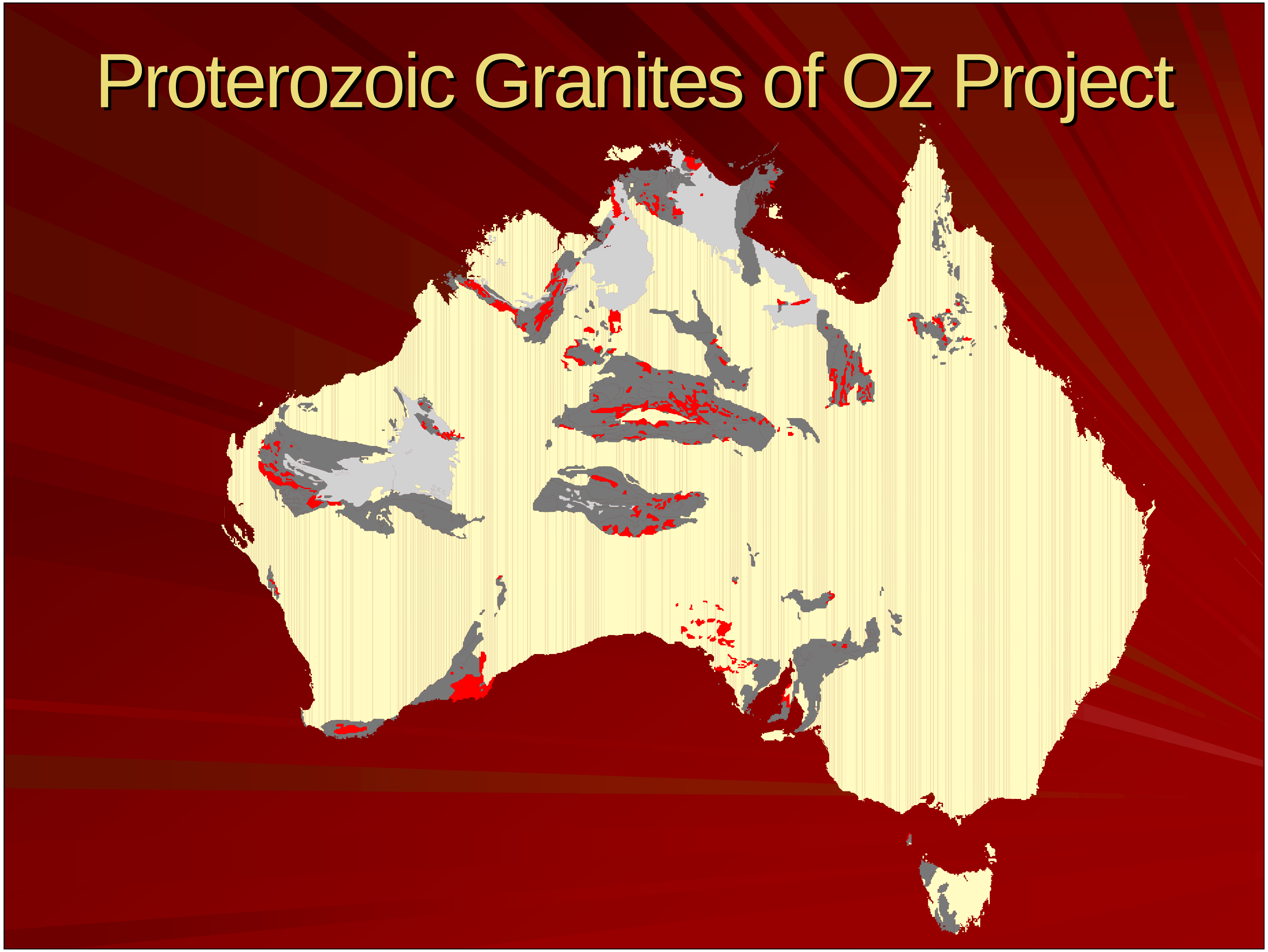
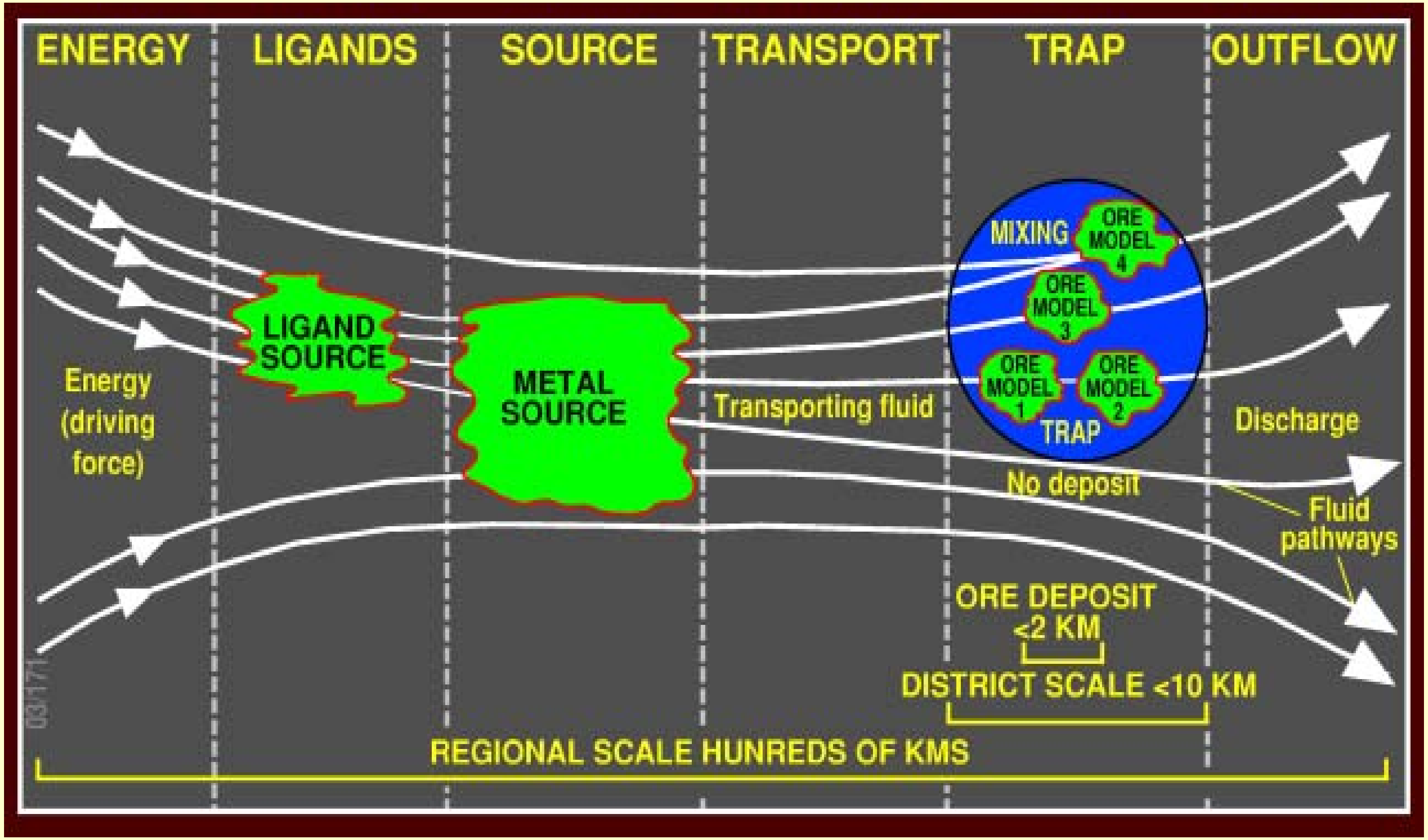
Project FIGS
(Felsic & Intermediate iGneous rockS of oz)

Geoscience Australia

Proterozoic Granites of Oz

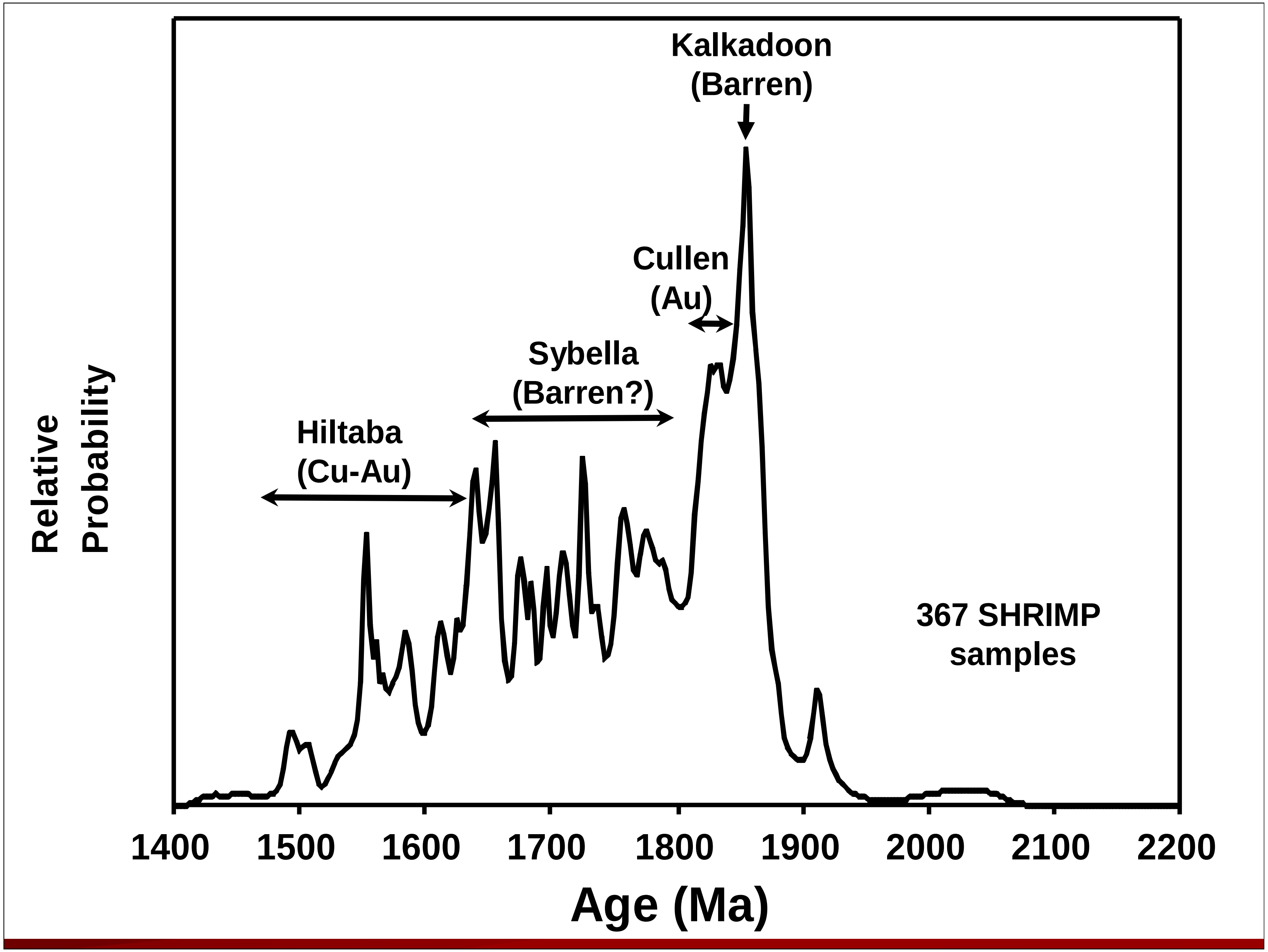
- Outline Methodology of Proterozoic Project
- Big picture scenario of Proterozoic Granites of OZ
- Compare and contrast various Proterozoic granite types
- Discuss the First Principles that influence metallogeny
  - P, T of source region
  - Composition of host rocks
- Even bigger picture: Proterozoic vs other eras
- Move into the dream time

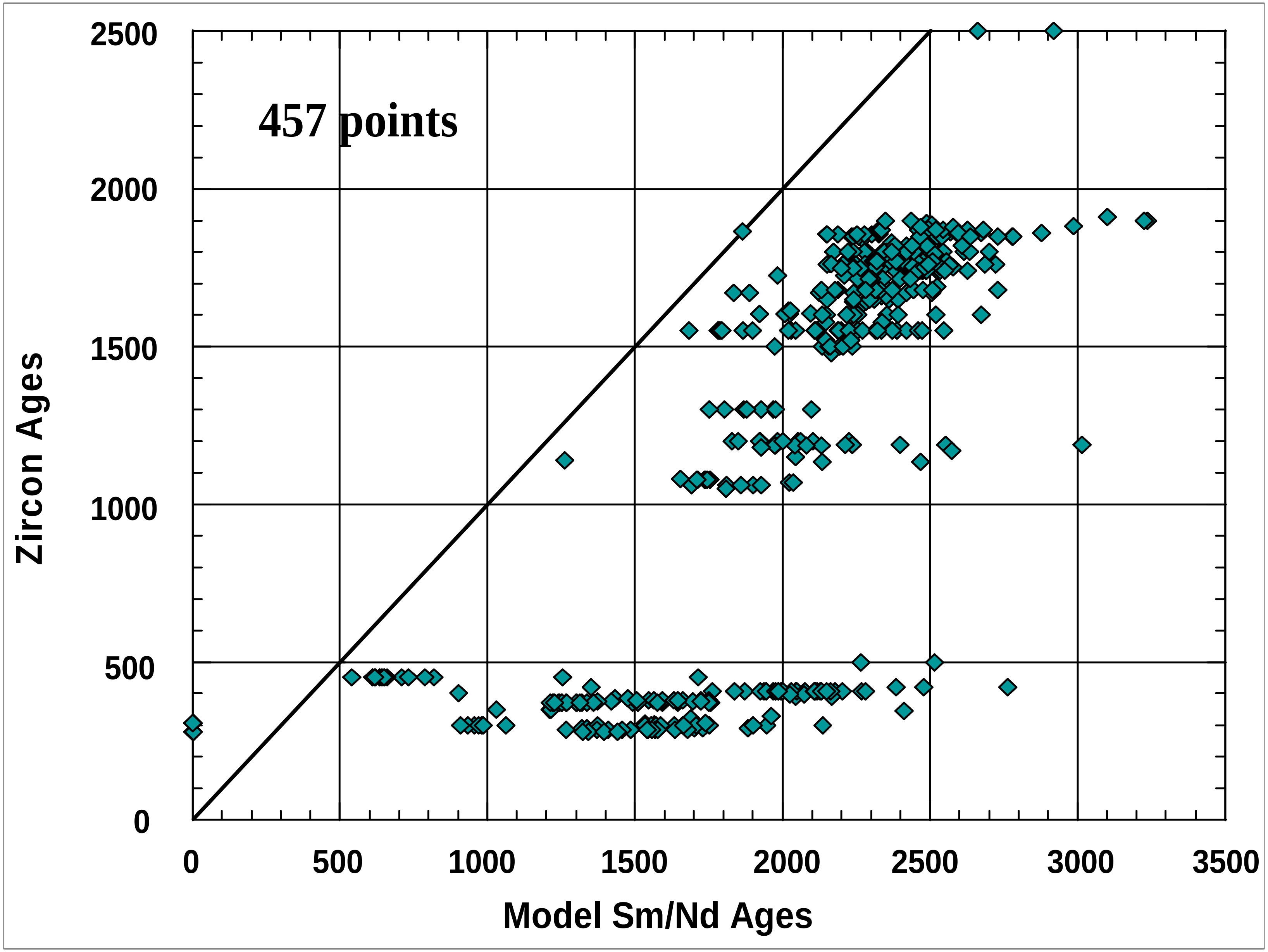

Proterozoic Granites of Oz Project


ENERGY
LIGANDS
SOURCE
TRANSPORT
TRAP
OUTFLOW
LIGAND SOURCE
METAL SOURCE
MIXING
ORE MODEL 4
ORE MODEL 3
ORE MODEL 1
ORE MODEL 2
TRAP
Energy (driving force)
Transporting fluid
No deposit
Discharge
Fluid pathways
ORE DEPOSIT <2 KM
DISTRICT SCALE <10 KM
REGIONAL SCALE HUNREDS OF KMS


OLYMPUS


1 2 3 4 5 6 7 8 9 10 cms
pink = plagioclase
yellow = k-feldspar

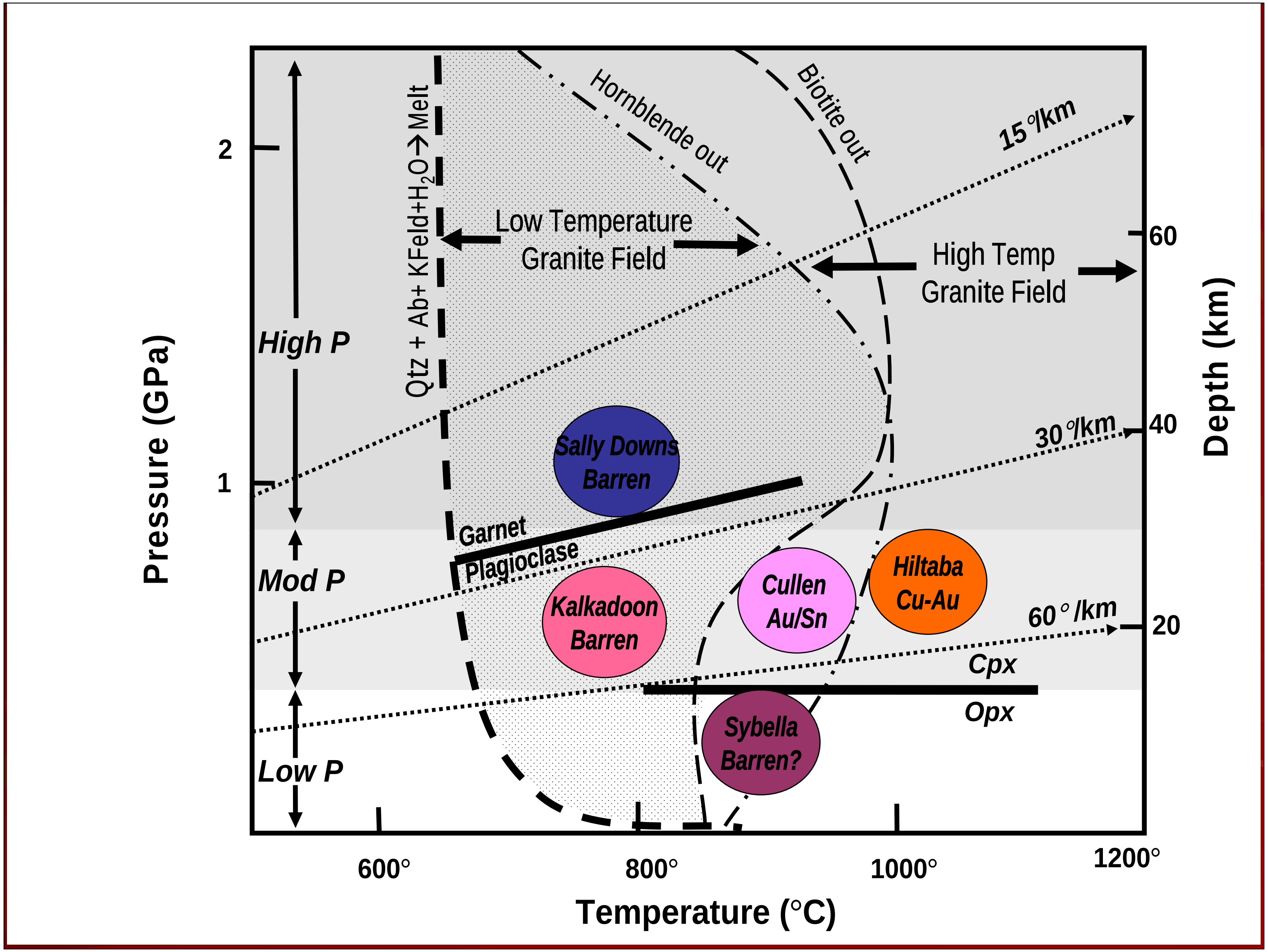

Kalkadoon
(Barren)
Cullen
(Au)
Sybella
(Barren?)
Hiltaba
(Cu-Au)
Relative
Probability
367 SHRIMP
samples
1400
1500
1600
1700
1800
1900
2000
2100
2200
Age (Ma)


457 points
Zircon Ages
2500
2000
1500
1000
500
0
0
500
1000
1500
2000
2500
3000
3500
Model Sm/Nd Ages

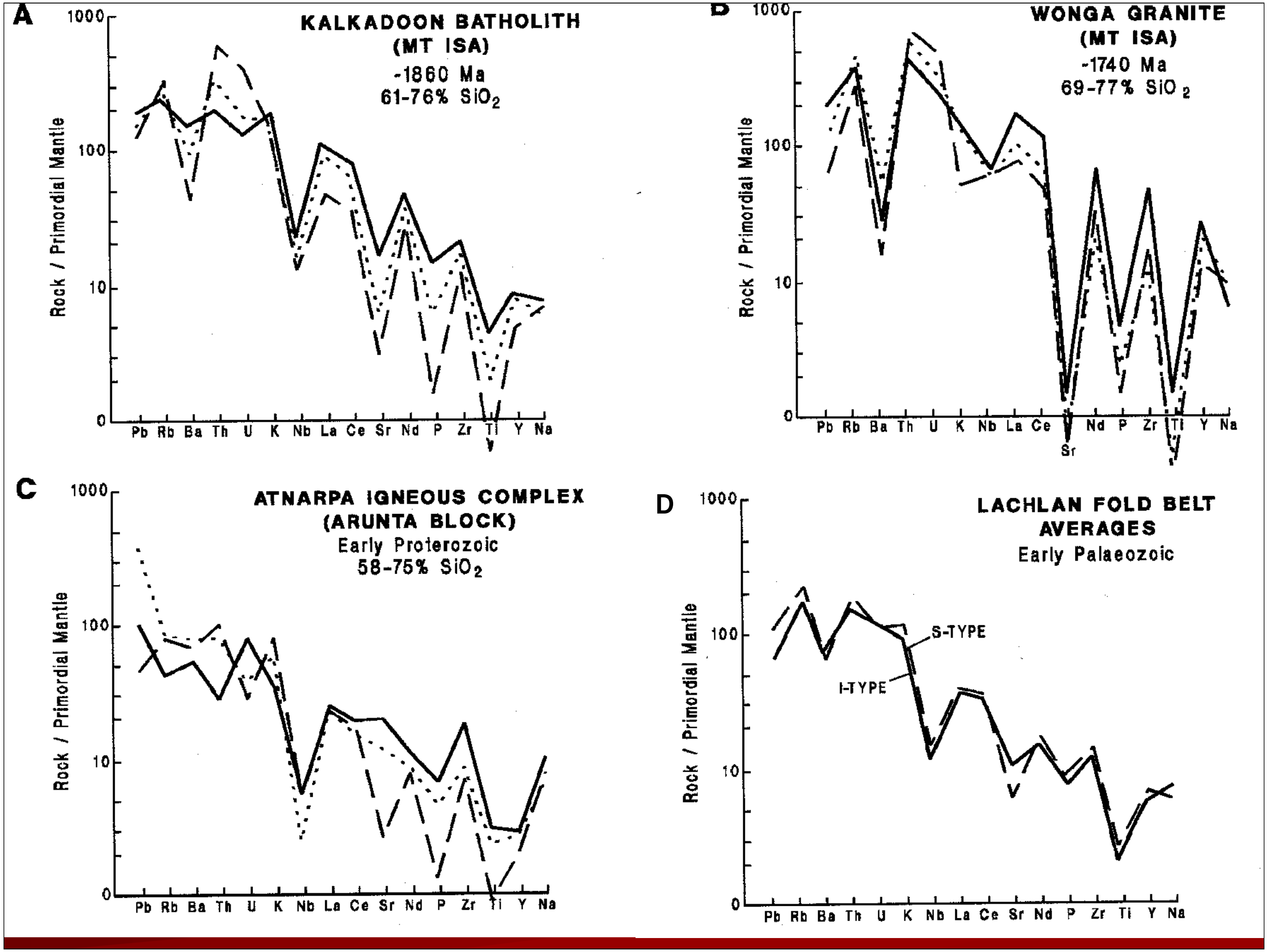
No.	Granite Association	Area (km²)	% of Area	Granite type (%)	Temp (% of Area)	Pressure (% of Area)	Metallogeny
1	Forsayth	3529	2.4	S-Type (2.9%)	Low (2.4%)	Moderate (81.8% Moderate (as above))	Barren
2	Allia	659	0.5		High (0.5%)		Sn ± Ta, W, Au
3	Kalkadoon	25673	17.7	I-Type (88.8%)	Low (31.0%)		Barren
4	Nicholson	19312	13.3				Minor Vein Sn, W, Cu
5	Sybella	8935	6.1		High (54.1%)	Low (6.2%)	Barren
6	Cullen	44126	30.4			Moderate (as above)	Au ± Sn, W, U, Cu, Bi
7	Hiltaba	25480	17.6				Cu + Au ± Ag, U
8	Maramungee	1845	1.3		Low (3.7%)	High (3.7%)	Barren
9	Sally Downs	3566	2.4				Minor Vein Au
10	Unclassified	12004	8.3	? (8.3%)	? (8.3%)	? (8.3%)	?
	Total	145129		100.0	100.0	100.0	

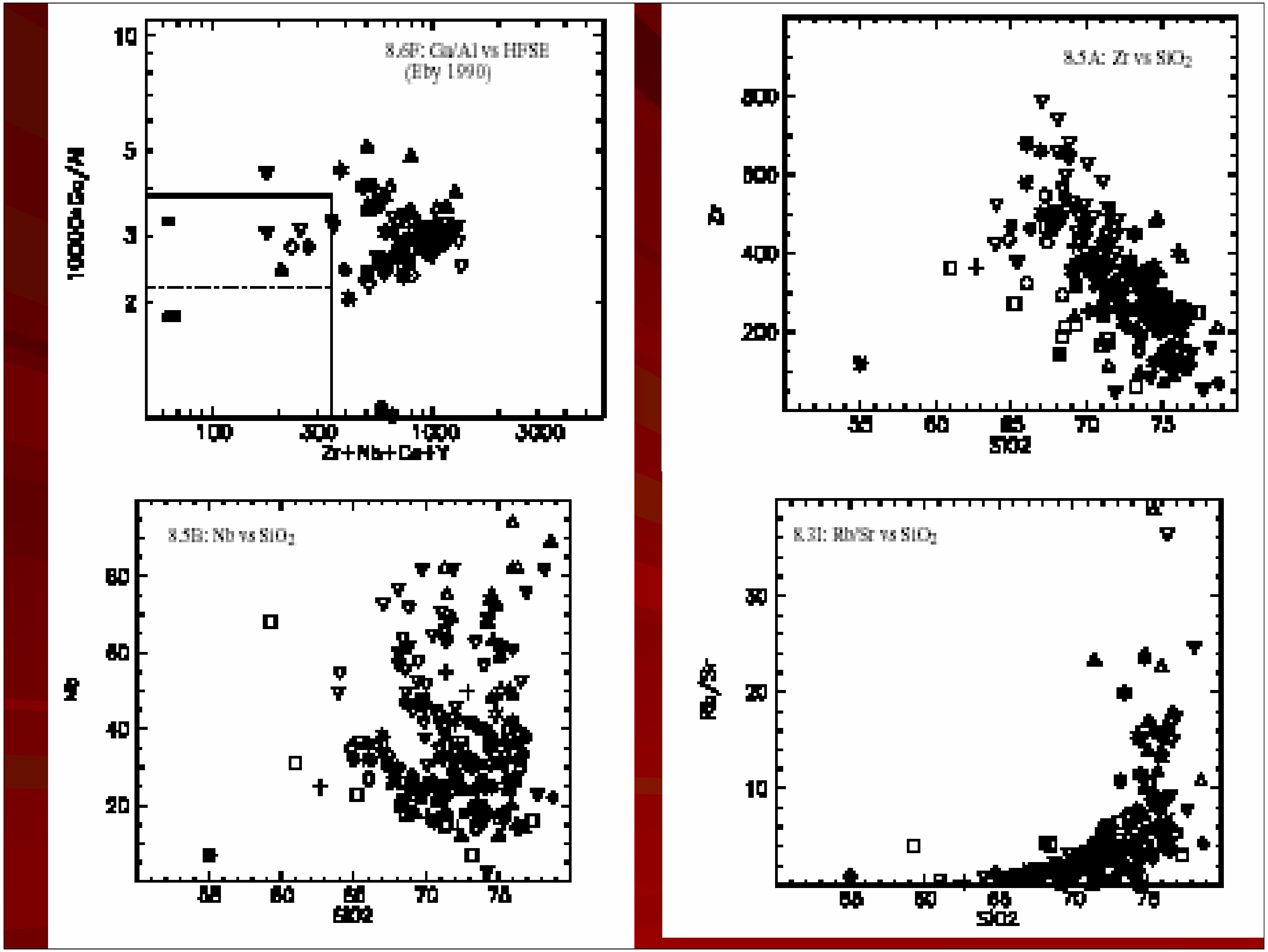
At the Start

- The Pressure in the source
- The Temperature in the source



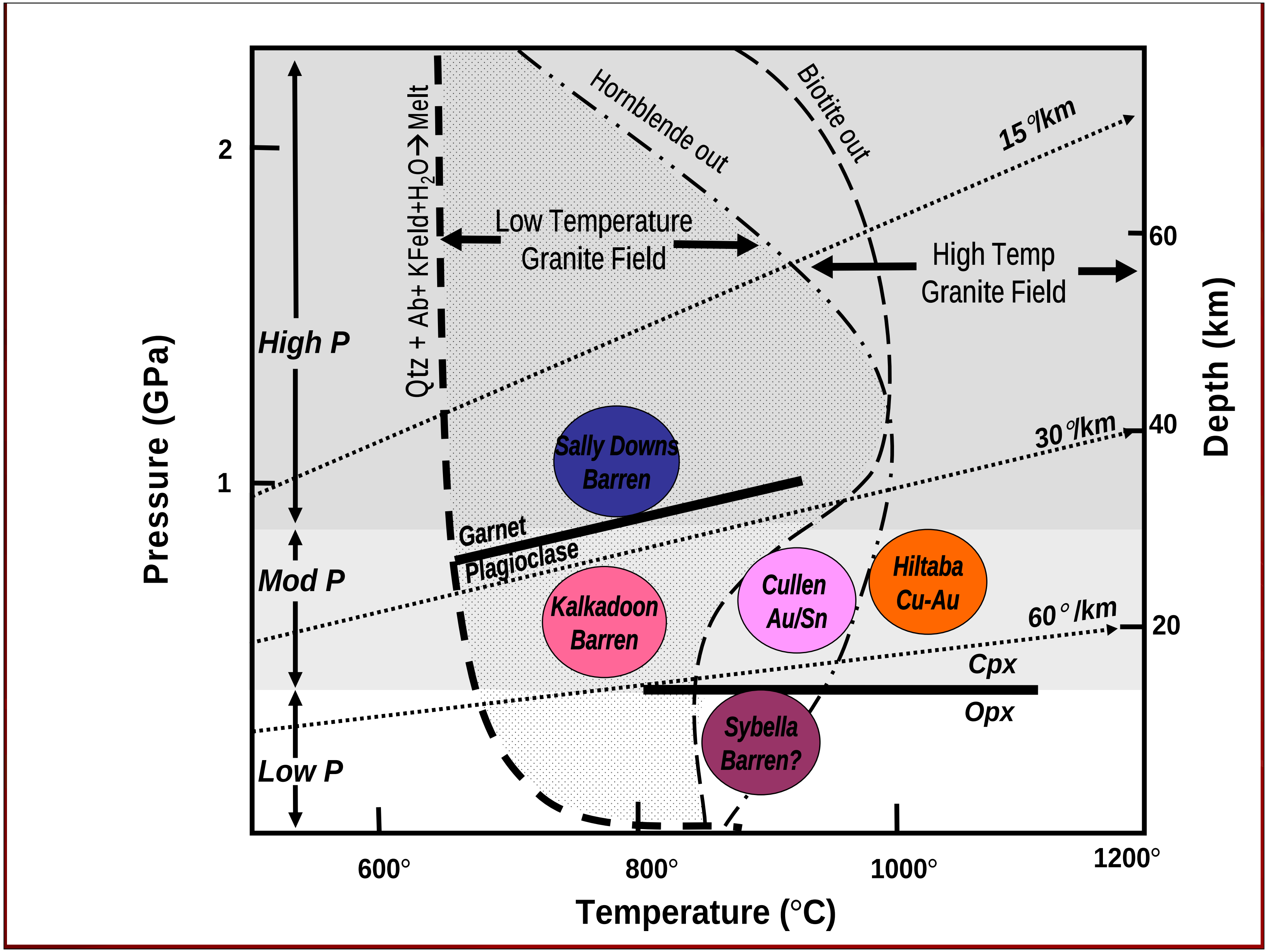
Pressure (GPa)
2
1
High P
Mod P
Low P
Qtz + Ab+ KFeld+H2O→Melt
Hornblende out
Biotite out
15 °/km
Low Temperature
Granite Field
High Temp
Granite Field
60
40
20
Depth (km)
30 °/km
60 ° /km
Sally Downs
Barren
Garnet
Plagioclase
Kalkadoon
Barren
Cullen
Au/Sn
Hiltaba
Cu-Au
Cpx
Opx
Sybella
Barren?
600°
800°
1000°
1200°
Temperature (°C)

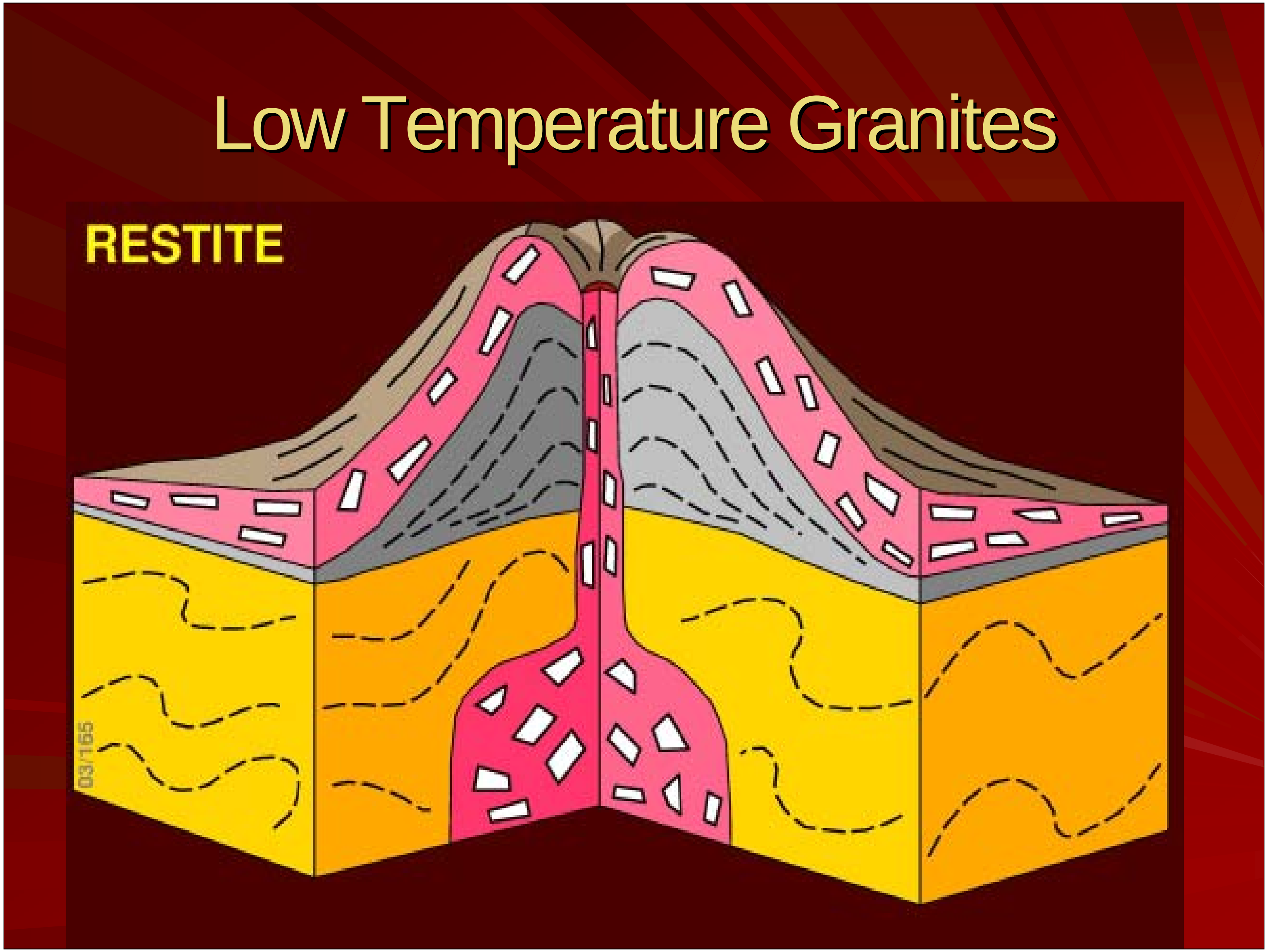

A
KALKADOON BATHOLITH
(MT ISA)
-1860 Ma
61-76% SiO_2
Rock / Primordial Mantle
1000
100
10
0
Pb Rb Ba Th U K Nb La Ce Sr Nd P Zr Ti Y Na
B
WONGA GRANITE
(MT ISA)
-1740 Ma
69-77% SiO_2
Rock / Primordial Mantle
1000
100
10
0
Pb Rb Ba Th U K Nb La Ce Nd P Zr Ti Y Na
Sr
C
ATNARPA IGNEOUS COMPLEX
(ARUNTA BLOCK)
Early Proterozoic
58-75% SiO_2
Rock / Primordial Mantle
1000
100
10
0
Pb Rb Ba Th U K Nb La Ce Sr Nd P Zr Ti Y Na
D
LACHLAN FOLD BELT
AVERAGES
Early Palaeozoic
S-TYPE
I-TYPE
Rock / Primordial Mantle
1000
100
10
0
Pb Rb Ba Th U K Nb La Ce Sr Nd P Zr Ti Y Na

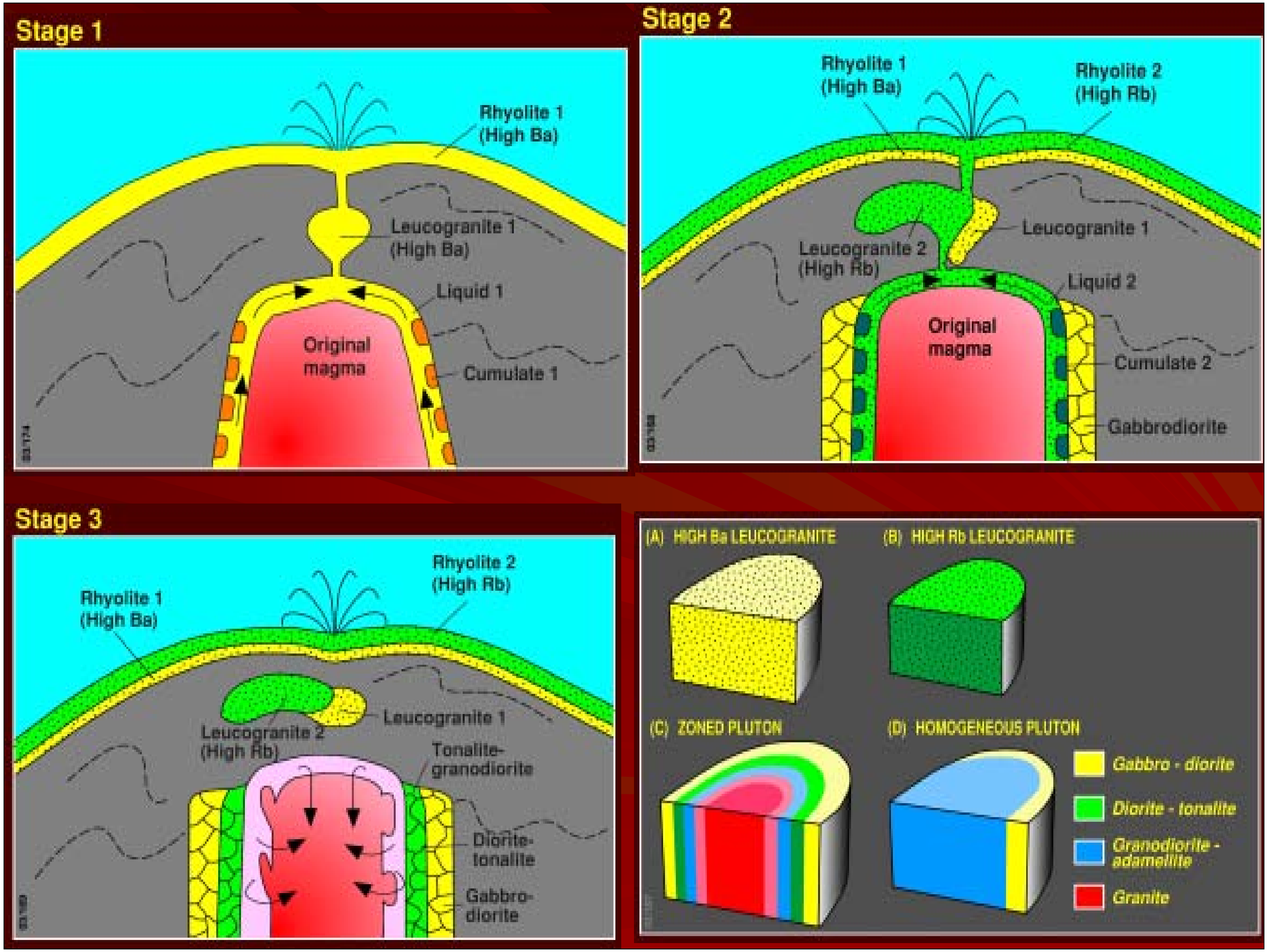


8.6F: Ga/Al vs HFSE
(Eby 1990)
10000*Ga/Al
Zr+Nb+Ce+Y
100
300
1000
3000
8.5A: Zr vs SiO2
Zr
SiO2
8.5B: Nb vs SiO2
Nb
SiO2
8.3I: Rb/Sr vs SiO2
Rb/Sr
SiO2

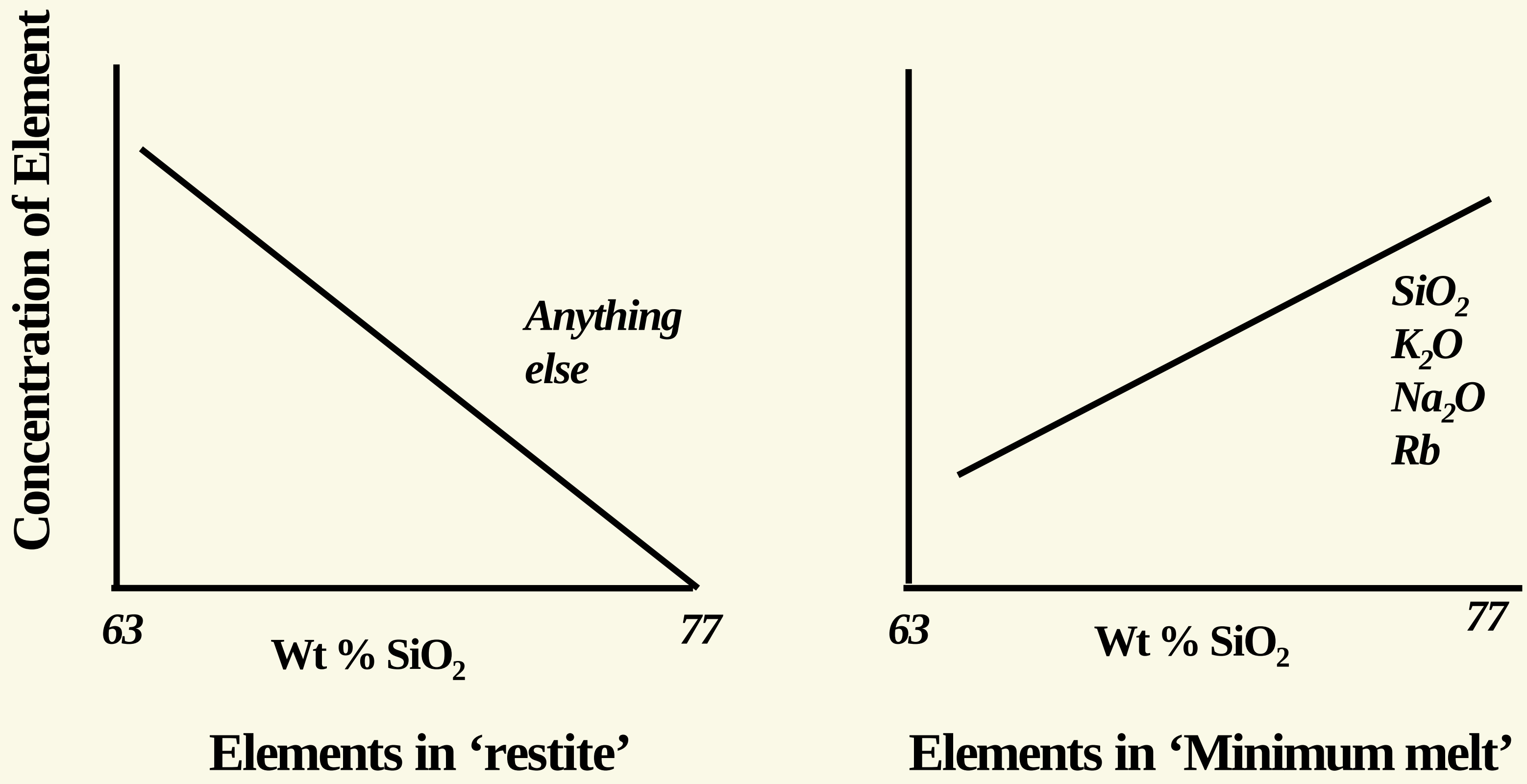

OLYMPUS


Qtz + Ab+ KFeld+H2O→Melt
Hornblende out
Biotite out
15 °/km
Low Temperature
Granite Field
High Temp
Granite Field
2
1
60
40
20
High P
Mod P
Low P
Pressure (GPa)
Depth (km)
Sally Downs
Barren
30 °/km
Garnet
Plagioclase
Kalkadoon
Barren
Cullen
Au/Sn
Hiltaba
Cu-Au
60 ° /km
Cpx
Opx
Sybella
Barren?
600°
800°
1000°
1200°
Temperature (°C)

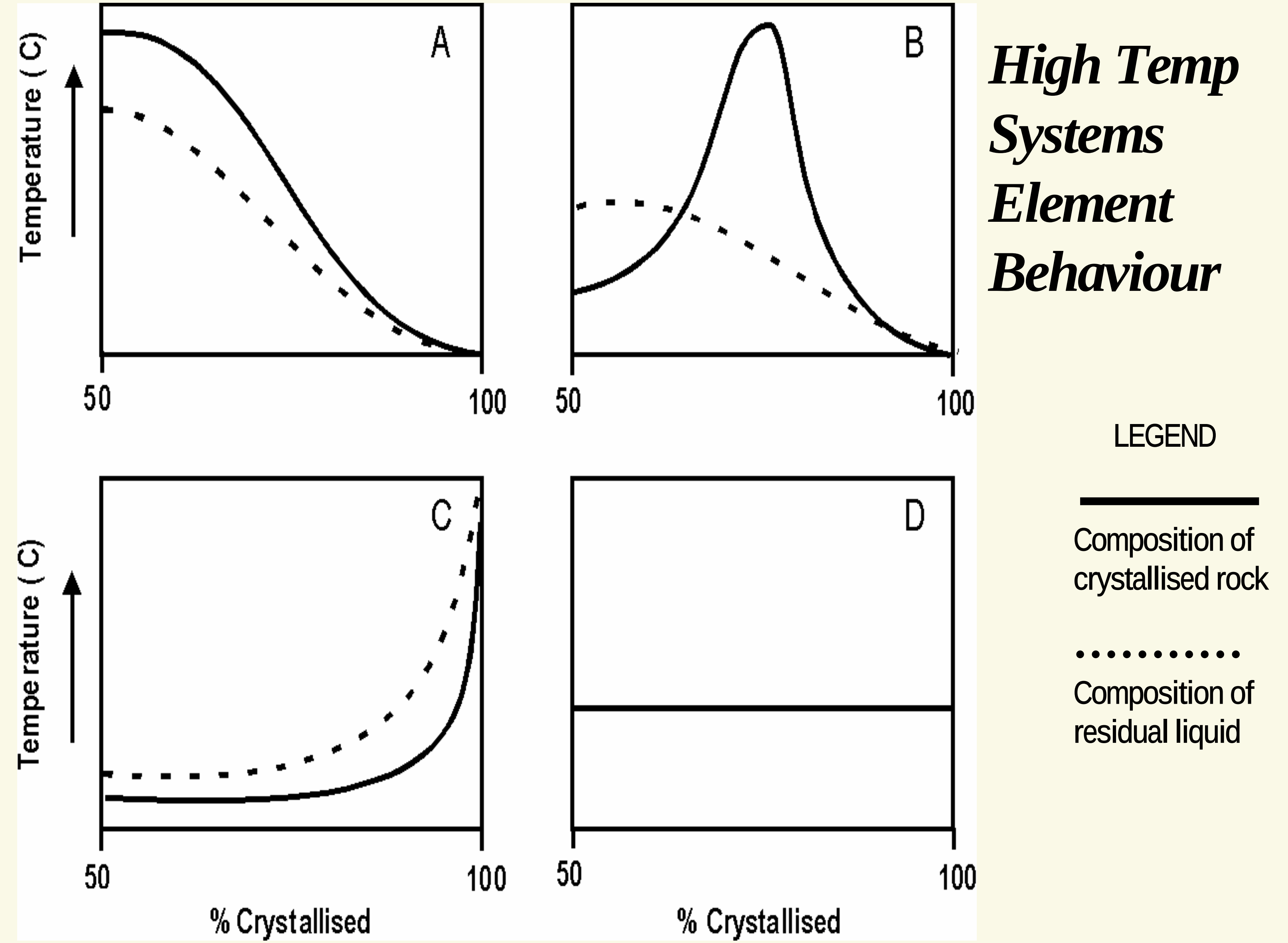

Low Temperature Granites
RESTITE
03/165


Stage 1
Rhyolite 1
(High Ba)
Leucogranite 1
(High Ba)
Liquid 1
Original
magma
Cumulate 1
Stage 2
Rhyolite 1
(High Ba)
Rhyolite 2
(High Rb)
Leucogranite 1
Leucogranite 2
(High Rb)
Liquid 2
Original
magma
Cumulate 2
Gabbrodiorite
Stage 3
Rhyolite 2
(High Rb)
Rhyolite 1
(High Ba)
Leucogranite 1
Leucogranite 2
(High Rb)
Tonalite-
granodiorite
Diorite-
tonalite
Gabbro-
diorite
(A) HIGH Ba LEUCOGRANITE
(B) HIGH Rb LEUCOGRANITE
(C) ZONED PLUTON
(D) HOMOGENEOUS PLUTON
Gabbro - diorite
Diorite - tonalite
Granodiorite -
adamellite
Granite

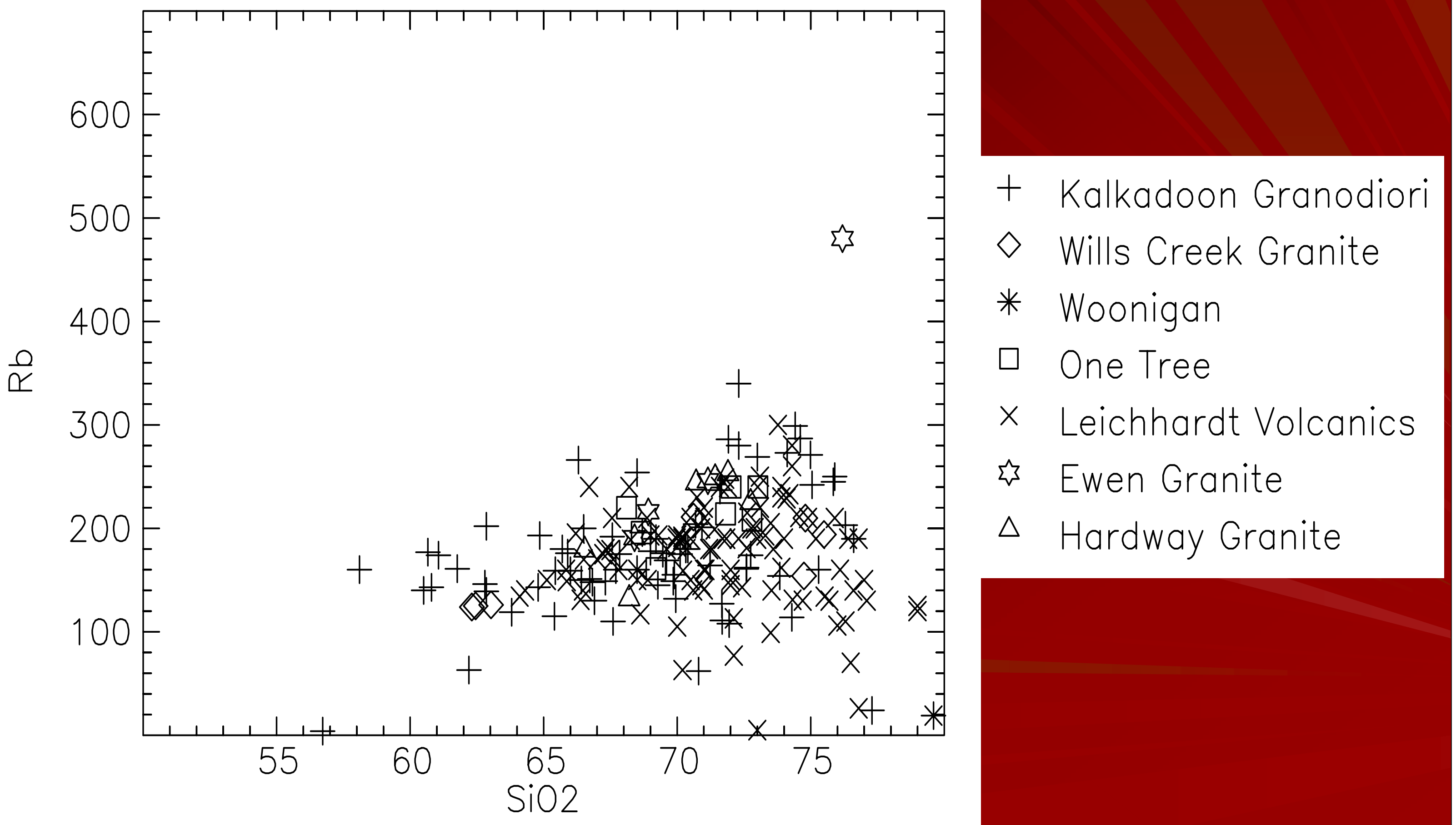
Low Temperature Systems – Element behaviour

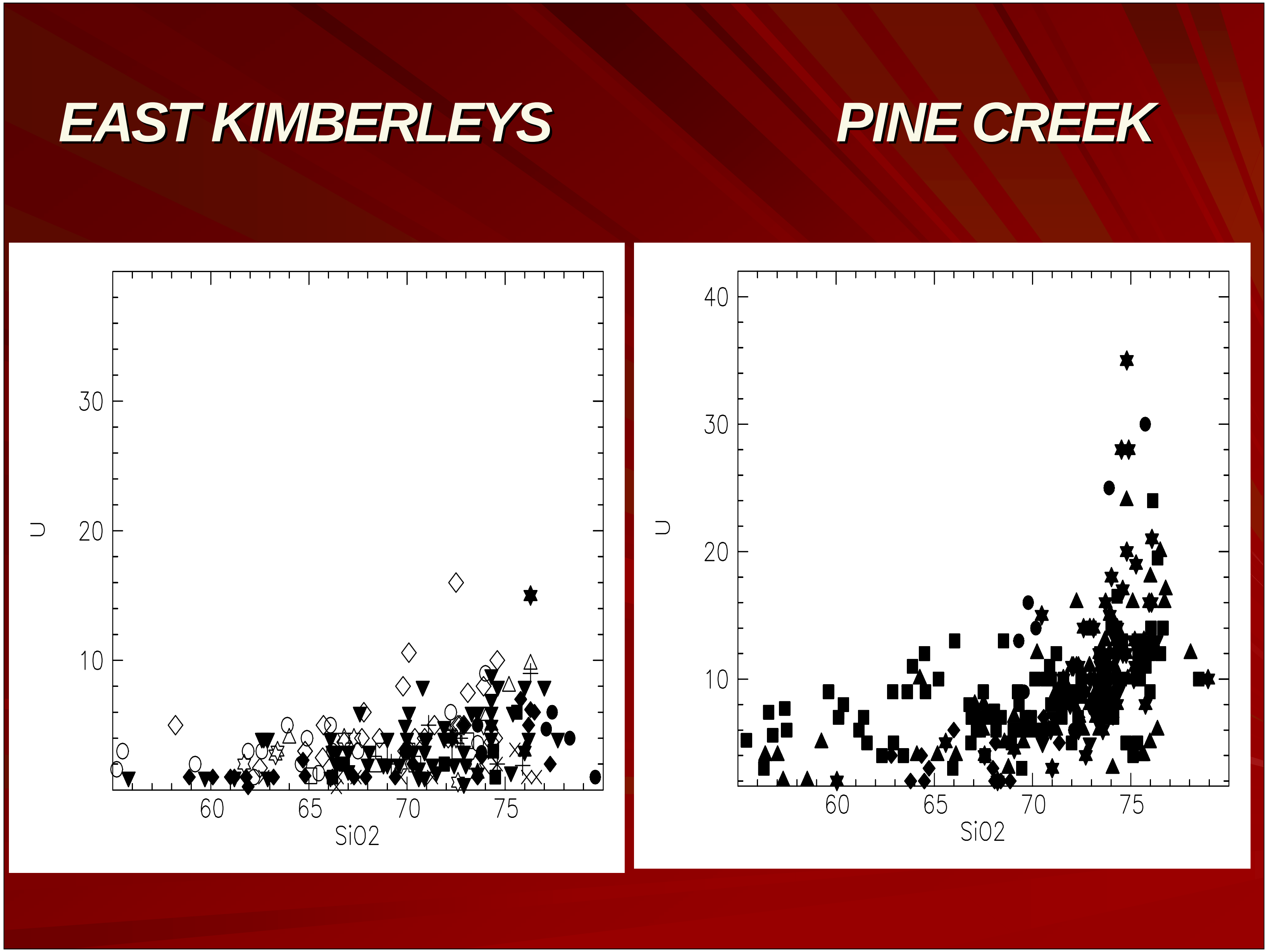


High Temp Systems Element Behaviour

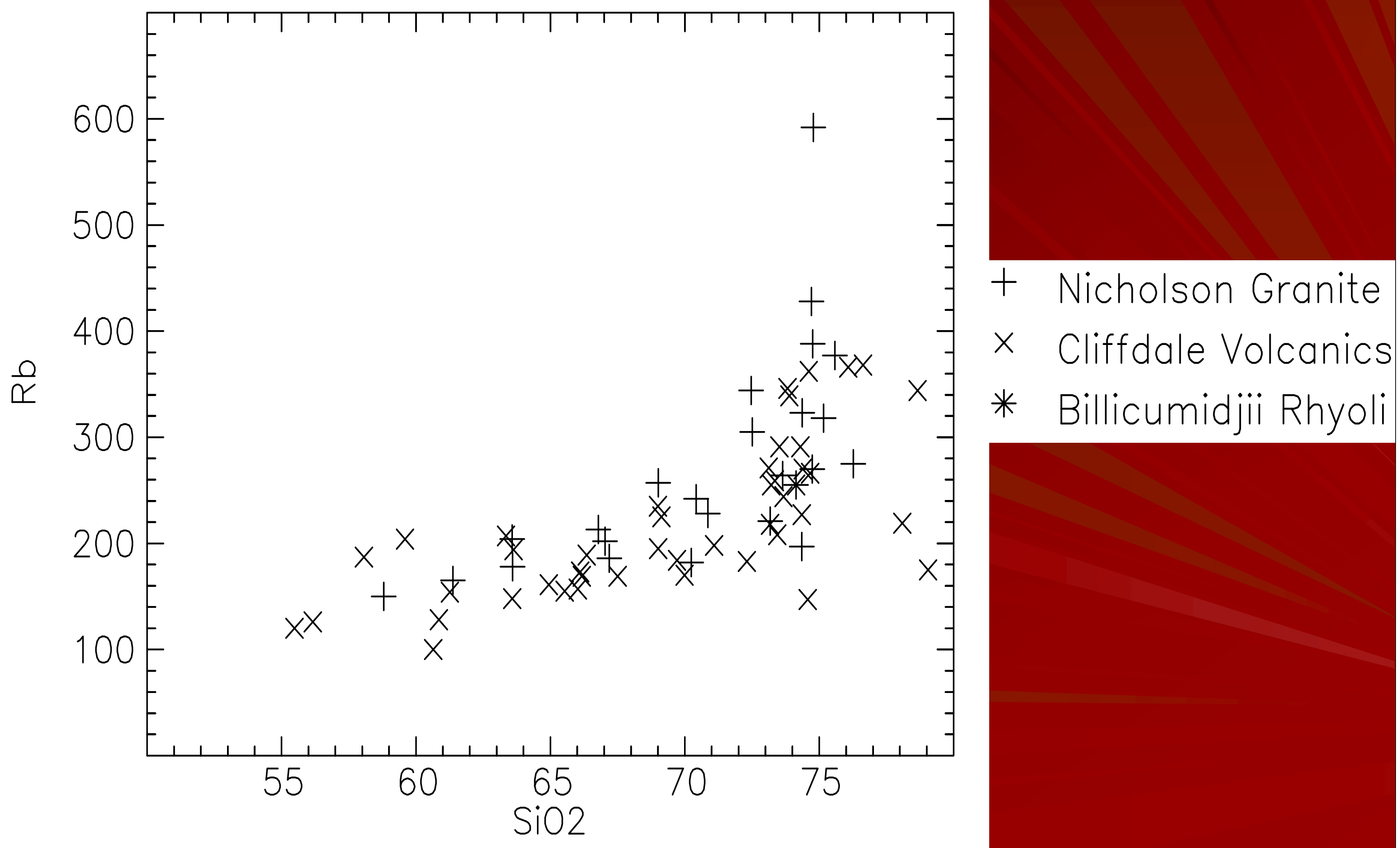


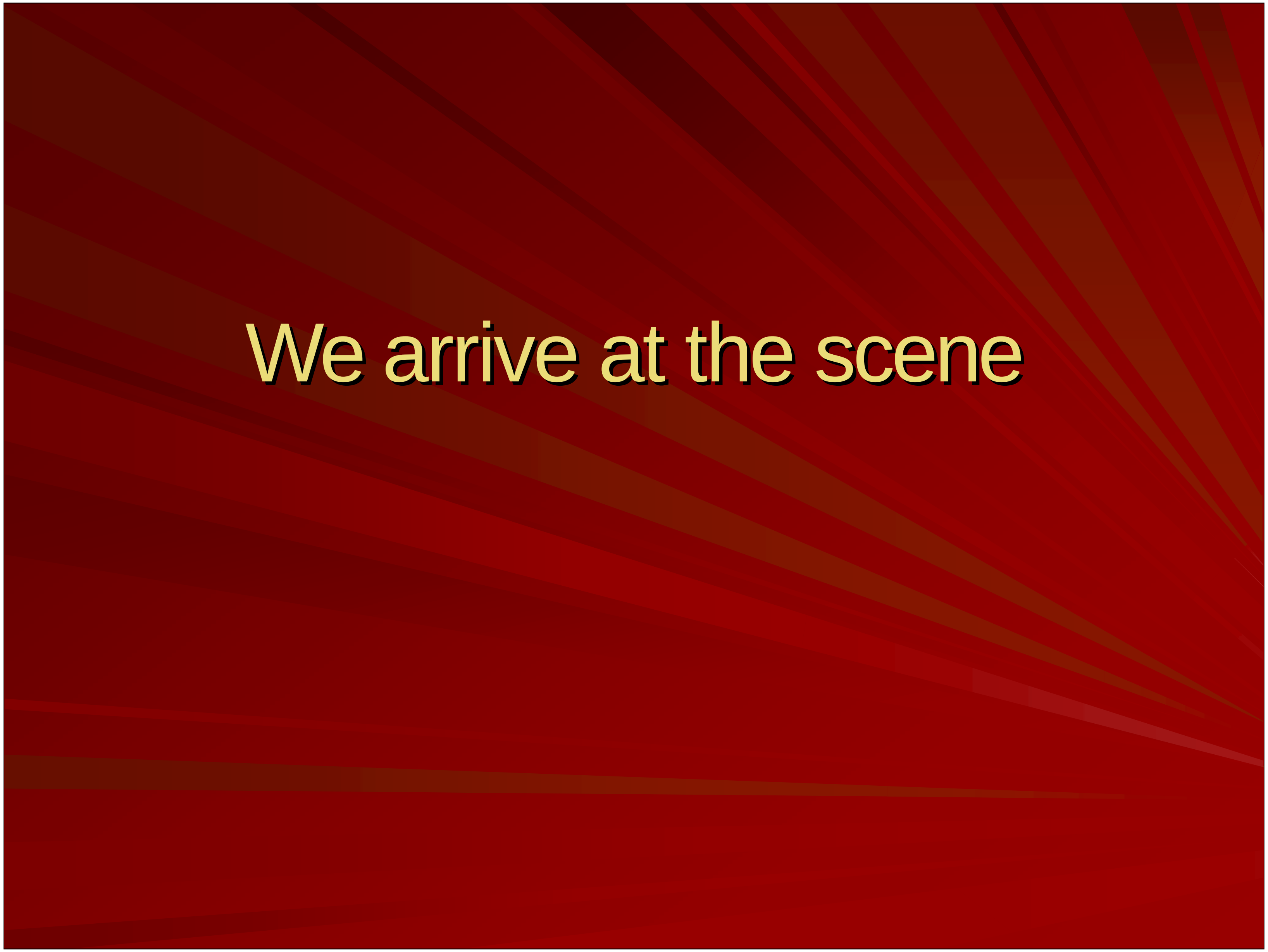
Kalkadoon Supersuite



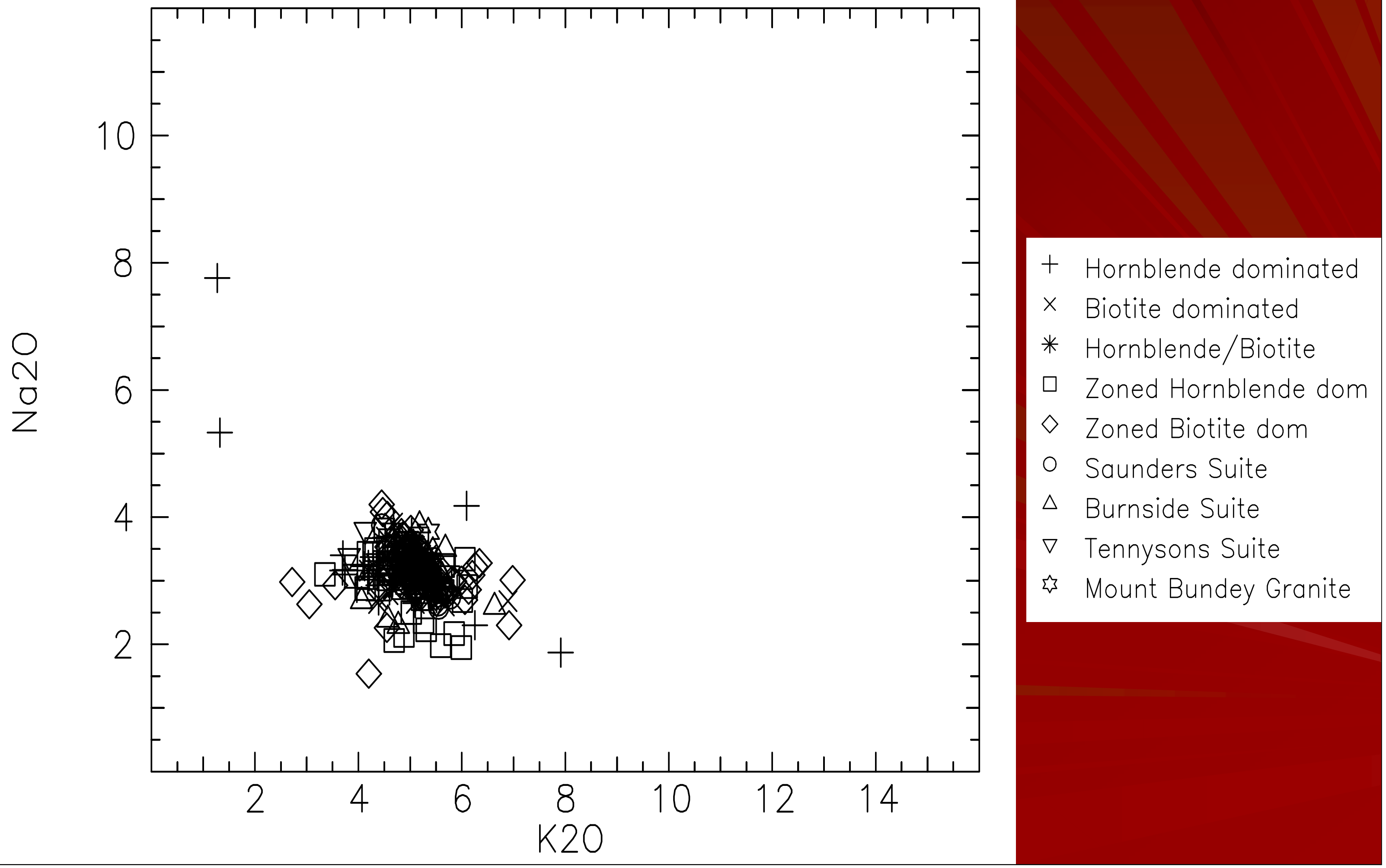

EAST KIMBERLEYS
PINE CREEK
U
30
20
10
60
65
70
75
SiO2
U
40
30
20
10
60
65
70
75
SiO2

Nicholson Suite

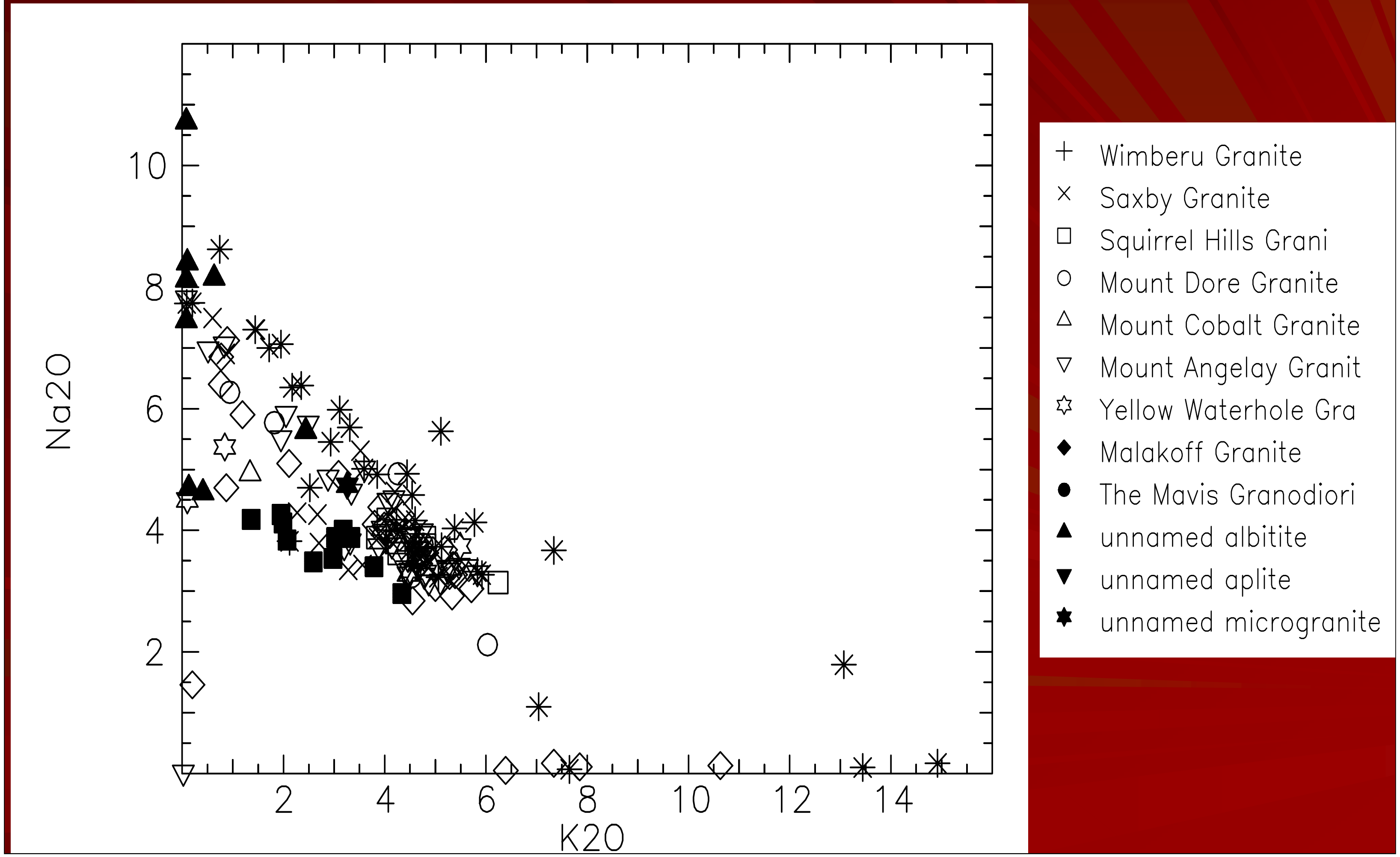


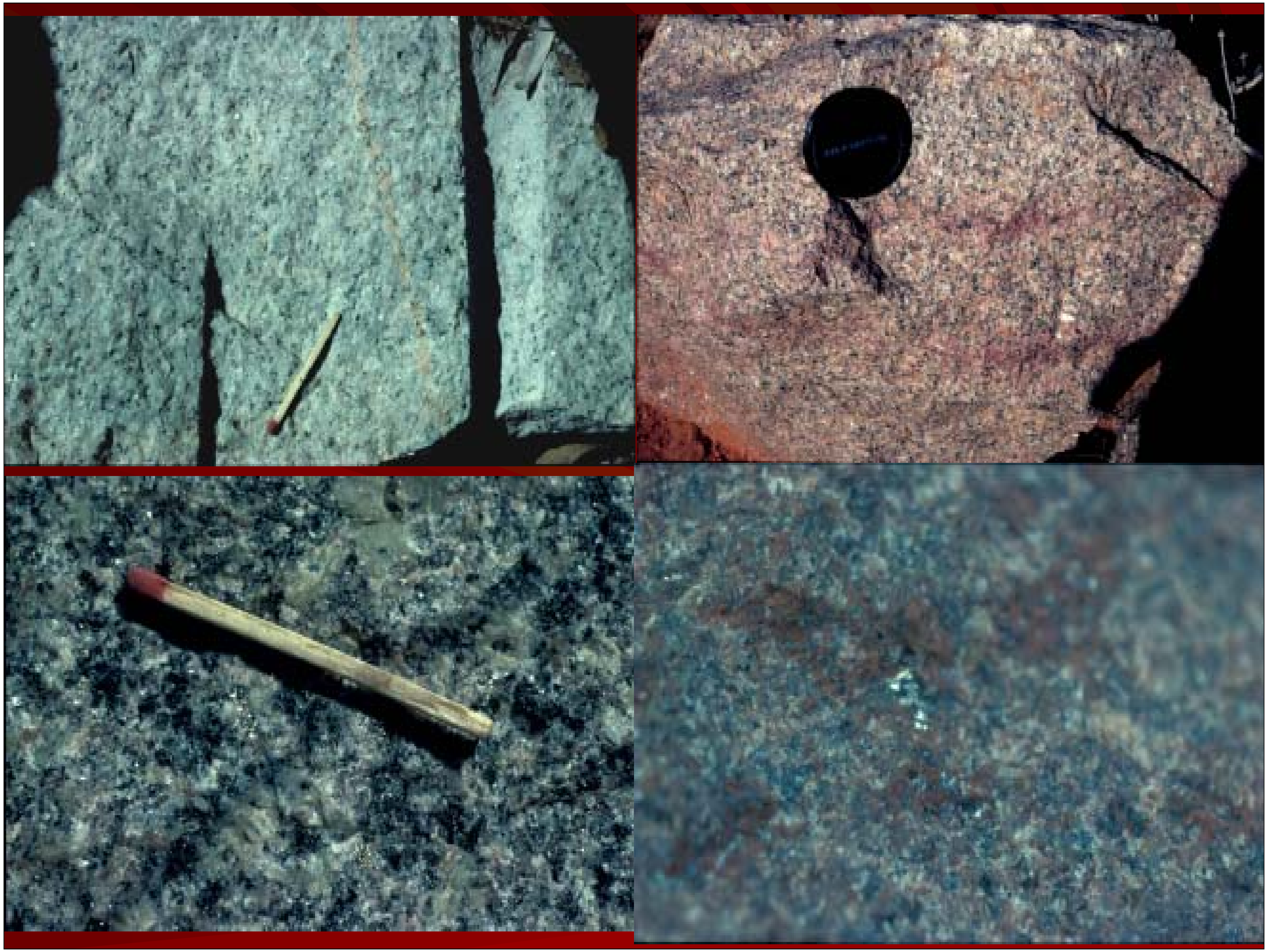

We arrive at the scene

Cullen Supersuite

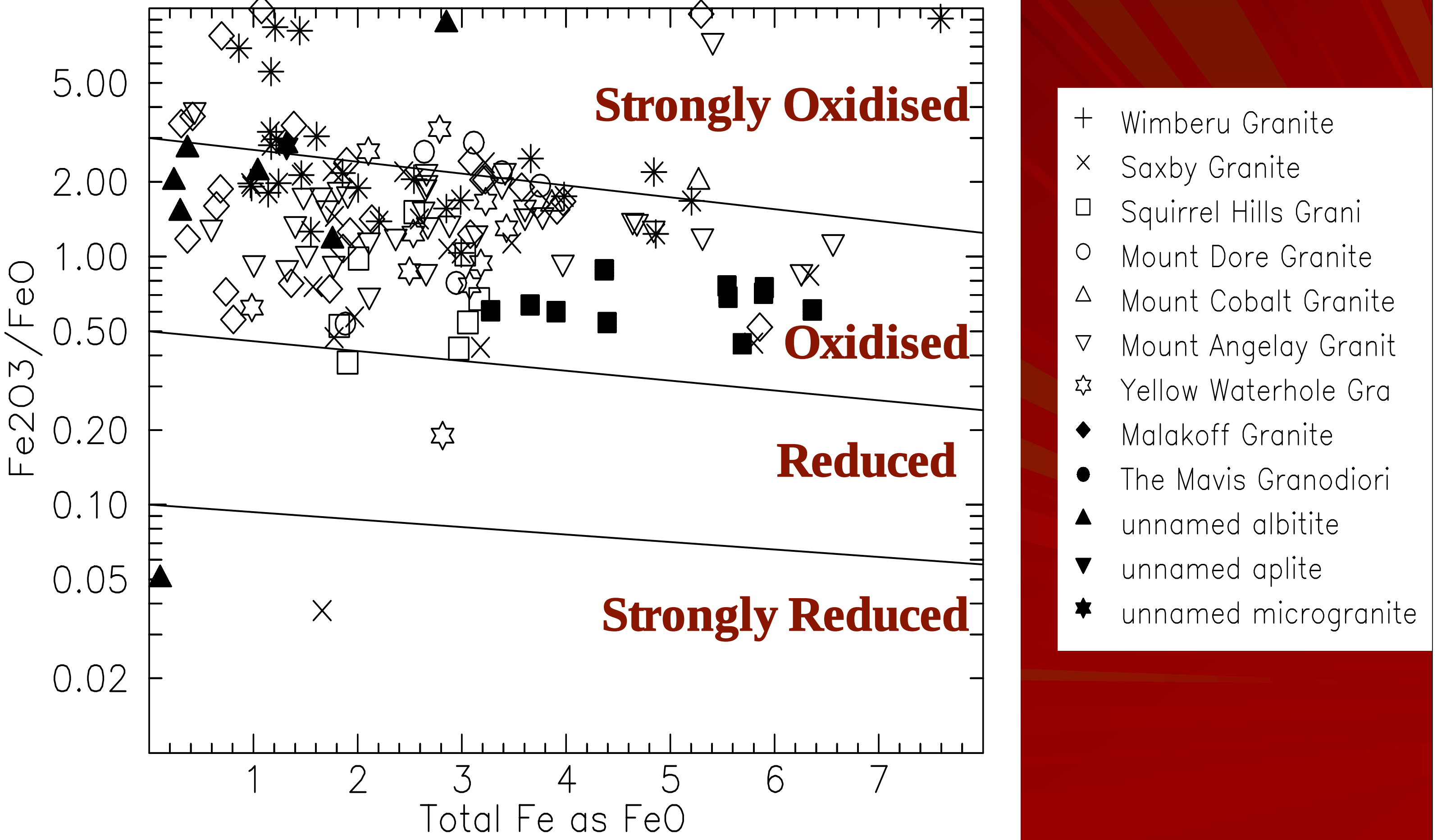


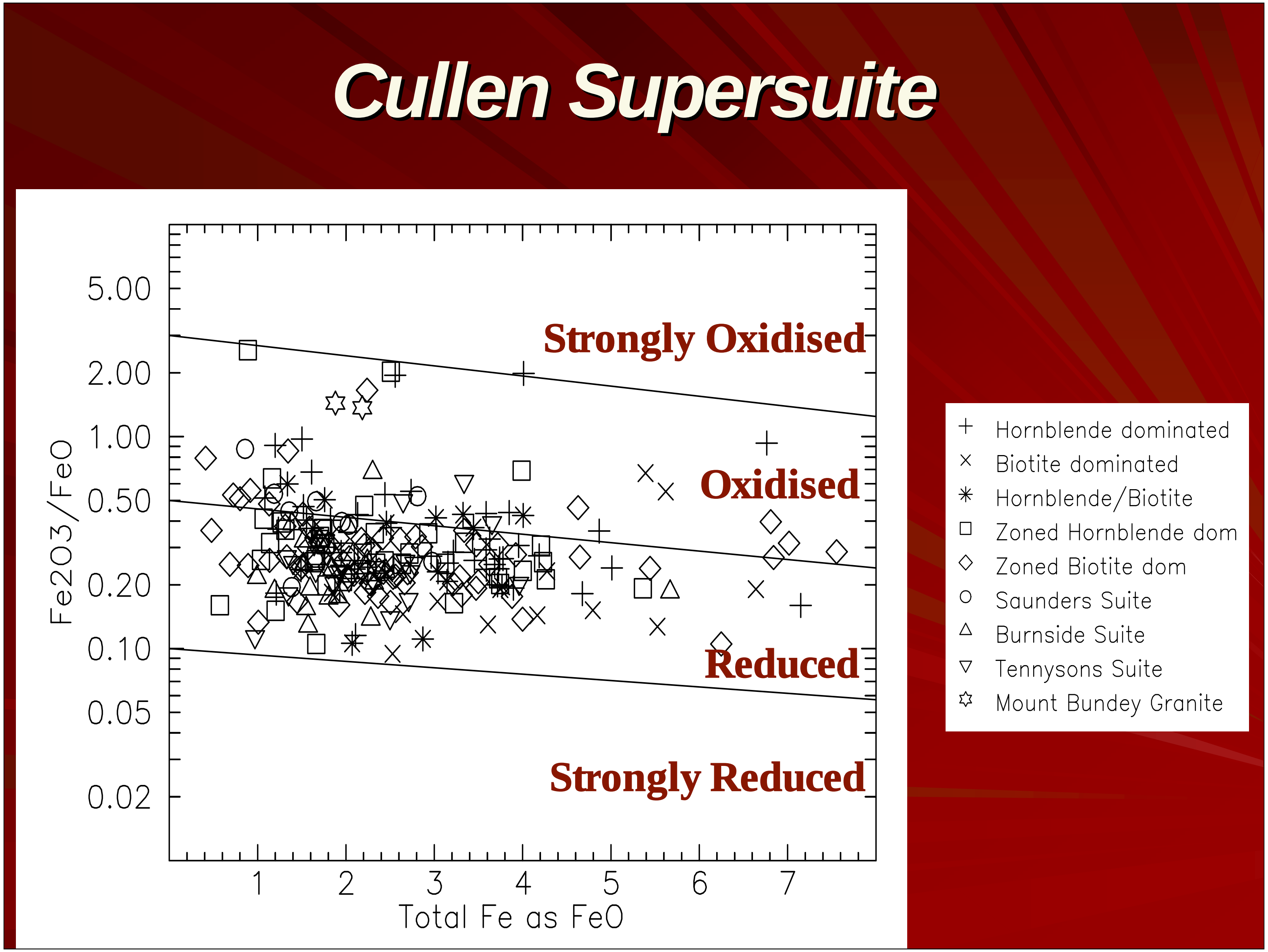
Williams Supersuite



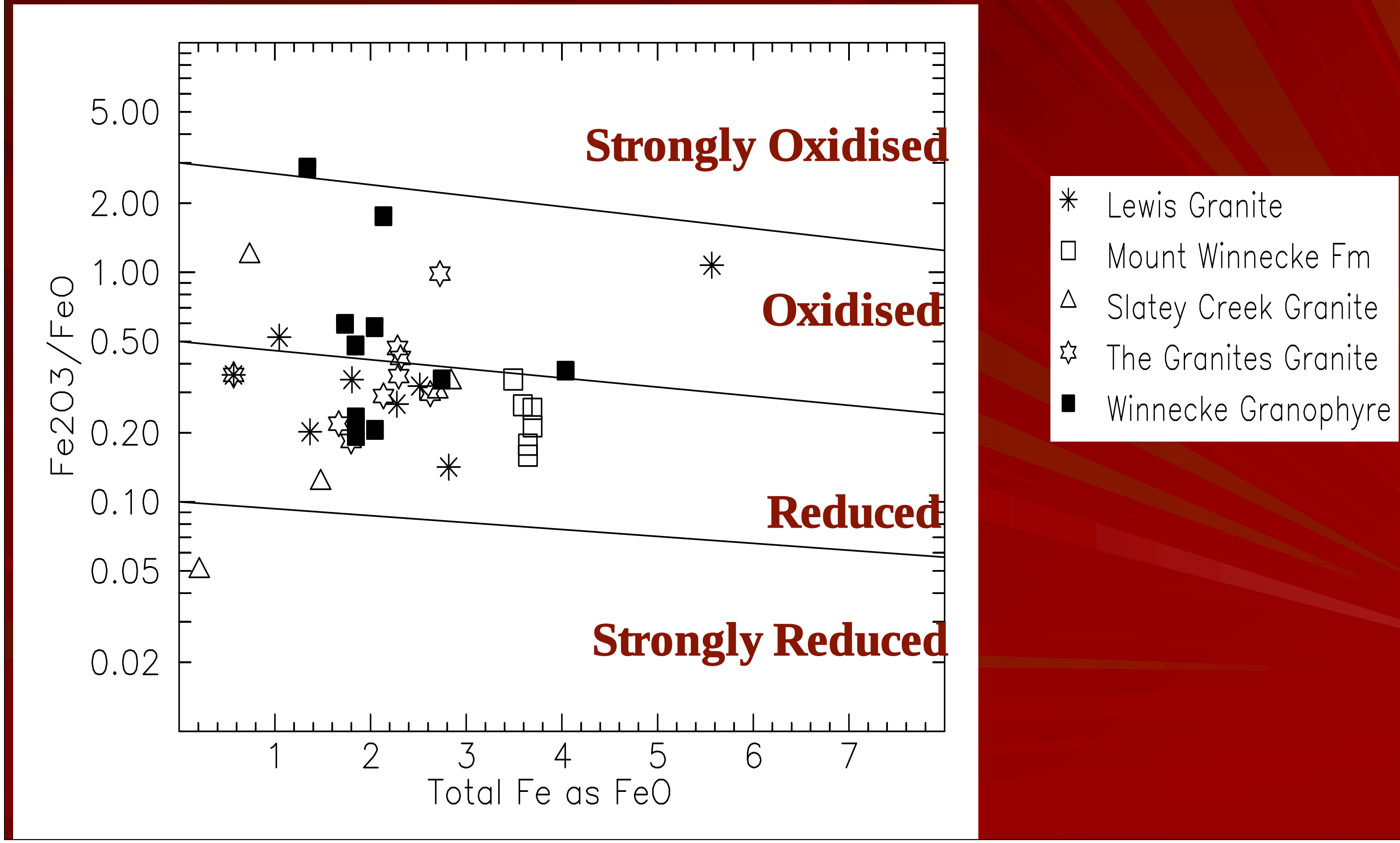


Williams Supersuite

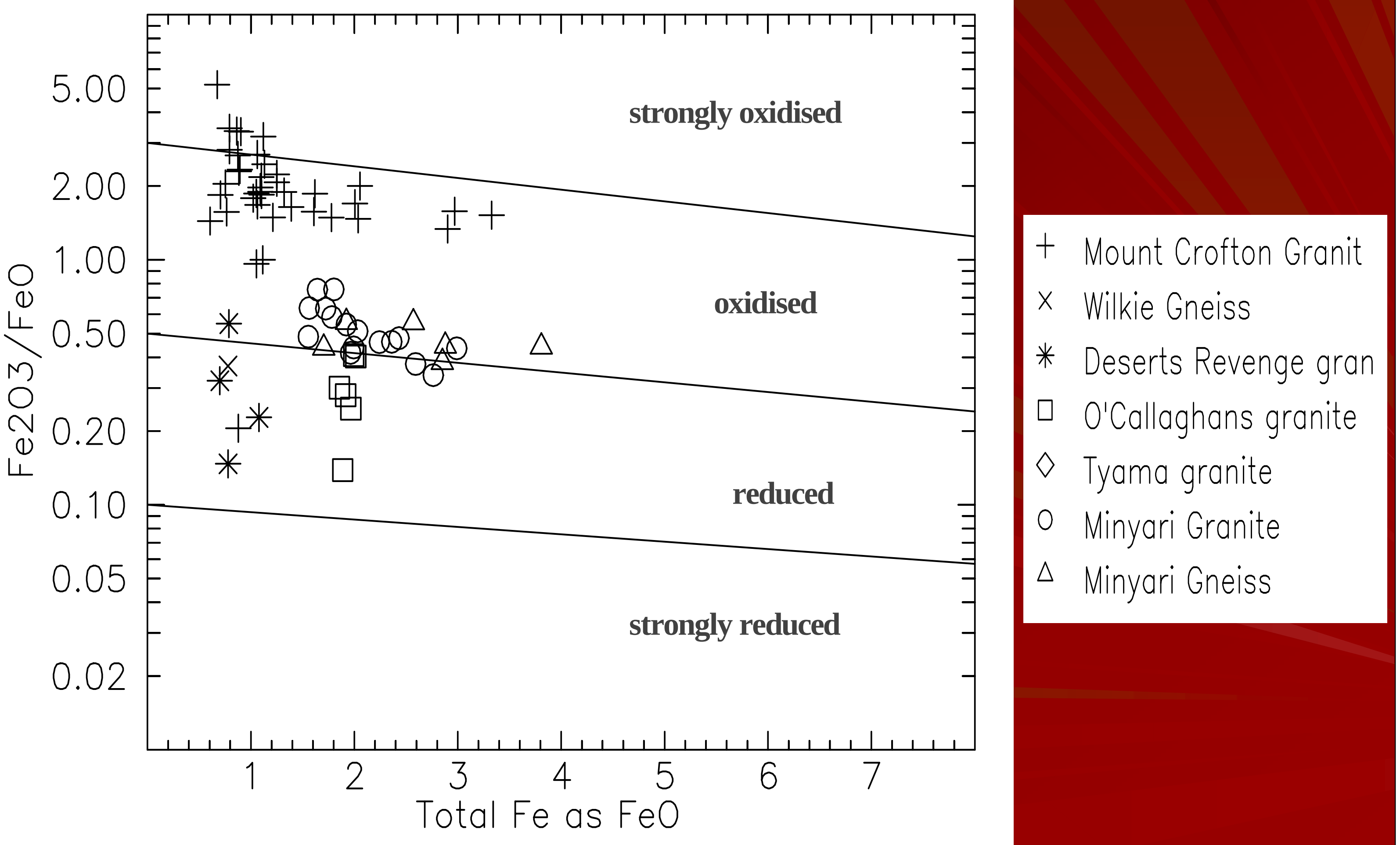


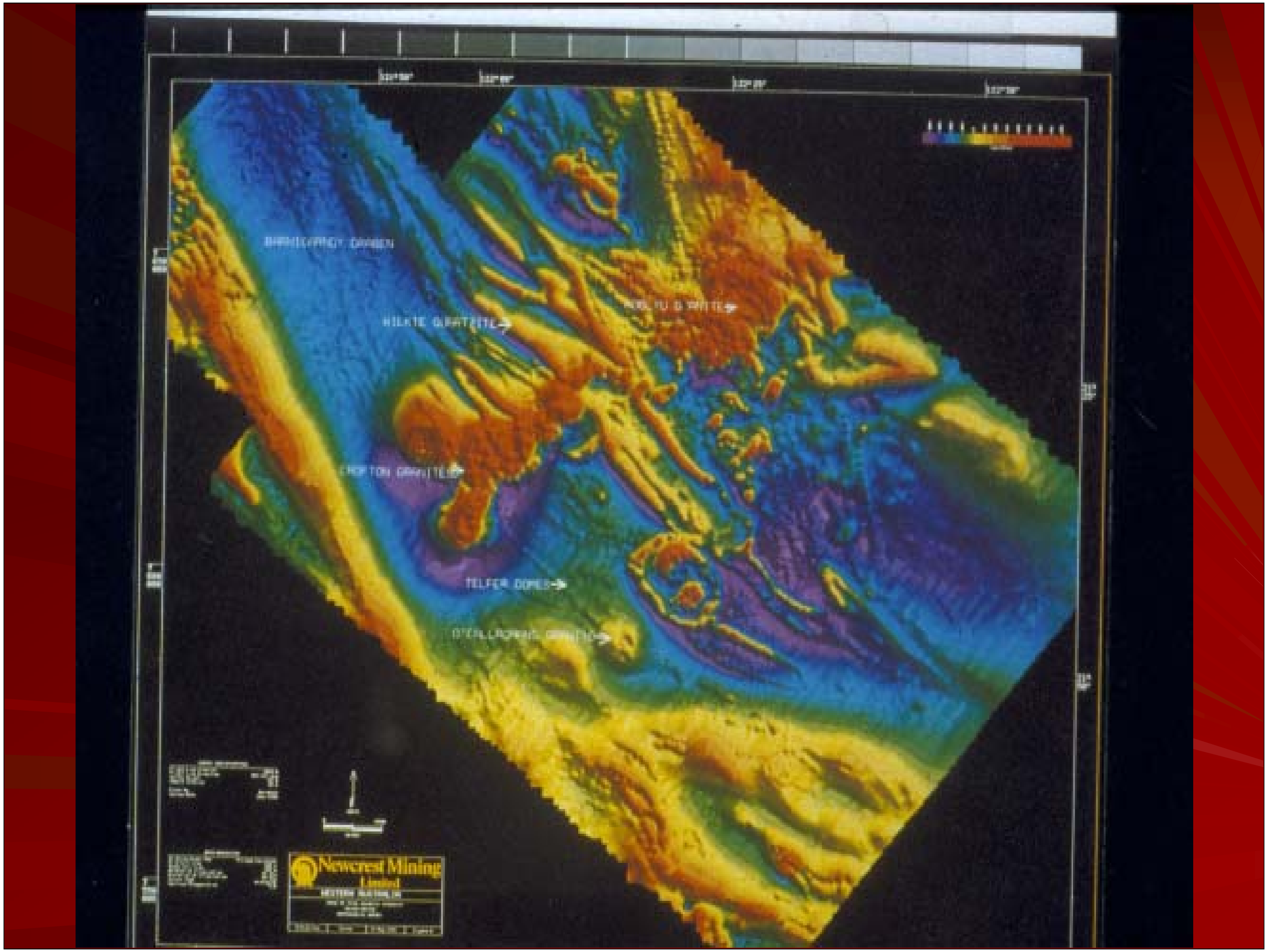

Cullen Supersuite
Strongly Oxidised
Oxidised
Reduced
Strongly Reduced
5.00
2.00
1.00
0.50
0.20
0.10
0.05
0.02
Fe2O3/FeO
1
2
3
4
5
6
7
Total Fe as FeO
Hornblende dominated
Biotite dominated
Hornblende/Biotite
Zoned Hornblende dom
Zoned Biotite dom
Saunders Suite
Burnside Suite
Tennysons Suite
Mount Bundey Granite

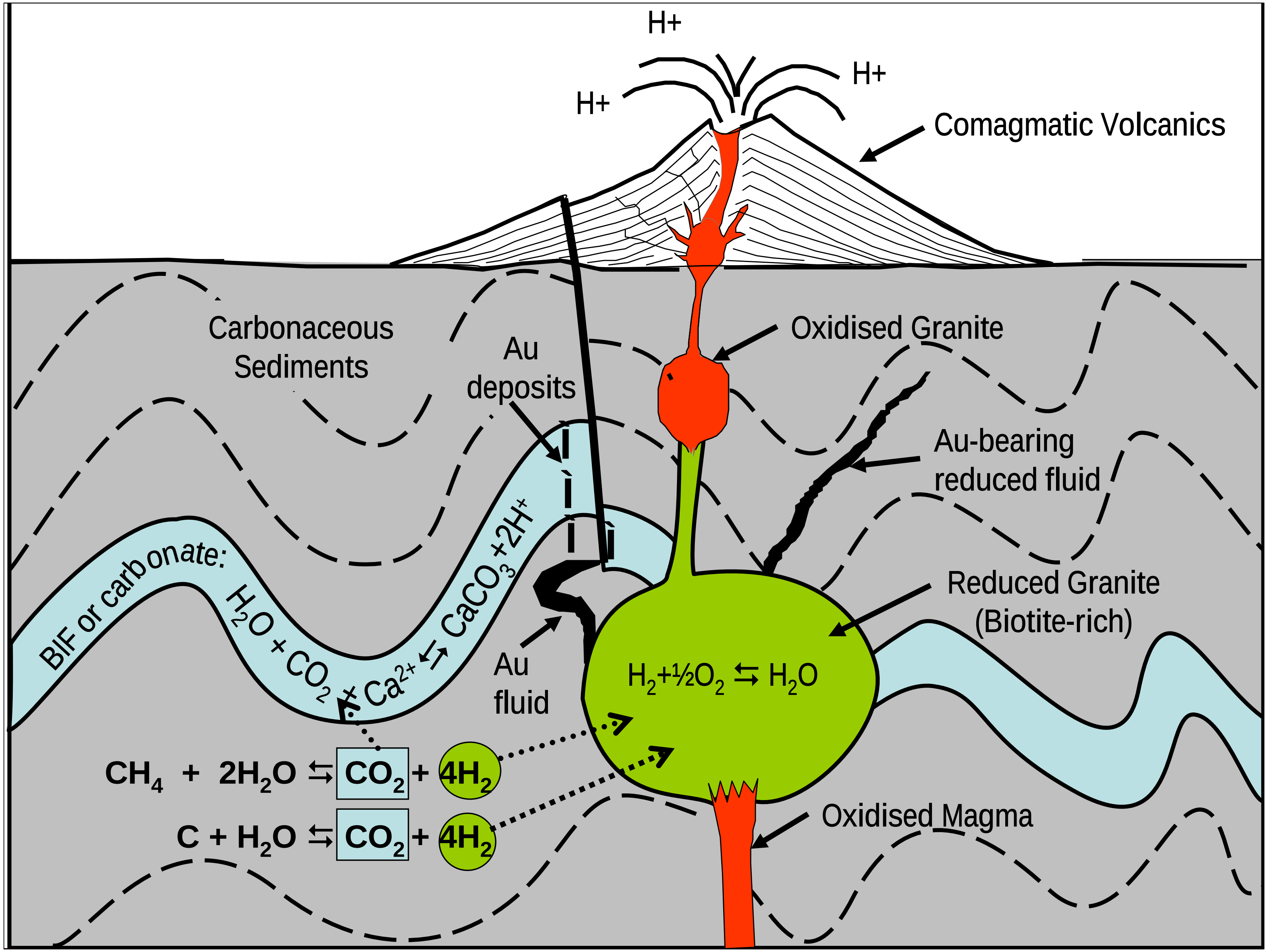
Tanami Province



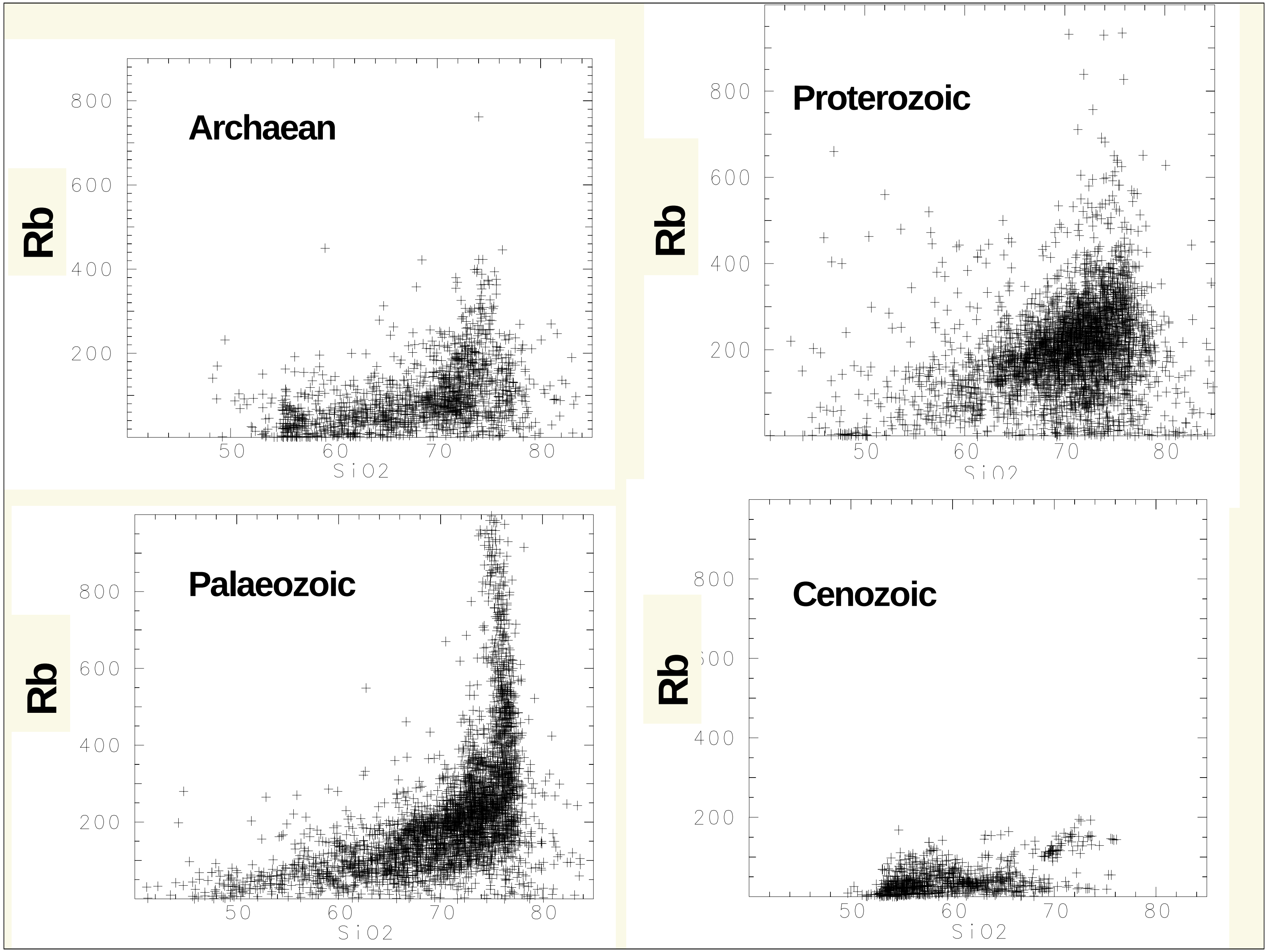
Telfer Supersuite

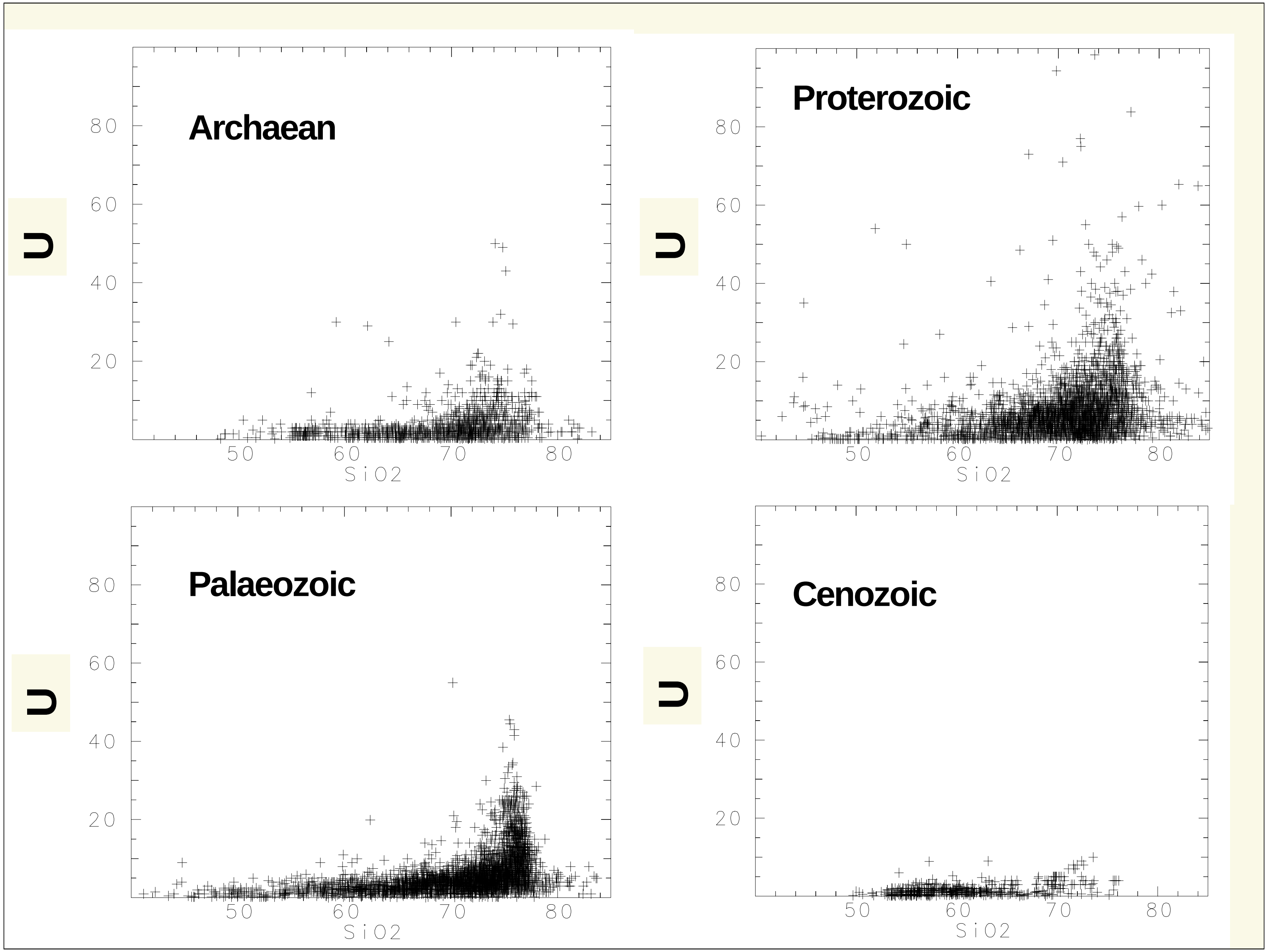


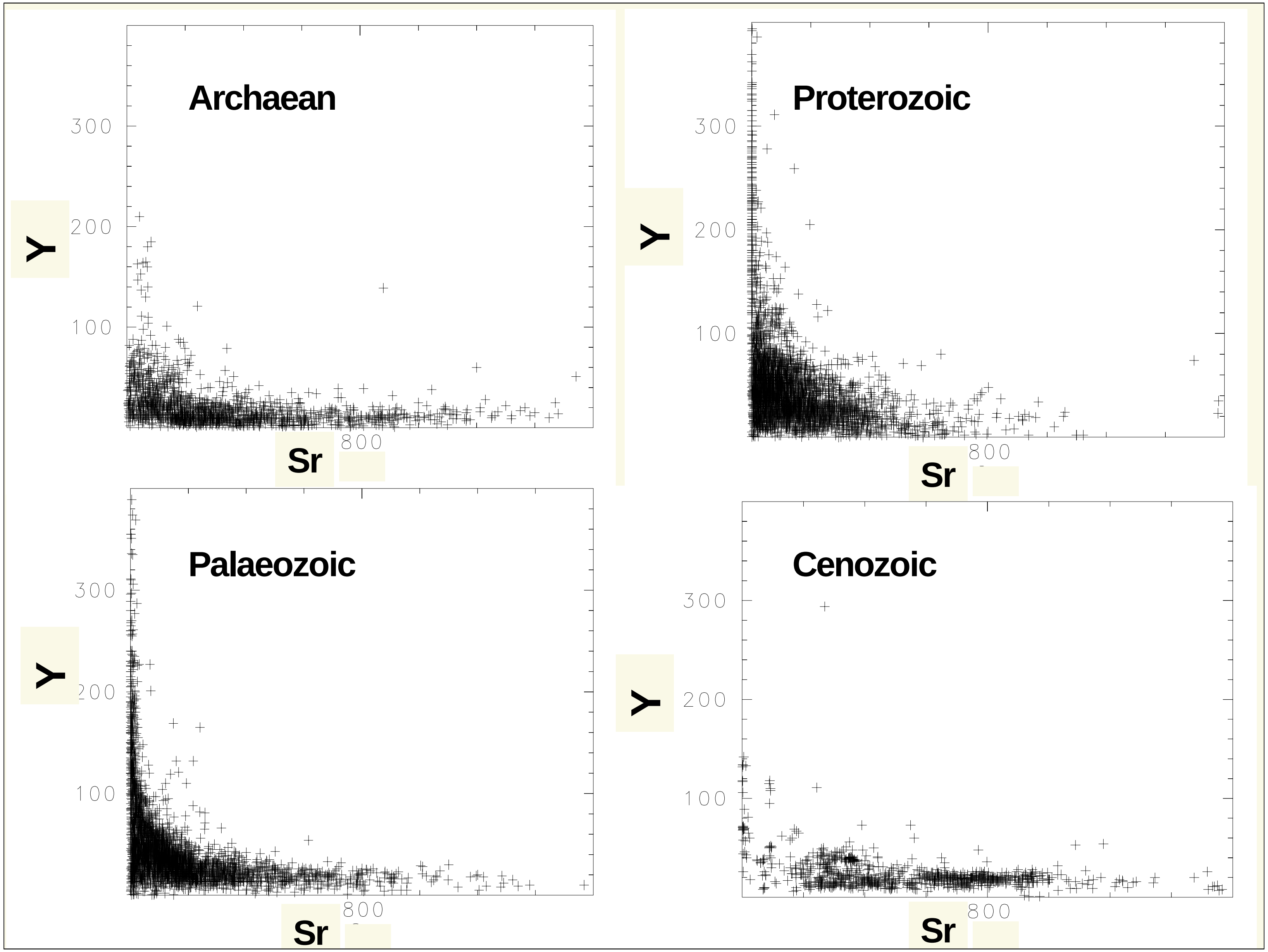

TELFER DOME
Newcrest Mining
Limited


H+
H+
H+
H+
Comagmatic Volcanics
Carbonaceous Sediments
Au deposits
Oxidised Granite
Au-bearing reduced fluid
Reduced Granite (Biotite-rich)
BIF or carbonate:
H2O + CO2 + Ca2+ ⇆ CaCO3 + 2H+
Au fluid
H2+½O2 ⇆ H2O
CH4 + 2H2O ⇆ CO2 + 4H2
C + H2O ⇆ CO2 + 4H2
Oxidised Magma

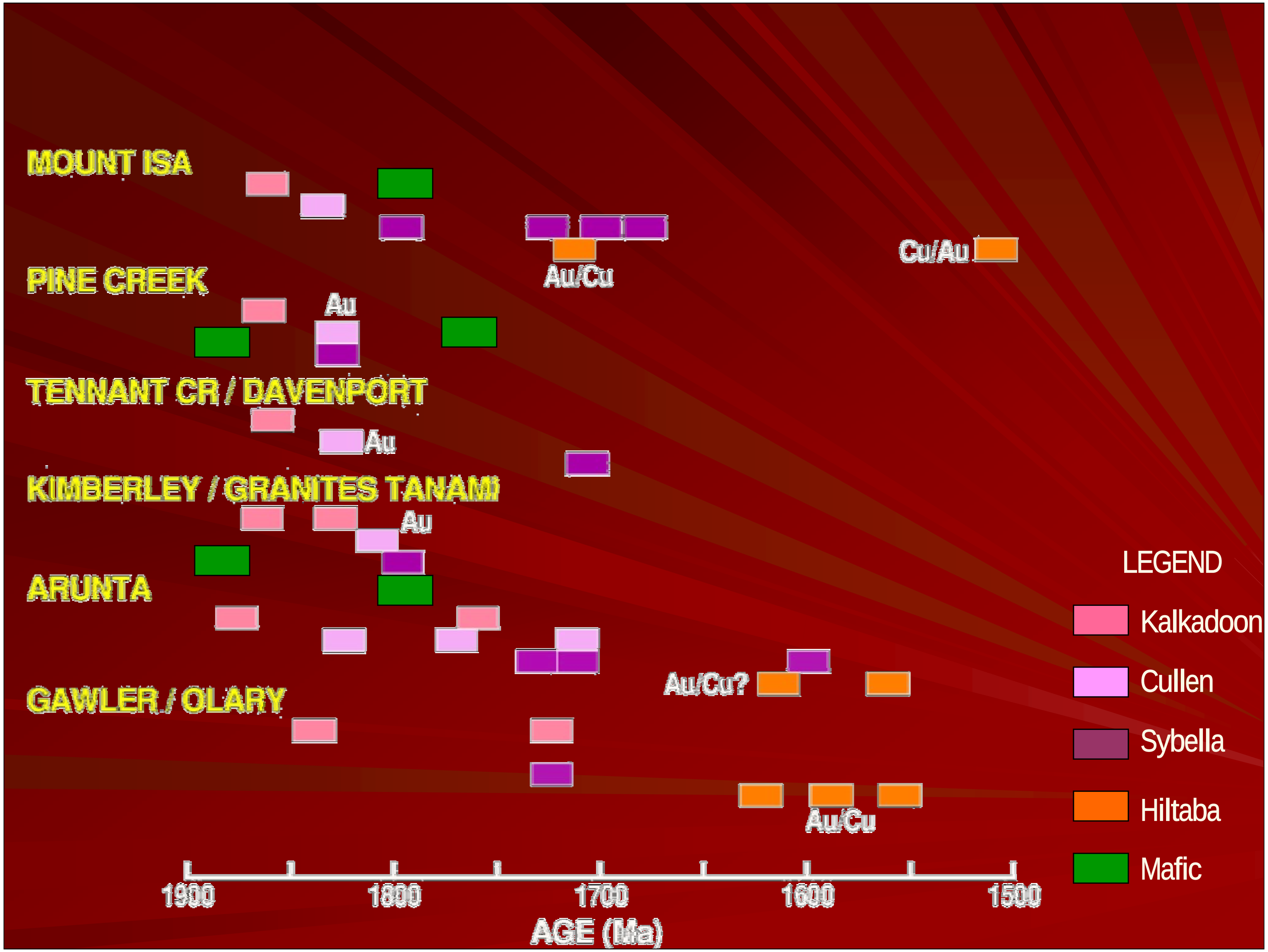
The Even Bigger Picture

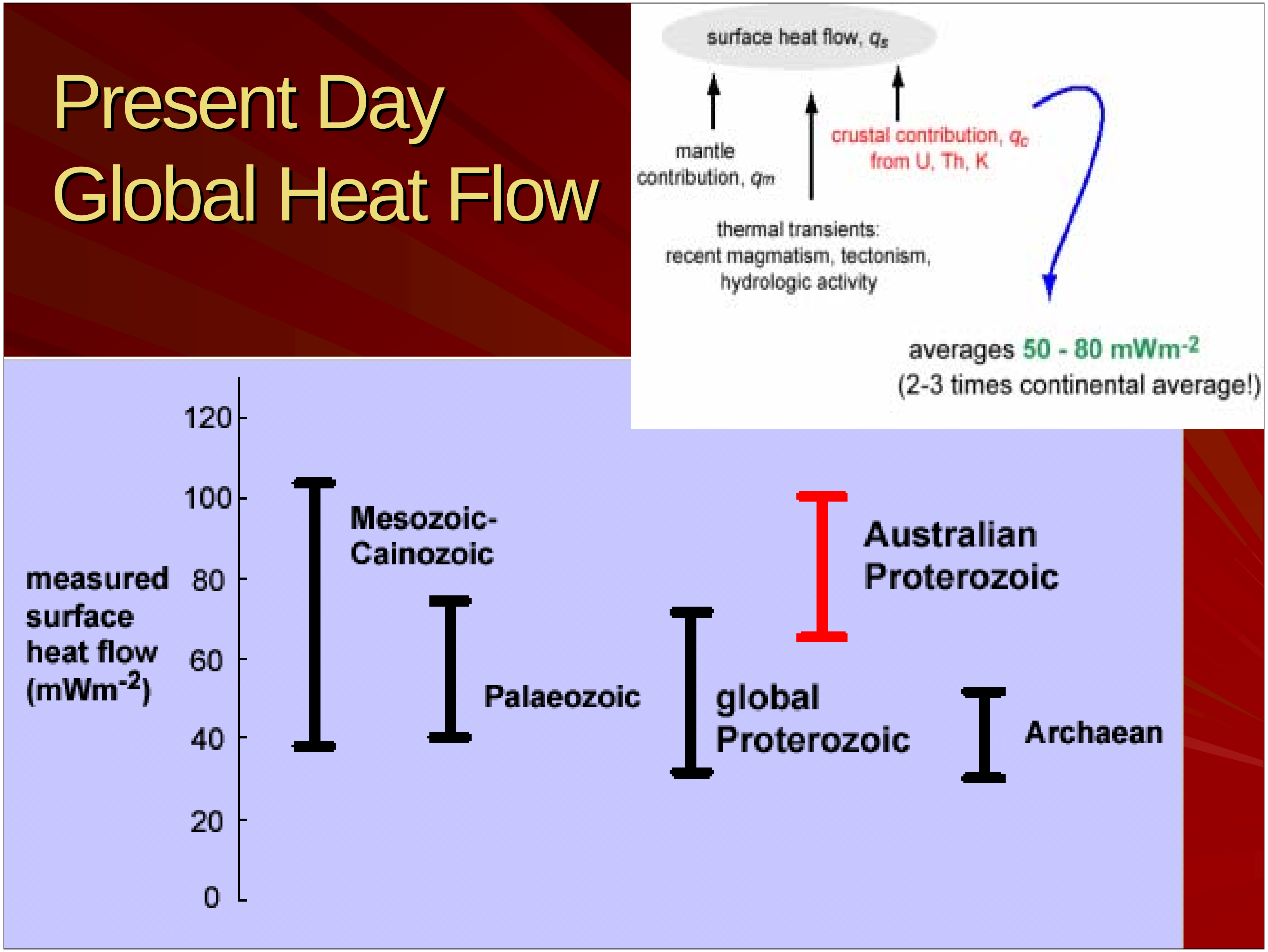

Archaean
Rb
SiO2
Proterozoic
Rb
SiO2
Palaeozoic
Rb
SiO2
Cenozoic
Rb
SiO2

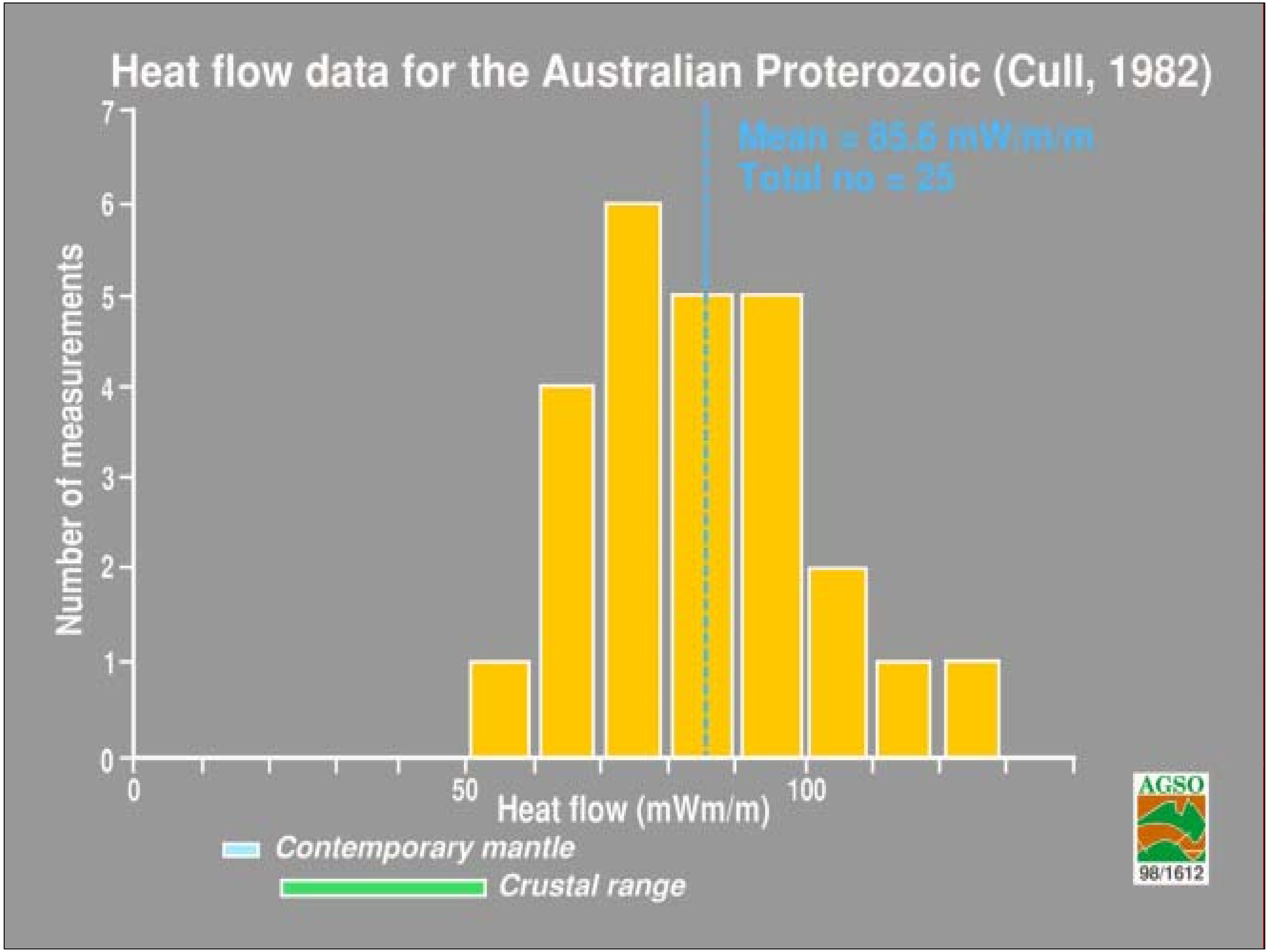

Archaean
Proterozoic
Palaeozoic
Cenozoic
U
U
U
U
80
60
40
20
80
60
40
20
80
60
40
20
80
60
40
20
50
60
70
80
50
60
70
80
50
60
70
80
50
60
70
80
SiO2
SiO2
SiO2
SiO2

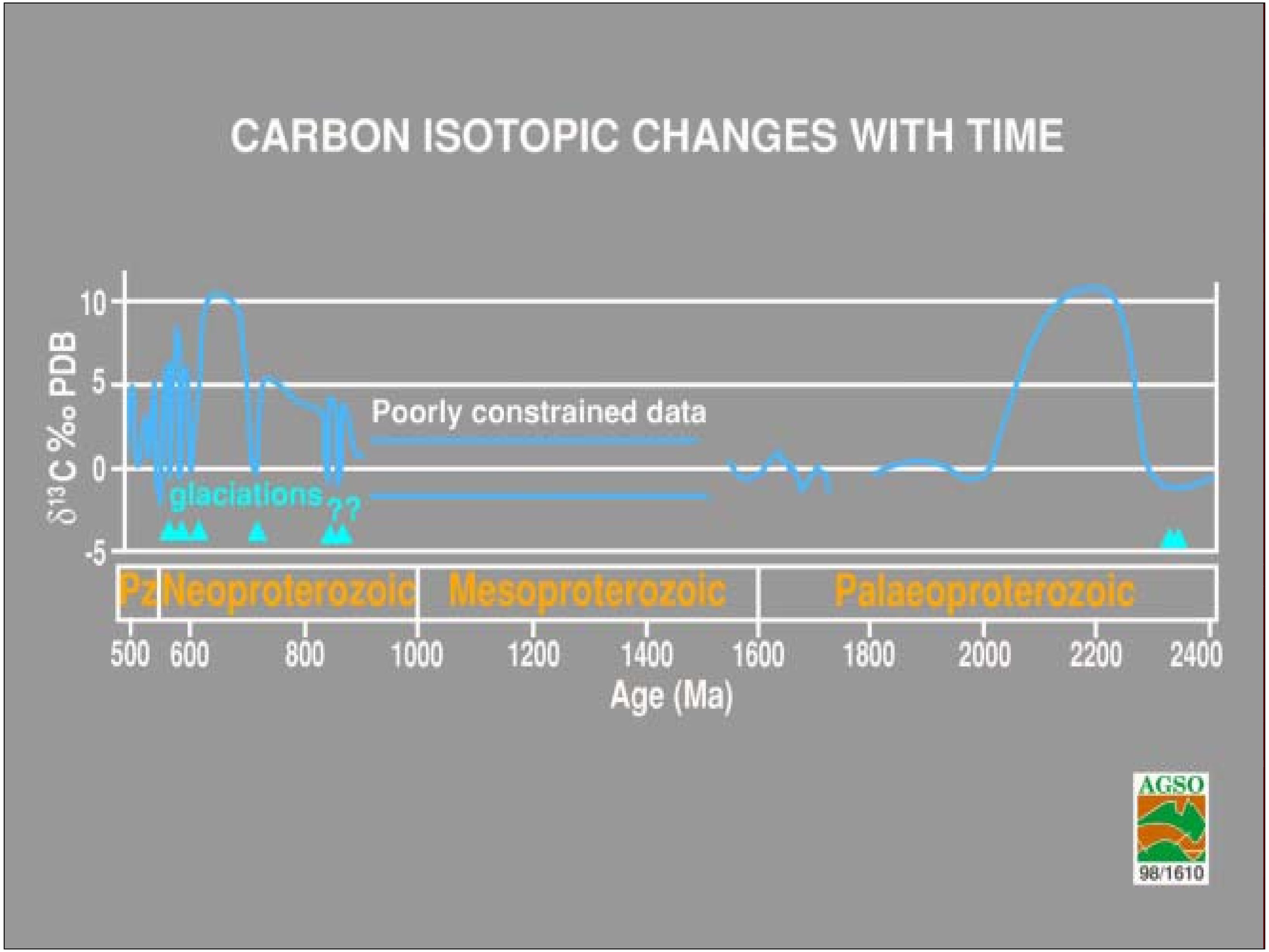

Archaean
Proterozoic
Palaeozoic
Cenozoic
Y
Sr
100
200
300
800

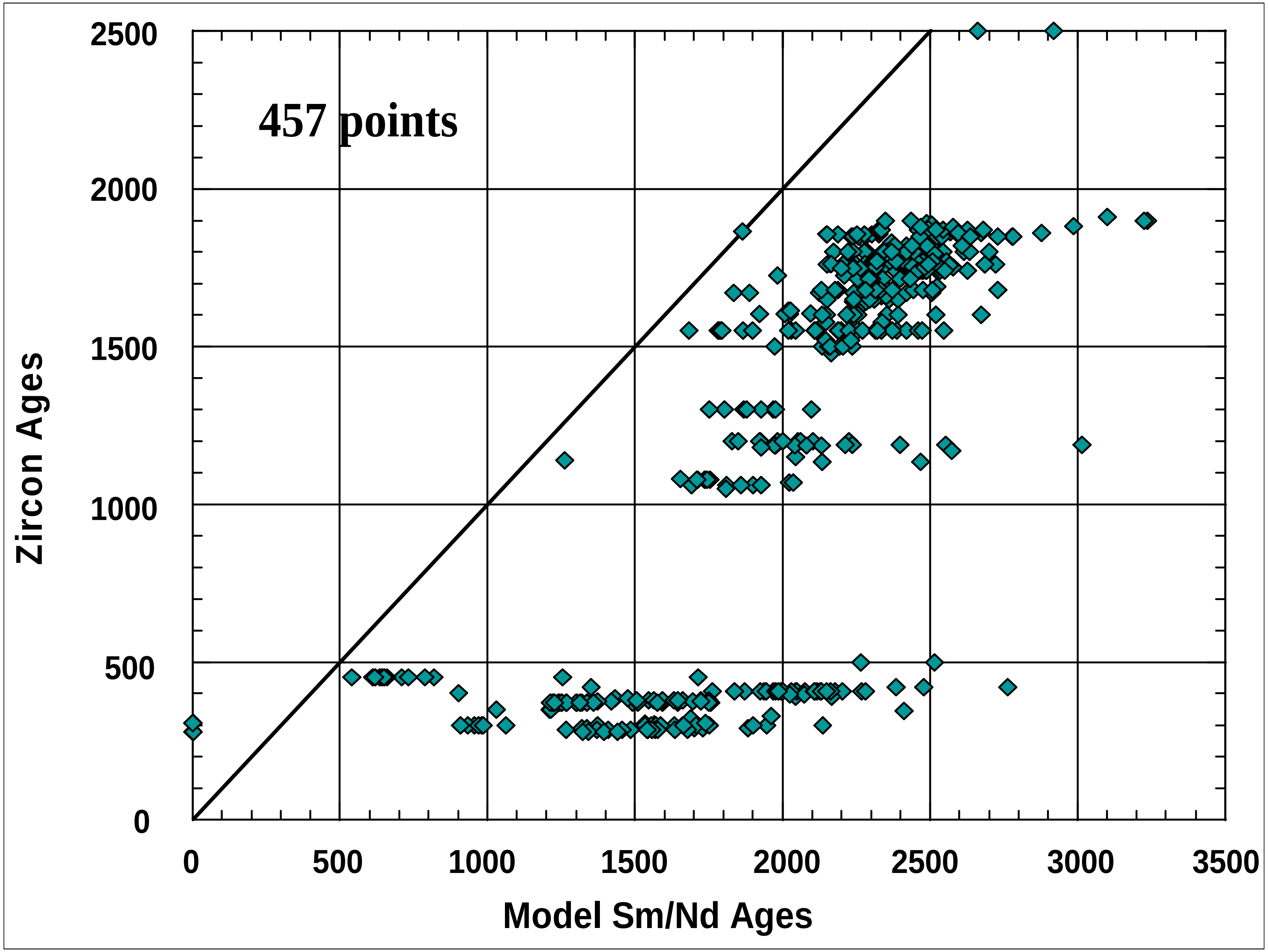
The Dream Time

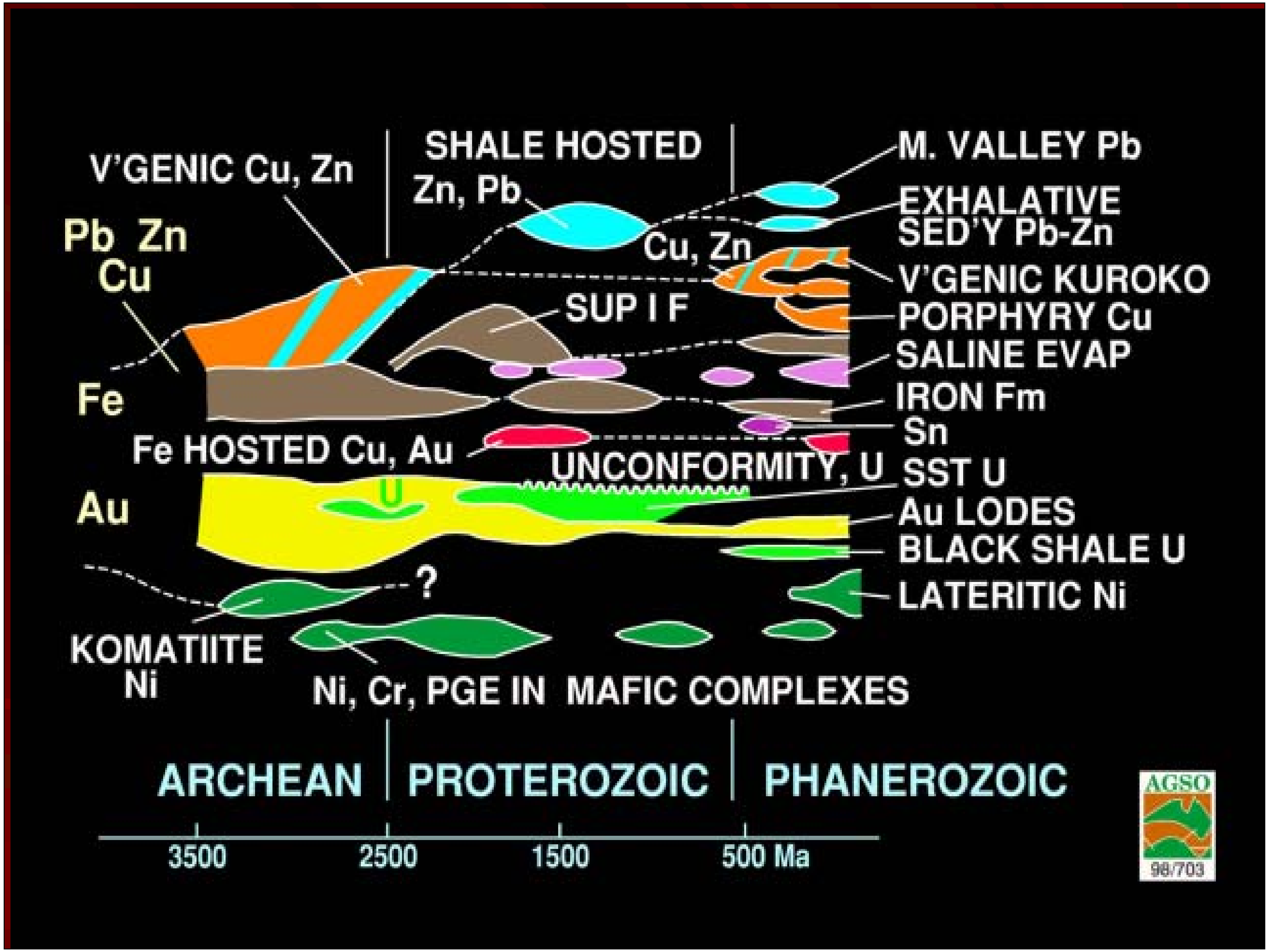

MOUNT ISA
Cu/Au
Au/Cu
PINE CREEK
Au
TENNANT CR / DAVENPORT
Au
KIMBERLEY / GRANITES TANAMI
Au
ARUNTA
Au/Cu?
GAWLER / OLARY
Au/Cu
1900
1800
1700
1600
1500
AGE (Ma)
LEGEND
Kalkadoon
Cullen
Sybella
Hiltaba
Mafic

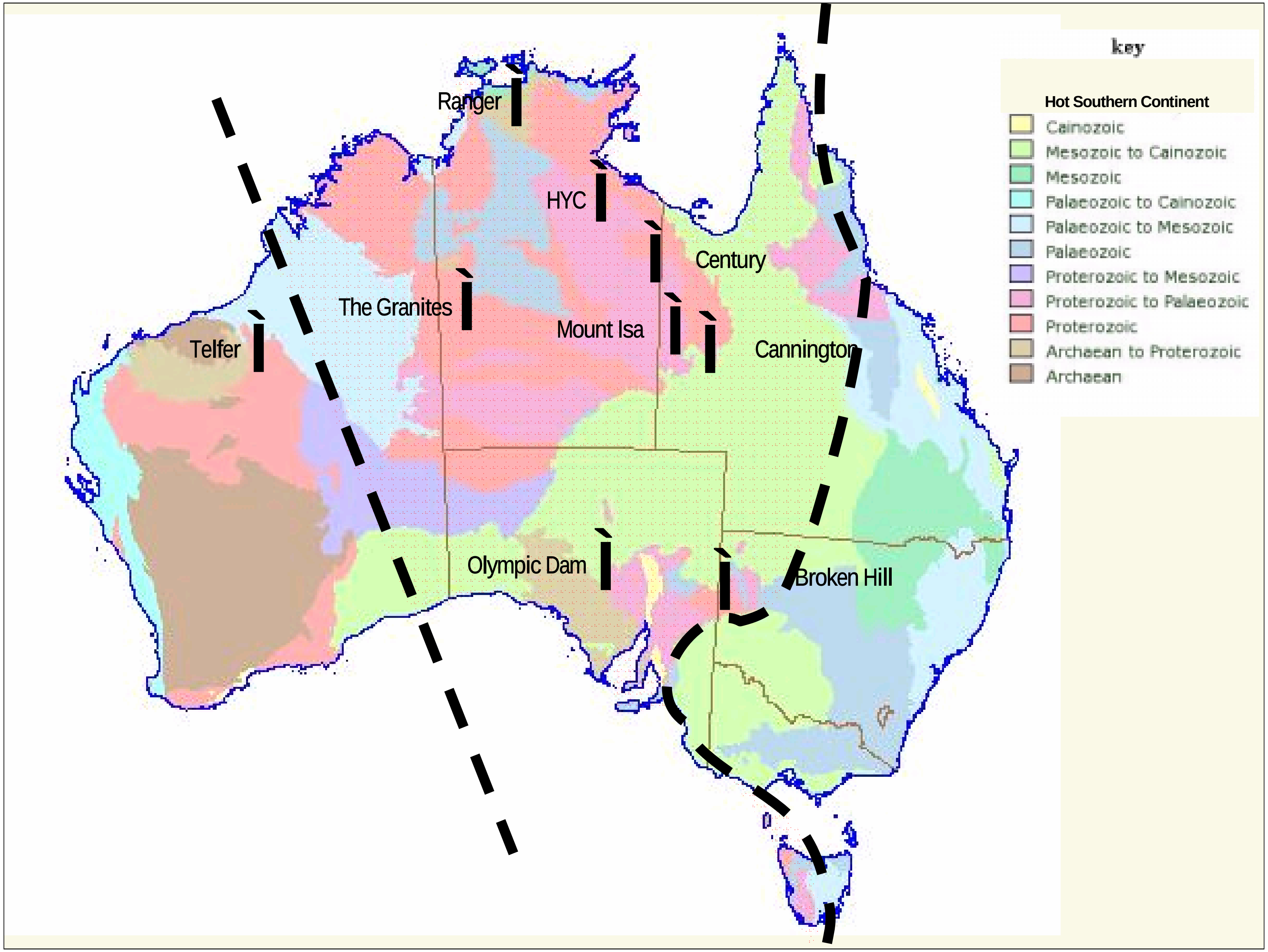

Present Day
Global Heat Flow
surface heat flow, q_s
mantle contribution, q_m
crustal contribution, q_c from U, Th, K
thermal transients: recent magmatism, tectonism, hydrologic activity
averages 50 - 80 mWm-2
(2-3 times continental average!)
measured surface heat flow (mWm-2)
120
100
80
60
40
20
0
Mesozoic-Cainozoic
Palaeozoic
global Proterozoic
Australian Proterozoic
Archaean


Heat flow data for the Australian Proterozoic (Cull, 1982)
Mean = 85.6 mW/m/m
Total no = 25
Number of measurements
0
1
2
3
4
5
6
7
0
50
100
Heat flow (mWm/m)
Contemporary mantle
Crustal range
AGSO
98/1612


CARBON ISOTOPIC CHANGES WITH TIME
δ13C ‰ PDB
10
5
0
-5
Poorly constrained data
glaciations
??
Pz
Neoproterozoic
Mesoproterozoic
Palaeoproterozoic
500
600
800
1000
1200
1400
1600
1800
2000
2200
2400
Age (Ma)
AGSO
98/1610


457 points
Zircon Ages
Model Sm/Nd Ages
0
500
1000
1500
2000
2500
3000
3500


V'GENIC Cu, Zn
SHALE HOSTED
Zn, Pb
M. VALLEY Pb
EXHALATIVE
SED'Y Pb-Zn
Pb Zn
Cu
Cu, Zn
V'GENIC KUROKO
SUP I F
PORPHYRY Cu
SALINE EVAP
Fe
IRON Fm
Sn
Fe HOSTED Cu, Au
UNCONFORMITY, U
SST U
Au
U
Au LODES
BLACK SHALE U
?
LATERITIC Ni
KOMATIITE
Ni
Ni, Cr, PGE IN MAFIC COMPLEXES
ARCHEAN
PROTEROZOIC
PHANEROZOIC
3500
2500
1500
500 Ma
AGSO
98/703


Ranger
HYC
Century
The Granites
Mount Isa
Telfer
Cannington
Olympic Dam
Broken Hill
key
Hot Southern Continent
Cainozoic
Mesozoic to Cainozoic
Mesozoic
Palaeozoic to Cainozoic
Palaeozoic to Mesozoic
Palaeozoic
Proterozoic to Mesozoic
Proterozoic to Palaeozoic
Proterozoic
Archaean to Proterozoic
Archaean

Key Points

- The Proterozoic is compositionally unique in time
- Proterozoic Granite Systematics are the same as other era’s
- Dominance of granites of the type that one would expect from high geothermal gradients
- Metalogenically important granites are all high temperature granites