

METALLOGENY OF GRANITIC ROCKS

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Empirical and theoretical evidence support a strong correlation between the compositional character of granites and ore element associations in related mineralisation (Blevin and Chappell; 1992, 1995). Cu(-Au) is associated with the more mafic end of the granite spectrum, W with intermediate compositional ranges, and Mo (\pm W) and Sn (\pm W) with felsic, fractionated granites. The oxidation state of granites is also critical, with Cu-Au-Mo associated with oxidised rocks and Sn with reduced rocks. W is associated with both series but is best developed in intermediate to relatively reduced granite suites.

Important Metallogenic Parameters

Parameters that are most important in determining the overall metallogenic “flavour” of intrusive igneous suites comprise: Granite Type, Compositional Evolution, Degree of Fractionation, and Oxidation State.

Granite type

Classification according to broad compositional character (I, S, A, metaluminous, peraluminous and peralkaline) is important as a guide to the abundance of elements and volatiles in the granites, and their behaviour during fractionation processes. Granophile elements are associated with silica-rich granites while Cu tend to be associated with granite of more intermediate silica contents. Peralkaline granites tend to be strongly compositionally evolved and high in Ta, Nb, Zr and related elements. Provinces with silica distributions skewed to high values are typically associated with Sn, Mo, U and related Au mineralisation, while those skewed to intermediate or lower SiO₂ values are more typically associated with Cu. Potassium and total alkali contents provide useful information on the petrographic character of granite suites.

Degree of Compositional Evolution

A granite can be thought of as being compositionally evolved if its chemistry is no longer compatible with direct derivation from mantle materials. Three stages of this evolutionary series can be recognised conceptually. First generation or primary granites those directly derived from mantle materials. They typically comprise oceanic plagiogranites and tonalitic rocks in primitive island arc settings. Second “generation” granites are derived via remelting or remagmatism of mantle derived rocks and their related materials. They are typically located in continental margin arc settings. These are the “I-tonalites” of Chappell and Stephens (1988) or Andean type of Pitcher (1982). Third cycle granites are the products of the fusion of these materials and their associated rocks within the crust. They are also termed I-granodiorites by Chappell and Stephens (1988) or Caledonian type by Pitcher (1982). In addition to these are the S-type granites, derived from metasedimentary material in the crust.

There is no inbuilt chemical or isotopic counter that can be used to measure evolutionary progress away from mantle compositions. As metallogenic associations depend on the compositional character of granites, ratios such as the Rb/Sr and K/Rb ratios are useful for this purpose although it must be emphasised that there are many processes that affect the behaviour of these elements. The K/Rb ratio is particularly useful in this regard. There is a progressive decrease in K/Rb values with granite evolution and this correlates in a crude way with the evolutionary progress of granites mentioned above (Fig.1). There are many notable

exceptions however (adakites, Archaean granites, igneous rocks derived from metasomatised sources etc).

Degree Of Fractionation

The degree and type of fractionation is important in determining both the potential for mineralisation and the type of mineralisation with which a granite suite is associated. Fractional crystallisation can be measured in many ways: use of compatible/incompatible element ratios (eg. Rb/Sr ratio) and the behaviour of selected trace elements that indicate the incoming or outgoing of crystallising phases (eg, inflections in Ti, Mg, Ca, Ba, Zr, Y etc). K/Rb ratios are also useful in highly fractionated melts near of at the minimum, which can show a steep decrease in the K/Rb ratio. Suites that show classic petrographic and compositional behaviour consistent with the processes of fractional crystallisation are also those suites most commonly associated with significant mineralisation.

Oxidation State

The relative oxidation state of magmas is of paramount importance in controlling the compatible/incompatible nature of many ore elements. The division of granites into ilmenite- and magnetite-series is very useful because Cu, Mo and Au deposits are typically related to magnetite-bearing (magnetite-series) granites and Sn (\pm W) deposits with magnetite-free (ilmenite-series) granites (Ishihara, 1981). Oxidation state is largely inherited from source although the effects of wall rock interaction can be locally important. There is a general trend to lower relative oxidation state in granites from arc settings through continental margin settings to those of continental interiors. S-types are almost invariably reduced.

Classification of oxidation state can be made using petrographic and mineralogical criteria, whole rock $\text{Fe}_2\text{O}_3/\text{FeO}$ ratios, and geophysical methods. Correlation of these parameters has allowed the development of a classification scheme based on whole rock $\text{Fe}_2\text{O}_3/\text{FeO}$ and FeO^* (total Fe). An oxidation parameter (ΔOx) has been introduced and can be determined from the following relationship:

$$\Delta\text{Ox} = \log_{10}(\text{Fe}_2\text{O}_3/\text{FeO}) + 0.3 + 0.03*\text{FeO}^*$$

where $\text{FeO}^* = (0.9*\text{Fe}_2\text{O}_3) + \text{FeO}$, and Fe_2O_3 , FeO and FeO^* are in weight percent.

Five oxidation classes are recognised (Fig. 2): very strongly, strongly and moderately oxidised; and moderately and strongly reduced. Very felsic granites usually have exaggerated $\text{Fe}_2\text{O}_3/\text{FeO}$ ratios or a susceptible to alteration effects and other methods need to be employed. Peralkaline granites behave differently because of compositional and melt structure considerations that result in high $\text{Fe}_2\text{O}_3/\text{FeO}$ ratios, and need to be treated differently. Rocks belonging to each of these divisions can be characterised by distinctive petrographic and mineralogical features, although *Very Strongly Oxidised* rocks are very rare. *Strongly Oxidised* rocks have abundant magnetite in addition to titanite, and high Mg biotite. Igneous suites associated with economic porphyry Cu-Au systems typically lie in the *Strongly Oxidised* field and have ΔOx values ranging from 0.5 to 0.8.

Metal Zonation and igneous metallogenic provinces.

The combination of the parameters used above, and the areal extent of suites having those features can be used on a district to regional scale to interpret relationships between igneous rocks and ore deposits. Deposit zoning and mineral occurrence data can also be used as a key input in recognising magmatic-hydrothermal “districts”. The most intrusion-proximal, high temperature metal association within these districts is defined as the “core metal association” (Fig. 3). Five such core metal associations (Cu-Au, Cu-Mo, Mo, W-Mo-Bi, Sn-W) are

recognised and relate back in a systematic way to compositional features of the related igneous suites. Gold is associated with all these core metal associations. The location of economic gold mineralisation within these hydrothermal systems changes from proximal in Cu-Au centred systems (e.g. Cadia, Australia), to the more distal base-metal zone in W-Mo-Bi centred systems (e.g. Kidston, Australia).

Such an approach has a predictive capacity in being able to recognise potential for particular metallic element associations in poorly explored igneous domains, and by reinterpreting under-explored hydrothermal systems through the use of metal zoning patterns.

References

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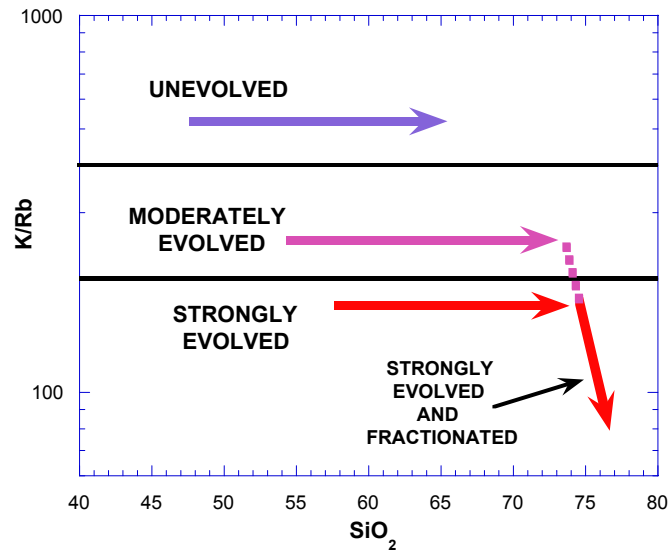


Fig 1 K/Rb classification scheme showing classification fields and typical trends.

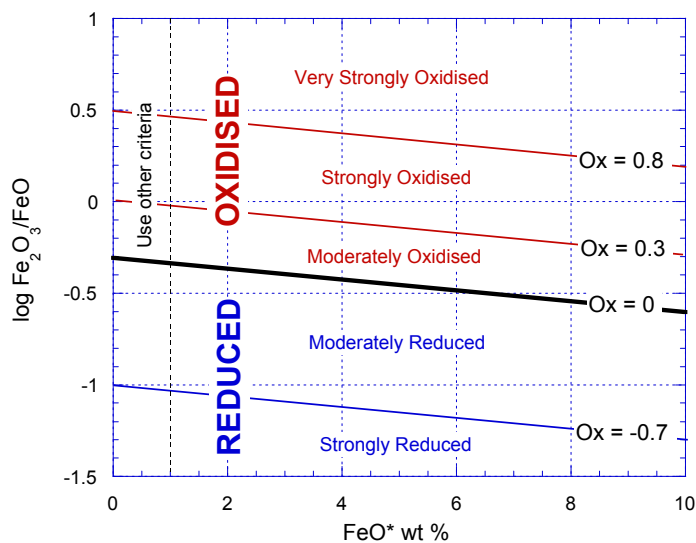


Fig. 2. Redox classification scheme for igneous rocks. FeO* refers to all Fe in the sample reported as FeO. Ox values refer to Δ Ox values as defined in the text.

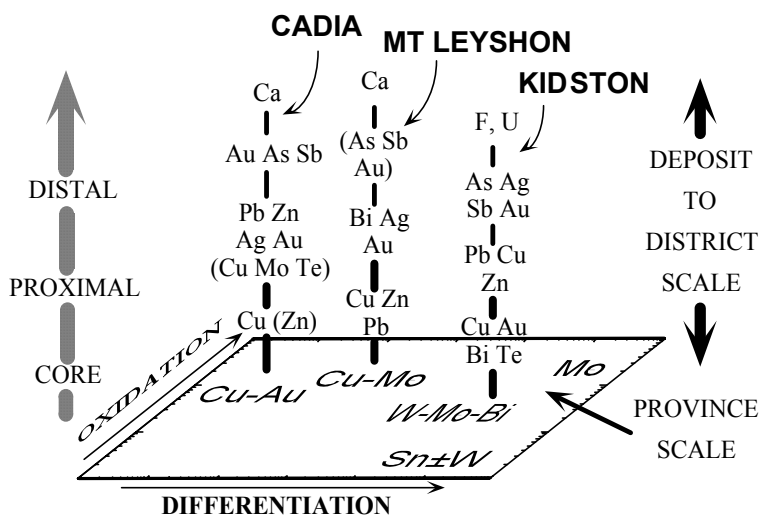


Fig. 3: Conceptual diagram illustrating relationships between metal zonation at the deposit or district scale and how it relates back to higher-temperature proximal igneous-centred systems (Cu-Au, Cu-Mo, W-Mo, Sn-W, Mo). These correspond to the main porphyry deposit types.

**METALLOGENY
OF
GRANITES**

Phil Blevin

ISHIHARA SYMPOSIUM

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The Scheme

- Ore associations are related to magmatic compositions and variables.
 - Cu-Au is associated with relatively unevolved, oxidised magmas
 - Mo with highly fractionated, oxidised magmas
 - Sn with highly fractionated reduced magmas
- Deposits change from chalcophile to granophile/lithophile as magmas become more evolved.

Important Variables

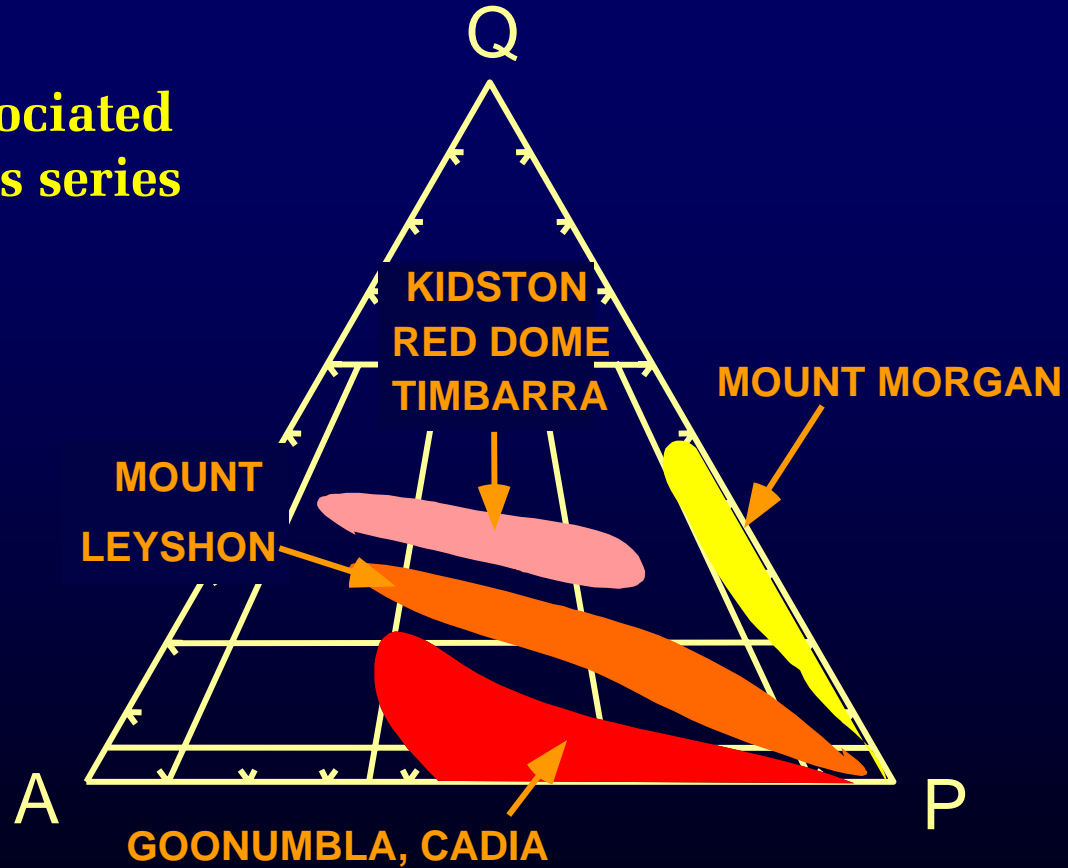
- Compositional type (I, S etc).
- Differentiation mechanism.
- Degree of compositional evolution.
- Oxidation state.
- Physical parameters:
 - Level of emplacement, etc

This scheme assigns metallogenic associations to granites.

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Modal QAP Classification

**Au-associated
igneous series**



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Granite Classification

Bulk compositional character -

Peraluminous = $Al > (Ca + Na + K)$ = S-types

Cordierite, primary muscovite, garnet

P behaviour

Metaluminous = $Al < (Ca + Na + K)$ = I-types

amphibole

Peralkaline = $(Na + K) > Al$

alkali minerals, hypersolvus feldspars

A-type = high temperature I-types, high Zr, Fe.

- Tholeiitic vs calc alkaline.
- Problems of I-S-A scheme with other granites, eg. Proterozoic granites (high Zr, Na etc), peralkaline.

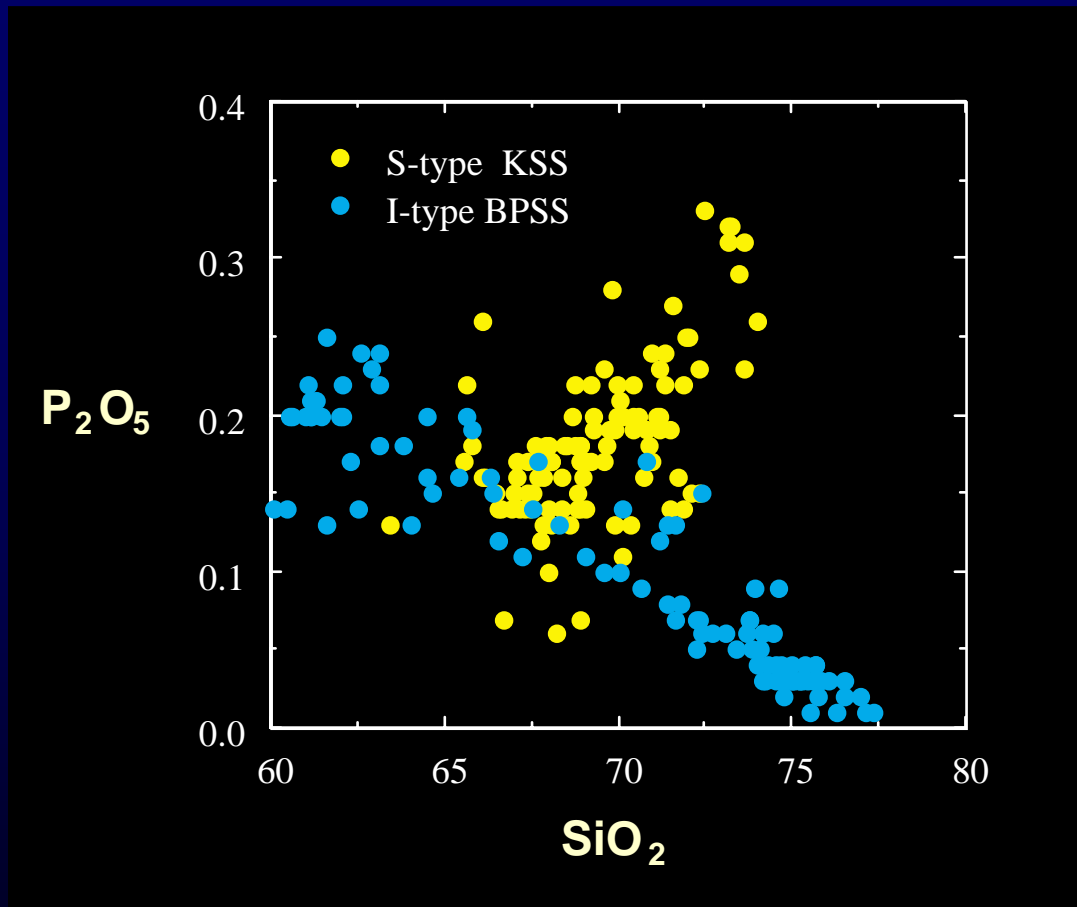
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A Classification of Granitoid Rocks Based on Tectonic Setting. After Pitcher (1983) in K. J. Hsü (ed.), *Mountain Building Processes*, Academic Press, London; Pitcher (1993), *The Nature and Origin of Granite*, Blackie, London; and Barbarin (1990) *Geol. Journal*, 25, 227-238. Winter (2001) *An Introduction to Igneous and Metamorphic Petrology*. Prentice Hall.

Table 18-4. A classification of granitoid rocks based on tectonic setting

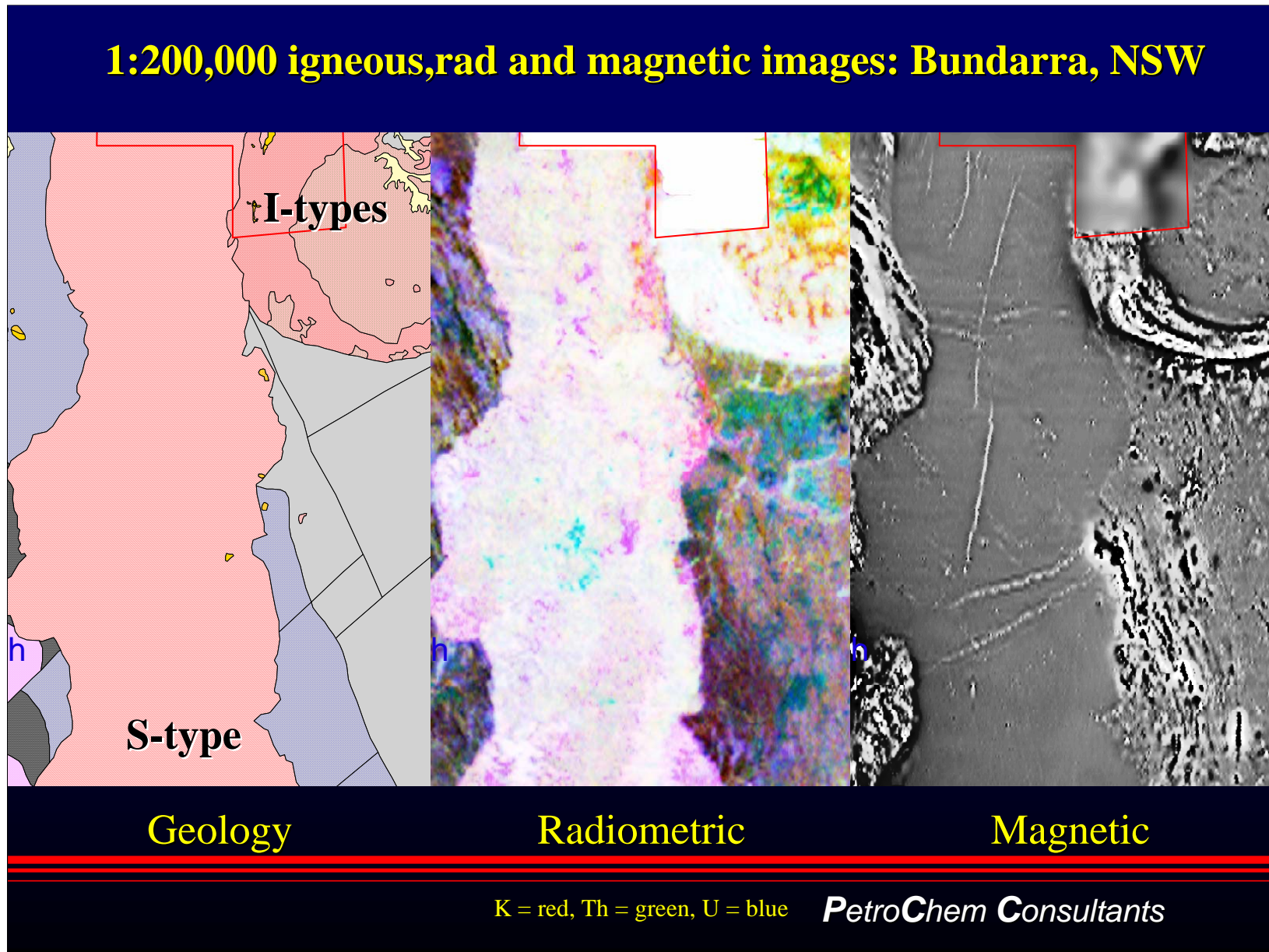
	OROGENIC			TRANSITIONAL	ANOROGENIC	
	Oceanic Island Arc	Continental Arc	Continental Collision	Post-Orogenic Uplift/Collapse	Continental Rifting, Hot Spot	Mid-Ocean Ridge, Ocean Islands
Examples	Bougainville, Solomon Islands, Papua New Guinea	Mesozoic Cordilleran batholiths of west Americas, Gander Terrane	Manaslu and Lhotse of Nepal, American Massif of Brittany	Late Caledonian Plutons of Britain, Basin and Range, late Variscan, early Northern Proterozoic	Nigerian ring complexes, Oslo rift, British Tertiary Igneous Province, Yellowstone hotspot	Oman and Troodos ophiolites; Iceland, Ascension, and Reunion Island intrusives
Geo-chemistry	Calc-alkaline > thol. M-type & I-M hybrid Metaluminous	Calc-alkaline I-type > S-type Met-Al to sl. Per-Al	Calc-alkaline S-type Peraluminous	Calc-alkaline I-type S-type (A-type) Metalum. to Peralum	Alkaline A-type Peralkaline	Tholeiitic M-type Metaluminous
Rock types	qtz-diorite in mature arcs	tonalite & granodior. > granite or gabbro	migmatites & leucogranite	bimodal granodiorite + diorite-gabbro	Granite, syenite + diorite-gabbro.	Plagiogranite
Associated Minerals	Hbl > Bt	Hbl, Bt	Bt, Ms, Hbl, Grt, Als, Crd	Hbl > Bt	Hbl, Bt, aegirine fayalite, Rbk, arfved.	Hbl
Associated Volcanism	Island-arc basalt to andesite	Andesite and dacite in great volume	often lacking	basalt and rhyolite	alkali lavas, tuffs, and caldera infill	MORB and ocean island basalt
Classification	Barbarin (1990) T_{IA} tholeiite island arc	H_{CA} hybrid calc-alkaline	$C_{ST} C_{CA} C_{CI}$ continental types	H_{LO} hybrid late orogenic	A alkaline	T_{OR} tholeiite ocean ridge
Pearce et al. (1984)	VAG (volcanic arc granites)		COLG (collision granites)		WPG and ORG (within plate and ocean ridge granites)	
Maniar & Piccoli (1989)	IAG island arc granite	CAG contin. arc granite	CCG cont. collision gran.	POG post-orogenic gran.	RRG CEUG rift & aborted/hotspot	OP ocean plagiogranite
Origin	Partial melting of mantle-derived mafic underplate	PM of mantle-derived mafic underplate + crustal contribution	Partial melting of recycled crustal material	Partial melting of lower crust+ mantle and mid-crust contrib	Partial melting of mantle and/or lower crust (anhydrous)	Partial melting of mantle and fractional crystallization
Melting Mechanism	Subduction energy: transfer of fluids and dissolved species from slab to wedge. Melting of wedge, transfer of heat upward		Tectonic thickening plus radiogenic crustal heat	Crustal heat plus mantle heat (rising asthen. + magmas)	Hot spot and/or adiabatic mantle rise	

After Pitcher (1983, 1993), Barbarin (1990)



Behaviour of P in peraluminous versus metaluminous suite

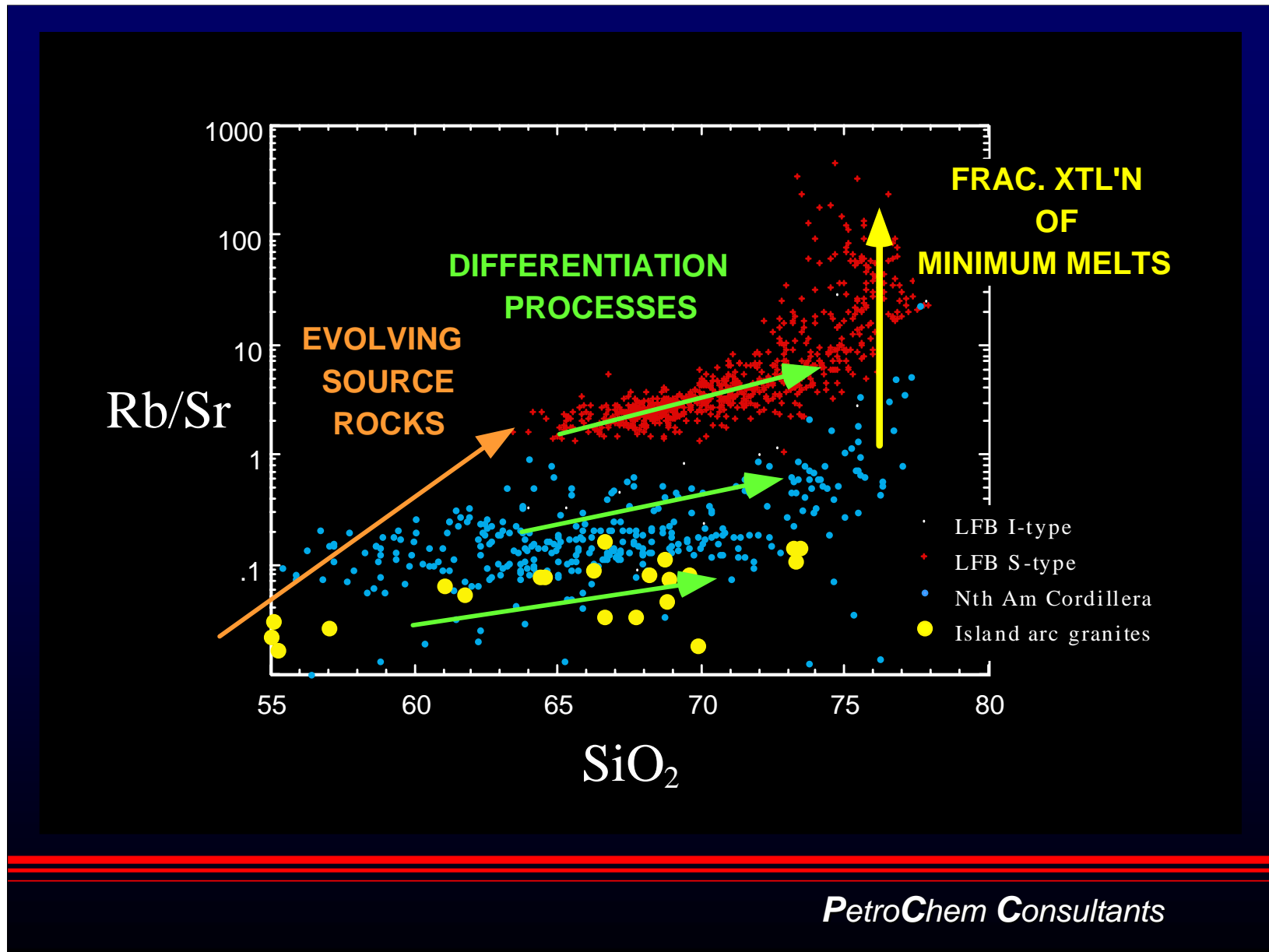
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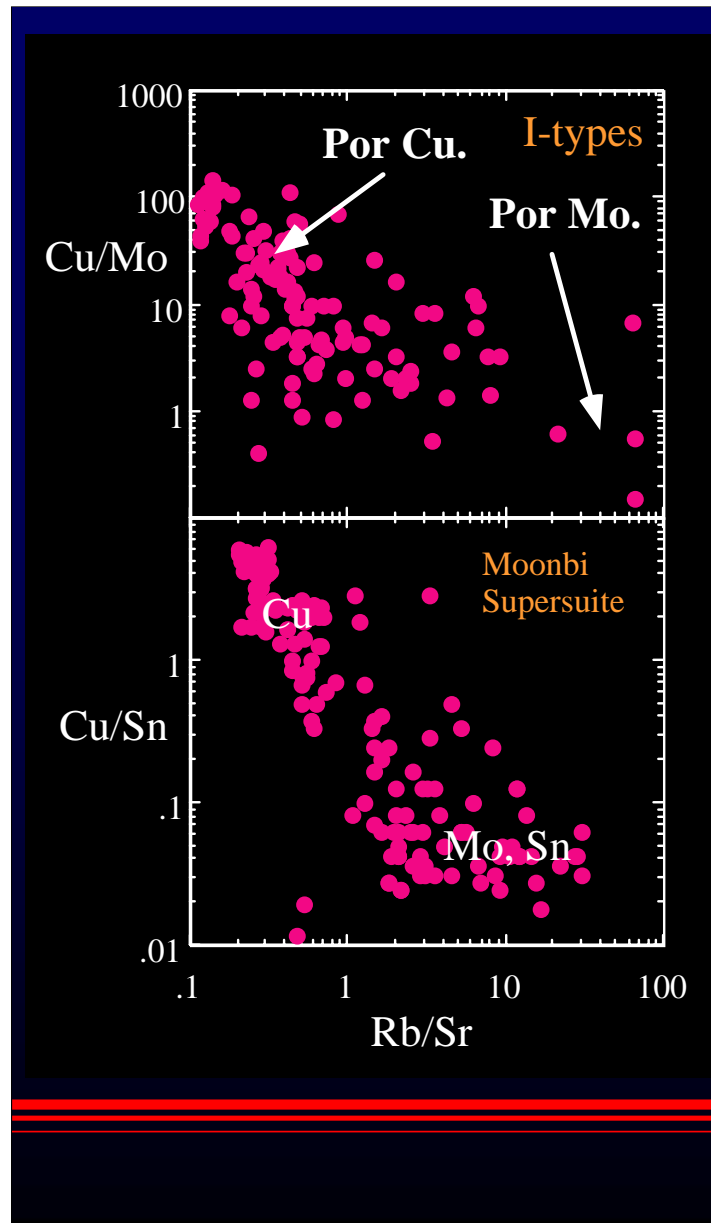
Differentiation Mechanisms

- Granite suites that show strong fractional crystallisation trends are those that tend to be mineralised.
- Can be measured using Rb, Sr and Ba.
- Fractionation concentrates incompatible elements, removes compatible elements.
- Ore element compatibility depends on oxidation state, mineralogy

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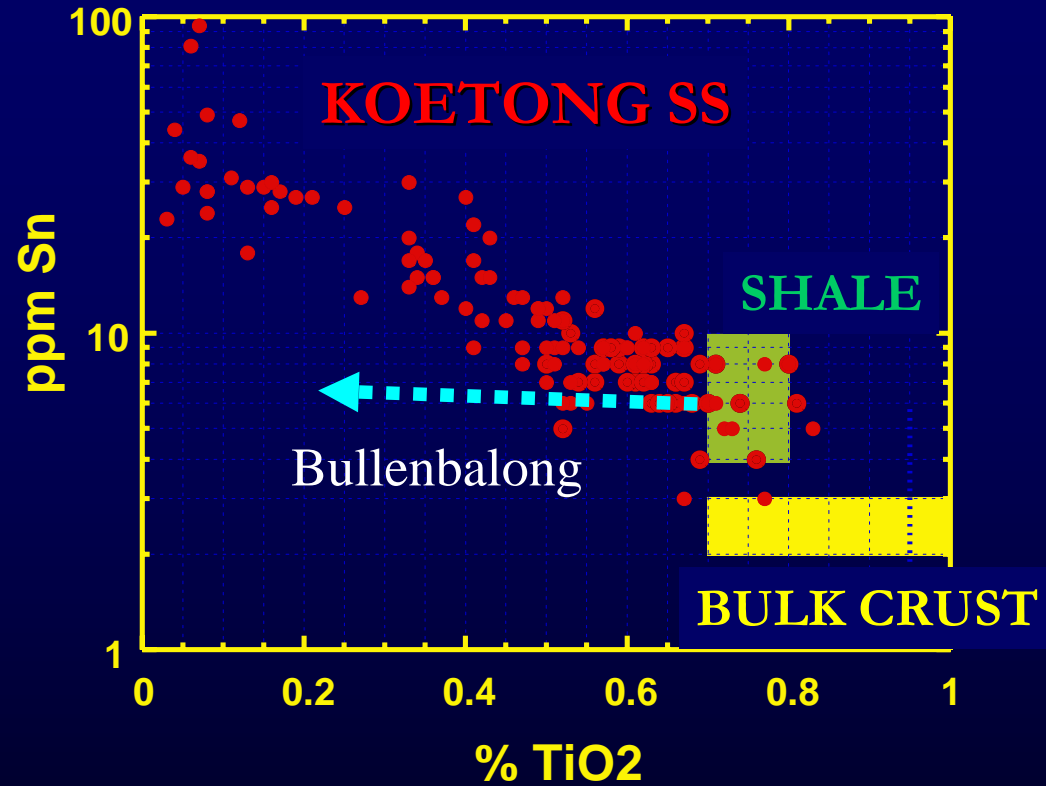
Magmatic Control on Metallogeny

Relative metal abundances in magmas are a function of compositional evolution, fractionation and oxidation state.

Cu-Au deposits are associated with oxidized, relatively unevolved suites.

Igneous metallogeny of Au is more complex, and is independent of Cu.

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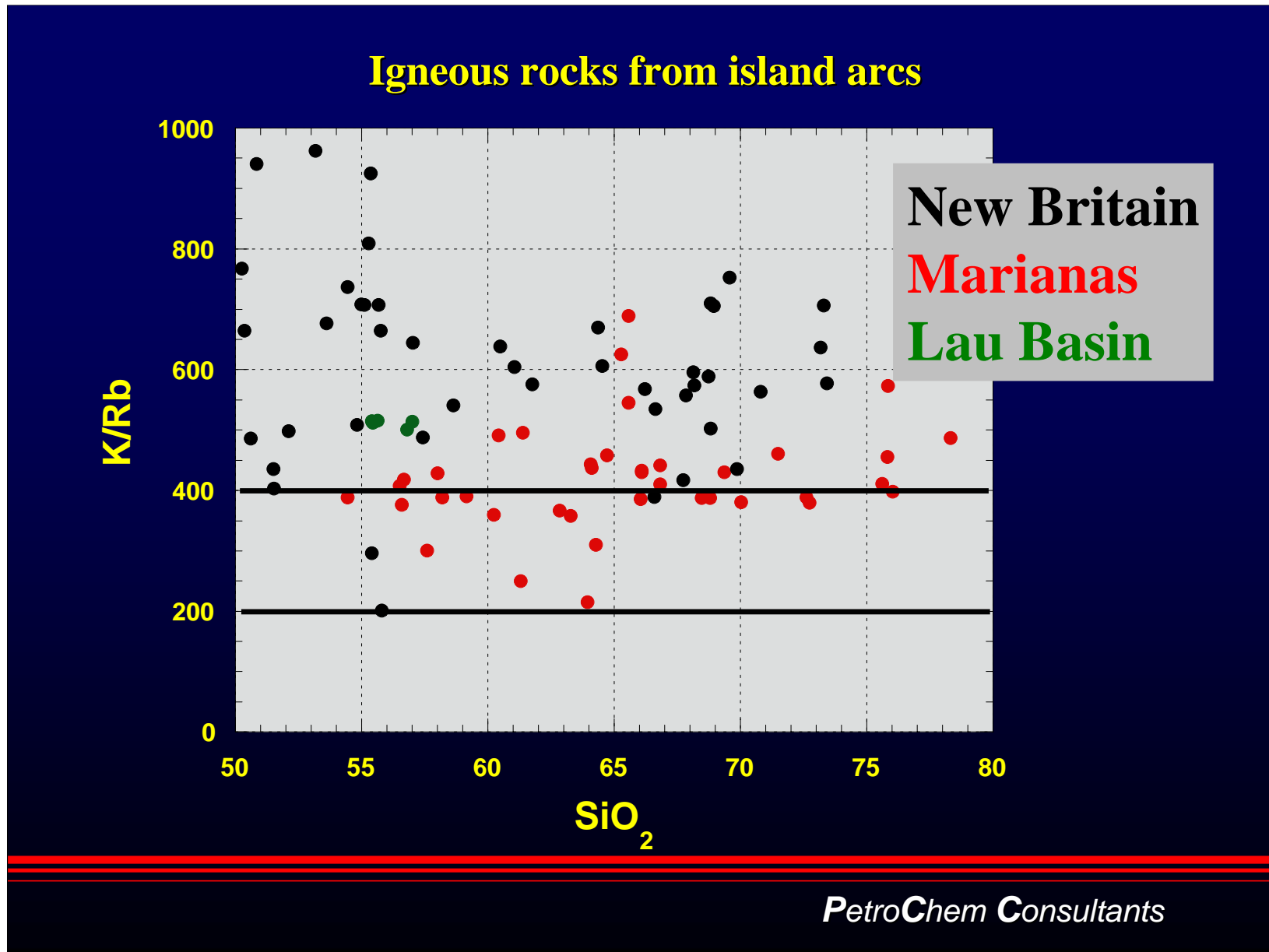


Sn is concentrated in this reduced supersuite because it is incompatible

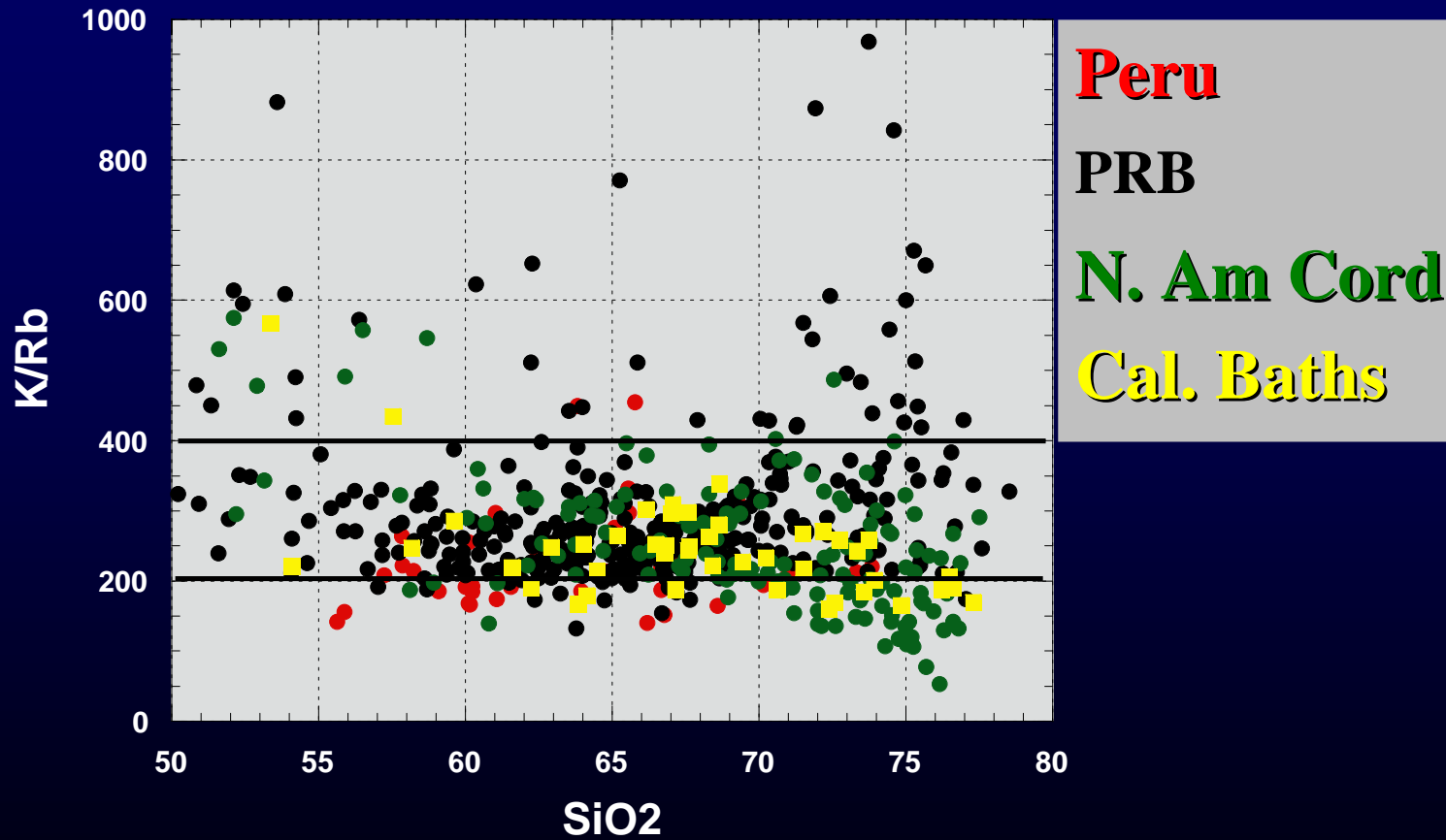
Degree of Evolution

- D. of E. relates to how evolved the magma is away from mantle compatible compositions.
- A trend from M-types, through I-tonalites, I-granodiorites, primary/secondary/tertiary, Oceanic/Cordilleran/Caledonian
- Correlates strongly with metal associations (chalcophile/siderophile to lithophile).
- Rb/Sr, K/Rb can be used with care.
- There is not simple monitor of granite evolution.

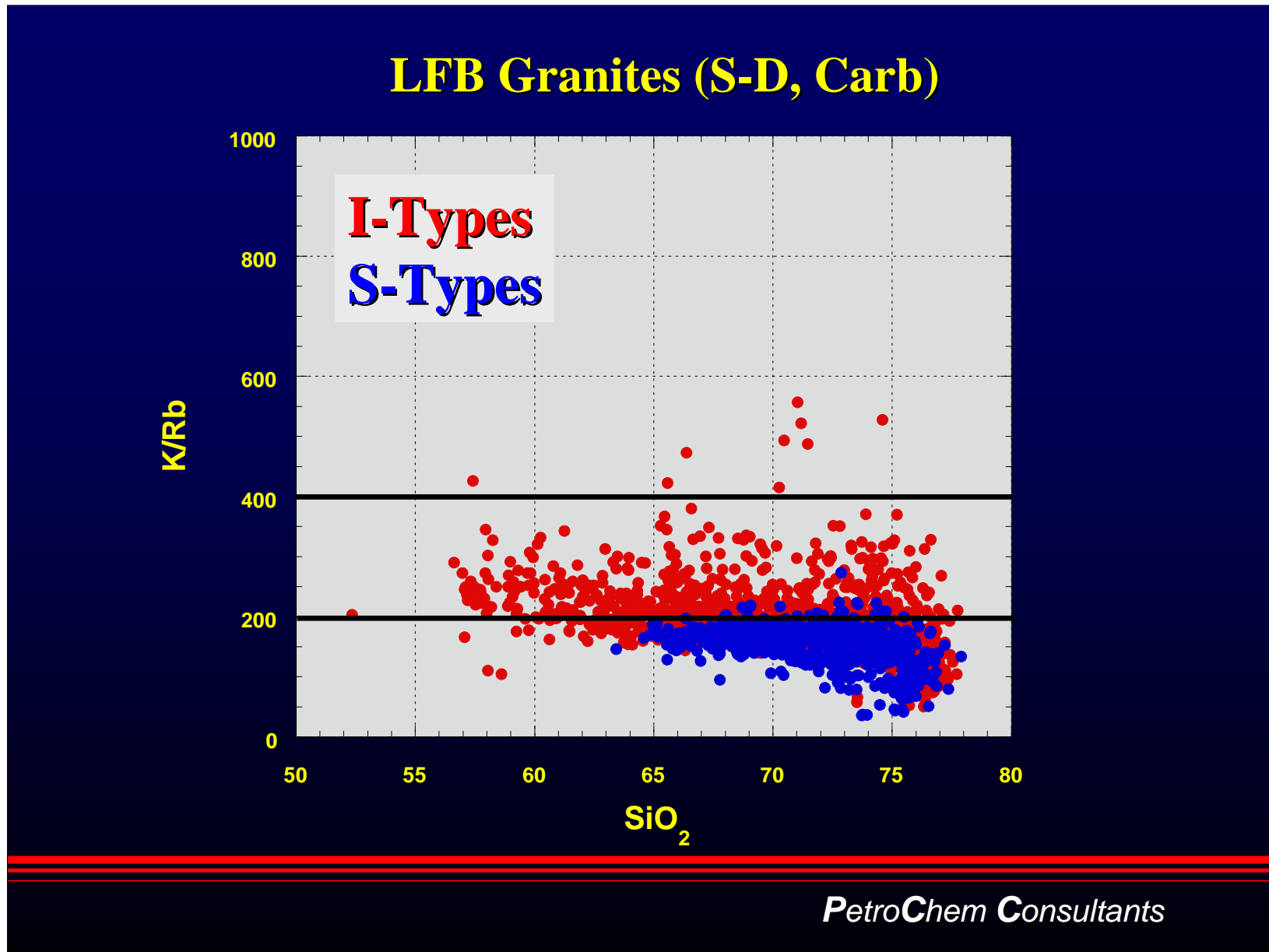
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Granites from Continental Margins

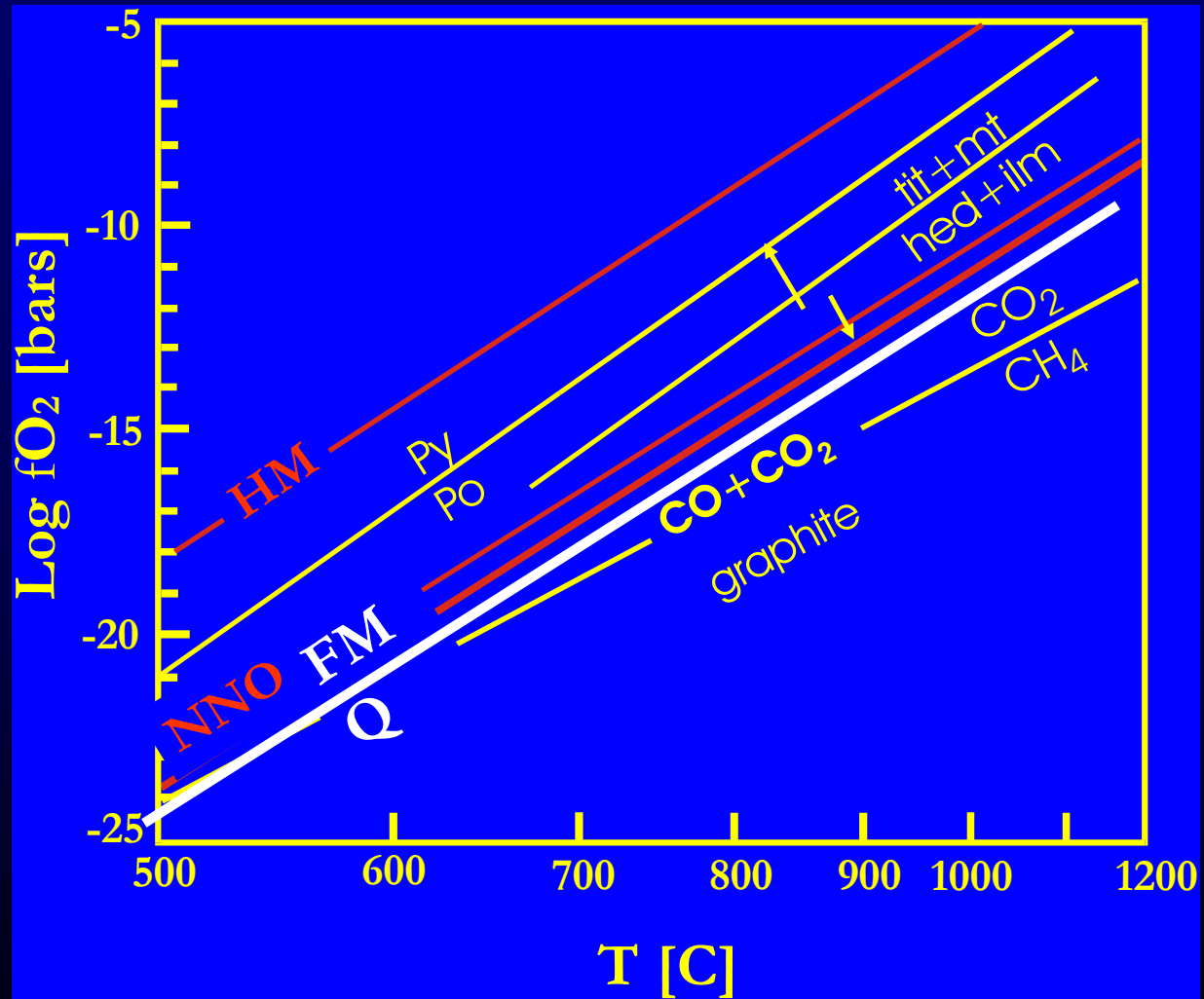


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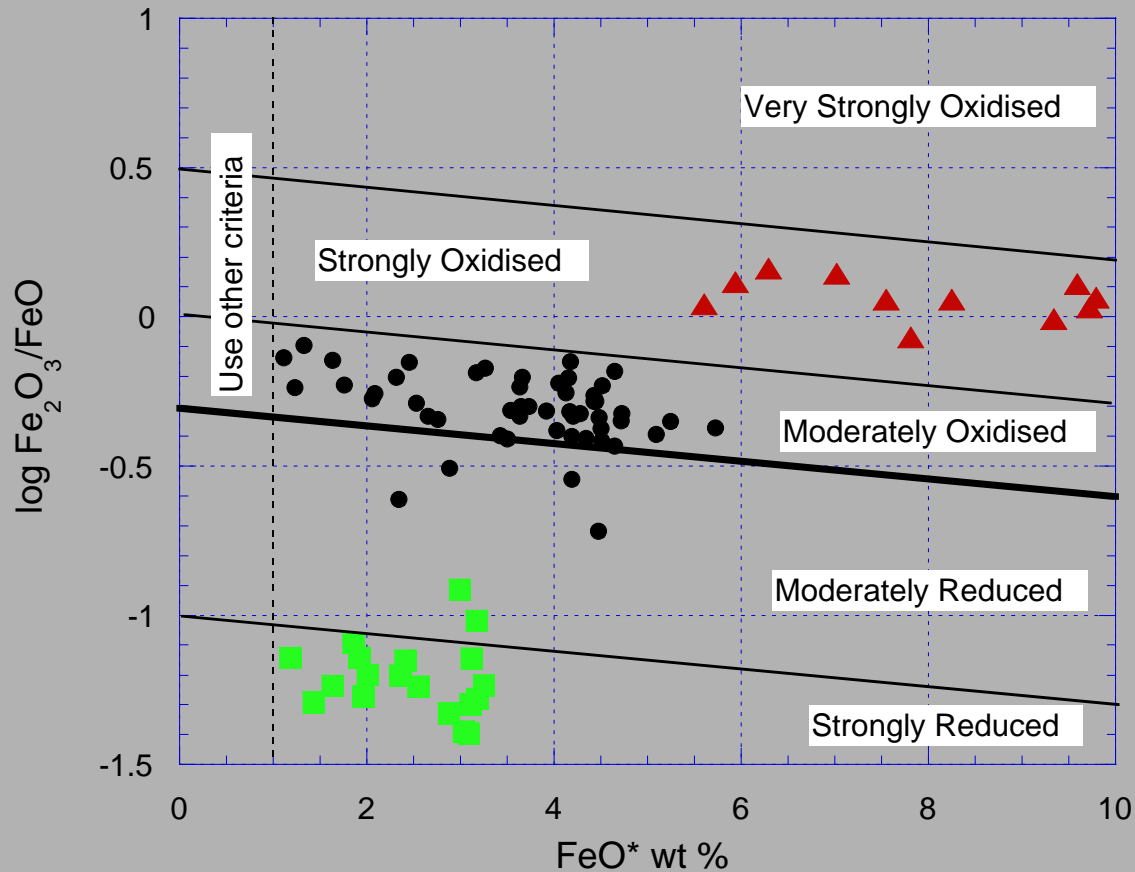
Oxidation State

- fO_2 is a measure of the chemical potential of O within a chemical system.
- The main indicator of fO_2 in magmas is the oxidation state of Fe. Fe^{2+} is accommodated in ilmenite ($FeTiO_3$) and Fe-Mg silicates, Fe^{3+} mainly in magnetite.
- Other elements in magmas also have multiple oxidation states: Mn, Ti, V, Eu, Ce. Importantly so do elements of economic interest: Sn, W, Mo, S.



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Redox scheme



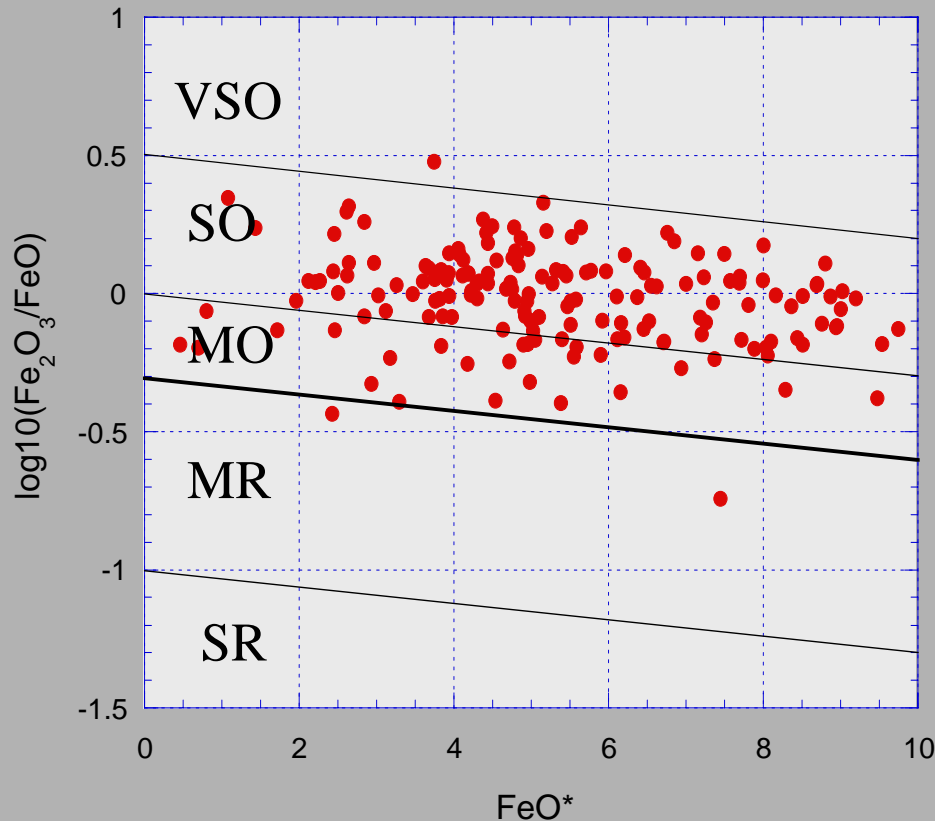
Cadia

Glenbrog

Strathbogie

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Redox - Porphyry Cu Systems



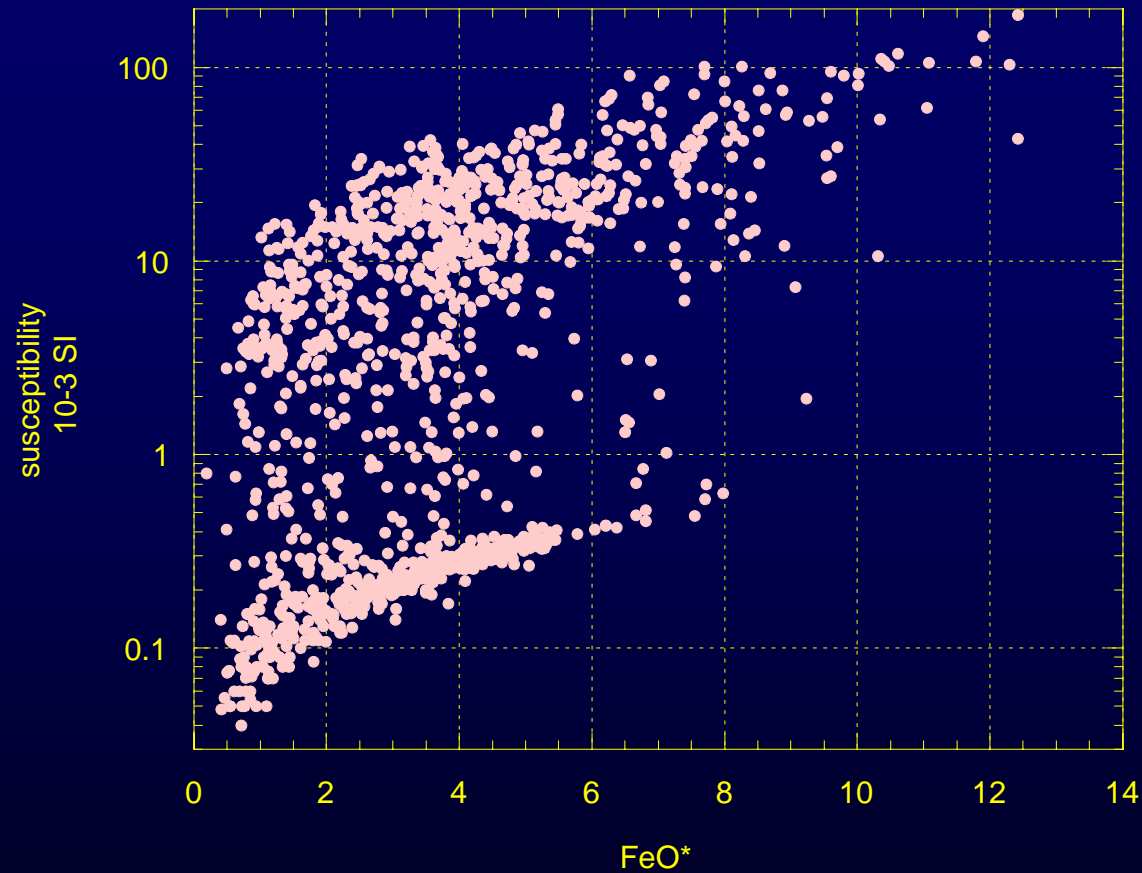
- Systems from LFB and SW Pacific.
- Biotite $\text{Mg}/(\text{Mg}+\text{Fe}) > 0.5$.
- Can be classified using colour index and Mag. Sus.

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Oxidation State - measuring:

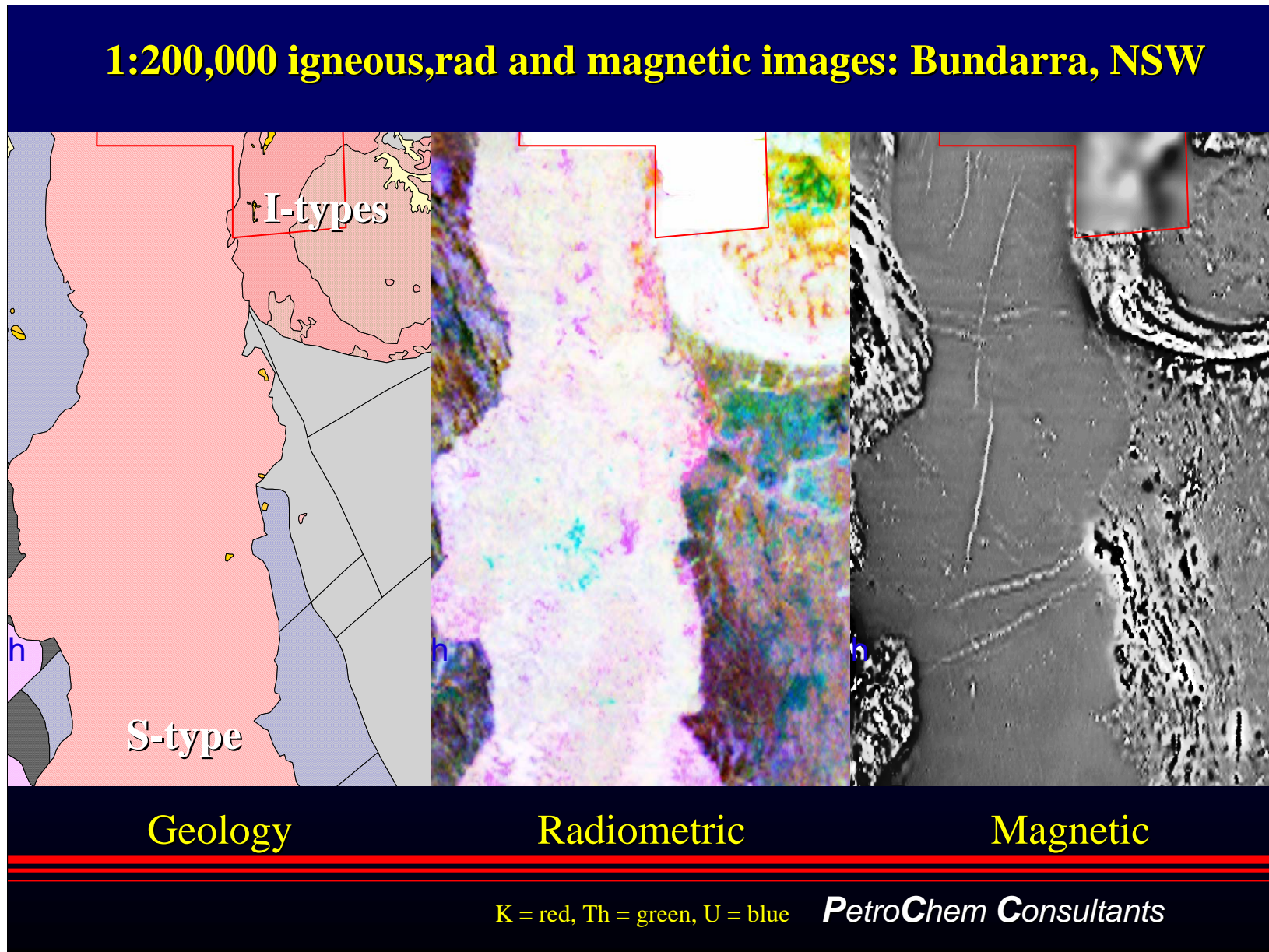
- Whole rock $\text{Fe}_2\text{O}_3/\text{FeO}$ ratio
- Mineral assemblages (magnetite, titanite, pyrrhotite)
- Mineral chemistry (Fe^{3+} in biotite and ilmenite, Mn in apatite)
- Mineral colours (eg. pink K-feldspar in oxidised rocks, foxy-red biotite in reduced rocks).
- Magnetic Susceptibility.

Most methods require care as these parameters can be affected by post-magmatic processes (slow cooling, weathering, hydrothermal alteration).

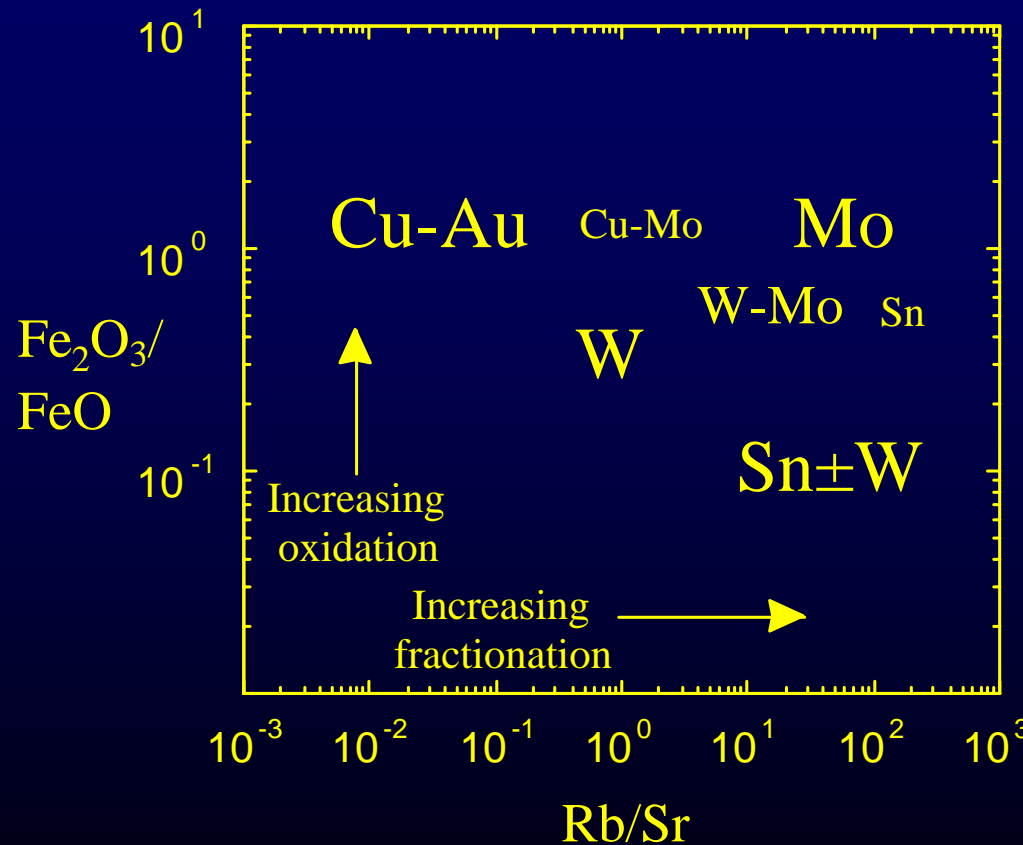


Magnetic susceptibility is a function of redox state and total Fe content of the rock - note strong relationship.

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Igneous Metallogenesi*s*



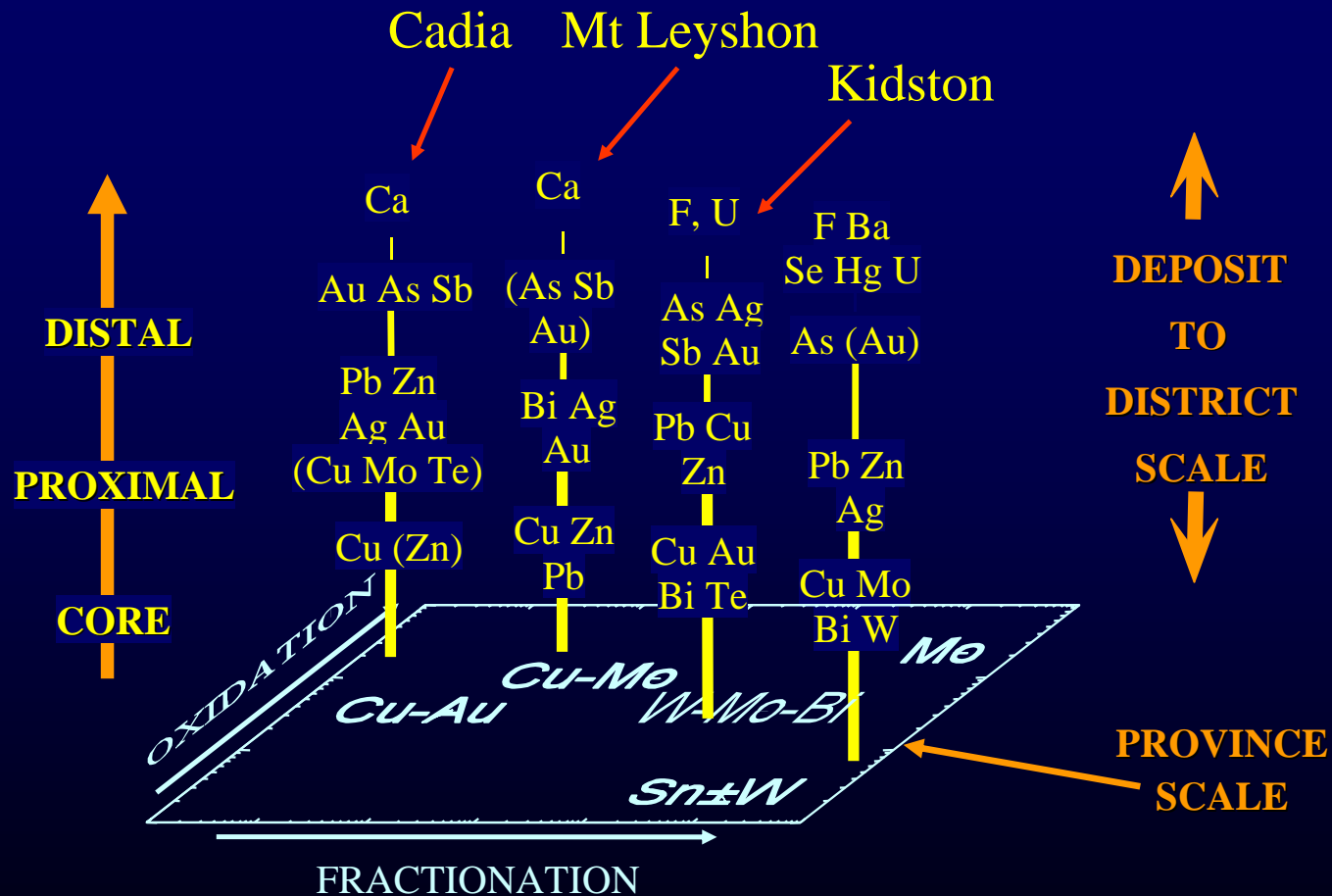
Different types of intrusion-related deposits correspond to magma properties such as:

- oxidation state
- compositional evolution
- silica content

It is the core element association that most closely relates to magma composition.

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Intrusion Related Gold - System Zonation



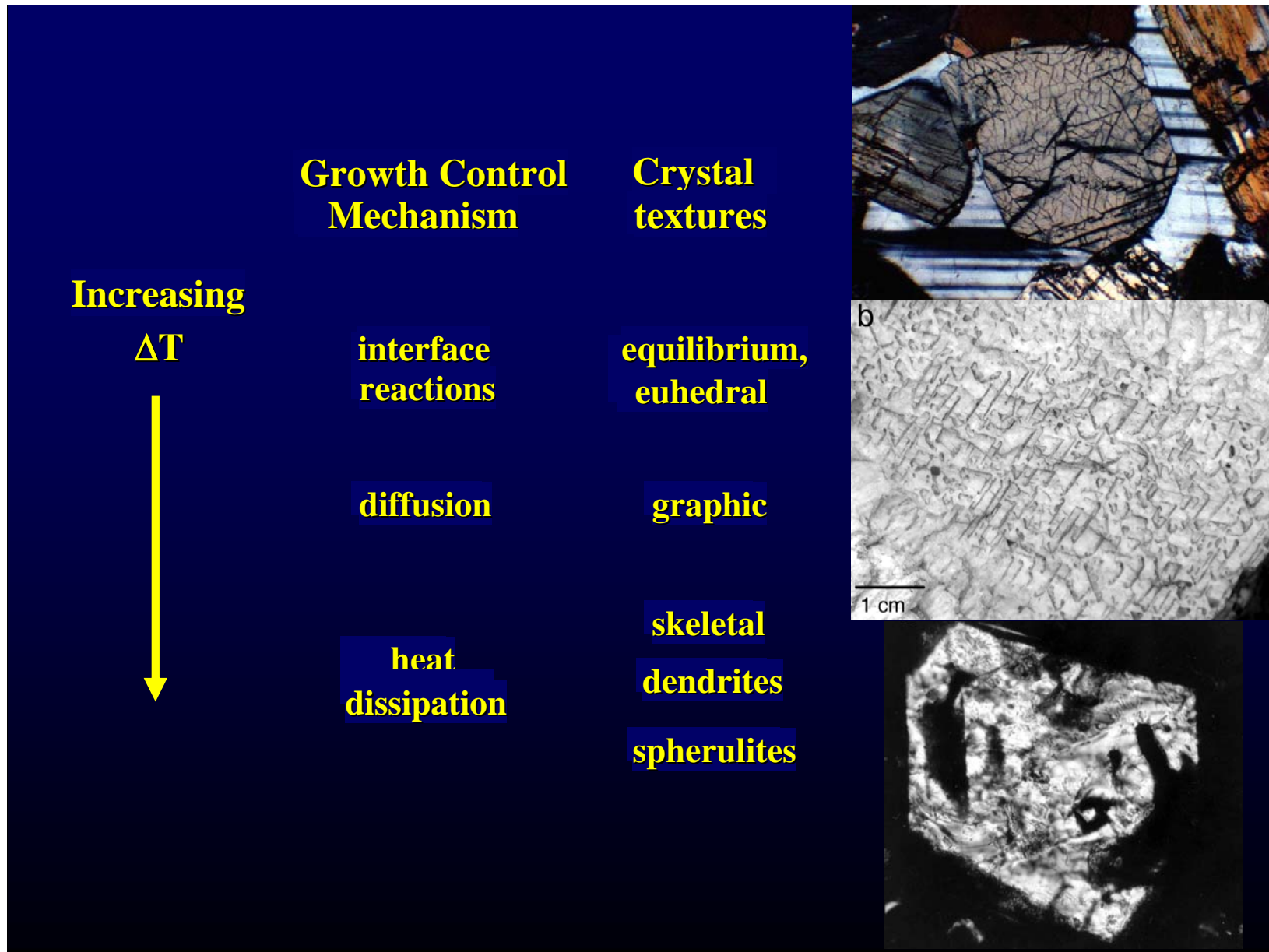
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Textures

- Textures of igneous rocks are important as they record of the crystallisation and volatile history of a magma.
- Nice equigranular medium-grained granites record equilibrium conditions of crystallisation - boring!!
- Diverse textures in granites record dynamic processes - magma flow, undercooling, mixing, volatile exsolution etc.



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Water Saturation

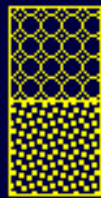
- During crystallisation, a volatile phase will exsolve. This phase may contain H₂O, CO₂, Cl, F, S, alkalis and metals.
- Timing is important as ore forming elements may substitute into minerals before a volatile phase exsolves.
- Usually, relatively early volatile exsolution at higher crustal levels is advantageous.
- The recognition of volatile saturation in granites during crystallisation is an important clue to metallogenic fertility.

Textures due to water saturation

Interconnected Miarolitic Texture: occurrence

IMT-bearing differentiates

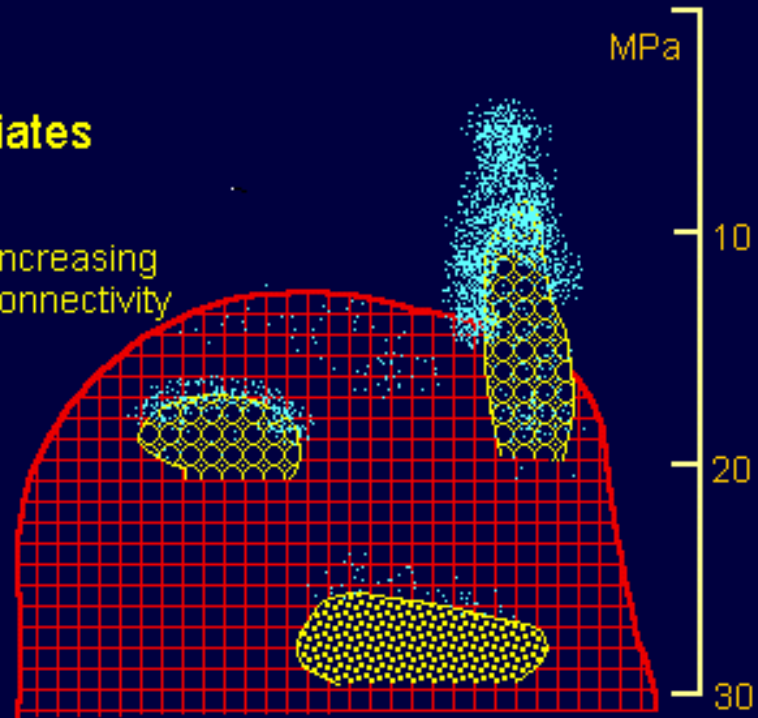
$$\frac{C_w^{\text{magma}}}{C_w^{\text{sat}}} \sim \frac{6}{6}$$



Increasing connectivity

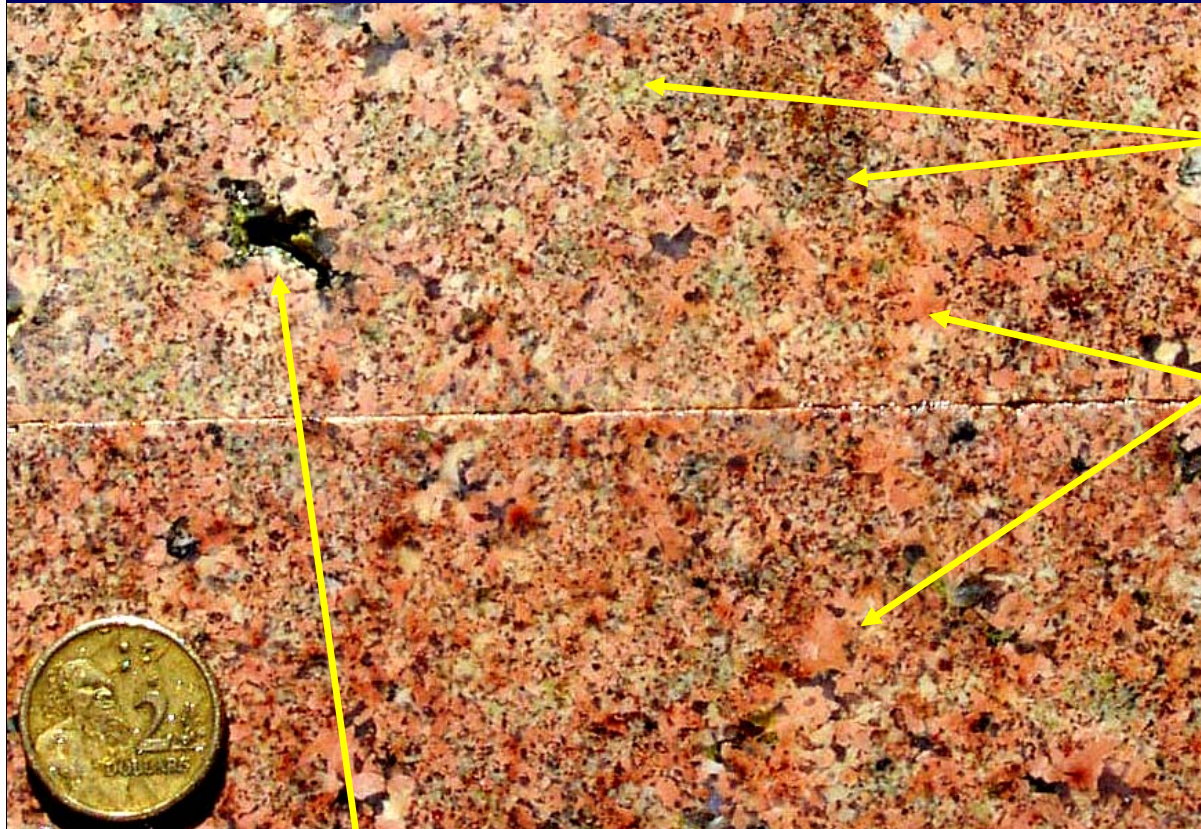
Granite

$$\frac{C_w^{\text{magma}}}{C_w^{\text{sat}}} \sim \frac{3}{6}$$



Interconnected Miarolitic Texture

Af > Plag ~ Qtz > Bi



Aplitic groundmass.
Represents early zones
xtlising prior to volatile
saturation.

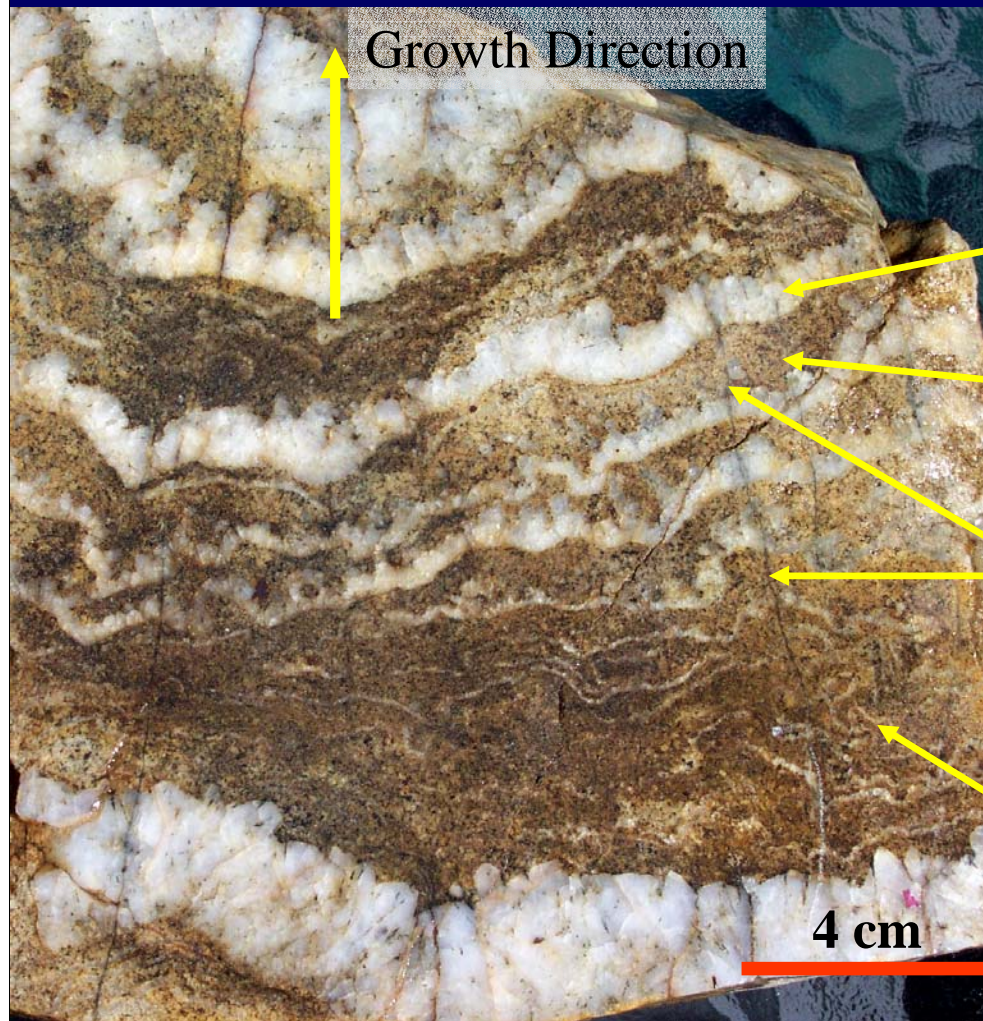
Coarser grained zones
are externally nucleated
micropegmatites
xtlising into original
open space. This gives
the rock the
interconnected texture.

**Miaroles + coarse
zones often equal
30% of the rock by
volume. Requires
pressures of <2.5
kb to form.**

Cavities lined with euhedral xtls, partly to
completely infilled with hydrothermal
minerals

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Unidirectional Solidification Textures



Alternating crystallisation of quartz and aplitic layers.

Quartz layer has smooth upper surface and toothy quartz xtls pointing in direction of growth.

Aplite layer represents return to normal crystallisation.

Quartz veins tangential to layering are common. Inferred to be volatile escape structures during overpressuring phase.

Layers can be fine, numerous and crenulated. The term "brain rock" is sometimes used.

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CONCLUSIONS

- Ore elements are a simple function of granite compositional parameters.
- Can not predict whether a granite will be mineralised.
- Many schemes are influenced by regional igneous characteristics and are not widely applicable.
- The scheme provides a mechanism by which granites can be classified according to metal potential

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