1 GRANITES & COPPER GOLD METALLOGENESIS IN THE AUSTRALIAN PROTEROZOIC

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1. INTRODUCTION

These notes focus on some basics of granites, their various types, and the relationship between Proterozoic granites and Au + base metal deposits. AGSO and the State and Territory Geological Surveys have built up a large whole-rock geochemistry granite database as part of their regional mapping programs and some specialised projects (*eg.* Champion & MacKenzie, 1994). Recently, all data on Proterozoic granites and felsic volcanics were complied as part of an industry funded project to look at the metallogenic potential of Australian Proterozoic granites (Wyborn *et al.*, 1998a, b). Using GIS techniques, the project investigated spatial relationships between specific granite types, host rock compositions and hydrothermal Au, Cu, Zn, Pb, Sn, W and Mo mineralisation. Mineralogical, geochemical (~7500 analyses), and age data of Proterozoic granites and felsic volcanics, as well as the age and mineralogical composition of sediments within 5 kms of granite boundaries, were collated for 20 provinces. This project highlighted significant spatial relationships between specific granite and mineral deposit types.

In most Proterozoic orogenic belts of Australia, regardless of age, granites and their comagmatic felsic volcanic occupy at least 20% by area and in some provinces, 40%. Because of the large aereal extent and inferred subsurface volume of granite bodies, defining the field characteristics, chemical composition, and processes of crystallisation for any given major granitic event is essential in understanding the metallogenic potential of any province. Even if the metals do not come from the granite itself, intrusion of hot magmas can cause major perturbations in the local geothermal environment. As well, the heat generated by radioactive decay has been considered important in raising the local geothermal gradient long after the emplacement of the granite (*eg.* Solomon & Heinrich, 1992; Sandiford & Hand, 1998).

These notes are divided into 6 parts:

Part 1 – Some basics on granites

Part 2 – The Proterozoic granites + base metal mineralising system

Part 3 – Australian Proterozoic Granite Associations

Part 4 – A synthesis of Australian Proterozoic Granites - broad characteristics, sources and possible mechaisms for derivation and emplacement

Part 5 – Predicting which Australian Proterozoic granites are likely to be associationed with mineralisation

Part 6 – A synthesis of granites and metallogeny in the Proterozoic - guidelines for other areas

1.1 WHAT ACTUALLY ARE GRANITES ?

One of the earliest references to 'granite' is Pryce (1778). He argued that the name of "granite (formerly called 'moorstone') is a modern name given by the Italian writers, on account of their being concreted into grains, or in a granulous structure" (Pryce, 1778, p78). About the only thing that people generally accept about granites is that they have been intruded into the crust as magmatic rocks. There is much debate about their sources, their mechanisms of emplacement and as to whether they have a role in the generation of mineral deposits.

In these notes, the term granite is applied to the broad spectrum of felsic intrusive rocks including tonalites, granodiorites, monzogranites and syenogranites (Streckeisen, 1973).

1.1.1 FIELD CHARACTERISTICS OF GRANITES

Traditional geological mapping has often resulted in the granite outline being defined, and then the boundary seen as a classic 'GO BACK -WRONG WAY' road sign. Very few of the 1:100 000 or 1:250 000 map sheets document features that are critical to determining mineral potential. Few maps attempt to distinguish internal mappable units within granite bodies. Some map legends describe textures of the granites (*eg*, foliated or massive), but rarely note important mineralogical constituents (*eg*, hornblende, cordierite, magnetite, etc). Granites tend to be named on geographical parameters, and superficially similar rocks (eg, leucogranites) from many different-age intrusive events are commonly shown a single mappable unit. For granites to be of use in metallogenic syntheses, individual intrusive units should be distinguished (*i.e.*, plutons) and then distinct phases within each pluton identified (*eg*, leucogranites, aplites, tonalites, diorites). Where possible, the main minerals present in each phase should be indicated on the map legend.

1.1.1.1 Metallogenically important field criteria

For metallogenic studies, it is important that the presence (or absence) of pegmatites, aplites, greisens, miarolitic cavities and other indicators of late magmatic segregations be observed. These are not always present in granite systems, and they are definitely more common in mineralised granitic systems. The presence of xenoliths is also significant: most xenolith-rich granite suites are unmineralised. Colour can also be important as the reduced (ilmenite or pyrite stable) granites are grey in colour, whilst oxidised (magnetite or hematite) stable granites are pink to red.

Other broad scale features include the size of the plutons (the more significant mineralisation is with the larger size suites), the width of the contact aureole and the presence of significant breccia zones within the granite and/or country rock. The shape of the pluton is also relevant, whether they are large elliptical or circular plutons, or whether they are amorphous blobs; most of the restite-rich suites do not form regular pluton shapes.

1.1.2 WHAT IS IMPORTANT TO SAMPLE IN GRANITES ?

In geochemical studies it is important to collect unweathered material that is truly representative of the sample site. The rule of thumb is that the individual sample should contain one million grains: in coarse-grained granites this is often over 30 kg per sample. The sampling program must also aim to maximise the SiO_2 variation within a granite pluton, thus in a zoned pluton, several samples need to be taken. It is frequently observed that 90% of the geochemical variation occurs in the outer 10% of the intrusion. Therefore, collecting geographically representative samples, may not give a true insight into the compositional variation of the intrusion, as the spatially insignificant, more mafic samples, which are critical to the interpretation of the nature of the source region, may not be sampled. It is important also to collect representative samples of all the more leucocratic phases in an intrusion, as metallogenically important geochemical distinctions may not be visible in hand specimen. Often those who are focussing on petrogenetic studies and/or determining the tectonic setting of the granites sample only the more mafic end members (tonalites, granodiorites etc) and do not touch the metallogenically important leucogranites.

Geochemical collections should also made of altered granites, regardless of whether the alteration is related to magmatic processes or to younger, magmatically unrelated hydrothermal events. Being relatively rich in feldspar and ferromagnesian minerals, granites often show an imprint of major regional hydrothermal alteration events, that are not seen in other rock types (eg, sandstones).

1.1.3 SUITES AND THEIR RELATIONSHIP TO PLUTONS AND BATHOLITHS.

1.1.3.1 Suites - a definition

In mapping any province there is a three-level hierarchy of intrusive classification: pluton, suite and supersuite. A *pluton* is the smallest definable intrusive unit and is formed by intrusion of a pulse of magma generated in a thermal event. A *suite* is formed by grouping together plutons of similar petrographic, chemical and isotopic composition (Chappell, 1984). Differences between suites are thought to correlate with differences in source rock composition, rather than processes of crystallisation or solidification (Chappell, 1984) Therefore individual suites comprise plutons that are both coeval and comagmatic. *Supersuites* comprise groups of similar suites that are not necessarily coeval. Supersuites and suites are thus the basic granite units in metallogeny (and also in tectonic reconstructions).

In view of the regional to national scale data compilations that are now being undertaken by organisations such as AGSO and the Australian National University, it is apparent that there is a higher level in the granite hierarchy. The term *Association* has been introduced to group together supersuites and suites with broad overall chemical similarities. Associations are broadly controlled by parameters such as composition of the source regions and the PT conditions existing at the time of generation of the melts. In reality, it is the abundance and composition of hydrous phases such as biotite, muscovite, and amphibole in the source region as well as non-hydrous phases such as plagioclase and garnet that control the individual chemical characteristics of associations.

Batholith is a non-genetic, structural term that implies a geographical area of granite. A batholith can contain granites of many ages and compositions: the term is somewhat useless in tectonic metallogenic syntheses and reconstructions. *Complex* is also a non-genetic term for areas of granite that show 'complex' relationships. Unfortunately in literature on the Australian Proterozoic the term 'complex' has been used for granites that intrude high-grade metamorphic terrains, and both the granite and the totally unrelated metamorphics are lumped into the one unit. In other cases, mixed mafic and felsic intrusives have been named a 'complex' even when there is no clear genetic association between the two disparate magmatic types.

1.1.3.2 How extensive can granite suites be?

Two surprising features that major regional granite databases have shown are that in any province, (a) granites show systematic compositional changes both with time and space, and (b) the actual number of different granite suites is normally quite small. For instance in the Mount Isa Inlier there are no more than 7 major granite suites, each defining a particular magma type that was intruded into the crust at a specific time, and each derived from a different source region. The geographical extent of some of these suites can be quite large: up to 9000 kms2. As granites are generated by partial melting of their source region, then the source regions must have a much larger volume at depth. Correlations between provinces of similar ages commonly show a remarkable uniformity of composition of granites and their comagmatic felsic volcanics on a continent-wide scale: such an event, covering at least 37 000 km^2, has been documented in the early Proterozoic of northern Australia between 1880-1840 Ma (Wyborn, 1988). The generation of this granitic suite requires a continent-wide tectonothermal event. One interesting observation is that suites in the Proterozoic have much larger dimensions than suites in the Palaeozoic, whilst Archaean suites seem even larger.

1.1.3.3 The importance of recognition of suites to metallogeny

Distinguishing the extent of plutonic suites is critical and may provide clues to potential areas of mineralisation. If one pluton in a suite is found to be mineralised then the whole suite, as well as compositionally equivalent granites in other related provinces, must be considered to have potential for mineralisation. For example, a particular type of leucogranite in the early Proterozoic Cullen Batholith of the Pine Creek Inlier is associated with Sn, W, and U deposits and is characterised by high and exponentially increasing values of Rb, U, and Y with increasing SiO_2. These same geochemical features are also found in granites from the Granites-Tanami Block (Lewis Granite, The Granites Granite, Winnecke Granophyre), unnamed porphyries in the Tennant Creek area, unnamed granites in the northwestern Arunta Inlier, and in granites of the Telfer region (Goellnicht *et al.*, 1991). Another example is the high-U Williams Supersuite of the eastern Mount Isa Inlier, which has associated Au, Ag and Cu mineralisation. Compositionally these granites are very similar to granites of the Hiltaba Suite (Wyborn, 1992).

1.2 CAN GRANITES BE CLASSIFIED METALLOGENICALLY ?

1.2.1 THE GRANITE ALPHABET: S, I, OR A?

The S- and I-type classification is really a classification based on the composition of the source regions. Chappell and White (1974) subdivided granites into *S-type* (sedimentary) and *I-type* (igneous): these terms were later modified to S-(supracrustal) and I-(infracrustal) type (White and Chappell, 1983). The distinction infers that either granites are S-type, derived from source rocks that have predominantly been affected by supracrustal processes, as opposed to I-type granites whose sources have not been exposed to surficial crustal processes.

Mineralogically true S-types are characterised by the presence of cordierite and *almandine* (Fe-rich) garnet in more mafic compositions (<70 wt.% SiO_2), whilst I-types are characterised by hornblende: biotite can be common to both. Note that fractionated granites of both S- and I-types can have muscovite and *spessartine* (Mn-rich) garnet. The presence of muscovite does not automatically infer that the granites are S-type (See White *et al.*, 1986; Dickson *et al.*, 1986, Miller *et al.*, 1986) and granites derived from very immature sediments derived from andesites or basalts may contain hornblende.

1.2.1.1 ASI Index

One of the indicators for differentiating more mafic granites into S- or I-type is the alumina saturation index (ASI; Zen, 1986) (molecular $Al_2O_3/(CaO-3.3*P_2O_5+K_2O+Na_2O)$) which is generally <1.1 for the more mafic I-type granites. However, note that:

1) Mafic magnetite- and hornblende-bearing I-types become more peraluminous with increasing SiO_2, and the ASI can be > 1.1 (*eg*, Cullen Batholith, Stuart-Smith *et al.*, 1993). Therefore granites suites that only have SiO_2 values >72 wt.%, which are classified as 'S-type' are under suspicion, unless the more mafic granite phases contain cordierite or almandine garnet;

2) The ASI index is very sensitive to both hydrothermal alteration and weathering;

3) Granites derived from sediments which have undergone little chemical fractionation during weathering can have ASI < 1.1.

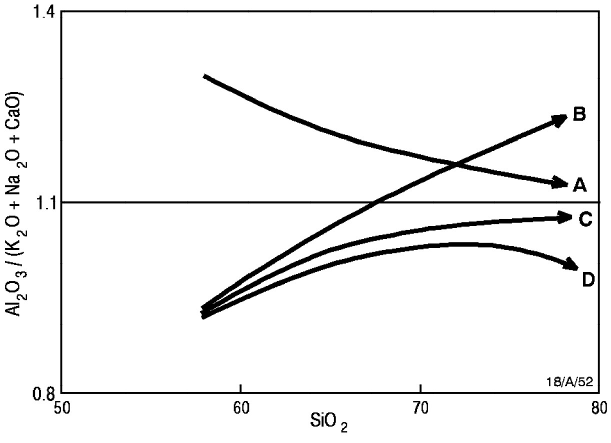


Figure 1.2.1.1a: Changing ASI index with increasing SiO_2. Path A is typical for S-types, whilst B, C and D are predominantly I-type. High SiO_2 samples from path B would have muscovite, but they are not 'S-types'

A-types are a specific class of granites that have low Al and Ca contents and high HFSE concentrations and FeO/MgO, Ga/Al and $(Na_2O+K_2O)/Al_2O_3$ ratios compared to normal metaluminous granites (Collins *et al.*, 1982; Patino Douce, 1997). Originally considered to be derived from granulitic sources that had previously been depleted in a hydrous felsic melt, A-types are now generally considered to be higher temperature melts in which incompatible elements are preferentially enriched due to breakdown of more refractory phases at higher temperatures. On the basis experiments of melting experiments, Patino Douce (1997) emphasised that the so called 'A-type' characteristics signify generation at very low pressures (~4kb), and temperatures of 900°C by melting of hornblende and biotite-bearing granites, leaving a residue rich in plagioclase and orthopyroxene.

Note also that the discriminant diagrams developed by Eby (1990) on Palaeozoic granites to distinguish between A and I-type granites do NOT work for Proterozoic granites as they are universaly more enriched in elements such as Zr, Nb, La, Ce and Y relative to their Palaeozoic counterparts. Using Eby's 1990 classification,

~85% of Proterozoic granites would be classified as A-type. With time, the A-type classification is gradually losing prominence.

1.2.2 METALLOGENICALLY IMPORTANT SUBDIVISIONS OF GRANITES.

1.2.2.1 Magnetite vs ilmenite series

The most important classification was developed by Ishihara (1977) who defined the magnetite and ilmenite series of granites. He noted that magnetite series granites have magnetite (0.1-2 vol.%), ilmenite, hematite, pyrite, titanite, epidote, high ferric/ferrous (and high Mg/Fe biotite). In contrast the ilmenite series have ilmenite (less than 0.1 vol %), pyrrhotite, graphite, muscovite, low ferric/ferrous (and low Mg/Fe) biotite. He further noted that the magnetite series granites were associated with porphyry copper-molybdenum deposits, whilst the ilmenite series were accompanied by greisen-type tin-wolframite deposits. As a rule of thumb (but not always), the ilmenite series corresponds to S-types, whilst the magnetite series corresponds to I-types. As we will see one of the important findings of the Proterozoic granites project was the variability of the redox state of the various plutons within individual suites.

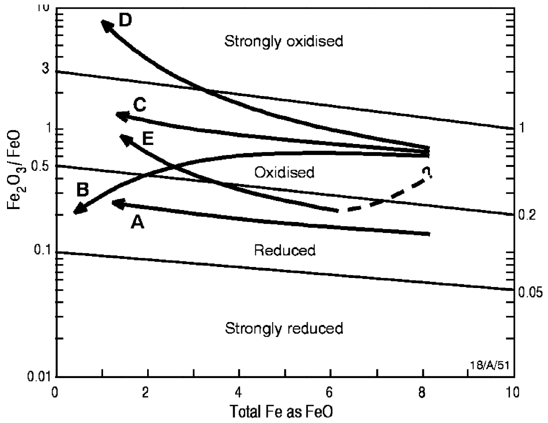


Figure 1.2.2.1a: Redox plot of Champion and Heinemann (1994).

Champion & Heinemann (1994) developed a plot to show the changing REDOX with increasing fractionation (Figure 1.2.2.1a). The line between oxidised and reduced is the line between magnetite- and ilmenite-bearing granites (provided the systems are low in S). Samples which plot in the strongly oxidised field (Path D) are often hematite bearing. The Cu-Au systems seem to plot in this field. Samples that plot in the oxidised field (Path C) or cross into the reduced field (Path B) are generally magnetite to ilmenite stable and can be associated with Au-dominant mineralisation. S-types are generally reduced and follow path A.

1.2.2.2 M-type vs I-(tonalitic) type vs I-(granodioritic) type

Recent subdivisions of I-types have useful metallogenic implications. M-types were defined by Pitcher (1982) to refer to small quartz-diorite and gabbros associated with island arc volcanism. Whalen (1985) considered that M-types were probably generated by the partial melting of subducted oceanic crust or of the overlying mantle in subduction zones. Chappell & Stephens (1988) refined the definition of M-types and further subdivided I-type granites into I-(tonalitic) type and I-(granodioritic) type. Chappell & Stephens (1988) suggested that M-types which typically consist of mafic diorites, quartz diorites and gabbros are chemically indistinguishable from andesitic magmas. They have average SiO_2 contents less than 60 wt.%. The I-(tonalitic) type granites, which are characteristic of the Cordillera of North America and Peru and have an average SiO_2 content of 65 wt.%, are dominated by tonalites which were probably derived by partial melting of such M-type rocks which had been underplated in the lower crust. Gabbros are frequently associated with the I-(tonalitic) type. In turn, the I-(granodioritic) type rocks, which are so characteristic of Proterozoic and Palaeozoic regions, were produced by partial melting of older I-(tonalitic) type granites: in the Palaeozoic Lachlan Fold Belt these I-(granodioritic) types have an average SiO_2 content of 69 wt %. Porphyry-style mineralisation is usually associated with either M-types or I-tonalite types, which dominate the early Archaean, late Palaeozoic to Cenozoic, whilst Proterozoic, early Palaeozoic and Archaean granites are dominated by I-granodiorites (Wyborn *et al.*, 1992).

1.3 HOW DO GRANITES FORM ?

This is where the greatest controversies over granites occur. However, by accepting a few basics on granite melting events and emplacement mechanisms, it becomes obvious why some granites are mineralised and some aren't.

1.3.1 ARE GRANITE MAGMAS PURE LIQUIDS OR CRYSTAL MUSHES?

They can be either. Granites are generated by partial melting at their sources and it is commonly assumed that all granites crystallise from liquids by a process of crystal fractionation and gravitional floatation or settling of these crystals. However, it is now known that just as granites contain xenoliths, they can also contain abundant xenocrysts or restite (White & Chappell, 1977; Chappell *et al.*, 1987). Granites are thus two component mixes consisting of the melt fraction and the restite, and the proportion of the two end-members varies from those that are pure liquids, to those that predominantly consists of restite with only a small amount of interstitial melt. Whether granites form crystal-rich magma or pure liquid melt is entirely dependant on the composition of the source region and the PT conditions predominating at the time of melting.

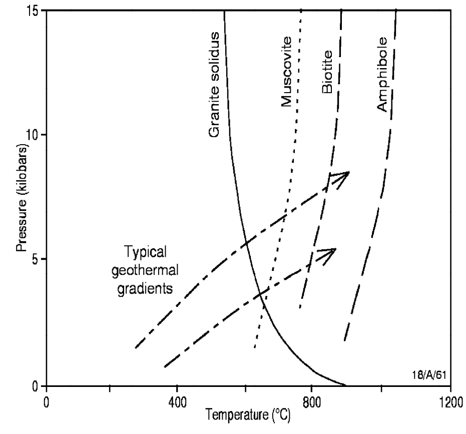


Figure 1.3.1a : Dehydration breakdown reactions for common hydrous minerals.

As most Proterozoic granites are I-(granodioritic) type, the sources must be tonalitic in composition (Chappell & Stephens, 1998; Patio Douce & Beard, 1995; Singh & Johannes, 1996a, b). Melting is more likely to be dominated with increasing temperature by dehydration reactions involving biotite and hornblende (Fig. 1.3.1a).

1.3.1.1 Mechanisms of granite crystallisation: restite unmixing vs convective fractionation.

Chappell (1998) has distinguished between granites that formed at low magmatic temperatures and those that formed at high temperature. Low temperature granites were formed by partial melting of rocks rich in quartz and feldspar. In these cases, the melt compositions were close to those determined by Tuttle and Bowen (1958) at the lowest magmatic temperatures (*i.e.*, minimum melt), and the composition of the granites overall is controlled by the restite which will comprise minerals such as hornblende, pyroxene, biotite, cordierite and garnet. Compositional variation is controlled by the separation of the restite from the melt. In some cases, if the restite separates out early there will be some fractionation of the residual melt. In contrast, in the higher temperature melts, more components in the source region melt and become incorporated in the melt.

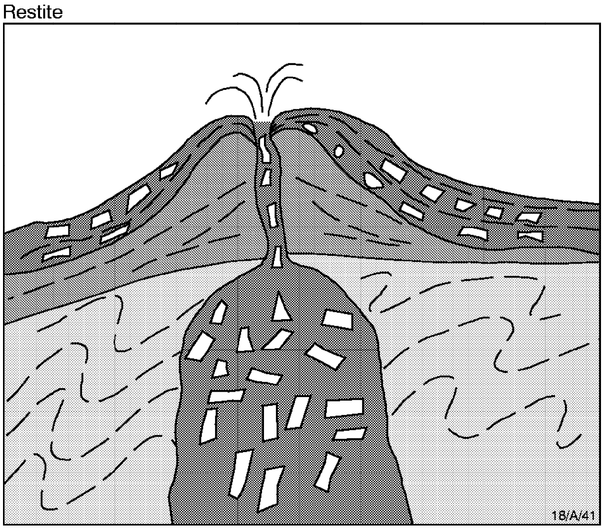


Figure 1.3.1.1a. Melts that are restite-rich produce homogenous plutons that are identical in composition with phenocryst-rich volcanics

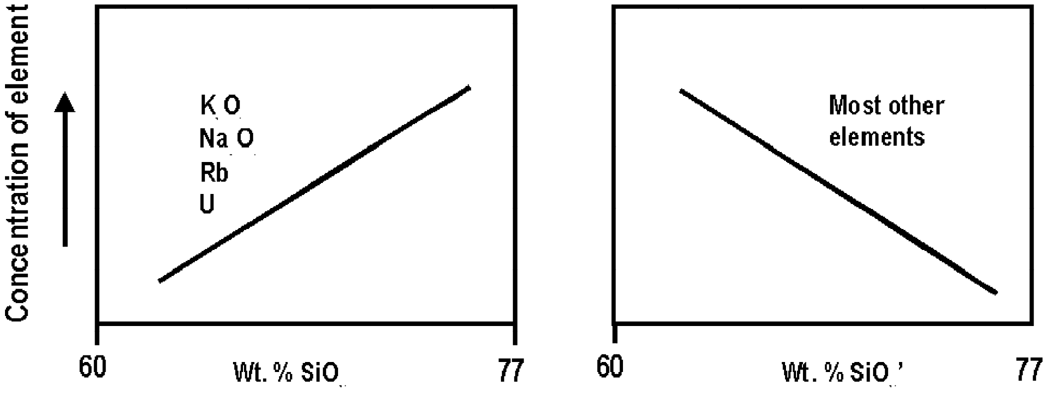


Figure 1.3.1.1b. Schematic illustration of chemical variation trends in a restite-dominated system

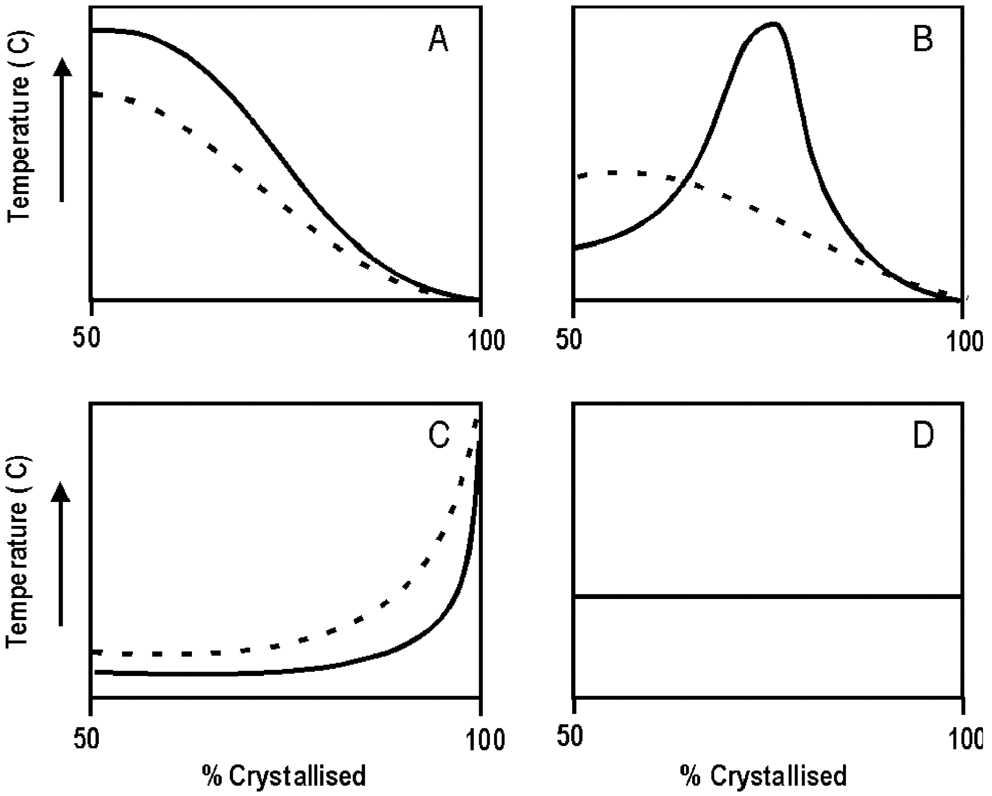
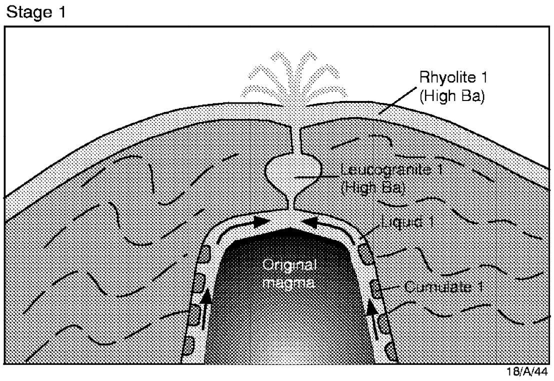


Figure 1.3.1.1.d: Various major and trace element plots for granites that crystallise from pure melts (based on Stanton 1990). Dotted lines represent the composition of the residual liquid, whilst solid lines represent the composition of the crystallised rock. In A, the element is preferentially concentrated in the crystallising phases. In B, initially the element is concentrated in the melt, but then partitions into crystallising phases (Ba and Zr very commonly show these trends). In C the element preferentially concentrates in the liquid (eg. Rb, K, and U) whilst in D the element is not preferentially partitioned into either melt or the crystallising phases.

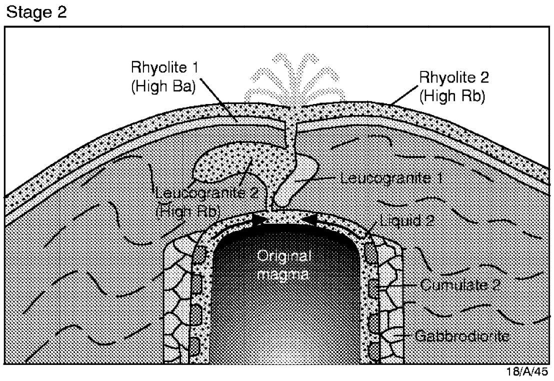
If a granite magma is full of restite, then there is very little capacity for the magma to fractionate, and crystallisation takes place by freezing of the interstitial liquid. Granites that are restite-rich have a high viscosity and are volatile undersaturated (Wyborn & Chappell, 1986). Comagmatic volcanics consist of the same crystal-liquid mix, and are often impossible to distinguish chemically from their comagmatic granites (Figure 1.3.1.1a). The volcanics contain abundant phenocrysts (up to 60%) (Wyborn & Chappell, 1986). Geochemically these volcanics/granites form straight line variation trends with any element vs SiO_2 (Figure 1.3.1.1b) and their compositions can be very uniform over 9000 kms^2. Because the latent heat of fusion is taken up by the restite crystals, restite-rich magmas rarely have pronounced contact aureoles, and contact effects are narrow (<10m).

Granites that intrude as liquids undergo cooling by a method called convective fractionation (Sparks *et al.*, 1984), a process in which the magma cools by side-wall accretion. As the more mafic mineral phases crystallise as cumulates on the sides and base of the magma chamber, the derivative interstitial liquid becomes less dense than the primary magma and ascends to the top of the magma chamber. Here, because of the large density difference between the primary liquid and the derivative liquid, the two remain segregated and cannot mix (Figure 1.3.1.1c-A). Periodically the lighter derivative liquid may move to the surface and extrude as volcanics, which are usually flow-banded, crystal poor rhyolites. Phenocryst abundances in these volcanics are generally less than 20% (Wyborn & Chappell, 1986). The derivative liquid may also crystallise at higher levels as leucocratic plutons. As the compositions of the crystallising minerals change, the composition of the more felsic derivative liquids also evolves towards high SiO_2 members that are enriched in Rb, U and Y and have lower K/Rb ratios (Figure 1.3.1.1c-B). In addition, as cooling proceeds, the density difference between the primary and derivative liquids decreases, so that convective overturning may take place and homogeneous plutons of granodiorite to monzogranite composition will be derived (Figure 1.3.1.1c-C) (Mahood, 1991). The final product is a concentrically zoned pluton, which becomes progressively more felsic towards the centre.

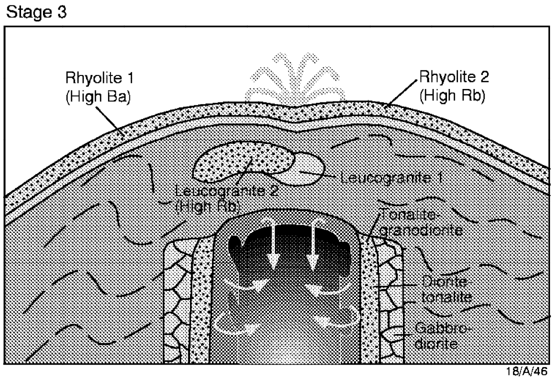
Thus, in contrast to the homogeneity of the restite-rich systems, the end product of granite systems undergoing convective fractionation is a heterogeneous chemical suite consisting of zoned plutons, leucocratic plutons and homogeneous plutons of granodiorite to monzogranite composition Figure 1.3.1.1c-D). Each individual pluton



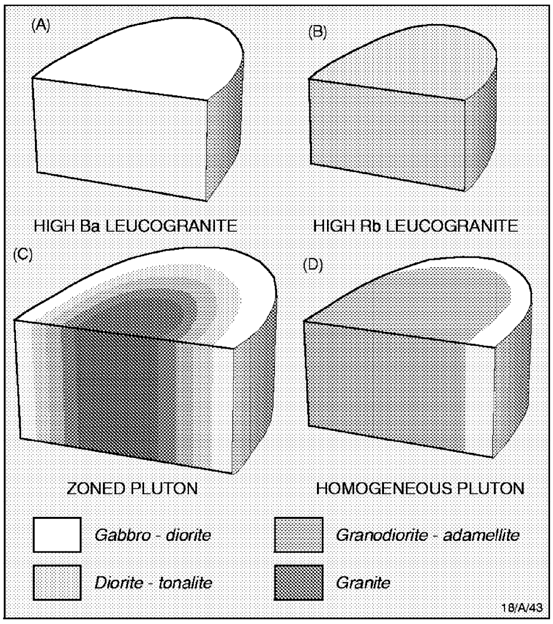
A. Stage 1: Granite melt is intruded. Denser more mafic minerals accrete to the sidewalls and form more mafic tonalites, diorites, gabbros etc. The residual liquid, being lighter and denser than the original magma rises to the top of the chamber. This liquid is high in Ba and can bleed off to form high-Ba leucogranites or aphyric rhyolites. Some of these early formed derivative intrusives can form pipe-like bodies that are relatively enriched in metals in comparison to the primary magma.



B. Stage 2: Provided there are no significant further additions to the primary magma, crystallisation proceeds inwards. The primary magma is evolving and the composition of cumulate minerals changes. The rocks accreted to the edge of the chamber now form granodiorites to tonalites. The derivative liquid is now more Rb enriched, but still has sufficient density contrast with respect to the primary melt to pond on top and to then bleed off to form more evolved leucogranites and rhyolites.



C. Stage 3: Again, provided there are no significant further additions to the primary magma, crystallisation attempts to proceed inwards but the derivative liquid no longer has sufficient density contrast wrt the primary melt to pond on top. The magma chamber convectively overturns and homogenises and produces more uniform adamellites to granodiorites. Some of the earlier formed outer zones can be lost and reincorporated in the melt.



D. The diversity of compositions produced via convective fractionation. The four broad groupings are A) the early formed high-Ba leucogranites (rhyolites), B) the more evolved high-Rb leuocgranites (rhyolites), C) zoned plutons and D) more homogeneous adamellite to granodioritic intrusions (which can have narrow more mafic rims). Compare and contrast the diversity with Figure 1.3.1.1a. Resitite systems produce broadscale homogeneous intrusions and extrusives.

Figure 1.3.1.1c. Diversity of rock types produced from a granitic melt that has undergone convective fractionation.

often has a distinct composition, and the comagmatic volcanics commonly have compositions distinct from most of the cogenetic intrusions: Harker variation diagrams will not necessarily relate them to the cumulate derived more mafic end members of the suite (eg, Wyborn *et al*., 1987). High temperature K-rich mafic melts usually produce the greatest compositional variation because they have such a large range of crystallisation temperatures (White *et al*., 1991, Wyborn, D., 1993). In the field, these granites are commonly characterised by contact aureoles that are several kilometres wide.

As illustrated in Figure 1.3.1.1d, granites which crystallise from melts are distinguished by heterogenous geochemical plots e.g. some plutons (but not all) show exponentially increasing values of Rb, U, Rb/Sr and decreasing K/Rb with increasing SiO_2. For most I-types, Y shows exponentially increasing tends, except for in the strongly oxidised (magnetite-hematite stable suites). In contrast element such as Ba and Zr can show increasing then decreasing trends. Comagmatic volcanics where they occur are compositionally distinct.

1.3.2 DO GRANITES SYSTEMATICALLY CHANGE THROUGH TIME?

Although the principles of uniformitarianism are fundamental to geoscience, the first question to be addressed is as to whether granite compositions change though time. If we are to use geochemical characteristics of modern metallogenic and tectonic settings to interpret the past, then there cannot be any secular variation in the composition of granites. However, it is clear that there are regular systematic changes in the compositions of major I-type granite suites with time, which had important implications for metallogenic and tectonic processes (Wyborn *et al*., 1988a, 1992).

Using mantle normalised element abundance plots (alias spidergrams) granites can be divided into two broad types: either they are Sr-undepleted and Y-depleted or they are Sr-depleted and Y-undepleted. The Y-depleted type implies derivation from a source that has residual garnet, but not plagioclase, whereas the Sr depletion suggests derivation from a source with residual plagioclase but not garnet. As most granites have a two stage origin, these chemical features reflect P-T conditions at either the time of melting or during the formation of the source from the mantle.

In time there are essentially four main groups of I-type granite (Figure 1.3.2a):

1) Archaean tonalites to granites
2) Proterozoic granodiorites to granites
3) early Palaeozoic granodiorites to granites
4) late Palaeozoic, Mesozoic and Cenozoic tonalites to granites

Groups 1 and 4 are dominated by Sr-undepleted, Y-depleted types, i.e. at some stage in their evolution they had residual garnet in their source region; many in Group 4 are regarded as subduction related. Groups 2 and 3 are dominated by Sr-depleted, Y-undepleted types, i.e. their source region had residual plagioclase.

1.3.2.1 Summary of changes in time in granite compositions: metallogenic implications

It is stressed that within any one of these time divisions only about 85% of I-type granites conform to these groupings and we accept that there are exceptions. Apart from the Sr depleted vs Y depleted change in composition with time there are other significant differences, including the relatively high abundance of elements such as K, Th, U and Sn in granites from the late Archaean to early Palaeozoic when compared with early Archaean and post-late Palaeozoic granites. Another difference (as already noted) is the dominance in the early Archaean and late Palaeozoic to Cenozoic of M-types or I-tonalite types, whilst Proterozoic, early Palaeozoic and Archaean granites are dominated by I-granodiorites (Wyborn et al., 1992). In compilations on the distribution of ore deposits throughout time, Meyer (1981) and Hutchinson (1981) noted that porphyry copper magmas are not common in the Proterozoic. Some suggestions have been made that the absence of this deposit type is a function of erosion in that the Proterozoic being older, is more deeply eroded, and that all porphyry-style deposits have been eroded away. The abundance of subareal volcanics mitigates against this. The absence of compositionally equivalent magmas to those associated with porphyry style mineralisation is a more likely cause.

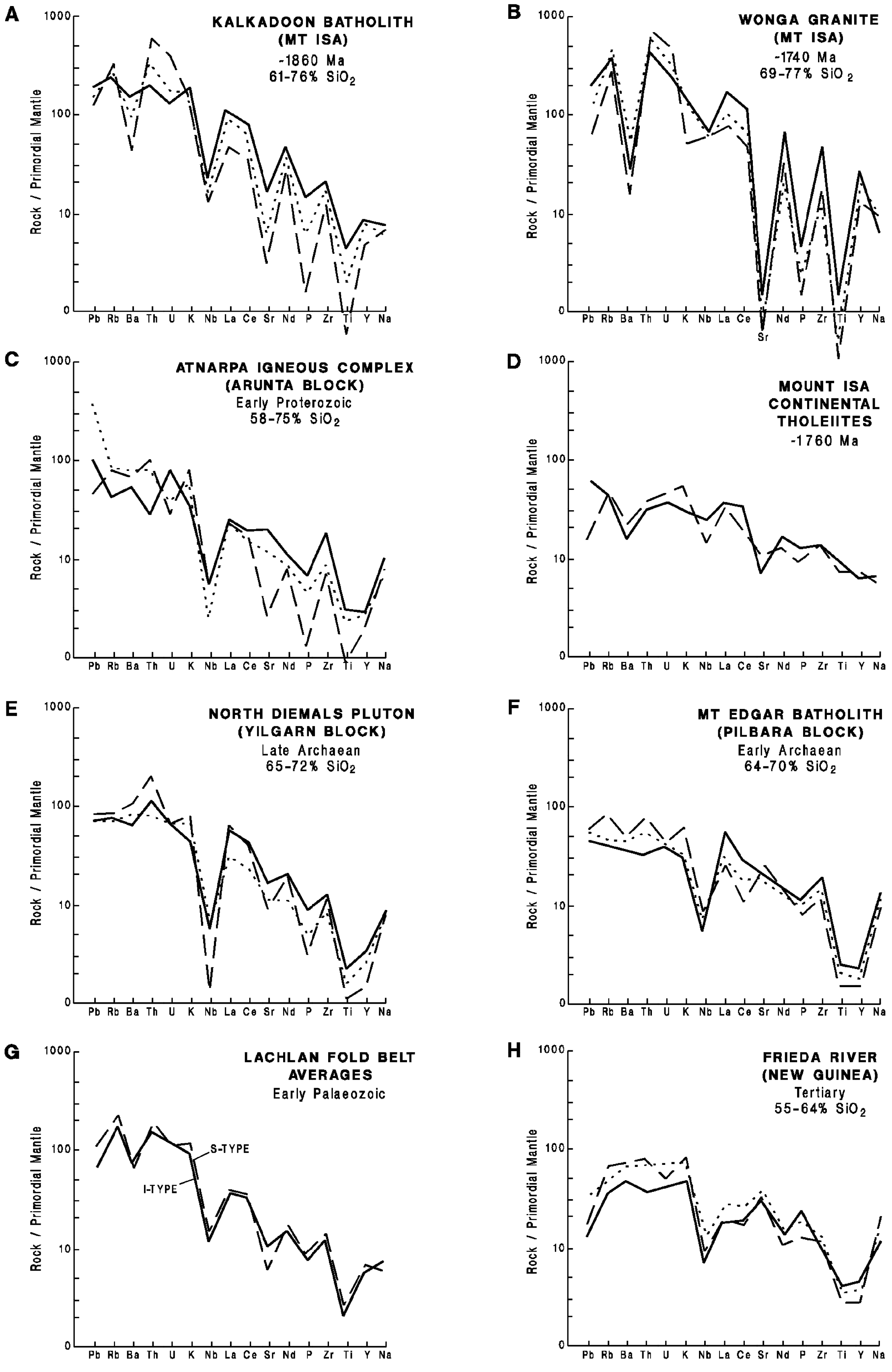


Figure 1.3.2a. Multi-element primodrial-mantle-normalised abundance diagrams for representative granites from the Australian Continent: normalising values are from Sun & McDonough (1989): in D the dashed line and the solid line are 2 individual samples; in G the dashed line is an average S-type and the solid line an average I-type granite of the Lachlan Fold Belt; in all other figures the solid line is the lowest SiO_2 content, the dotted line an intermediate SiO_2 and the dahsed line the highest SiO_2 content.

2. THE PROTEROZOIC Au + BASE METAL GRANITE MINERALISING SYSTEM.

It is clear that granite-related mineralisation in the Proterozoic, requires not only a specific granite type, but also a particular host rock, as well as suitable structures to connect the metals from their source to a trap site. In order to examine the spatial relationships between granites and mineralisation in the Proterozoic a mineral systems concept was used and a GIS built to attempt to understand if there were specific granites that did have a consistent spatial relationship to mineralisation. The minerals systems concept was chosen because the project was aiming to find the large scale geological features that are common to areas that contain coeval granite intrusives and Cu-Au mineralisation.

2.1.1 THE MINERAL SYSTEMS CONCEPT

Traditionally ore deposits have been located by either finding out cropping ore or gossans or by following up geochemical or geophysical anomalies. The source of the fluids carrying the metals or the fluid pathways were rarely considered in exploration programs. The emphasis of exploration is now changing with the greater acceptance that an ore deposit results from an exceptional 'coincidence' of ordinary mechanical and chemical processes, many of which are quite common in the geological record. The relatively rare 'coincidence' in space and time of the several essential component processes is what makes ore deposits uncommon. Because an ore deposit rarely exceeds more than several kilometres in length or breadth, it represents a very localised, specific target for exploration. However the formation of most ore deposits results from the influence of various associated geological factors many of which can cover tens of kilometres (district scale) if not hundreds of kilometres (regional scale). The ore deposit is therefore the central point of a regional mineral system. Ore-forming systems of these magnitudes are therefore likely to have left observable geological evidence well away from the deposit (eg, Henley & Hoffman, 1987) on a scale comparable with modern regional geoscientific mapping programs.

2.1.2 MINERAL SYSTEMS - A DEFINITION

For many years the Petroleum industry has followed the concept of the 'Petroleum System' which was defined by Magoon & Dow (1991) as 'a pod of mature source rocks and all its generated oil and gas accumulations, and includes all the geologic elements and processes necessary for oil and gas to exist'. This principle can also be applied to mineral deposits, although it is recognised that in contrast to petroleum systems, mineral systems are both more diverse and more complex. Mineral systems have been defined by Wyborn *et al.* (1994a) as *'all geological factors that control the generation and preservation of mineral deposits, and stress the processes that are in involved in mobilising ore components from a source, transporting and accumulating them in more concentrated form and then preserving them throughout the subsequent geological history'.*

Important geological factors defining the characteristics of any *hydrothermal* system include (Figure 2.1.2a):

1) sources of the mineralising fluids and transporting ligands;
2) sources of the metals and other ore components;
3) migration pathway, which must include inflow as well as outflow zones for large amounts of fluids (in contrast to petroleum migration paths);
4) thermal gradient (does the fluid move from hotter to cooler zones or visa versa?);
5) energy source to physically mobilise sufficient quantities of fluid to transport economic amounts of metal;
6) a mechanical and structural focusing mechanism at the trap site, and
7) a chemical and/or physical cause for enriched mineral precipitation at the trap site.

2.1.2.1 The Proterozoic granite related Au + base metal mineral system - the concept

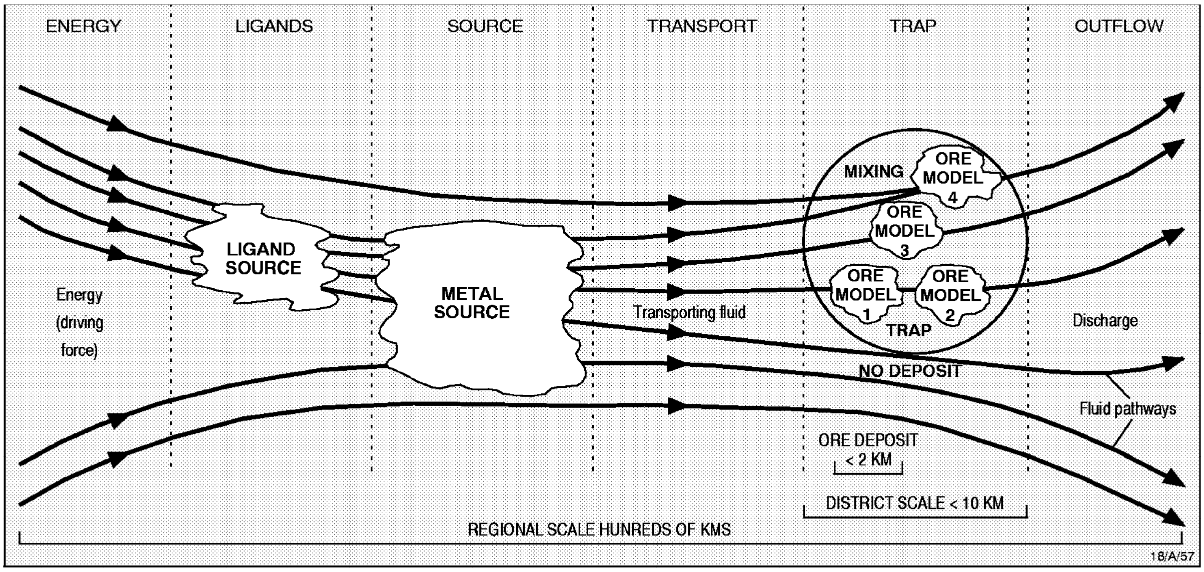


Figure 2.1.2a: the components of a mineral system.

At the start of the project, our understanding of the Australian Proterozoic granite-related mineral system (based mainly on the Pine Creek and Mt Isa Inliers) was that specific granite types and distinctive host rocks tend to be associated with certain types of Au, Cu, Zn, Pb, Sn and W mineralisation. Rarely is mineralisation hosted by the granites: it is more commonly hosted in the country rock several kms from the granite contact. Using whatever data were available the aim of the project was to determine 1) which Proterozoic granites have metallogenic potential, 2) what commodities they may be associated with and 3) where the better host rocks are located for potential ore deposits.

2.1.2.2 The GIS construction

To investigate potential relationships Australia-wide, three data sets were built. The granite data set comprised data for 648 plutons for 60 attributes including field criteria (size, shape, mineralogy, breccication, *etc*) and chemical criteria (~7500 analyses were assessed). Most plutons were grouped into suites and supersuites: these were then divided quantitatively into 9 Associations, based on similarities to known mineralised granite systems (*eg*, Hiltaba Association, Cullen Association, *etc*). The second data set focussed on the host rocks and for 380 units compiled information on 40 attributes including lithology, the abundance of reactive minerals (*eg*, carbonate, graphite, magnetite) and the commodities that occur in these units. Both data sets recorded the age of the unit: if not available a relative age was calculated. The registered number for each unit from the Stratigraphic Names database was included to give a unique identifier to all units Australia-wide. The third data set comprised digital maps of all provinces, at 1:250 000 scale or smaller, highlighting the granite polygons and host rocks within a 5 km buffer from the granite contact. Using GIS techniques, the granite and host rock data sets were joined to the maps and host units that were of an equivalent age to the granite or older were selected and integrated with the MINLOC database to determine which commodities occurred within the 5 kms buffers and whether the mineral occurrences were in preferred host rock types.

In essence, this project was a data-driven, 'bottom-up' exercise in which simple proximity analysis was undertaken to determine which commodities were related to specific granite types. Advantages of this non-model driven approach were that interesting and unexpected relationships were uncovered for subsequent 'forensic' analysed to determine a cause. Although the final model of the Proterozoic granite-related mineral system can be portrayed as a simple cartoon, in reality it is an empirical model built on a scale that has never been attempted before in Australia, if not globally.

3. AUSTRALIAN PROTEROZOIC GRANITE ASSOCIATIONS

As illustrated in Figure 3.1a, Australian Proterozoic granites were classified into 9 major associations (note 8.3% could not be classified due to limited data).

3.1 AUSTRALIAN PROTEROZOIC S-TYPES

S-types comprise only 2.9% by area of the Australian Proterozoic and can be divided into 2 associations, the lower temperature restite-dominated Forsayth Association (2.4%) and the higher temperature fractionated Allia Association (0.5%).

3.1.1 THE FORSAYTH ASSOCIATION

3.1.1.1 The Forsayth Association - type example.

The type example is the *Forsayth Supersuite* in the Georgetown Inlier which includes the Aurora, Delany, Forsayth, Goldsmith, Mistletoe, Ropewalk and Welfern Granites. The Mywyn and Mount Hogan Granites, and the Fig Tree Hill Complex also appear to be part of this Supersuite. Members of this supersuite mostly comprise light to dark grey, biotite granite and granodiorites. Alkali feldspar megacrysts and muscovite are relatively common constituents. Cordierite is reported in the Mistletoe Granite, and metasedimentary xenoliths are common particularly in the Mistletoe, Ropewalk and Forsayth Granites.) U-Pb zircon dates on the Mistletoe and Forsayth Granites are 1550±6 Ma and 1544±7 Ma respectively (Black & McCulloch 1990). Because of the dominance of restite in the melt, the Forsayth Supersuite is not considered to have any metallogenic potential. Although there is a spatial association with Au, Ag, Pb, Zn and Cu deposits and occurrences the mineralisation is believed to be Palaeozoic in age.

3.1.1.2 Forsayth Association - other examples.

The *Potosi Supersuite* in the Broken Hill Inlier comprises the intrusive Alma and Rasp Ridge Gneisses, as well as 'Potosi type' gneisses in the Hores Gneiss and Parnell Formation. Most age determinations obtained are ~1690 Ma including the Hores Gneiss at 1690 ± 5 Ma (Page & Laing, 1992), Alma Gneiss at 1691 ± 12 Ma and Rasp Ridge Gneiss at 1688 ± 18 Ma (Nutman & Ehlers, 1998). The Potosi Supersuite is divided into 3 chemical groups: i) the primary magma, (ii) epiclastic sediments derived from this magma ('Potosi Gneiss'), and (iii) rocks adjacent to the Broken Hill Main Lode (BHML) that have undergone an alteration overprint. The primary magma is characterised by the intrusive biotite-rich Alma and Rasp Ridge Gneisses and rare lavas of the Hores Gneiss and Parnell Formation. These components resemble normal granite compositions and for most elements on Harker diagrams intersect the SiO_2 axis near 77 wt.%. The Supersuite is strongly peraluminous, and ASI values decrease with increasing SiO_2. The Supersuite is reduced and has low levels of incompatible elements (*eg*, Zr <400 ppm, Nb < 35 ppm). The primary magma is unfractionated with no evidence of a change in K/Rb or Rb/Sr ratios with increasing SiO_2. The Potosi Supersuite has no direct relationship to the Broken Hill Main Lode of Pb-Zn-Ag mineralisation.

The *Bradshaw Suite* of the Arnhem Block was emplaced around 1860 Ma and is a poorly exposed sequence of paragneisses, migmatites, granitic gneisses, granites and rare pegmatites that is basement to the McArthur Basin sediments. The Suite outcrops in two main localities: along the Arnhem Bay/Gove Peninsula areas (undivided Bradshaw Complex, Drimmie Head Granite) and the Mitchell Range area (Mirarrmina Complex). This suite is dominated by restite-rich garnet-bearing S-type granites and migmatites. It is too restite-rich to have any metallogenic significance, and there is little evidence of fractionation.

Other examples of the Forsayth Association possibly include the Miltalie Gneiss of the Gawler Craton, part of the Gin Creek Granite (Mount Isa Inlier) and some granites in the northern Gascoyne Province.

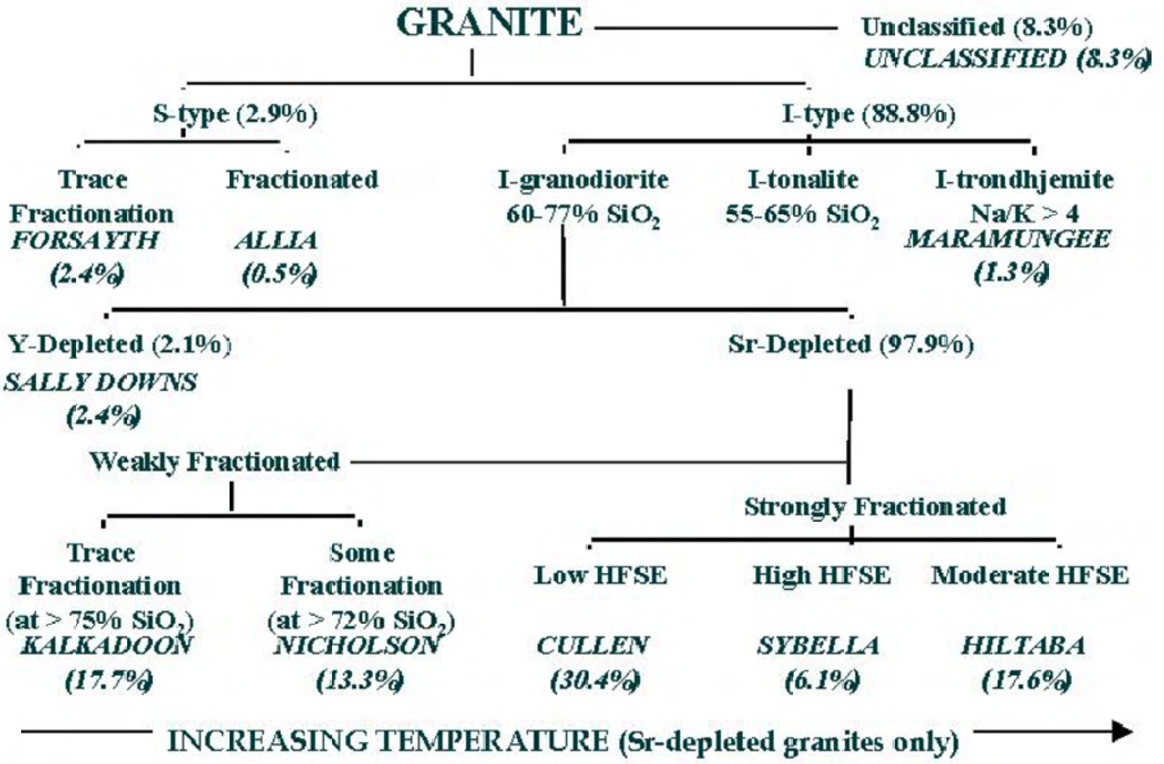


Figure 3.1a: Classification of the various Australian Proterozoic Granite types. Percentages that are in italics represent the area of that particular association as a percentage of the total exposed areas of Australian Proterozoic granites. Subsurface extents of the individual associations have not been taken into account.

3.1.1.3 The Forsayth Association - key points.

The Forsayth Association is a peraluminous, S-type association that is characterised by a high restite component. The ASI values decrease with increasing SiO_2. The source region was dominated by feldspar-rich greywackes. Crystallisation was dominated by separation of resited. There is no significant mineralisation spatially related to this suite.

3.1.2 ALLIA ASSOCIATION

3.1.2.1 Allia Association - type example.

The type example is the *Allia Suite* in the Litchfield Block of the western Pine Creek Inlier and comprises the Two Sisters Granite, Mount Litchfield Granite, Murra-Kamangee Granodiorite, Fish Billabong Adamellite, Jamine Granite, Allia Creek Granite, and Soldiers Creek Granite. Units previously mapped as the Turnbull Bay Granite and the Roberts Creek Granite are now mapped as the Two Sisters Granite. The Allia Suite is around 1840 Ma in age and is clearly S-type, containing peraluminous minerals such as andalusite, cordierite and muscovite. Some members of the suite are characterised by abundant pegmatites which occur both within the granite and which extend out into the adjacent country rocks. Alteration is commonly associated with these phases. Some Sn, Ta with minor Au and W mineralisation is spatially associated with the Allia Suite, in particular the Two Sisters and Soldiers Creek Granites. As a fractionating, reduced, peraluminous granite, the Allia Suite has high potential for further discoveries of Sn given the strong evidence for a amount of late stage pegmatites and the extent of hydrothermal alteration.

3.1.2.2 Allia Association - other examples.

The *Barrow Creek Suite* of the Arunta Inlier, dated at 1713 Ma, is felsic, fractionated, has abundant pegmatite, and is host to several Sn-Ta-W mines. It is comprised of the Bean Tree Granite, and a large, unnamed pegmatite body. The suite trends from reduced to oxidised with fractionation.

The *Harverson Suite*, also in the Arunta Inlier, was intruded at 1820 Ma. It is comprised of the Harverson Granite, the Anmatjira Orthogneiss, Yaningidjara Orthogneiss, and Mount Airy Orthogneiss. The suite is fractionated, felsic, peraluminous, and trends from reduced to oxidised with fractionation. The three orthogneiss are described as coarse-grained grey granitic augen gneisses. The Harverson Granite is described as a leucocratic very coarse-grained/megacrystic/porphyritic grey granite, which is extensively deuterically altered. Pegmatites and aplites are found in all four units. Several copper mines occurrence nearby the Suite, but no tin deposits are known. This is taken to downgrade the potential of this suite for Sn-Ta-W.

3.1.2.3 Allia Association - key points.

The Allia Association is a higher temperature S-type than the Forsayth Association. It contains insignificant amounts of restite and has fractionated extensively. It is associated with Sn mineralisation. ASI values also decrease with increasing SiO_2.

3.2 PROTEROZOIC I-TYPE GRANITES

3.2.1 OVERVIEW

I-types comprise 85.15 % by area of all Australian Proterozoic granites and the majority are I-(granodioritic) types: there are no major suites of I-(tonalitic) types. There is a minor suite of high SiO_2 trondhjemites (Maramungee Association) which comprise 1.3% by area. By far the greater majority of Proterozoic Granites are I-(granodioritic) type. On the basis of mantle-normalised element plots these can be divided into two: those that are Sr-undepleted and Y-depleted (garnet-stable source regions) as opposed to those that are Sr-depleted, Y-undepleted (plagioclase-stable). As noted, this subdivision is essentially between granites derived from source regions at pressures > 10kb (garnet-stable source regions) as opposed to those granites that have been derived from <10 kb (plagioclase-stable source regions) (see Singh & Johannes, 1996a, 1996b; Patino Douce & Beard, 1995).

The Sally Downs Association is the only association of I-(granodioritic) types with Sr-undepleted and Y-depleted signatures and comprises < 2.4% of the total area of Proterozoic granites.

The remaining associations area all Sr-depleted, Y-undepleted indicating that the bulk (85.1%) of Australian Proterozoic granites are I-(granodioritic) types that were derived from plagioclase-rich source regions at pressures < 10 kbar. What this also implies is that they were derived from source regions that are at depths of no greater than 35 kms (Johannes & Holtz, 1996) and had above average geothermal gradients (>25°C per kms). The I-(granodioritic) types can be divided into 5 associations, the Kalkadoon, Nicholson, Cullen, Sybella and Hiltaba. The differences between each association is believed to be controlled by temperature and pressure conditions in the source region.

3.2.2 THE MARAMUNGEE ASSOCIATION

3.2.2.1 The Maramungee Association - type example.

The type example of the Maramungee Association is the Maramungee Suite in the Mount Isa Inlier. Essentially a trondhjemite, the suite is exposed as a small pluton in the eastern part of the Eastern Fold Belt which appears to appears to have been emplaced syn- or just pre-D_2. (Williams & Heinemann, 1993). The Maramungee Suite, comprising the Maramungee Granite is predominantly trondjhemitic with some tonalitic compositions preserved and has a Sr-undepleted and Y-depleted trace element pattern. Although the Maramungee Granite is close to the subeconomic Maramungee zinc deposit, there is no evidence that the granite itself played a direct role in the mineralisation. The granite itself shows no evidence of fractionation, it is of small volume and it is unlikely to play a primary role in any form of mineralisation.

3.2.2.2 The Maramungee Association - other examples.

The *Forest Home Supersuite* comprises the Forest Home and Talbot Creek Trondhjemites in the Georgetown Inlier. The Supersuite consists mostly of grey biotite trondhjemite, and the Forest Home Trondhjemite has been dated at 1550±50Ma (Black & Holmes, cited in Withnall *et al.*, 1988). This supersuite is low in K_2O but high in Na_2O, and is Sr-undepleted, Y-depleted. It has no known genetically associated mineralisation.

The *Alice Springs Granite* is another example of the Maramungee Trondhjemite, emplaced at ~1750 Ma in the Arunta Inlier.

3.2.2.3 The Maramungee Association - key points.

The Maramungee Association is of limited extent and has no significant mineralisation associated with it. It is characterised by a high SiO_2 range (generally > 70 wt. %.) and high Na_2O/K_2O.

3.2.3 THE SALLY DOWNS ASSOCIATION

3.2.3.1 The Sally Downs Association - type example.

The type example is the *Sally Downs Suite* in the east Kimberley region, emplaced between 1830 to 1810 Ma synchronously with major gabbroic bodies and layered mafic/ultramafics (Sheppard *et al.*, 1996). The Sally Downs Supersuite, which intrudes all three zones of the Halls Creek Orogen (Tyler *et al.*, 1995), contains the following plutons: Mabel Downs Tonalite, Sally Downs Tonalite, McHale Granodiorite, Corrara Granite, Grimpy Monzogranite, Mount Fairbairn Granite, and Shepherds Bore Granite. Many plutons show extensive interaction with coeval gabbroic intrusions at their margins (Blake & Hoatson, 1993; Sheppard, 1996). The plutons of the Sally Downs Supersuite were intruded into a wide variety of rock types, many of which would be potential host rocks for hydrothermal mineralisation. The lack of significant mineralisation associated with the Sally Downs Supersuite may be attributed to the lack of evidence of strong fractionation within the granite system. The relatively more mafic tonalitic plutons show strong evidence of restite, particularly in the most mafic end-members. Overall, members of the Sally Downs Supersuite only show weak evidence for fractionation at the high SiO_2 end members. Only one area of significant leucogranite has been identified and that is within the Shepperds Bore Granite: there are no strongly zoned plutons. This would suggest that crystallisation was dominated by restite-unmixing in the initial phases, with the minor fractionation occurring later in the residual fluid after total separation of the restite.

Several small Cu and Au shows and prospects occur within and in the vicinity of members of the Sally Downs Supersuite. The Nicholson Gold mine occurs in this supersuite. Their relationship to any of the granites is not clear, even for those that are hosted by granite and they may be related to later deformation processes. The Mount Amherst gold deposits are quartz vein deposits located within the Grimpy Monzogranite some 70 kms south-southeast of Halls Creek (Jones, 1938). Other gold deposits that are in the vicinity of the Supersuite may not necessarily be related to magmatic processes (*eg*, Warren, 1994a, b; Pirajno, *et al.*, 1994). Witt & Saunders (1996) made an analogy between breccia dykes and hydrothermal alteration described in the McHale Granodiorite approximately 10 kms southeast of Turkey Creek and mineralised porphyry-copper and epithermal environments. However, these authors also noted that many of the small copper deposits are associated with hematite, epidote, and carbonate alteration and appear spatially related to the Halls Creek Fault and suggested that they may be related to movements on this fault system.

3.2.3.2 The Sally Downs Association - other examples.

The *Dougalls Suite* outcrops in the east Kimberley region, mainly on the east part of the Dixon Range 1:250 000 Sheet area. The suite was emplaced along the eastern margin of the Central Zone (Griffin & Tyler, 1992) and includes the Dougalls Granitoid, Corkwood Tonalite, Dead Finish Tonalite, Monkey Yard Tonalite, and the Reedy Creek Tonalite. The suite was emplaced as a series of sheets into the Tickalara Metamorphics at ~ 1850 Ma. The suite consists predominantly of tonalite, trondhjemite, and leucogranite. Most samples are strongly recrystallised and contain mainly plagioclase, quartz, and subordinate mafic minerals. Biotite is the dominant ferromagnesian mineral, with edenitic amphibole and minor clinopyroxene. Chemically the suite has very little evidence of fractionation and due to the occurrence of these granites as narrow sheets, the metallogenic potential is likely to be low.

The *Atnarpa Suite* in the Arunta Inlier was emplaced at 1880 Ma. It is an Sr-undepleted, Y-depleted suite which ranges from tonalite to aplite has unknown potential, due to the difficulty in determining the extent of fractionation in this suite. There are numerous Au occurrences nearby and within this suite, and although some of these deposits have been related to the Palaeozoic Alice Springs Orogeny (Warren *et al*., 1974), some of the gold may be sourced from this suite.

The *Entia Suite* (comprising the Entia Gneiss, and the Huckitta and Inkamulla Granodiorites) was emplaced at ~1760 Ma in the Arunta Inlier.

The *Krackatinny Suite* at ~ 1310 Ma (?) is a Sr-undepleted, Y-depleted suite which crops out as scattered exposures amongst sand dunes in the far eastern part of the Paterson Orogen, mainly on the Tabletop 1:250 000 Sheet area (Bagas *et al*., 1995; Bagas & Smithies, in prep). Data on this suite are very limited but there does appear to be minor evidence of fractionation at high SiO_2 values. The suite appears to intrude rocks of the Rudall Complex and some banded quartz-magnetite-amphibole gneisses occur in the vicinity: these are clearly potential hosts for mineralisation. It is to be stressed that there is insufficient data to confidently recommend this suite for further exploration, but there are enough sufficiently interesting characteristics both in the granite and their hosts to argue that further investigations in this area may be profitable.

3.2.3.3 The Sally Downs Association - key points.

The Sally Downs Association is characterised by Sr-undepleted, Y-depleted normalised element patterns signifying that it has been derived form depths of >10 kbar. It is a minor type in the Proterozoic of Australia and has no significant mineralisation associated with it.

3.2.4 THE KALKADOON ASSOCIATION

3.2.4.1 The Kalkadoon Association - type example.

The type example is the Kalkadoon Supersuite which was emplaced in the Mount Isa Inlier at about 1860 Ma (Wyborn & Page, 1983) and comprises the Kalkadoon Granodiorite, Wills Creek Granite, Woonigan Granite, One Tree Granite, Hardway Granite, Ewen Granite and the Lecihhardt Volcanics. It is classified as I-(granodiorite) type and with its comagmatic felsic extrusives it covers approximately 4600 kms^2. The granites range from biotite ± hornblende bearing tonalite (rare) through granodiorite and monzogranite to syenogranite. The boundaries between each of the main petrographic types is gradational, and there are no major separate leucogranite intrusives. Greisens and pegmatites are extremely rare and any alteration is related to later metamorphic or deformation events. Although the Kalkadoon Supersuite is predominantly overprinted by later metamorphic events, major contact aureoles have not been documented in the lower grade areas.

Considering the size of the system, the members of the Kalkadoon Supersuite are extremely uniform chemically and on chemistry alone the intrusive granite samples cannot easily be distinguished from the comagmatic volcanics. All trends are linear on Harker variation diagrams, and the K/Rb ratio is flat. It has been proposed that the majority of the Kalkadoon Supersuite has crystallised by restite unmixing (Wyborn & Page, 1983) and that the crystallisation process is one of restite (hornblende, biotite, calcic plagioclase) unmixing from a minimum melt component which is dominated by quartz, K-feldspar and albite. To the north in the Dobbyn area, there is some evidence for minor fractionation, possibly caused by the magma losing most of its restite and the remaining melt commencing to fractionate.

There is no significant mineralisation associated with the Kalkadoon Supersuite. Small copper shows are abundant in the upper greenschist or higher metamorphic grades (above biotite) and predominantly occur adjacent to dolerite dykes. They are probably related to metamorphic mobility of Cu within the dolerites (Ellis & Wyborn, 1984). Some Cu in the north near Dobbyn, may be related to the minor fractionation in the granite system. In the Ewen Granite, McDonald & Collerson (1998) have noted fractionation, but unfortunately most of the potential host country rock is covered by later sequences.

3.2.4.2 The Kalkadoon Association - other examples.

The *Nimbuwah Suite* comprises the Nimbuwah Complex (Needham, 1982) of the Pine Creek Inlier and was emplaced at ~1860 Ma (Page *et al.*, 1980). The dominant intrusive rock types are hornblende- and biotite-bearing tonalites, granodiorites, and granites, which are strongly porphyritic in places with K-feldspar phenocrysts. Granitic pegmatites form veins up to 1m wide, commonly interlayered with aplite. These may be derived during metamorphism rather than as a result of magmatic processes as the Nimbuwah Complex has itself been metamorphosed to granulite facies possibly at around 1800 Ma (based on a regional Rb-Sr isochron, Page *et al.*, 1980). The Nimbuwah Suite is dominantly a restite suite with little or no evidence of fractionation. It has no known mineral deposits associated with it, although it could be argued that exploration in this area has been minimal. Uranium deposits in the vicinity are related to post-intrusive hydrothermal events at ~1600 Ma. Because of the dominance of restite, the Nimbuwah Suite is not considered to have any potential.

The *Tennant Creek Supersuite* of the Tennant Creek Inlier comprises the Tennant Creek Granite, Mumbilla Granodiorite, Cabbage Gum Granite, Hill of Leaders Granite, Channinggum Granite as well as various porphyries and volcanics of the Bernborough and Warramunga Formations, the Epenarra Volcanics and the Warrego Volcanics (Donnellan *et al.*, 1995; Blake *et al.*, 1987). Ages range from 1872 to 1837 Ma, with the Supersuite becoming progressively younger towards the southeast (Black, 1984). The Tennant Creek Supersuite is I-(granodiorite) type and is mainly unfractionated, although there is evidence of weak fractionation in the more felsic end members. The mineral potential of the Tennant Creek Supersuite is regarded as low. The supersuite is associated with very minor W mineralisation in the southeast in the Mosquito W field, where the Supersuite is weakly fractionated. Although the Supersuite appears to have no direct relationship to the Au-Cu-Bi mineralisation it may have acted as a possible heat source to enhance the circulation of the basinal brines that formed the ironstone hosts to Tennant Creek Au-Cu-Bi mineralisation.

Other examples include the 1880 Ma Narwietooma Suite and the 1660 Ma Madderns Yard Suite of the Aunta Inlier; the 1700 Ma Biranup Supersuite and the 1190 Ma Nornalup Supersuite of the Albany Fraser Province, and the ~1880 Ma Gerowie and ~1850 Ma Wagait Suites of the Pine Creek Inlier.

3.2.4.3 The Kalkadoon Association - key points.

The Kalkadoon Association is I-(granodioritic) type derived from a plagioclase-stable source at low melting temperatures. It commonly has phenocryst-rich comagmatic volcanics. Being full of restite, it has not fractionated and the association has no significant mineralisation.

3.2.5 THE NICHOLSON ASSOCIATION

3.2.5.1 The Nicholson Association - type example.

The type example of this association is the Nicholson Suite of the Murphy Inlier. The suite is predominantly felsic and comprises the Nicholson Granite and its comagmatic volcanics, the Cliffdale Volcanics (including the Billicumidji Rhyolite Member). There are coeval basic dykes intruding at the same time as these felsic rocks but they are not extensive. Many samples have a regional metamorphic overprint, some up to amphibolite grade. The suite has distinct mappable phases present (Gardner, 1978; Ahmad & Wygralak, 1989). The Nicholson Suite only shows evidence of fractional crystallisation in the high SiO_2 end members when some trends increase/decrease exponentially from > 72 wt. % SiO2. In the more mafic end members, the volcanics and the granites plot very closely together, suggesting that the early stages of this suite were dominated by restite-unmixing, and that fractionation only started to occur after the restite crystals were lost from the magma. The fact that the Cliffdale Volcanics become more phenocryst-poor higher up stratigraphic sections would support this view. As fractionation only begins at relatively high SiO_2 levels, the potential for forming large tonnage deposits is restricted and any ore deposits associated with this suite are likely to be of low tonnage, although they could be of high grade. In the vicinity of the granites there are no significant potential host rocks documented, although graphitic rocks are likely to have been present. Potential exist for small Sn, and W deposits within the granite and for more distal smaller Cu and Au deposits.

3.2.5.2 The Nicholson Association - other examples.

The 1860 Ma Paperbark Supersuite of the Kimberley region is one of the largest felsic granitic events in the Australian Proterozoic. It comprises what was formerly called the Hooper Suite (Griffin *et al.*, 1993) of the West Kimberley region and the Bow River Batholith of the east Kimberley region as well as the aereally extensive Whitewater Volcanics. This study argues that the potential of the granites of the Kimberley Province is limited by the abundance of restite in the granite suites. For the large volume of granite present in the Kimberley Province, no regional or district scale alteration zones have been defined, and aplites and pegmatites are very scarce (Sheppard *et al., in prep*.). Despite the presence of highly reactive rock types (mafic igneous rocks, carbonates, iron formations, carbonaceous shales), which in other provinces host significant granite-related mineralisation, no major Au or base metal deposits have been located either within the granites or the associated country rock. The Paperbark Supersuite is relatively homogeneous over wide areas and there are few major distinctive leucocratic plutons developed within it. The felsic Whitewater Volcanics are phenocryst rich (up to 50% crystals (Gellatly *et al*., 1974a, b)) and are compositionally identical to their comagmatic intrusives (Griffin *et al*., 1993). These factors support the concept that crystallisation of granites of the Kimberley region was largely dominated by restite-separation. Late separation of restite resulted in limited fractionation in the West Kimberleys, particularly in the Lennard 1:250 000 sheet area. There is some evidence that has occurred in the east Kimberleys but more analyses are required of rocks of high SiO_2 contents (>75 wt. %) to confirm this. Because of the dominance of restite in the early phases of the crystallisation, it is expected that any mineralisation would be small.

The ~1850 Ma *Donington Suite* (Gawler Craton) is another example of this association.

3.2.5.3 The Nicholson Association - key points.

The Nicholson Association is compositionally in between the Kalkadoon and Cullen Associations. It is restite-dominated in the more mafic end members, but the restite separates out to allow for some fractionation over a limited silica range. It is associated with small vein deposits of Sn, Cu and W. It is not likely to have significant mineralisation associated with it.

3.2.6 THE CULLEN ASSOCIATION

3.2.6.1 The Cullen Association - type example.

The type example is the *Cullen Supersuite* of the Pine Creek Inlier (Stuart-Smith *et al*., 1993) which crystallised by a process of convective fractionation. It is a typical I-(granodioritic) type with most SiO_2 contents > 68 wt. %. It is a much more complex system than the Kalkadoon or Nicholson Associations. The Cullen Supersuite consists of three major pluton types:

1) Leucogranites
2) Uniform granodiorite to granite suites
3) Concentrically zoned plutons

Greisens and pegmatites are common in the more fractionated leucogranites. Chemical variation within the plutons is controlled by the mineral phases present, particularly hornblende, biotite, muscovite, apatite, zircon and allanite and the relative abundance of these minerals changes systematically with progressive fractionation. Each zoned or granite-dominated pluton has its own mineralogical characteristics, which in some cases are strikingly dissimilar from any other pluton in the Batholith. The Cullen Batholith also has a fairly wide and high temperature contact aureole, implying that the initial emplacement temperatures were relatively high, and that the granite introduced significant heat into the local environment.

Alteration is common although is not necessarily caused by hydrothermal alteration as a result of magmatic processes, as many samples that were analysed and/or dated were both highly deformed and metamorphosed. Deformed samples in the dominant Pine Creek Shear Zone have a definite chlorite grade overprint which is related to younger deformation, whilst samples in the northwest of the system, have a biotite grade overprint.

Compared to the uniformity of the Kalkadoon Association, the chemistry of the Cullen Supersuite is much more complex and consists of several groupings.

Group 1) Leucogranite dominated plutons.

The leucogranite dominated plutons are chemically characterised by having >70 wt.% SiO_2 and can be subdivided into three suites depending on the degree of fractionation with increasing SiO_2.

A) Saunders Suite.

The Saunders Suite consists of two plutons, the Saunders and Foelsche Leucogranites. These granites show no sign of decreasing K/Rb, and when compared to the other two leucogranite suites have relatively small increases in Rb (<240 ppm), Li (<28 ppm), U (<13 ppm), and Y (<26 ppm) with increasing SiO_2. For both plutons the ASI is < 1.1 and the $Fe_2O_3/(FeO + Fe_2O_3)$ is > 0.24. There is no vein mineralisation associated with either of these plutons, and only one alluvial tin occurrence in the vicinity.

B) Burnside Suite:

Plutons of the Burnside Suite include the Burnside Granite, Douglas Leucogranite, Frances Creek Leucogranite and Wandie Granite. These plutons show exponentially increasing Rb (<390 ppm), Li (<102 ppm), U (<35 ppm), and Y (<70 ppm) and decreasing K/Rb with increasing SiO_2. The ASI is still < 1.1 and the $Fe_2O_3/(FeO + Fe_2O_3)$ ranges from about 0.3 to 0.1. Although plutons from this group only have one vein molybdenite occurrence located within granite, the surrounding contact aureoles contain numerous vein Au, Cu, Sn, Ag-Pb occurrences and deposits.

C) Tennysons Suite.

The Tennysons Suite includes the Tennysons Leucogranite, Wolfram Hill, Fenton Granite and Umbrawarra Leucogranite and is characterised by exponentially increasing Rb (<392 ppm), U (<20 ppm), Y (<64 ppm), Li (<90 ppm) and decreasing K/Rb with increasing SiO_2. The ASI is > 1.1 and the $Fe_2O_3/(FeO + Fe_2O_3)$ at < 0.24 is lower than any other pluton or suite in the Cullen Batholith. This suite hosts many vein U, Sn, W, topaz, fluorite and monazite occurrences.

Group 2) Granite dominated plutons.

The more mafic granite dominated plutons can be subdivided by the dominant mafic mineral (hornblende or biotite) in the more mafic samples, combined with the wt.% at which hornblende disappears with increasing SiO_2. The two distinct chemical end members are represented by the hornblende-dominated Fingerpost Granodiorite, which has hornblende present up to 69 wt.% SiO_2, and the biotite-dominated eastern pluton of the McMinns Bluff Granite, in which hornblende is only present up to 64 wt.% SiO_2. At similar SiO_2 values, the hornblende-dominated plutons are enriched in MgO, CaO, Na_2O, Ni, and Cu, and depleted in K_2O, total Fe, TiO_2 and Al_2O_3, Li, Zn, and F relative to the more biotite enriched plutons. Accessory minerals also affect the compositions of the plutons. The early hornblende-rich plutons are low in Zr and P_2O_5 presumably because of late crystallisation of zircon and apatite respectively from the melt. La and Ce are high in those samples that have allanite, which appears to be more common in the biotite-rich coarse granite samples which have ASI < 1.1.

Group 3) Concentrically zoned transitional granite and leucogranite dominated plutons.

Concentrically zoned transitional granite and leucogranite-dominated plutons include the Allamber Springs, Driffield, Bonrook, Tabletop and Shoobridge Granites. These granites contain a wide range of SiO_2 contents. The mafic end members of these zoned plutons show similarities to either the hornblende or biotite dominated suites, whilst the more felsic end members show characteristics of at least one of the leucogranite suites.

With increasing SiO_2, the chemical changes can be summarised as follows:

1) The ASI increases with fractionation, and the rate of increase is accelerated by the crystallisation of hornblende, which has a low ASI. Thus the hornblende-rich Fingerpost Granodiorite has the lowest ASI, and the Tennysons Suite, the most fractionated leucogranite suite, has the highest ASI.

2) The decrease in $Fe_2O_3/(FeO + Fe_2O_3)$ with progressive crystallisation can have at least two possible causes. Firstly, some plutons intrude reduced, carbonaceous sediments and interaction with these reduced sediments may lead to a decrease in $Fe_2O_3/(FeO + Fe_2O_3)$. However, the plutons with the lowest $Fe_2O_3/(FeO + Fe_2O_3)$ are also those with some of the highest ASI values. Dickenson & Hess (1986) argued that the ratio of FeO

to Fe_2O_3 increases with increasing K_2O to Al_2O_3, and thus the transition to more reduced compositions with increasing fractionation may depend on the chemistry of the crystallising phases, rather than on interaction with reduced country rock.

3) The abundance of Ba, Sr, Pb and Rb is in part controlled primarily by feldspar. Ba tends to decrease with increasing fractionation, whilst Rb increases and the K/Rb ratio decreases. With progressive crystallisation of the magma the composition of leucogranites evolves. Initially the leucogranites will be high in Ba and low in Rb, U, Y and other incompatible elements, and will also have a low ASI and high K/Rb (as is observed in the Saunders Suite). As crystallisation progresses, Ba will decrease, and Rb, U, Y and ASI will increase, and K/Rb will decrease (e*g*, Burnside Suite), with the maximum Rb, U, Y and Li and the highest ASI and lowest K/Rb being found in the last and most fractionated leucogranites.

The high and exponentially increasing values of Rb, U, Li and Y and the decreasing K/Rb ratios with increasing SiO2 shown by the Cullen Batholith is characteristic of I-type granitic suites which have undergone chemical fractionation. These exponentially increasing trends as well as the decreasing K/Rb ratios are not found in the Kalkadoon-Leichhardt Suite or its analogues.

The chemical changes within the Cullen System can be related to metallogeny and there appears to be an association of mineral deposit types either within or surrounding particular chemical types. The degree of fractionation within the leucogranite suites controls the associated mineral deposits and occurrences. The Burnside Suite shows signs of fractionation (decreasing K/Rb, some increase in Rb and U) and has most mineralisation types in the nearby contact aureoles. The most fractionated leucogranites group, the Tennysons Suite (ASI > 1.1, Rb, U, Y and low $Fe_2O_3/(FeO + Fe_2O_3)$), has vein mineralisation associated with it, particularly Sn, W and U. In contrast, the Saunders suite is the least fractionated (high Ba, low Rb, low ASI), showing virtually no signs of fractionation: this suite is also unmineralised.

There appears to be an association of mineral deposit types with distance from the granite contact (Stuart-Smith *et al*., 1993). As Cu, Au, Pb, Ag, and Zn deposits are mostly located in the contact aureole, it is difficult to relate some of the more distal deposits to a particular granite pluton especially as Au, Pb and Zn can occur up to 3000 m from the pluton boundary. Precipitation of these metals appears to occur by interaction with a specific host rock rather than a set distance from the contact aureole. Au deposits are hosted by either reduced carbonaceous mudstone or pyritic chert-banded dolomitic host rock in the contact aureole (*eg*, Koolpin Formation, Mount Bonnie Formation), and recent studies on Burrell Formation in the Mount Todd district, highlights the amount of graphite in this unit, and suggest that this unit should be more seriously considered as a prospective host for Au mineralisation. Pb and Zn are predominantly hosted by carbonate-rich rocks (*eg*, parts of the Koolpin Formation). Small Cu deposits are associated with the zoned plutons, particularly those rich in hornblende. Although hosted by similar lithologies to the Au deposits, they are not spatially related to them and are also confined to within 1500 m of granite boundaries.

3.2.6.2 The Cullen Association - other examples.

The *Treasure Suite* occurs in the Tennant Creek Inlier and Davenport Province. It is mainly composed of volcanics, and shallow level intrusive granophyres and porphyries of the Wundirgi Formations, Treasure Volcanics, Arabulja Volcanics, and Newlands Volcanics in the Davenport Province; unnamed diorites to monzodiorites in the Tennant Creek Province and felsic to intermediate volcanics of the Hayward Creek Formation of the Tomkinson Creek Subgroup (Blake *et al.*, 1987; Donnellan *et al.,* 1995). The suite is fractionated, with the more mafic end members preserved in the northwestern Tennant Creek area and the more felsic fractionated members in the southeast. The level of emplacement is also different, with volcanics and granophyres being more common in the southeast. Ages of members of this suite range in age from 1829 to1816 Ma (Blake & Page, 1988). These ages are roughly equivalent to the Ar-Ar ages of muscovite associated with Au-Cu-Bi mineralisation at Tennant Creek, that is 1830-1825 Ma (Compston & McDougall, 1994). With regard to mineral potential, the Treasure Suite is clearly related to the Hatches Creek W field. Dunnet & Harding (1967) suggested a connection between the mafic diorites of the Treasure Suite and the Au mineralisation at Tennant Creek. Not only is Au mineralisation in the Tennant Creek Province similar in age to the members of this suite, the total metal budget in the two deposit types is similar with the Hatches Creek W deposits containing Cu, Co, Bi, Mo with minor U and Sn, whilst the associated elements in the Au deposits at Tennant Creek are Cu, Bi, Mo, Se, Pb, Co, with minor W and Sn (Large, 1974; Ferenczi, 1994). Perhaps the dominance of W in the

Davenport Province may be related to the more felsic compositions and the predominance of extrusive volcanics in the southeast.

The *O'Callaghan's Supersuite* of the Paterson Province, adjacent to the Telfer gold deposit is a fractionating I-(granodioritic) type with obvious potential for mineralisation. The Supersuite has a variable oxidation state, with the earlier intrusions being reduced and the later ones being quite oxidised. The subdivision of Goellnicht *et al.*, (1991) and Goellnicht (1992) into an ilmenite-bearing Mount Crofton type (Mount Crofton Granite, Hansens Folly Granite, Desert's Revenge Granite) and the Minyari type (Koolyu Granite, Minyari Granite, O'Callaghan's Granite) has been followed, although it is argued that the main difference between the granite types is that Mount Crofton type is more oxidised and the Minyari type is reduced. The whole Supersuite is believed to have originally been fairly oxidised at its source region, but the earlier phases were more reduced by interaction with reduced basinal brines. Mineralisation is believed to be related to the more reduced granite types. Although known predominantly as a gold mine, the Telfer mine carries significant Cu, and some base metal skarns have been described in the vicinity of the O'Callaghans Granite. The O'Callaghans Supersuite has obvious potential and is still highly prospective for further discoveries. The area has a unique smorgasbord of a fractionated granite system combined with highly reactive rock types and suitable structures.

The *Granites Supersuite* of the Granites-Tanami Block comprises the Winnecke Granophyre and The Granites Granite. Probable members include the Slatey Creek Granite and the Lewis Granite: on Rb-Sr age determinations these units are much younger, but the initial Sr^{87}/Sr^{86} ratios are anomalously high and may have possibly been reset by subsequent deformation (Blake *et al.*, 1979). Other potential members include any post-Tanami Complex unnamed granites in the northern Tanami Block. The supersuite consists predominantly of non-magnetic, reduced, fractionated, metaluminous rocks. The highly reduced nature of the early phases of this suite is anomalous, as gold-bearing granites are usually assumed to be oxidised and magnetic. It is suggested that the reduced nature of this suite results from the infusion of H_2 from carbonaceous country rocks into the magma early in the magmatic history. With increasing evolution, the Supersuite then became more oxidised due either the H_2 ceasing to be able to pass into the magma chamber from the country rock or because H_2 has diffused into the atmosphere (Czamanske & Wones, 1973; Wyborn, 1983).

The gold deposits in the Granites-Tanami area are hosted by predominantly iron-rich, graphite-rich or sericite/chlorite-rich lithologies. All the deposits appear to be developed from reduced fluids and seem to have pyrite-quartz-sericite alteration associated with the mineralising event. As the majority of granites within the area are reduced fractionating I-types, it seems more than likely that fluids derived from these granites are a component of the mineralising fluids, a suggestion that is supported by fluid inclusion work (*eg*, Tunks, 1996; Valenta & Wall, 1996). There is a possibility that some Sn may be found around the Lewis Granite and there is also potential for W mineralisation. It is also possible that there may be some mineralisation related to the late magnetic phases of the granite, although these will probably have hosts of different composition to those deposits in The Granites-Tanami Block that are associated with reduced fluids. The better known deposits are located in an area where it has been interpreted that the granite intrusions are relatively deep (Blake *et al.*, 1979; Wall, 1989). In the north, the oxidised Winnecke Granophyre has intruded to a much shallower depth and has altered and greisenised its own comagmatic volcanics in the Mount Winnecke Formation. If any mineralisation exists in this area it is more likely to be of an epithermal or porphyry style, and hosted within or close to the volcanics or the granophyre.

It is accepted that the connection to a granite source for the mineralisation could be regarded as tenuous as all known mineralisation is distal to the granites. Ding (1997) has argued that the Granites Gold Deposit is an example of a strata bound pre-orogenic deposit (pre-1980 Ma) whilst Wall (1989) and Valenta & Wall (1996) argue for a granite related model. The point at issue with this study is that The Granites Supersuite shows clear evidence of fractionation and is a type of granite that is similar to those found in both the Pine Creek and Telfer areas. Hence, the granites of this Supersuite must be considered as viable components in any model trying to explain at least some of the controls on the distribution of mineralisation in The Granites-Tanami Block.

Other members of this Association include the 1190 Ma *Kulgera Supersuite* of the Musgrave Block; the 1567 Ma *Southwark*, 1775 Ma *Napperby*, 1680 Ma *Madderns Yard*, 1605 Ma *Iwupataka*, 1713 Ma *Alarinjela* and 1770 Ma *Jennings Suites* of the Arunta Inlier; the 1780 Ma *Kalkan Supersuite* of the Paterson Province, and the ~1800 Ma *Minnie Creek Suite* of the Gascoyne Province.

3.2.6.3 The Cullen Association - key points.

Indirect evidence would suggest that this association is derived by melting at ~800-900°C at <10 kbars. The source was tonalitic and rich in biotite. The amount of restite was minimal, but did include plagioclase and hornblende. Where the members of this association intruded organic rich rocks, the granites became reduced and ilmenite stable (Cullen Supersuite, Granites Supersuite, O'Callaghans Supersuite). This association has only limited comagmatic volcanics possibly because it was more water-rich and crystallised at depth.

There is significant mineralisation associated with this suite, mainly Au, with some Bi, Cu, and W. Where the granites fractionate and become peraluminous, then Sn becomes prominent. The Cullen Association suites/supersuites are never as oxidised as those of the Hiltaba Association, and although Cu can locally be important, it is never as abundant as in mineralisation associated with the Hiltaba Association.

3.2.7 THE SYBELLA ASSOCIATION

3.2.7.1 The Sybella Association - type example.

The type example is the 1670 Ma *Sybella Suite* of the Mount Isa Inlier which consists of series of elongate plutons which extend meridionally for 180 kms and cover 1600 km^2. Four main phases are recognised: a main phase, β-quartz phase, micrograntes, and pegmatites (Wyborn *et al*., 1988). The suite also includes the Caters Bore Rhyolite.

The Sybella Suite was emplaced some 60 Ma prior to the main deformation and metamorphic events that affected the Western Fold Belt; the suite was affected by this deformation. Greenschist grade rocks occur only in the north and northwest whilst most of the remainder of the suite and its country rocks are amphibolite grade. Despite the metamorphic overprint the original primary rock types can be discerned. The main phase ranges from a granodiorite to an alkali-felspar granite and is even grained to porphyritic, with coarse K-feldspar augen up to 30 mm in length. Particularly in the felsic compositions, rapakivi textures are common with individual K-feldspars having albite or oligoclase rims. Plagioclase, biotite, hornblende (ferrohastingsite), apatite and titanite are common to both phases: fluorite is ubiquitous. The Sybella Suite is dominantly pink to grey in colour, reflecting the relatively high oxidation state. Microgranites are most common in the northeastern part of the Suite where they contain abundant metasedimentary xenoliths. They are hornblende-free and contain more K-feldspar and less ferro-magnesian minerals than the main phase or the β-quartz phase.

The Sybella Suite has a more restricted silica range than any of the other Associations, varying from 68 to 78 wt.% SiO_2. The main phase and the β-quartz phases can be distinguished in that at the same SiO_2 levels, the β-quartz phases has higher Ba, Sr, MnO, Nb, La, Ce, Zr and Y, and lower Al_2O_3, Th, Rb and Pb. Both have higher TiO_2, Fe, K_2O, P_2O_5, Th, U, Zr, Nb, Y, La, and Ce and lower Al_2O_3 and Sr contents than the pre-1820 Ma Mount Isa granites. Also some elements, *eg* Th, F, Rb and U show exponentially increasing trends with increasing SiO_2, suggesting that the Sybella Suite evolved by fractionation. Rapakivi textures may have developed as a result of increasing F in the melt: such an increase would cause the ternary minium during crystallisation to move towards albite (Manning, 1981; Pichavant & Manning 1984).

From mineralogy and chemistry we infer that the main and β-quartz phases of the Sybella Suite are fractionated I-types. The greater chemical variations within the Suite contrast with the more uniform compositions of the Kalkadoon Supersuite, which is thought to have crystallised by a process involving the separation of restite from a minimum-melt liquid. Crystallisation of the phases of the Sybella Suite on the other hand was dominated by fractional crystallisation from a predominantly liquid magma. Despite this the only mineralisation associated with the Sybella Suite are the Sn and Be pegmatites in the Mica Creek Area. Most of these are thought to be formed during regional metamorphism and are unrelated to the magmatic processes. However, some of these granites are believed to have been the source for U mobilised during later deformation events.

3.2.7.2 The Sybella Association - other examples.

The *Argylla Suite* is mainly extrusive and was emplaced in the Mount Isa Inlier from about 1810 to 1746 Ma. The suite comprises volcanics of the Argylla and Bottletree Formations, and the intrusive Bowlers Hole Granite and the Mairindi Creek Granite. This suite is predominantly a volcanic suite and the granites contain quartz, K-feldspar, plagioclase, biotite ± hornblende. Chemically they have a restricted SiO_2 range and have anomalously high concentrations of High Field Strength Elements (HFSE) such as Zr, Nb and Y as well as F. The Argylla Suite is probably a genuine A-type suite, is predominantly volcanic, and because of these factors is not considered to have significant metallogenic potential.

The *Wonga Suite* is a group of granites and volcanics emplaced into the Kalkadoon-Leichhardt Belt and the Eastern Fold Belt of the Mount Isa Inlier (Blake, 1987) during a major early extensional event between 1760 Ma and 1720 Ma (Holcombe *et al.*,1992; Passchier, 1986). Holcombe *et al.* (1992) and Pearson *et al.* (1992) divided the granitic intrusives in the Mary Kathleen Fold Belt into two types: lower plate and upper plate intrusives. Holcombe *et al.* (1992) and Pearson *et al.* (1992) proposed that the lower plate intrusives were emplaced as elongate sills in the lower plate of a major midcrustal extensional zone, and the lower plate intrusives are equivalent to the Wonga Suite whilst the upper plate intrusives are equivalent to the Burstall Suite (see Hiltaba association section for a full description of these). The Wonga Suite comprises the Birds Well Granite, Bushy Park Gneiss and as yet undefined named units of the Wonga Batholith on the Mary Kathleen, Marraba, Prospector and Quamby 1:100 000 map sheet area (Mount Maggie Granite, Natalie Granite, Scheelite Granite, Winston Churchill Granite) which mainly intrude the Argylla Formation. The individual granite intrusions are all heterogeneous implying that the melts never homogenised. The more dominant intrusive type is a coarse-grained strongly porphyritic granite with minor even-grained granite and leucocratic alkali feldspar granite: alteration is not all that common. Minerals present are quartz, K-feldspar, plagioclase, biotite ± hornblende: accessory minerals include titanite, apatite, zircon, fluorite, allanite and tourmaline. Pegmatites are common and contain quartz, feldspar ± tourmaline. Plutons of the Wonga Suite are elongate, heterogeneous and high in F and they are possibly in part comagmatic with the Argylla Suite. There is no significant mineralisation associated with this suite. The high F-content of these granites combined with the small size of the intrusions and the lack of suitable host rocks downgrades the potential of this suite.

The *Fiery Supersuite* of the western Mount Isa Inlier comprises the Fiery Creek and Peter Creek Volcanics, unnamed granophyres and the high level 1678 Ma Weberra Granite (Wyborn *et al*., 1988). The intrusives are mainly non-porphyritic medium to coarse-grained syenogranite to alkali granite. An alteration overprint is very pervasive throughout this supersuite and the primary igneous geochemistry is difficult to ascertain with confidence. Even allowing for the extensive alteration overprint, the members of this supersuite do not appear to have undergone any significant magmatic fractionation which would allow for the concentration of significant amounts of Au or base metals.

The *Devils Suite* of the Tennant Creek/Davenport Province, intruded at ~1710 Ma, is an extremely fractionated, oxidised, fluorite-bearing I-(granodiorite) type which is associated with minor vein-W mineralisation. The suite comprises the Devils Marbles, Elkedra and Warrego Granites. It has a high and limited SiO_2 range and has abundant evidence of late magmatic-hydrothermal alteration, both within the granite and for some distance into the surrounding country rocks. The Rb and Rb/Sr increase rapidly and exponentially with increasing SiO_2. The related thermal event has also caused considerable isotopic disturbance of the ore deposits in the northwestern part of the Tennant Creek Province (Black, 1977; Compston & McDougall, 1995), but no significant mineralisation events have been attributed to this suite. Although Stoltz & Morrison (1994) considered the Warrego Granite to be genetically related to the Au-Cu-Bi mineralisation in the Warrego deposit, Wedekind and Love (1990) showed that the Warrego Granite contact metamorphosed the deposit. Despite the abundant evidence of release of late magmatic fluid, the suite is only considered to have limited potential for vein W. Although cassiterite was found in ubiquitous quantities in stream sediments (Hoatson & Cruickshank, 1985) and alluvial Sn has been extracted from streams draining the Wauchope W field, the highly oxidised nature of the granite means Sn will probably occur as disseminated cassiterite within the granite itself rather than forming in late veins.

The *Jim Jim Suite* was emplaced in the Pine Creek Inlier at ~1825 Ma. It comprises the Jim Jim, Malone Creek, Tin Camp, Grace Creek Granite, Eva Valley, Yeuralba and Nabarlek Granites and volcanics of the Edith River and parts of the El Sherana Groups (Gimbat Ignimbrite of Jagodzinski, 1991, 1992). This suite occurs in the eastern part of the Pine Creek Inlier mainly along the western border of Arnhem Land. The suite appears coeval with the Cullen Supersuite, but has some distinctive characteristics. The Jim Jim Suite contains both granites and volcanics and represents a significant felsic magmatic episode. All plutons show evidence of a shallow level of emplacement, with some grading into volcanics and others showing evidence of faulted contacts that are filled with quartz breccias. The late fractionated phases have associated greisens and abundant late stage alteration. Because of the high level of emplacement, only minor hornfelsing has been recorded at the contact. The suite is dominated by more felsic end-members. Significant fractionation has taken place above about 74 wt.% SiO_2 and the values of Rb, U, Y and F increase exponentially to relatively high levels with increasing SiO_2. Compared with other felsic igneous suites in the Pine Creek Inlier, the Jim Jim suite is predominantly oxidised. Although there is evidence of late stage magmatic fluids, there is little interaction with the adjacent country rocks. Some mineralisation appears to be related to late stage fractionation, after separation of the restite. The main commodities associated with this suite are Sn, W and minor Au. Although there is evidence of fractionation and the presence of late magmatic fluids, the limited silica range over which the fractionation has occurred, combined with the presence of fluorite would lower the potential of this suite and help explain the limited associated mineralisation.

The *Giddy Suite* was emplaced into Arnhem Block at ~1835 Ma and comprises the Bukudal, Giddy, Garrthalala and Dhalinybuy Granites (Madigan *et al.*, *in prep*). Granites of this suite are unusually high iron, relatively anhydrous, fayalite-bearing granites, and contain abundant fluorite. Chemically the suite has a high and limited SiO_2 range and have undergone fractionation to high levels of Rb. The suite is considered to only have limited potential for Sn, Mo and W.

The *Fagan Suite* was emplaced progressively over about 20 Ma from ~1720 to 1700 Ma and is widely distributed throughout the McArthur Basin from the Murphy Tectonic Ridge to the eastern Pine Creek Inlier. The felsic magmas of this supersuite are predominantly coarse porphyritic quartz-feldspar rhyolites emplaced as high-aspect ratio lava domes and flows (Hobblechain Rhyolite, West Branch Volcanics, Fagan Volcanics, Yanungbi Volcanics: Rawlings, 1994) and only has three small granites associated with it (Latram Granite, Jimbu Granite and Packsaddle Microgranite). The metallogenic potential of this supersuite is not rated highly. The intrusives are mostly small high-level granites that intrude their own comagmatic ejecta. They are not strongly fractionated, although they do contain high levels of high field strength elements.

The ~1710 Ma felsic igneous rocks from Olary and Broken Hill Domains comprise leucocratic quartz-albite gneisses which include granites, volcanics and related epiclastics. In the Olary Domain they occur in the 'lower albite' unit of the quartzofeldspathic suite and the 'upper albite' unit of the calcsilicate suite. Age determinations include the Ameroo Hill metagranitoid at 1703 ± 6 Ma, a felsic metavolcanic near Abminga Station dated at 1699 ± 10 Ma (Ashley *et al*., 1996) and a similar metavolcanic near Weekeroo station dated at ~1710 Ma. In the Broken Hill Domain, this suite is represented by high Zr and Nb 'leucocratic quartz + plagioclase' rocks of the Thackaringa Group, Ednas Gneiss and Redan Gneiss. The ~1710 Ma rocks are leucocratic, high in silica and are usually albitic, although there are gradations into types with appreciable K-feldspar. They have high Zr (326-640 ppm), Nb (34-93 ppm), and Y (70 - 285 ppm) contents and have been termed 'A-type' by Ashley *et al.* (1996). The Rb and Rb/Sr increase rapidly and exponentially with increasing SiO_2. Due to pervasive albitisation most samples have $Na_2O \gg K_2O$ and high $Fe_2O_3/(FeO+Fe_2O_3)$ ratios. The alteration also affects other feldspar-bearing metasedimentary units within the host sequences, and hence not all quartz + albite rocks are of igneous origin. No direct economic significance is attached to these ~1710 Ma igneous rocks. However, in the Olary Domain there is a spatial association with exhalative iron formations and related barite-rich rocks, as well as with epigenetic ironstones. The iron and barium-rich rocks locally host Cu-Au mineralisation: it is equivocal as to whether Cu-Au was deposited syndiagenetically or whether it is due to an epigenetic event (Ashley *et al*., 1996).

The *Ennugan Mountains Suite* of the Arunta Inlier was emplaced at 1600 Ma, and is enriched in HFSE. It contains abundant fluorite, and has several tin, tantalum and uranium occurrences associated with it. It has moderate potential for further tin, molybdenum and tantalum occurrences.

The *Jinka Suite* of the Arunta Inlier, emplaced at 1713 Ma, is felsic, fractionated, enriched in the heat-producing elements, shows evidence of a fluid phase, is an I-type, and is associated with known mineralisation. It is also a high fluorine suite, associated with known fluorite and scheelite deposits, and has high potential for further tungsten, tantalum and molybdenum deposits.

Other possible examples of this suite include the *San Sou Suite* (Kimberley region), ~1670 Ma granites of the Gascoyne region and the *Winburn Suite* (Musgave Block).

3.2.7.3 The Sybella Association - key points.

The Sybella Association is enigmatic. It is clearly fractionated but does not have any significant mineralisation associated with it, other than small vein Sn and W deposits. It has high concentrations of HFSE and a limited SiO_2 range. The exponentially increasing Rb and Rb/Sr with increasing SiO_2 contents are usually taken to indicate fractionation and hence mineral potential. All I-(granodioritic) intrusions that are spatially related to mineralisation show these exponentially increasing Rb, U and Rb/Sr with increasing SiO_2 to some extent, but from the Sybella Association it is quite clear that the converse is not true, that is, not all granites with exponentially increasing Rb, U and Rb/Sr are mineralised. Metallogenically it is critical to try to develop some empirical criteria to distinguish fractionating barren granite suites from mineralised ones. As noted previously, Collins *et al*. (1982) introduced the term 'A-type' for a particular type of granites that had low Al and Ca contents, high FeO/MgO and $(Na_2O + K_2O)/Al_2O_3$ and high HFSE concentrations. The Sybella Association fit these criteria, and can be distinguished from the Hiltaba Association by higher HFSE contents and a more restricted SiO_2 range which is usually >70 wt.%. Based on experimental work, Patino Douce (1997) has suggested that these so-called 'A-type' characteristics can be generated shallow ($P \leq 4$ kbar) dehydrating melting of hornblende- and biotite-bearing tonalites and granodiorites. This leads to a residue dominated by plagioclase + orthopyroxene. Given the H_2O-poor nature of the proposed source region, and the limited SiO_2 range of both the source and the resultant magma, it is perhaps easy to rationalise why these granite systems are not mineralised (even though it is accepted that distinguishing the members of the Sybella Association from the more felsic end members of the Hiltaba Association is not easy!!).

The other important feature of the Sybella Association is that although in some regions (in particular the Devils Suite in the Tennant Creek/Davenport 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, there is no significant associated Au or Cu mineralisation. For those that argue that all that is needed is a hot granite to release a fluid phase into the country rock and the metals will be mobilised from the country rock, this may pose a problem. Further, these granites are enriched in radiogenic elements such as K, Th and U. Again, for those that propose circulation of meteoric fluids driven by radiogenic heat as a mechanism for generating Au mineralisation, there needs to be an explanation as to why these granites are barren.

3.2.8 THE HILTABA ASSOCIATION

3.2.8.1 The Hiltaba Association - type example.

The type example of this association comprises volcanics and granites of the *Hiltaba Suite* (Drexel *et al*., 1993) which occur throughout the Gawler Craton, and probably extend to the Curnamona Province including the Olary Domain. The Hiltaba Suite can be divided into two types, the Roxby Downs type and the Kokatha type (Budd *et al*., 1998).

The Roxby Downs type is composed of the following recognised granites - Moonta monzogranite (Drexel *et al*., 1993), Charleston Granite, granite at Cultana, Hiltaba Granite, Tickera Granite, Arthurton Granite, granite in the Olympic Dam area (including the Roxby Downs Granite, and Wirrda and White Dam subsuite), and granite in the Nuyts Archipelago area. The Balta and Calca Granites have no available geochemical analyses, but they are probably of this type. The Lower Gawler Range Volcanics ("development" phase of Stewart, 1992) is comagmatic with this type. The Roxby Downs type includes granite, syenogranite, quartz monzodiorite, quartz monzonite, syenite, aplite, monzogranite, and leuco-tonalite. Coarse-grained, porphyritic and megacrystic varieties are common. In comparison to the Kokatha type, granites of this type are commonly altered, contain haematite and magnetite, and are a distinctive brick-red colour. The Roxby Downs type is more enriched in Rb and the high field strength elements (HFSE), U, Th, Zr, Nb, and Ce, and is more fractionated. It is mostly metaluminous, and strongly oxidised, evolving to magmatic compositions in which haematite was the stable iron oxide. The Lower Gawler Range Volcanics is magnetite-stable (Stewart, 1992), and ranges in composition from basalt and andesite to dacite, rhyodacite and rhyolite with a variable silica gap between the tholeiitic basalt-andesite series and the felsic series. Felsic lithologies are dominant.

The Kokatha type is composed of the following recognised granites - granite in the Kokatha, Tarcoola, Kingoonya, Kychering Rockhole, Minnipa, Wudinna and Buckleboo areas. The Upper Gawler Range

Volcanics ("mature" phase of Stewart, 1992) is comagmatic with this type. The Kokatha type comprises syenite, granodiorite, monzogranite, and granite (*sensu stricto*). Grainsize varies from medium to coarse with porphyritic textures common. The granites are white to pink, and pyrite is a common accessory, indicating that they are more reduced than the Roxby Downs type. The type is less fractionated (lower Rb, U, Nb and Ce at equivalent wt.% SiO_2 than the Roxby Downs type, and mostly peraluminous. The Upper Gawler Range Volcanics comprises flat-lying sheets of massive porphyritic dacite and rhyodacite, and has more extensive outcrop than the Lower Gawler Range Volcanics (probably overlies much of the Lower Gawler Range Volcanics), and is ilmenite- and titanomagnetite-bearing (Stewart, 1992). Both suites of granites contain common accessory fluorite and apatite.

The more oxidised Roxby Downs type is associated with Fe-oxide Cu-Au deposits such as Olympic Dam (Johnson & Cross, 1995), Moonta-Wallaroo (Conor, 1996) and the Acropolis, Wirrda Well, Emmie Bluff, Oak Dam and Murdie deposits described by Gow *et al*. (1994). The less oxidised Kokatha type is associated with vein Au(±Sn±Ag) deposits such as at Earea Dam (Daly, 1993a), Glenloth (Daly, 1993b), Tarcoola (Daly *et al*., 1990), along with recent discoveries on the Yarlbrinda Shear Zone (Martin, 1996).

3.2.8.2 The Hiltaba Association - other examples.

The *Williams Supersuite* of the eastern Mount Isa Inlier, comprising the major part of Williams and Naraku Batholiths, was emplaced between 1560-1480 Ma (Wyborn *et al*., 1988b). The batholiths outcrop over at least 2400 kms^2 and contain a minimum of two ages of granite intrusions. The Supersuite is extremely heterogeneous, and three important genetic variables determined mineralogical and chemical variations: (1) primary magmatic variation, (2) chemical interaction with the adjacent country rocks, and (3) regional metasomatic alteration. The Williams Supersuite consists of a series of compositionally distinct I-(granodioritic) type intrusions, is believed to have crystallised by convective fractionation, and comprises a composite suite of zoned plutons, mafic plutons, and predominantly high-SiO_2 fractionated plutons. The more mafic granites are dominated by biotite + hornblende + magnetite, and most granites tend to be reddish-pink owing to hematite-dusted K-feldspar.

In the higher SiO_2 parts of the Williams Batholith, K-rich aplite dykes are present: where they intrude the more mafic phases, they are either associated with massive hematite dykes at the contact, or else there are zones of granite breccias with hematite and/or quartz as the dominant mineral in the matrix. Where these high-SiO_2 plutons intrude calc-silicates, albitites dykes and pipes are common in the granites, extending into the adjacent country rock. Regionally developed breccias in both the granite and the country rock are also associated with the high-SiO_2 granites. Some of these breccias may be related to faulting, *eg*, some of the bodies present along the Cloncurry Fault Zone on the Selwyn Sheet area. However, most of the breccias on the Mount Angelay and Cloncurry Sheets are interpreted to have developed in the roof zone of the batholiths. These breccias extend over a strike length of 80 kms.

Mineralogical and chemical interactions between the country rock and the granite are widespread. Where the granite intrudes calc-silicate rocks, a 'skarn-like' assemblage is produced and the granite is white, consisting of albite + clinopyroxene + red- brown euhedral titanite. In contrast, where the granite intrudes carbonaceous sediments, particularly those of the Kuridala Formation, the granite is green, and sulphide, rather than magnetite becomes the dominant opaque phase.

'Red Rock' alteration is widespread in the granites and country rocks, but appears more common at the contacts between the high-SiO_2 granites and the breccia zones. The alteration can be of two types: either the rocks are high in K_2O and low in Na_2O, or they are high in Na_2O and low in K_2O. Boundaries between fresh granite and both alteration types are very sharp. These altered rocks also have more elevated Fe_2O_3:FeO ratios than the unaltered granites. There appears to be a progression in alteration with early high K alteration (rocks are pale pink to dull red) overprinted by high-Na_2O albitites (rocks are generally white in colour) overprinted by late very high-K_2O alteration (these rocks are deep brick red and nearly always carry sulphides). The alteration does not appear to be a potential indicator of mineralisation, as it is everywhere (particularly the late K-rich sulphide-bearing type). It also appears to be most intense near areas of calc-silicates, which in turn are nearly devoid of any significant mineralisation.

Au, Ag, Cu and U deposits (Osborne, Ernest Henry *etc*) are located either within granites of the Williams Supersuite, or in the adjacent country rocks. Skarn-like (magnetite-rich) rocks are a common host for Cu-Au mineralisation, but they replace silicate, rather than carbonate rocks. Units containing pure carbonate or calc-silicate rocks are relatively barren.

The ~1740 Ma Burstall Suite intrudes the Mary Kathleen Zone of the Mount Isa Inlier and consists of a series of comparatively small plutons (Mount Godkin Granite, Burstall Granite, Overlander Granite, Mount Erle Igneous Complex, Revenue Granite, Saint Mungo Granite and possibly the Myubee Igneous Complex). There is a north-south zonation of pluton types with more mafic plutons in the northern- and southern-most parts of the Mary Kathleen Zone and the felsic, more fractioned plutons (Overlander and Burstall Granites) in the central part. There is a clear spatial association with members of the Burstall Suite with a series of small but rich Cu-Au deposits including Duchess (Cu-Au-Ag), Trekalano (Cu-Au-Ag) and Revenue (Cu-Au). With the exception of the Saint Mungo Granite and the Myubee Igneous Complex, members of the Burstall Suite are oxidised. The Saint Mungo Granite, which is relatively reduced, is the closest pluton to the Tick Hill Au deposit. There is further potential for Cu-Au deposits, and although these are likely to be of low tonnage, they have the potential to be of high grade. Although speculative, it is possible that epithermal-style Au deposits may be found within these sediments, related to the fractionating magmatism of the Burstall Suite (particularly as some of these sediments contain graphitic schist).

The *Esmeralda Supersuite* of the Georgetown Inlier comprises the Esmeralda, Nonda, Mooremount, Little Bird, Macartneys, Olsens, Dregger and Bimba Granites, and is comagmatic with the Croydon Volcanic Group. The suite comprises granites and monzogranites with lesser granodiorites. A feature of the granites is the presence of locally abundant graphite inclusions. The supersuite is felsic, fractionated, reduced to oxidised, weakly peraluminous to peraluminous, and hydrothermally altered in parts. Traditionally, this supersuite has been classified as a S-type granite, mostly because of its high Aluminium Saturation Index (ASI). Quite a few of the samples have ASI between 1 and 1.1 (*i.e.*, are weakly peraluminous), and show what may be described as an increasing trend with increasing SiO_2. This trend is typical of that seen in other strongly fractionated Australian Proterozoic I-type granites (such as the Kokatha type of the Hiltaba Suite). Hornblende was found in two samples of the Esmeralda Granite by Sheraton & Labonne (1978), which they considered to be relict primary hornblende. The oxidation state of the granites is another factor which is inconsistent with the granites being S-type. S-type granites are most commonly reduced, and this has led to the belief that the Esmeralda Supersuite is S-type. However, several of the granites and volcanics are oxidised, while the others are reduced. This change may be the result of an oxidised magma assimilating the locally-abundant graphitic sediments, and becoming more reduced.

The Esmeralda Supersuite is spatially related to the Sn deposits of the Stanhills and Mount Cassiterite areas and to the Croydon goldfield, although there is considerable debate about the age of the Au mineralisation. Bain *et al*. (1990) suggested that Au-bearing quartz vein deposits such as the Golden Gate lode in the Croydon goldfield are likely to be Proterozoic, as they are associated with extensive areas of hydrothermal alteration that appear to be related to Croydon Group volcanism, and there are no nearby Palaeozoic igneous rocks. Denaro *et al*. (1997) also support the Proterozoic age and state that the nature of the gold lodes suggests that ore deposition was post-magmatic into fractures and faults within the consolidated Croydon Volcanic Group and Esmeralda Granite. The lodes have been classified as plutonic veins by Morrison & Beams (1995). In contrast, some workers have interpreted these deposits as Palaeozoic in age, based on the structural setting and K-Ar ages of alteration of the Esmeralda Granite and sericite alteration (*eg* Lawrie *et al*., 1998). Henderson (1989) considered these ages to be a Carboniferous to Permian thermal event superimposed on earlier Proterozoic mineralisation and alteration.

The *~1590 Ma Regional Suite* (Cook *et al*., 1994, Wyborn *et al*., 1998) is one of the most extensive suites in the Olary Domain and comprises the so-called 'regional S-type suite'. Age determinations include the Triangle Hill granite at ~1590 Ma and 1570-1580 Ma for granites of the Crockers Well area (Cook *et al*., 1994; Ludwig & Cooper, 1984). Inherited zircons are common (Cook *et al*., 1994), as is typical of peraluminous magmas. Igneous rocks of the ~1590 Ma event comprise fractionated, magnetite-bearing magmas. Although the rocks are peraluminous and muscovite bearing, ASI values positively correlate with SiO_2, as is more characteristic of I-type magmas. The Rb/Sr ratios exponentially increase to high values of 20, indicating significant fractionation. Although the ~1590 Ma intrusions have intimate relationships with composite gneiss and migmatite, mineralogically and geochemically they are also very similar to the more fractionated, peraluminous muscovite-bearing varieties more reduced Kokatha type of the Hiltaba Suite of the Gawler Craton. The ~1590 Ma intrusions are clearly related to U-Th-REE mineralisation at Crockers Well and have a spatial relationship to deposits such as Walparuta, Kalkaroo and Portia. Further work is required to confirm if these ~1590 Ma rocks (or even the 1630-1640 Ma rocks) are magmatically similar to the Hiltaba Suite, which is related to the Olympic Dam Cu-Au-U deposit. In the Olary Domain it is desirable to determine if late plutons visible in gravity and aeromagnetic images as lows, are more felsic fractionated end-members of the primary magma or else are more mafic end-members that have reduced from magnetite- to ilmenite/titanomagnetite-stable assemblages. In the Hiltaba Suite this redox change distinguishes between hematite-stable Cu-Au systems and less oxidised, more Au-rich systems. The 1590 Ma Suite in the Olary Domain does not seem to fractionate through to the oxidised hematite-stable granites that occur in the Roxby Downs type of the Hiltaba Suite. Interestingly Skirrow & Ashley (1998) noted that the deposits of the late Cu-Au deposits of the Olary region are not as oxidised as the ore-stage conditions at Olympic Dam.

The ~1640 Ma *Mount Webb Suite* (Wyborn *et al.*, 1998 - reproduced in this volume) in the western Arunta Block comprises the Mount Webb Granite, and felsic volcanics of the Pollock Hills Formation and the Kintore Volcanics. It is a fractionated granite system, which has extensive alteration effects including sodic-calcic, sericitic and hematite-K-feldspar in the granite and evidence of metallogenically significant hydrothermal interaction with the country rock. The Mount Webb Granite itself is heterogeneous, comprising several types of unaltered granite, sodic-calcic-altered granite, sericite-altered granite, and aplite. Essentially unaltered granite ranges from mafic diorite/tonalite through granodiorite, monzogranite (dominant), and syenogranite, to aplite. Some late felsic fractionated phases contain fluorite and nodules of tourmaline ± quartz. These rocks have a typical I-type mineralogy, and are composed of hornblende, biotite, magnetite, plagioclase, K-feldspar, and quartz. Magnetite, generally with exsolution lamellae of ilmenite, is common in most samples, but is more abundant in the diorite/tonalite; sulphides are extremely rare. Rimming of the magnetite by titanite is one of the tangible effects of alteration. Sodic-calcic alteration is characterised by the assemblage diopside + epidote ± tremolite (only present in the more deformed samples). Neither sulphides nor anomalous concentrations of elements are apparent in the samples. Sericite alteration is more restricted than the sodic-calcic alteration, and is usually associated with brecciated and fractured granite cut by quartz veins with open spaces. A higher modal abundance of sulphides accompanies this type of alteration.

Recent exploration results have confirmed that this truly 'greenfields' area may have some economic significance. Semicontinuous rock-chip sampling returned results of 9.1% Cu, 3 g/t Ag, and 0.38 g/t Au over a true width of 4 m, and 0.3% Cu and 8 g/t Ag over a true width of 10 m. An aircore-drilling program has confirmed the presence of three Cu-Au-Ag anomalous areas, of which the largest returned peak values of 0.21 ppm Au and 896 ppm Cu on three adjacent 800-m-spaced grid lines (Aurora Gold Ltd, quarterly report, December 1997).

3.2.8.3 The Hiltaba Association - key points.

The Hiltaba Association contains a spectrum of granite types from oxidised, hematite to magnetite-stable suites (Roxby Downs type of the Hiltaba Suite, Williams Supersuite, Burstall Suite, Mount Webb Suite) to more reduced, magnetite to ilmenite stable suites (Kokatha type of the Hiltaba Suite, 1590 Ma Olary Regional Suite, Esmeralda Supersuite). Cu-Au is spatially associated with the more oxidised type, whilst Au-Sn is with the more reduced type. More than any other Proterozoic granite Association, mineralisation is, in places, found to occur *internal* to the granites. The Hiltaba Association is believed to be derived at high temperatures (>1000°C) (Creaser & White, 1991) from breakdown of amphibole in the source region. The members of the Hiltaba Association always seem to occur late in the history of any terrain that they occur in.

At higher crustal levels the suites can become reduced by either interaction with reduced rocks and/or fractionation processes. The Kokatha type is believed to become more reduced when the earlier Roxby Downs type fractionated through to more peraluminous compositions. If this happens whilst the magma is still crystallising ferromagnesian minerals it is possible for the magma to become more reduced due to the instability of Fe^{3+} in peraluminous melts (Dickenson & Hess, 1986). It is clear therefore in the Australian Proterozoic Cu is associated with high temperature, oxidised granitic melts that are late in the history of any province/terrain.

4. A SYNTHESIS OF AUSTRALIAN PROTEROZOIC GRANITES: BROAD CHARACTERISTICS, SOURCES AND POSSIBLE MECHANISMS FOR DERIVATION AND EMPLACEMENT.

The results in the preceding section can be summarised as follows. Most Australian Proterozoic felsic melts were emplaced between 1880 to 1500 Ma, with minor episodes occurring between 1200 to 1050 Ma and at 600-700 Ma. I-type granites predominate. S-types are a minor component and comprise <3 % of the total area of granite exposed. Although I-type granites show distinct compositional changes with time, there are 3 characteristics common to most suites:

1) The majority are I-(granodioritic) type in character with a SiO_2 range of 60 to 77 wt.% and there are no significant suites of I-(tonalitic) type or M-types as defined by Chappell & Stevens (1988).

2) Most Australian Proterozoic granites have high K_2O/Na_2O. This high ratio is unique in Australian granites: Archaean granites generally are higher in Na_2O contents, whilst Palaeozoic granites have lower K_2O values. Granites from modern subduction zones have higher Na_2O and ever lower K_2O contents than their Palaeozoic counterparts.

3) Proterozoic mantle normalised element patterns are characteristically Sr-depleted, Y-undepleted and imply derivation from source regions in which plagioclase was stable. This also infers that the granites were derived from depths of <35 kms and required geothermal gradients of >35°C.km^{-1}. These high gradients are compatible with the High Temperature Low Pressure (HTLP) metamorphism that is endemic to Australian Proterozoic terrains. The dominance of Sr-depleted types is also in common with lower Palaeozoic granites of the Lachlan Fold Belt. Sr-undepleted, Y-depleted granites, implying a garnet residual source, comprise <4.0% of Australian Proterozoic granites. This contrasts against granites from subduction environments from mid Palaeozoic to recent times which have a far greater abundance of Sr-undepleted, Y-depleted compositions. Australian Archaean granites contain roughly 50% of each type (D.C. Champion, *pers. comm*, 1998).

The dominant Sr-depleted, Y-undepleted I-(granodioritic) types can be further divided into 5 associations which show a time progression in geochemistry. The oldest groups (Kalkadoon and Nicholson Associations) at 1870-1820 Ma, consists of restite-rich granite suites which are characterised by phenocryst-rich volcanics. On Harker variation diagrams the volcanics and granites are chemically indistinguishable, and with increasing SiO_2 most major and trace elements show a linear pattern. The Nicholson Association shows an inflection as about 72 wt.% SiO_2 indicating where restite separation occurred.

The Cullen Association, emplaced at 1840-1800 Ma, shows evidence of magmatic fractionation. There is increasing heterogeneity between individual plutons and leucogranites can clearly be identified. On Harker variation diagrams major and trace element patterns increase exponentially for Rb, U, and Rb/Sr with increasing SiO_2.

The Sybella Association (1800 to 1650 Ma) is the most enriched in incompatible elements. It has a narrow and high SiO_2 range (usually > 70 wt % SiO_2).

The Hiltaba Association emplaced from 1640 to 1500 Ma, is more oxidised with a wide range in SiO_2 values and higher CaO and Na_2O contents. This group has lower values of Y, Zr and Nb that the Sybella Association.

Based on the argument that 'Granites are images of their source rocks' (Chappell, 1979) the chemical parameters above constrain source characteristics. The I-(granodioritic) character argues against a direct mantle derivation, and implies an I-(tonalitic) source (Chappell & Stephens, 1988; Patino Douce & Beard, 1995; Singh & Johannes, 1996a, b). As the exposed Australian Archaean Crust is strongly bimodal, Proterozoic granites are unlikely to be sourced from Archaean crust as it is either too felsic or too mafic to form the vast quantities of Proterozoic I-(granodioritic) types. Age constraints on the source region are provided by Sm-Nd model ages which range from 2600 to 2000 Ga for granites emplaced between 1880 to 1500 Ma and 2200 to 1600 Ma for granites emplaced at 1400 to 700 Ma (Figure 4).

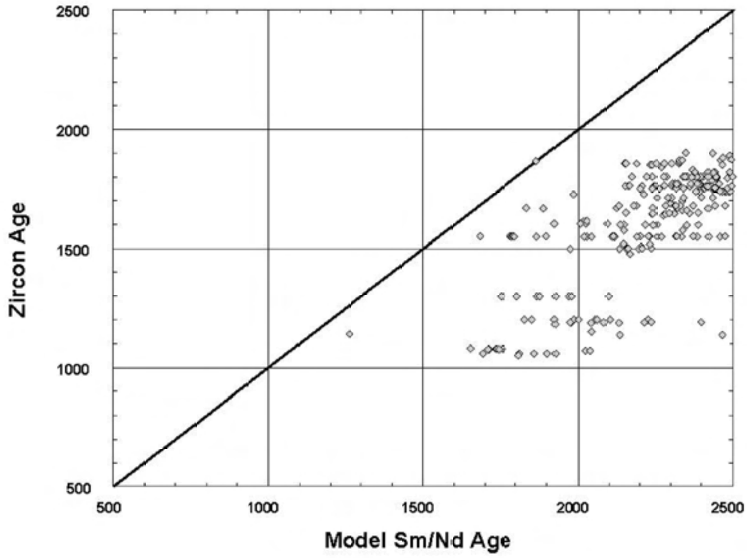


Figure 4a. Plot of model Sm/Nd age vs zircon age for Australian Proterozoic Granites. Data from OZCHRON, AGSO's national geochronological database.

It has been argued that the sources were underplated, evidence for which is seen in seismic refraction data, which also indicate a plagioclase bearing lower crust (Wyborn *et al.*, 1992; Goncharov *et al.*, 1998) as is required by the mantle-normalised trace element patterns of the granites. The high K2O contents also require the presence of K-rich minerals such as K-feldspar, biotite and amphibole in the source region. A simple explanation for the geochemical evolution with time for each of the major I-(granodioritic) type associations from about 1880 to 1500 Ma is that as the temperature in the source region increases, the magma production is dominated initially by minium melting of quartz, K-feldspar, albite and some biotite, with calcic plagioclase, amphibole and some biotite being restite phases (*i.e.*, restite-rich Kalkadoon, Nicholson Associations). As the temperature increases in the source region, melting is initially dominated by biotite breakdown (Cullen and Sybella Associations) and is then followed by amphibole breakdown as source temperatures reach >1000°C, finally producing the Hiltaba Association. In reality there is a continuum between these five associations, which simply reflects increasing temperature in the source region (note that 'fresh' material is being melted each time).

The Sr-depleted, Y-depleted character requires plagioclase to be stable in the source region and that the melts were formed at <35 kbars (Johannes & Holtz, 1996). Geothermal gradients must be >25°C.km^{-1} to achieve this. In addition, according to the experimental work of Patino Douce (1997), the Sybella Association with its high HFSE and restricted SiO_2 contents may be formed at lower pressures (4kbs at 900°C) than the Cullen and Hiltaba associations. This would require extremely high geothermal gradients.

However, the high lower crustal temperatures between 1880 to 1500 Ma based on the granite data clashes strongly with evidence from the mafic igneous rocks which infer a temperature decrease over the same period, with high Mg-tholeiites dominating before ~1850 Ma and continental tholeiites after ~1850 Ma (with the exception of high Fe-tholeiites at Broken Hill and Mount Isa at ~1690 to 1670 Ma). Most granite suites, particularly in the 1840-1880 Ma range, do show some evidence of coeval mafic intrusions, but these are never comagmatic: nor are they present in sufficient quantities to be the 'heat engine' for generating the required massive crustal melting. Further, recent modelling suggests that temperatures generated by emplacement of mafic intrusions are not likely to reach the high temperatures required for the Hiltaba Association (1000°C) and that the time taken to generate sufficient crustal melting could actually be >30 Ma (Wyborn *et al.*, 1997). In reality, the tectonic setting in terrains where many of these granites are emplaced are actually characterised by thermal subsidence phases, inferring that the mantle lithosphere is cooling and thickening (*eg*, Sandiford *et al.*, *in press*).

Several researchers (*eg*, Chamberlain & Sonder, 1990; Sandiford & Hand, 1998; Hobbs *et al.*, 1998) have investigated the consequences of high contents of heat producing elements (K, Th and U) within the crust to generate abnormally high geothermal gradients, and ultimately HTLP metamorphism and anatexis. Their work is highly relevant given that Australian Proterozoic granites are more enriched in K, Th, U than at almost any other time with the exception of some late Archaean granites. Independent validation of how high these high K, Th and U values are comes from present day heat flow measurements in the Australian Proterozoic which average 85 mWm^{-2} with values locally in excess of 100 mWm^{-2} (Sandiford & Hand, 1998; based on Cull, 1982). As modelled by Sandiford *et al*. (*in press*) and Hobbs *et al*.(1998), the end result of these high heat values are high mid-crustal temperatures that do not necessarily cause melting within the lower crust, but that they are capable of it, and perhaps even able to cause minor mantle melting at shallow levels.

What is clear is that modelling by these researchers show that it is possible to generate high temperatures at relatively low pressures without the need for 'active' mantle-driven processes *eg*, mantle plumes, mantle underplating or subduction. The conditions for melting come from within the crust, and as each successive granite event in the Proterozoic becomes more enriched in the heat producing elements it may help to explain why the temperatures of formation of the granites are increasing with time, whilst the mantle is cooling - in fact it is paradoxically the mantle cooling that is indirectly causing the crustal melting as the more radiogenic heat sources are progressively buried to deeper levels within the crust by the addition of sediments on top of the crust during thermal subsidence. The efficiency of the heating process is in part controlled by the absolute contents of radiogenic elements in the felsic igneous rocks and in sediments derived from them. The thermal conductivity of the 'burying' sediments also plays an important role in determining the temperatures that are ultimately reached in the crust. It is significant that those Proterozoic terrains containing sequences dominated by quartz sandstones do not have the younger, high temperature granites of the Hiltaba Association. Given the correct conditions, it is possible to generate widespread granitic melting events, instead of linear belts of granite that are commonly associated with subduction or extensional environments. In the Proterozoic many granite suites are large 'amorphous blobs'.

Having created the melts without invoking subduction or mantle plumes, a mechanism is probably still required to allow the melts to intrude into the upper crust. The shape of the apparent polar wander path (APWP) between 1800 to 1500 Ma, confirms that the Australian plate was reasonably mobile at the time of major felsic magma generation. Magma emplacement was also coincident in time with inflection points on the APWP. These inflection points are recognised as significant interplate tectonic events with associated intraplate effects that cause major episodic migration of basinal fluids. Similar intraplate tectonic responses distal to plate boundary tectonic effects may have also allowed granitic melts to migrate into the upper crust (Wyborn *et al*., 1998c)

It is proposed that crustal heating as a result of high K, Th and U contents within the crust, was possibly responsible for the generation of Sr-depleted, I-(granodioritic) type magmas which dominate the Australian crust from the late Archaean to the Siluro-Devonian. However, similar Sr-depleted I-(granodioritic) types from each major era are distinct in composition, with the radiogenic and incompatible elements decreasing in abundance in each type with time. As the I-(granodioritic) types are ultimately derived from distinct major underplating events, then each successive event must be of a different composition, which is possibly controlled by mantle characteristics changing with time in response to a cooling earth. As the abundance of radiogenic elements clearly decreases with time in I-(granodioritic) types after an initial late Archaean peak, then the ability for radiogenic crustal heating processes to generate significant magma volumes would also diminish with time. This is reflected in the decrease in dominance of Sr-depleted, I-(granodioritic) types after the lower Palaeozoic. Subduction-related processes then appear to become a major granite-generating mechanism resulting in the greater prominence of I-(tonalitic) types (*i.e*. Cordilleran granites) in Australia from the mid Palaeozoic onwards.

Hence the granite types defined as a result of the Proterozoic granites project are likely to be globally specfically related to the Proterozoic and there are unlikely to be precise analogues in the modern environment. In particular, if it is true that Late Archaean to Palaeoproterozoic granites are enriched in K, Th and U, then there may not be sufficient radiogenic heat in the crust to generate to high temperatures that are required to form melts of the Hiltaba and Sybella Associations in modern terranes.

5. PREDICTING WHICH GRANITES ARE LIKELY TO BE ASSOCIATIED WITH MINERALISATION - ARE THERE SYSTEMATIC PATTERNS???

It has often been argued that it is possible to predict which granites have the potential to be mineralised and there are several important parameters which can provide clues to the mineral potential (*eg*, White *et al.*, 1991; Wyborn, D., 1993). These parameters include the abundance of restite in magmas, the temperature range over which the magmas crystallise, the oxidation state of the magma, the abundance of K and the range in silica composition. White *et al.* (1991) and Wyborn (1992) defined a granite classification for the economic geologist and using these parameters subdivided granites into 8 different metallogenic types. Their classification, developed mainly on Palaeozoic and younger systems, has broad applications to the Proterozoic, although in the Proterozoic, the composition of the rocks surrounding the granitic intrusions appears to have greater importance.

5.1 THE ABUNDANCE OF RESTITE IN A MELT.

For metallogenic syntheses of provinces it is critical to distinguish between granites that are restite-rich and those that crystallise by convective fractionation. Whalen *et al.* (1982) argued that restite-rich granites cannot give a greater concentration of any element than that contained in the initial melt or restite. In contrast, convective fractionation provides a better mechanism whereby elements, particularly those of economic importance, can be concentrated. This explains why granites such as those of the Forsayth Association (S-type) and the Kalkadoon Association (I-type) are not mineralised whilst the Cullen and Hiltaba Associations are.

5.2 THE TEMPERATURE RANGE OVER WHICH CRYSTALLISATION TAKES PLACE.

Granites which have a large proportion of their liquid crystallising over a small temperature range are restricted in their ability to undergo fractional crystallisation. This characteristic is typical of the high Na_2O, low K_2O continental margin subduction-related tonalitic rocks of the western Americas which, like the restite-rich granites, also form large homogeneous plutons with little or no known mineralisation (Wyborn, D., 1993). Their homogeneity results from a large proportion of crystallisation occurring over a small temperature range around 900°C, which effectively locks the derivative liquid into the interstices of the early crystal network and fractional crystallisation cannot proceed (Wyborn, D., 1993).

In contrast, high temperature potassic liquids, particularly those rich in volatiles such as F, B, Li, are important because firstly they crystallise over a wide temperature range and have a greater capacity to concentrate economically important metals, and secondly there are large density differences between the primary liquid and the derivative liquid so that the process of convective fractionation is much more effective. Convective fractionation produces liquids that are progressively more enriched in volatiles and important trace metals such as Li, Be, Sn, Mo, Sb, Ta, W, Bi, Pb and U (Wyborn, D., 1993). Thus the most prospective granites for Cu-Au mineralisation are the Cullen Association and the even higher temperature Hiltaba Association

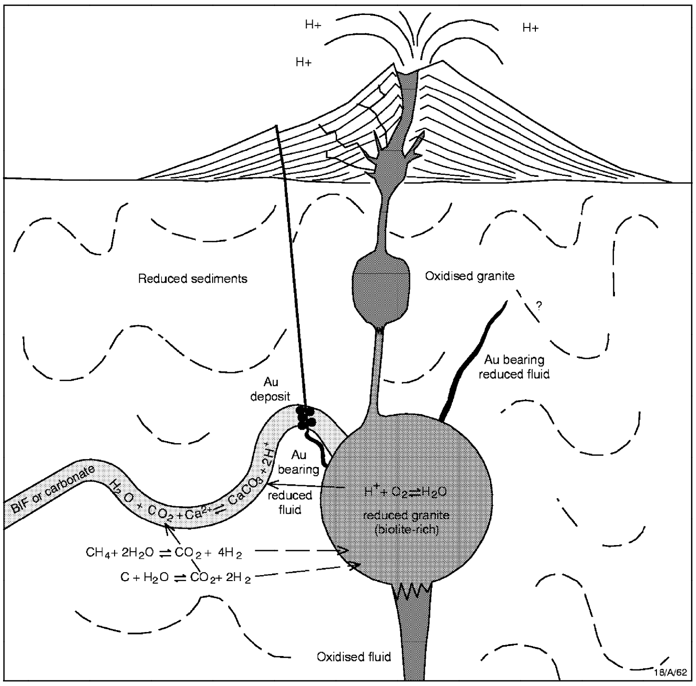


Figure 5.1.3a. Generation of reduced granites by interaction with methane and carbon bearing sequences.

5.3 OXIDATION STATE

As noted by Ishihara (1977) reduced or ilmenite-bearing granites (usually S-types), can have associated Sn and some W mineralisation. Granites which are oxidised or magnetite-bearing (usually I-types), can have associated Cu and Mo mineralisation. Au is usually associated with oxidised granites. Note that the Cullen system did not develop significant Sn mineralisation until the ASI became > 1.1 and the $Fe_2O_3/(FeO+Fe_2O_3)$ dropped. Note also that many of the Cullen Association intrusives as well as the Esmeralda Suite (Georgetown Inlier) of the Hiltaba Association have reduced due to interaction with graphitic and methane-bearing country rock as illustrated in figure 5.1.3 a.

5.4 TEMPERATURE CONTRAST

Higher-temperature granites also have the capacity for greater thermal disequilibrium in the local geothermal system. Note the greater evidence for regional scale alteration in the hotter Williams Association (1000 °C) as opposed to the Cullen Association (800-900 °C). Whalen *et al.* (1982) argued that a higher temperature melt is capable of providing a better thermal source for alteration and possibly metal leaching.

5.5 SIZE OF THE INTRUSIVE SUITE

It is obvious that the larger the granite suite the larger associated mineralising system will be. There are a few suites of granites in the Proterozoic which show evidence of convective fractionation, but are relatively small in area. These are unmineralised or only weakly mineralised, presumably because they are too small to concentrate sufficient metals or volatiles and too small to cause any major changes in the local geothermal gradient. Note that the small Burstall Suite (Mount Isa Inlier) of the Hiltaba Association had only small tonnage (although high-grade) deposits spatially associated with it.

5.6 DEPTH OF EMPLACEMENT

Empirically it does appear that the majority of Australian Proterozoic granites that are spatially related to mineralisation have been emplaced at relatively deeper levels in the crust. This contrasts against the more shallow porphyry-style mineralisation in which the deposits are at the margins or disseminated within the intrusion itself.

Many Proterozoic granites that are spatially related to mineralisation do not appear to have any coeval or comagmatic volcanics. This could be a function of erosion: it also could indicate that these Proterozoic mineralisation-related granite systems were water-rich and hence were unable to get to shallow levels.

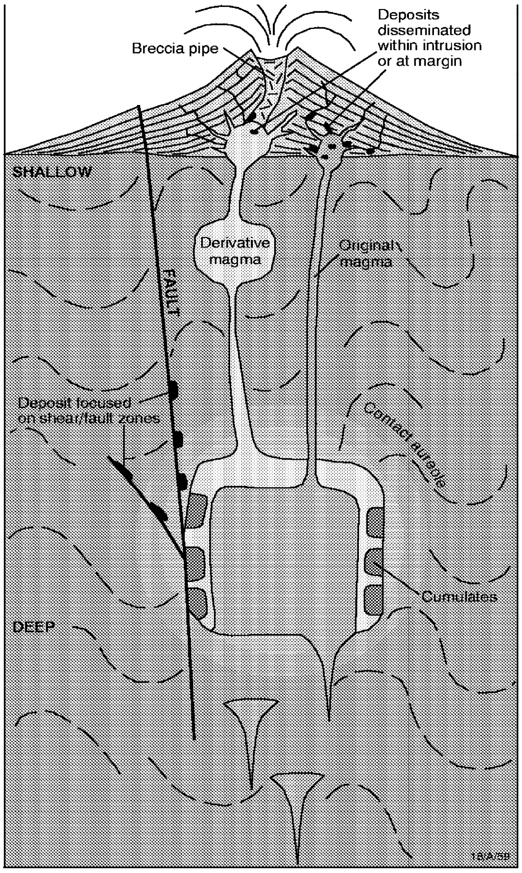


Figure 5.1.6a. The Proterozoic granite-related mineral system.

Many Proterozoic deposits that are spatially related to granites are focussed in shear zones that appear to be connected to the granitic intrusions. Therefore, structure becomes a critical ingredient in many Proterozoic granite-related mineralising systems and major shear zones operating at the time of emplacement of the granites appear control the localisation of the mineral deposits (Figure 5.1.6a).

5.7 HOST ROCKS

There is a spatial association between granites and host rocks. With the more oxidised Hiltaba Association Suites and Supersuites ironstones are an important host as are graphitic rocks: carbonate is not all that important. In contrast with the more reduced ilmenite-stable granites carbonate becomes a more important host. In the lower grade terrains it is possible using some fundamental knowledge of the systematics of evolving

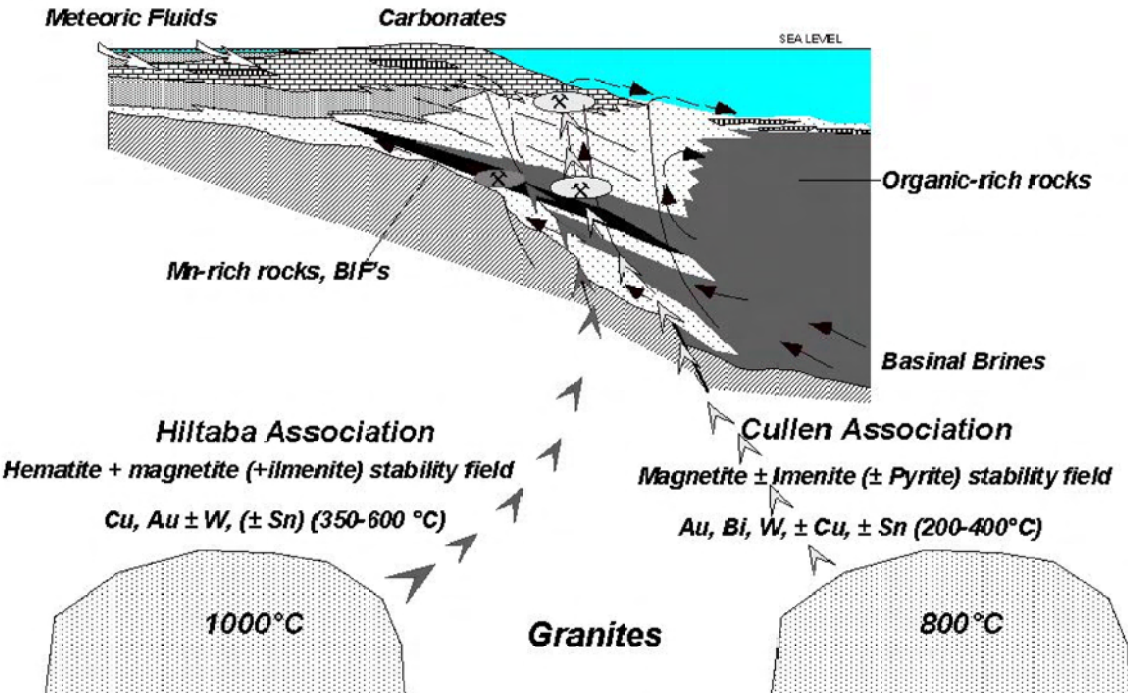


Figure 5.1.7 a: Relationship mineralisation of the Hiltaba and Cullen granite associations to sedimentary facies.

sedimentary basins and, given the knowledge of the redox state of the granite system, to predict where potential hosts will be located (Figure 5.1.7a). The hematite-magnetite stable associations will react with different parts of the stratigraphy to the magnetite-ilmenite sequences.

5.8 IS TECTONIC SETTING IMPORTANT IN DIFFERENTIATING GRANITES WITH MINERAL POTENTIAL??

It is clear that the P and T conditions operating in the source region control the type of granite that is being produced, which in turn controls the mineral potential. It is also clear that tectonic setting controls the PT conditions. However, tectonic setting is considered as a second-order control and searching for a particular mineralising type based on the inferred tectonic setting is not considered as important as understanding the conditions existing in the source region at the time of melting.

One of the surprising results of this Proterozoic granite synthesis was the realisation of just how systematic the compositions of the major Australian granite suites are. Given that the most popular tectonic model is that the Australian Proterozoic was dominated by a series of microplates and interaction between these microplates in a subduction environment generated many of our major granite batholiths, it would have been expected that the granite compositions would have been more random with time. More importantly, if this tectonic model was correct, then one would expect to see a far grater abundance of I-(tonalitic) and M-types present, in particular those which had garnet stable in the source region. Instead, the Australian Proterozoic is dominated by I-(granodioritic) types which have plagioclase stable in the source region and which therefore require high geothermal gradients and melting to have take place at < 35 kms.

Discrimination variation diagrams such as those developed by Pearce *et al*. (1984) are supposed to determine the tectonic setting operating at the time based on a few trace elements. These diagrams do not take into account changing compositions of most granite types with time and are therefore of limited use. In addition, there are plenty of barren granites in subduction zones, thus arguing that a granite has formed in a subduction setting based on a few trace elements and therefore should have potential for porphyry-style mineralisation is likely to waste many exploration dollars.

5.9 IS AGE IMPORTANT IN DIFFERENTIATING GRANITES WITH MINERAL POTENTIAL?

Using age as a guide to mineral potential is not effective. Although there are broad time groupings of the various associations, they are not unique. Primary magmatic variation and the composition of the country rock is a far better guide to mineral potential.

5.10 FIELD RECOGNITION OF IMPORTANT GRANITES

Although detailed geochemical studies provide better insights into the metallogeny of granites of provinces, such data is not always available. Field observations alone can still provide sufficient clues to identify granites with mineral potential. If coeval plutons vary from zoned intrusions through to leucogranites, and there is a wide variation in the mineralogical composition, then this is an indication that the pluton crystallised from a liquid. Observations on mineralogy such as the presence of hornblende, biotite, or cordierite will argue as to whether it is an S-type (more common for Sn) or an I-type (more commonly Au, or Cu or Mo). It is important to record the opaque phases (*eg*, ilmenite, magnetite, sulphide). Colour can also be an indicators, as many (but not all) oxidised, magnetite-rich granites are pink to red in colour. The width and mineralogical composition of the contact aureole can give an insight into the temperature of the intruding magma. The presence of pegmatites *etc* can indicate late stage magmatic fractionation and concentration processes.

6. A SYNTHESIS OF GRANITES AND METALLOGENY IN THE PROTEROZOIC - GUIDELINES FOR OTHER AREAS

1) There is a spatial relationship, particularly for Au and Cu mineralisation, very few deposits and occurrences are actually sited with in the granites themselves, but rather are sited in the country rock often up to 5 kms.

2) The Proterozoic granites associated with significant Au + base metal deposits are of two types: the Cullen Association, and the Hiltaba Association. These two distinctive granite types are each associated with a specific type of mineral district: the Cullen Association is spatially associated with Au-dominant deposits with minor Cu + base metals (*eg*, Cullen Mineral Field, Granites-Tanami area), whilst the mineral district associated with the oxidised Hiltaba Association is Cu-dominated with Au + U (*eg*, Olympic Dam, Ernest Henry, Osborne), in mineralisation is more likely to be hosted internally to the granite.

3) It is not necessary for the felsic intrusions to be tonalitic or monzonitic in composition, similar to those intrusive types which are associated with porphyry-style mineralisation: mineralisation can also be associated with suites which have >60 % SiO2.

4) It is not necessary for granites to be magnetite-bearing to be prospective for Au: many granites spatially associated with Au deposits in the Proterozoic are Au-bearing.

5) The mineralogy of the country rock was found to play a crucial role not only in determining the site of mineralisation, but also in affecting the redox state of the granite

6) I or S-type granites designated as unfractionated were restite-rich and consistently unmineralised.

7) The Sybella Association is clearly a fractionated I-type. It is believed to not be associated with mineralisation as it has been derived by partial melting of relatively anhydrous tonalites to granodiorites at pressures of about 4 kbars.

8) Rare fractionated S-types are commonly associated with Sn mineralisation.

9) There is evidence to suggest that the ore bearing solutions, particularly those carrying Au, may move up to 5 kms from the pluton boundary. Thus exploration in these granite-related systems should not just target the actual intrusions or carbonate bearing contact rocks.

10) Au-only mineralisation may be hosted in, or near, graphite-rich, but sulphide- and magnetite-poor sediments. Such a scenario exists in the vicinity of the Cullen Batholith (Stuart-Smith *et al*., 1993) where Au dominant deposits are hosted in, or near, graphite-bearing units.

11) Electrical methods are likely to be more successful in targeting favourable hosts for Au-only mineralisation. Magnetic methods, in reality, are essentially targeting iron-rich host lithologies: these will inevitably cause precipitation of Cu as well as Au.

12) The significance of this work is that the specific granites that are spatially associated with mineralisation in the Proterozoic occur in the Proterozoic only, as that composition is dictated by the major underplating events that occurred earlier in the history of the individual provinces.

13) That is parameters defined in this study are only likely to work on I-(granodioritic) types that are Proterozoic in age: they will not work on Phanerozoic intrusives that are intermediate in composition or are associated with active subduction zones.

14) In any province it is logical that the lower temperature I-(granodioritic) types will be early in the evolutionary history of the province and that the temperature of the source region will increase with increasing age. Provided the lower crust is heated progressively, the pattern of intrusions will be restite-rich granites early, followed by those that are formed by biotite, and then amphibole breakdown. It is possible to speculate that the oxidised Cu-Au granites that form by amphibole breakdown will be late in the history of the province and will only occur in those terrains that have a complex history.

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