THE METALLOGENIC POTENTIAL OF AUSTRALIAN PROTEROZOIC GRANITES

Geoscience Australia Record 2001/12

Anthony R. Budd, Lesley A.I. Wyborn, Irina V. Bastrakova

Geoscience Australia

Executive Director: Dr Neil Williams

Department Of Industry, Tourism & Resources

Minister for Industry, Tourism & Resources: The Hon. Ian MacFarlane, MP

Parliamentary Secretary: The Hon. Warren Entsch, MP

ISSN: 1039-0073

ISBN: 0 642 46690 4

Geoscience Australia Catalogue number: 33388 (Volume)

36204 (GIS)

Bibliographic Reference: Budd, A.R., Wyborn, L.A.I. and Bastrakova, I.V. 2001. The Metallogenic Potential of Australian Proterozoic Granites, *Geoscience Australia, Record* 2001/12.

Table of Contents

ABSTRACT 1

INTRODUCTION 3

1 GRANITES & COPPER GOLD METALLOGENESIS IN THE AUSTRALIAN PROTEROZOIC. 5

2 ALBANY-FRASER PROVINCE 52

3 ARNHEM BLOCK/McARTHUR BASIN 54

4 ARUNTA INLIER. 57

5 BROKEN HILL BLOCK 62

6 TENNANT CREEK/DAVENPORT 65

7 GASCOYNE PROVINCE. 69

8 GAWLER AND CURNAMONA CRATONS 72

9 GEORGETOWN INLIER 76

10 GRANITES-TANAMI BLOCK. 81

11 KIMBERLEY PROVINCE SYNTHESIS. 85

12 MOUNT ISA INLIER 92

13 MUSGRAVE BLOCK SYNTHESIS 97

14 PATERSON OROGEN SYNTHESIS 100

15 PINE CREEK INLIER 103

16 OTHER PROVINCES 107

17 ORIGINAL PROPOSAL, 1995 110

18 METHODS 117

19 ABSTRACT 1 - Crustal Heating 129

20 ABSTRACT 2 - Granite-related Ore Systems 134

21 ABSTRACT 3 - Interactions Between Crust & Mantle 136

22 ABSTRACT 4 - Australian Proterozoic Intraplate Igneous Activity 138

23 ABSTRACT 5 - Mount Webb Granite Alteration System 140

24 ABSTRACT 6 - Proterozoic Granites: Characteristics, Sources, Derivation & Emplacement 148

ABSTRACT

This Volume contains the results of a Project, 'The Metallogeny of Australian Proterozoic Granites' undertaken by the then Australian Geological Survey Organisation in collaboration with 20 minerals exploration companies. The project was a data driven exercise that asked the simple question 'Where hydrothermal Au, Cu, Zn, Pb, Sn, W, and Mo mineralisation occurs within 5 kms of the boundaries of Proterozoic Granites, are there any specific characteristics of either the granites and/or their host rocks?'

The project compiled data on the mineralogy, geochemistry (~7500 analyses), and age of Proterozoic granites and felsic volcanics, as well as the age and mineralogical composition of sediments within 5 kms of Proterozoic granite boundaries for 20 provinces. The project investigated a spatial association only, and hence it was not considered of major importance if the metals came from the granite or were leached from the country rock by processes related to granite emplacement. Further, the compilation made every effort to focus on factual data. As the determination of the tectonic setting operating at the time of emplacement of the granites, particularly in rocks as old as Proterozoic, was considered to be highly interpretative, this parameter was not included, due to the data-driven approach of the project.

Having compiled the data, a forensic data mining approach was applied. That is, rather than developing a computer derived 'best-fit model' from the data, or taking an existing model and finding areas that matched the prescribed model, a more descriptive approach was tried. Our goal was to investigate the spatial relationship to gain understanding by uncovering patterns and relationships. Nine major associations were identified based on granite type and spatially related mineralisation.

Our results showed that overall there are a strong spatial relationship with specific granite types for many commodities. I or S-type granites designated as unfractionated were restite-rich and consistently unmineralised. Fractionated I-type granites can be divided into 2 groups: those that were either F-poor or F-rich throughout most of their fractionation history. The F-rich granites are often the true rapakivi types and have little mineralisation presumably because Cl had been partitioned into the granite melt early. Fractionated F-poor I-type granites can be further divided into 2 classes: Oxidised and Reduced. The Oxidised granites are most commonly associated with Cu-Au deposits and crystallised at higher temperatures than the Reduced class. Although it is commonly stated that Au mineralisation is only associated with oxidised granites, an unequivocal spatial association occurs between the Reduced class and Au-dominant mineralisation which also has variable amounts of Cu, Sn, W, and Bi. Reduction is due to several causes including increasing ASI, interaction with country rock and perhaps magma cooling. Rare fractionated S-types are commonly associated with Sn mineralisation.

An unexpected pattern emerged within the five larger I-type associations. The lower temperature granites were always early in the evolution of a province and that with time the temperatures of the magmas increased. As the magma temperatures increased a pattern emerged of a progression of early barren granites (e.g. the restite-rich Kalkadoon Association) followed by the weakly mineralised Nicholson Association where late vein mineralisation was associated with late fractionationation over a narrow range of silica content (~72-77 wt %). The next association was the predominantly Au ± base metal endowed Cullen Association. This suite is low in Ca and is believed to have formed by breakdown of biotite in the source region. The Sybella Association generally followed next and is characterised by high concentrations of high field strength elements and fluorine. This association is believed to be formed by dehydration melting of hornblende- and biotite-bearing tonalites and granodiorites at very shallow depths ($P \leq 4$ kbar), and is only weakly mineralised. The Hiltaba Association was the generally youngest major I-type association in this progression. It is characterised by spatially related major Au-Cu mineralisation and was formed at temperatures of ~1000°C by breakdown of amphibole in the source region.

INTRODUCTION

Reviews of geological and geochemical data in several Proterozoic provinces by Geoscience Australia have shown that Proterozoic granite suites which have hydrothermal ± base metal mineralisation within 2 to 3 km of the contact have many easily determined field, petrographic and geochemical characteristics in common; whilst unmineralised granite suites also have distinctive features. The mineralogical composition of the host rock is also considered an important factor controlling precipitation.

The Metallogenic Potential of Australian Proterozoic Granites project has compiled data on not only geological and chemical features of all Proterozoic granite suites, but also of their host rocks, to highlight new areas of potential granite-related Au ± base metal mineralisation.

In essence, our approach has been one of 'forensic data mining'. Data mining was defined by Westphal and Blaxton (1998), and has two end members: predictive and descriptive. Predictive methodologies rely on developing a computer derived 'best-fit model' from the data, or taking an existing model and finding areas that matched the prescribed model. In descriptive data mining, the goal is to gain understanding by discovering patterns and relationships within the data. Hitzman and Williams (2000) suggested that a new research paradigm in economic geology could emerge based on work in criminal forensic science. Hitzman and Williams (2000) suggested that that if ore bodies were examined like bodies at the scene of the crime, we would collect data in a systematic and completely objective fashion. 'Forensic data mining' has been the underlying philosophy of the project: to systematically and objectively compile data on all granites and all sediments within 5 kms of all Proterozoic granites of all Australian Proterozoic provinces. As the project progressed, many patterns and relationships were uncovered (and are still being uncovered from this base data set).

Because of the diversity of findings, the results are presented in several ways. Firstly Chapter One of this record contains a synthesis on granites and copper-gold metallogenesis in the Australian Proterozoic. That is the results are synthesised on the basis of the nine broad associations found Australia-wide. Chapters 2 to 16 contain the results of the project from each Proterozoic granite province of Australia. These chapters are summaries of the accompanying CD–ROM which contains the full data set on the individual granite suites/supersuites and their hosts in all Proterozoic provinces of Australia, as well as a GIS. The GIS contains maps of each province with most of the data attached as attributes to the individual granite and sediment polygons.

Chapter 17 provides the original Project proposal whilst Chapter 18 fully describes the compilation and interpretation methods used by the project. As an indicator of the additional patterns and relationships that have emerged from the results of this compilation, several abstracts and papers, which have been published so far on the findings of this work, are included in Chapters 19 to 24.

References:

Hitzman, H., and Williams, N., 2000. Scene of the Crime – the future forensic science of sediment-hosted base metal deposits. *Geological Society of America, Annual General Meeting*, 32 (7), A3.

Westphal, C., and Blaxton, T., 1998. Data Mining Solutions: Methods and Tools for Solving Real-World Problems. John Wiley and Sons, New York

1 GRANITES & COPPER GOLD METALLOGENESIS IN THE AUSTRALIAN PROTEROZOIC

Lesley A.I. Wyborn

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.

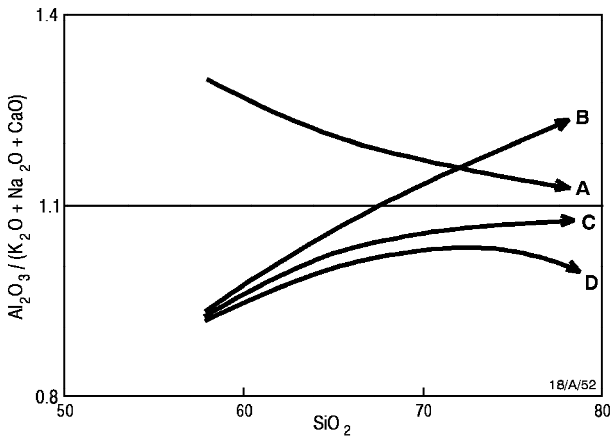


Figure 1.2.1.1a: Changing ASI index with increasing SiO_2. Path A is typical for S-types, whilst B, C and D are predominantly I-type. High SiO_2 samples from path B would have muscovite, but they are not ‘S-types’

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.

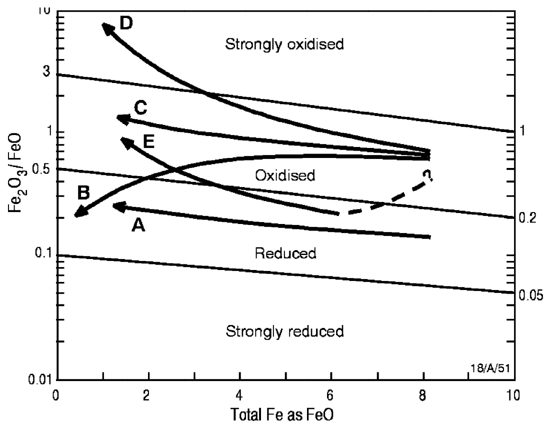


Figure 1.2.2.1a: Redox plot of Champion and Heinemann (1994).

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.

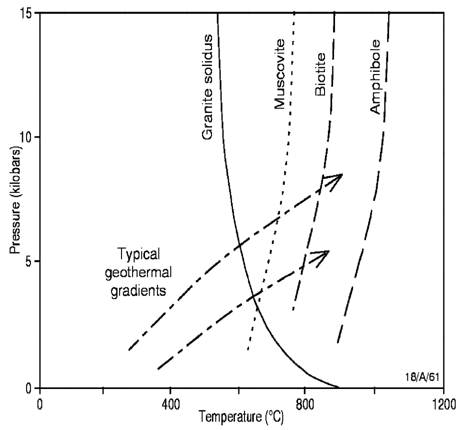


Figure 1.3.1a : Dehydration breakdown reactions for common hydrous minerals.

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.

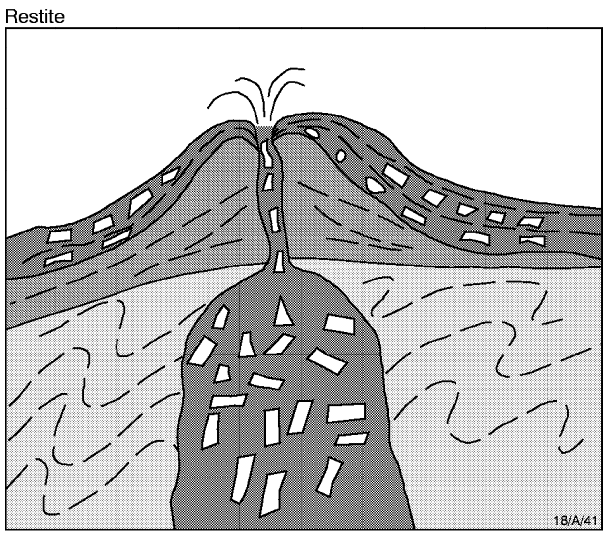


Figure 1.3.1.1a. Melts that are restite-rich produce homogenous plutons that are identical in composition with phenocryst-rich volcanics

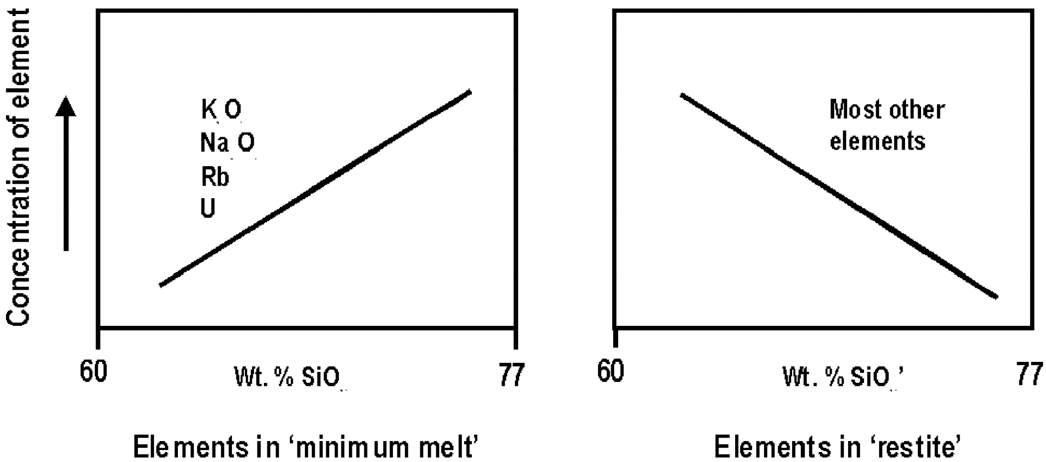


Figure 1.3.1.1b. Schematic illustration of chemical variation trends in a restite-dominated system

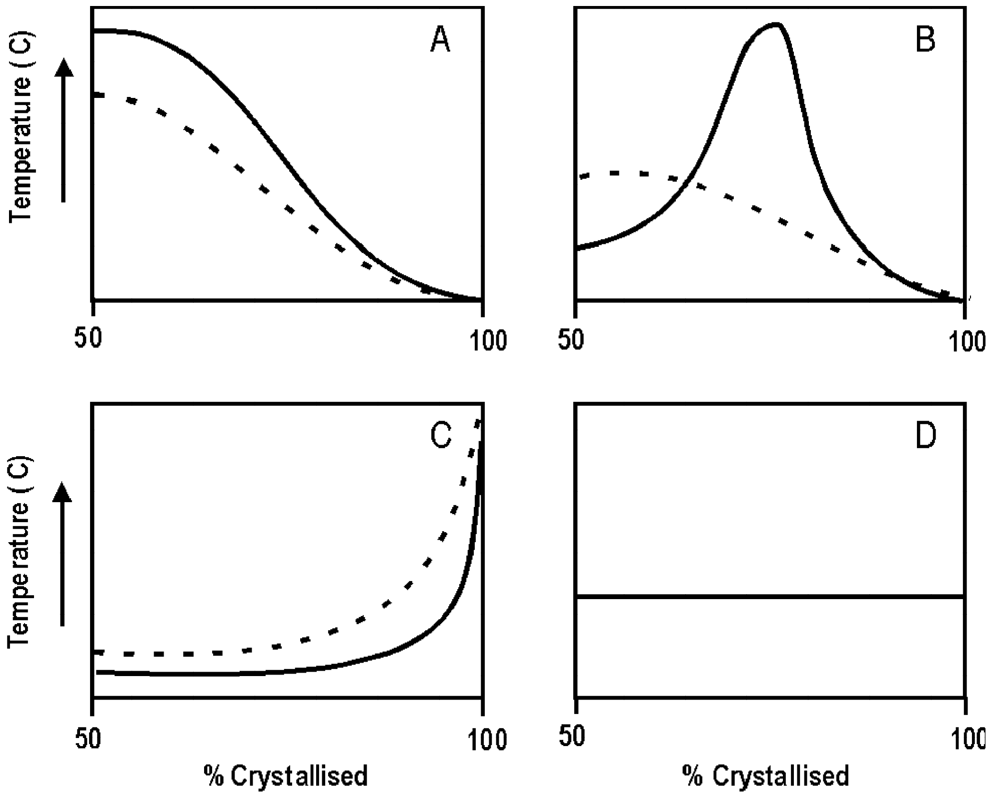


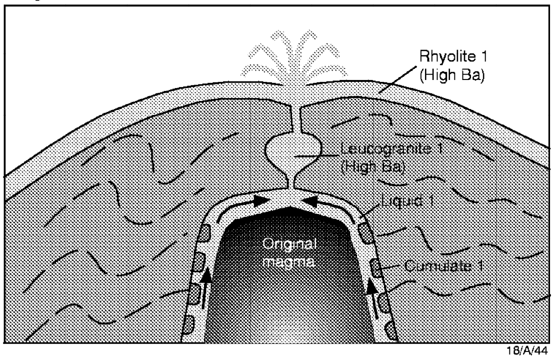
Figure 1.3.1.1.d: Various major and trace element plots for granites that crystallise from pure melts (based on Stanton 1990). Dotted lines represent the composition of the residual liquid, whilst solid lines represent the composition of the crystallised rock. In A, the element is preferentially concentrated 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.

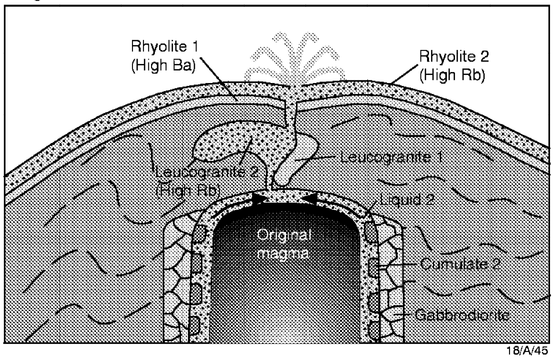
Thus, in contrast to the homogeneity of the restite-rich systems, the end product of granite systems undergoing convective fractionation is a heterogeneous chemical suite consisting of zoned plutons, leucocratic plutons and homogeneous plutons of granodiorite to monzogranite composition Figure 1.3.1.1c-D).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

Stage 1



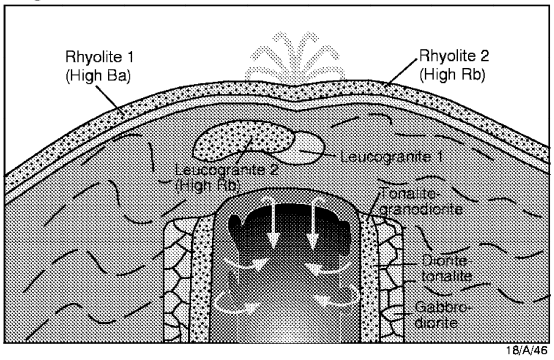
A. Stage 1: Granite melt is intruded. Denser more mafic minerals accrete to the sidewalls and form more mafic tonalites, diorites, gabbros etc. The residual liquid, being lighter and denser than the original magma rises to the top of the chamber. This liquid is high in Ba and can bleed off to form high-Ba 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.

Stage 2

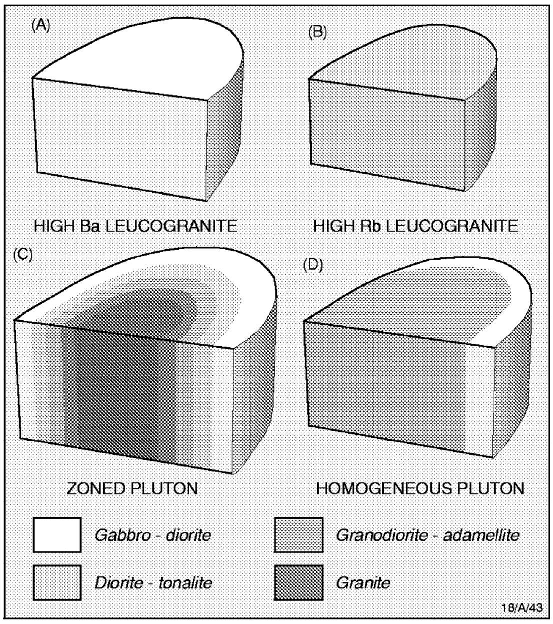


B. Stage 2: Provided there are no significant further additions to the primary magma, crystallisation proceeds inwards. The primary magma is evolving and the composition of cumulate minerals changes. The rocks accreted to the edge of the chamber now form granodiorites to tonalites. The derivative liquid 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.

Stage 3



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.

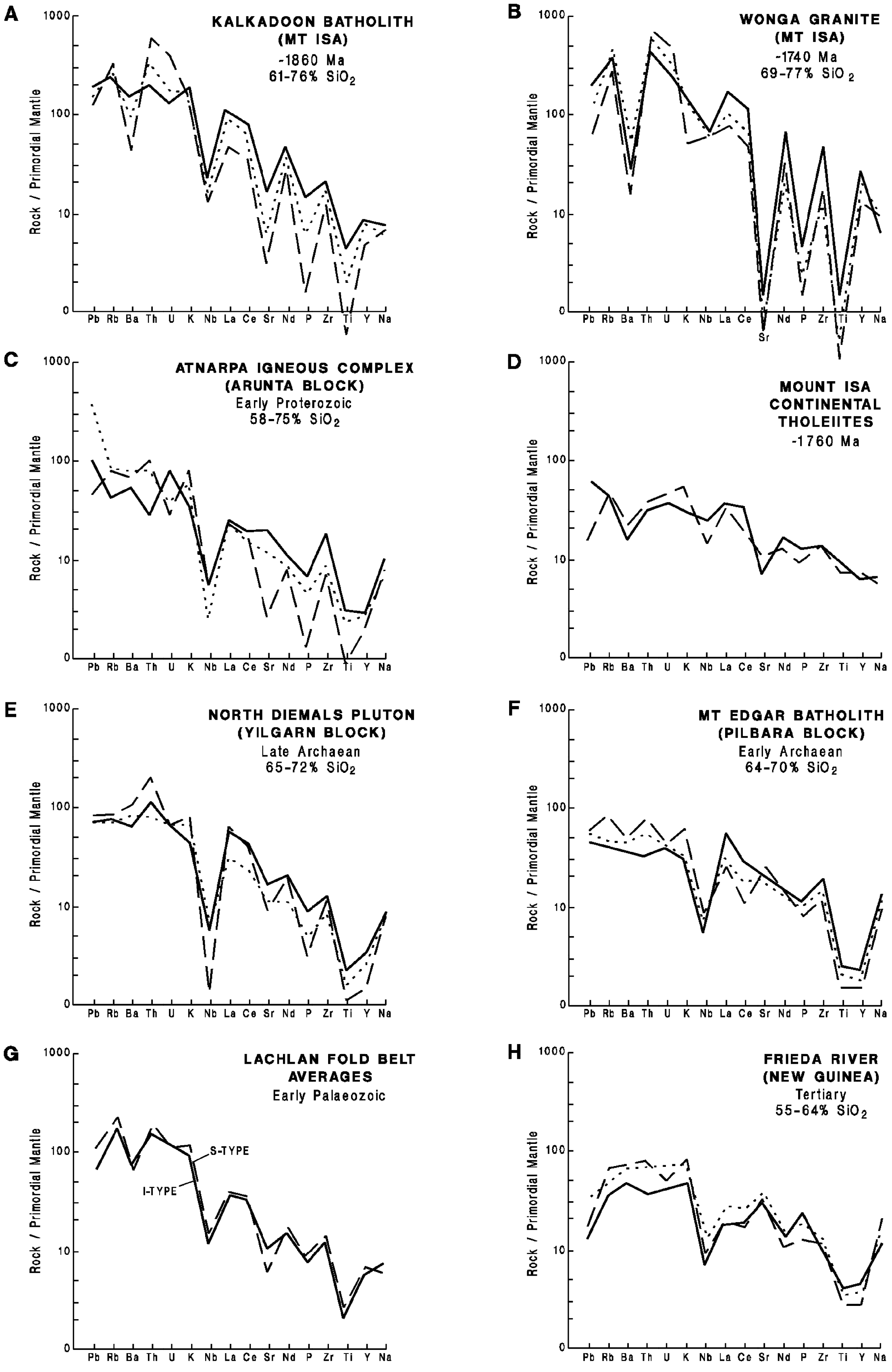


Figure 1.3.2a. Multi-element primodrial-mantle-normalised abundance diagrams for representative granites from the Australian Continent: normalising values are from Sun & McDonough (1989): in D the dashed line and the solid line are 2 individual samples; in G the dashed line is an average S-type and the 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

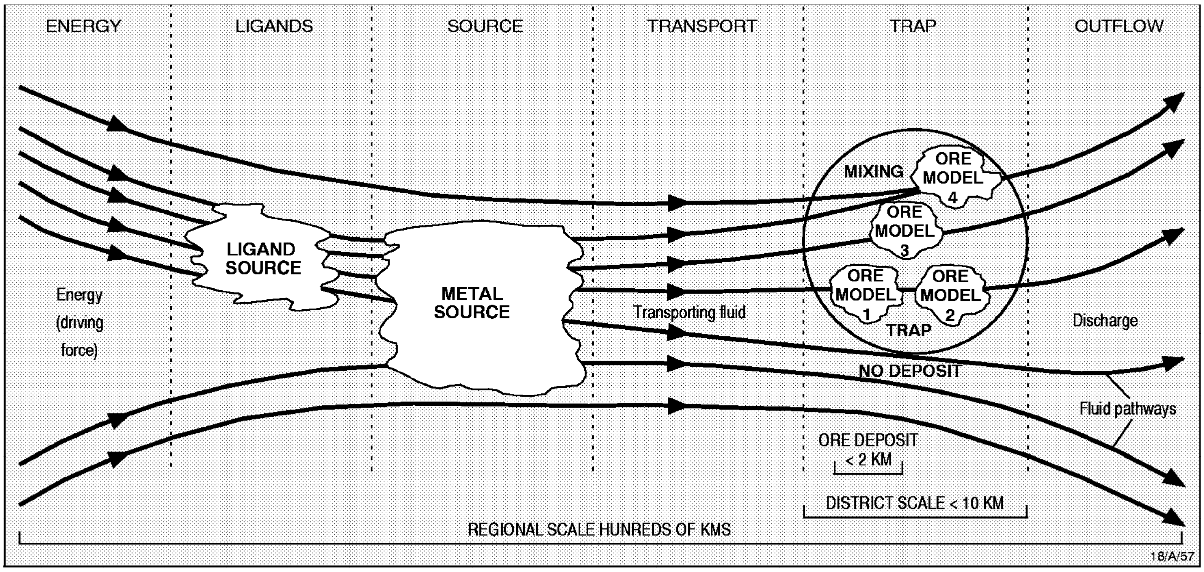


Figure 2.1.2a: the components of a mineral system.

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.

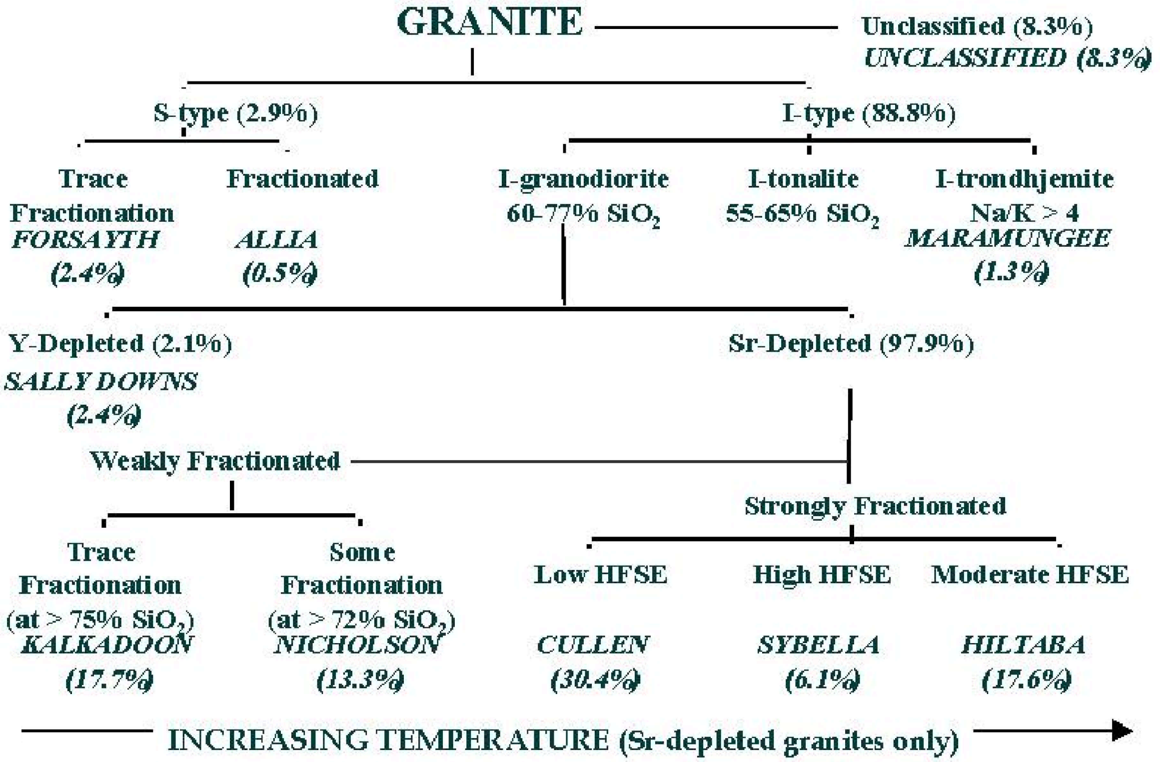


Figure 3.1a: Classification of the various Australian Proterozoic Granite types. Percentages that are in italics represent the area of that particular association as a percentage of the total exposed areas of Australian Proterozoic granites. Subsurface extents of the individual associations have not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

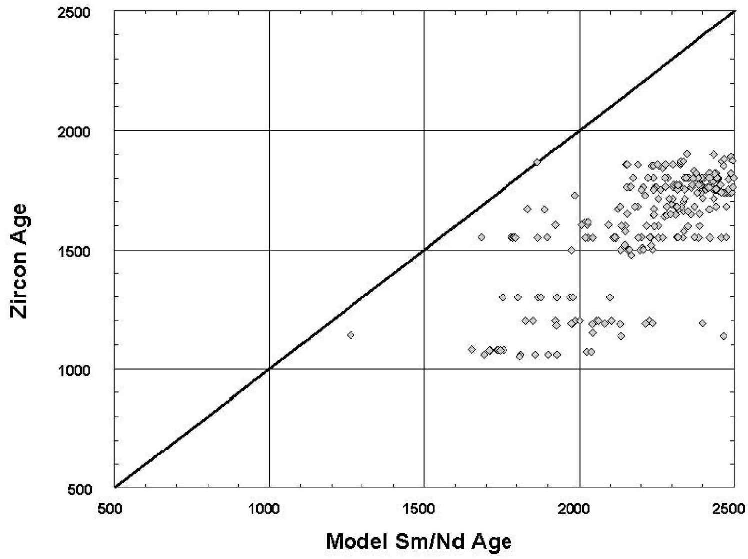


Figure 4a. Plot of model Sm/Nd age vs zircon age for Australian Proterozoic Granites.
Data from OZCHRON, AGSO's national geochronological database.

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

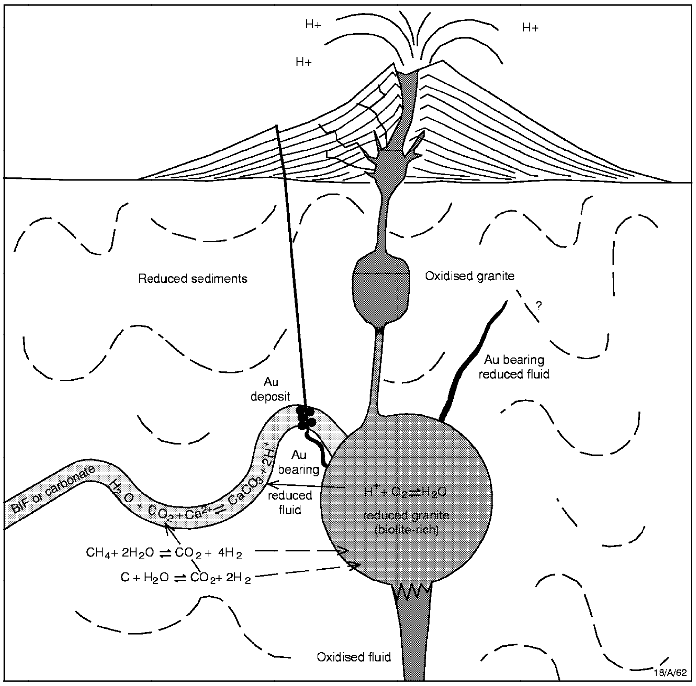


Figure 5.1.3a. Generation of reduced granites by interaction with methane and carbon bearing sequences.

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.

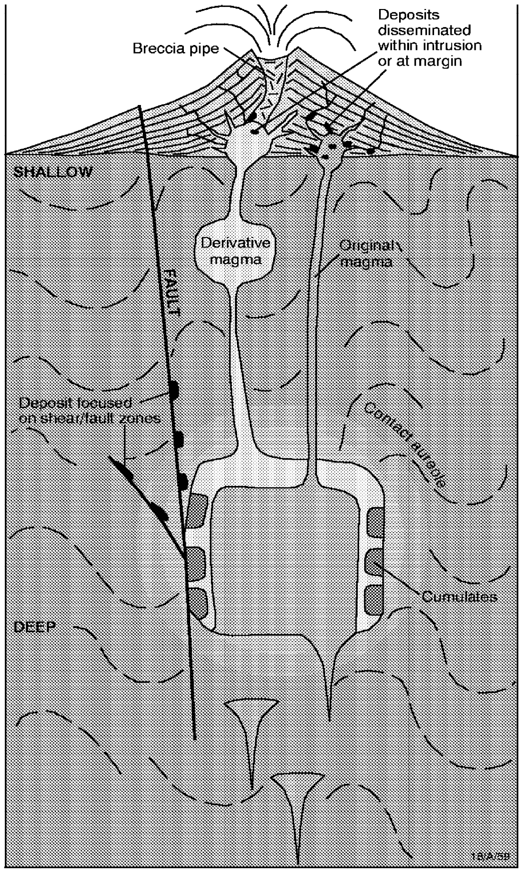


Figure 5.1.6a. The Proterozoic granite-related mineral system.

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

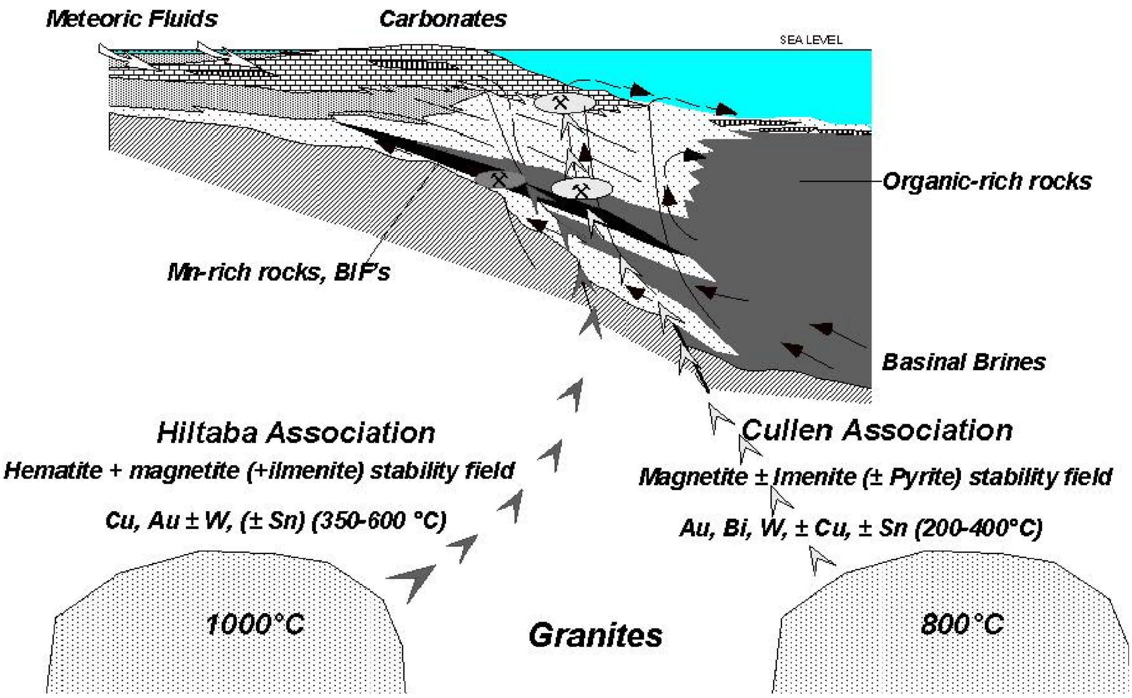


Figure 5.1.7 a: Relationship mineralisation of the Hiltaba and Cullen granite associations to sedimentary facies.

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.

7. REFERENCES

Ahmad, M. & Wygralak, A.S., 1989. Calvert Hills SE53-8 explanatory notes and mineral deposit data sheets. *Northern Territory Geological Survey 1:250 000 Metallogenic Map Series*.

Ashley, P.M., Cook, N.D.J. & Fanning, C.M., 1996. Geochemistry and age of metamorphosed felsic igneous rocks with A-type affinities in the Willyama Supergroup, Olary Block, South Australia, and implications for mineral exploration, *Lithos*, 167-184.

Bagas, L., & Smithies, H., *in prep*. Connaughton 1:100 000 Explanatory Notes. *Geological Survey of Western Australia*.

Bagas, L., Grey, K., & Williams, I.R., 1995. Reappraisal of the Paterson Orogen and Savory Basin. *Geological Survey of Western Australia, Annual Review*, 1994-1995, 55-63.

Bain, J.H.C., Withnall, I.W., Oversby, B.S. & Mackenzie, D.E., 1990. North Queensland Proterozoic inliers and Palaeozoic igneous provinces - regional geology and mineral deposits, *in* Hughes, F.E., (Ed) *Geology of the Mineral Deposits of Australia and Papua New Guinea , Australian Institute of Mining and Metallurgy*, 963-978.

Black, L.P., 1977. A Rb-Sr geochronological study in the Proterozoic Tennant Creek Block, central Australia. *BMR Journal of Australian Geology and Geophysics*, 2, 111-122.

Black, L.P., 1984. U-Pb zircon ages and a revised chronology for the Tennant Creek Inlier, Northern Territory. *Australian Journal of Earth Sciences*, 31, 123-131

Black, L.P. & McCulloch, M.T. 1990. Isotopic evidence for the dependence of recurrent felsic magmatism on new crust formation: An example from the Georgetown region of Northeastern Australia. *Geochimica et Cosmochimica Acta*, 54, 183-196.

Blake, D.H., 1987. Geology of the Mount Isa and Environs, Queensland and Northern Territory 1:500 000 scale map. *Australian Geological Survey Organisation*, Canberra.

Blake, D.H., & Page, R.W., 1988. The Proterozoic Davenport Province, Central Australia: regional geology and geochronology. *Precambrian Research*, 40/41, 297-327.

Blake, D.H., Hodgson, I.M., & Muhling, P.C., 1979. The geology of the Granites-Tanami Region, Northern Territory and Western Australia. *Bureau of Mineral Resources, Geology and Geophysics, Bulletin*, 197, 91 pp.

Blake, D.H., Stewart, A.J., Sweet, I.P., & Hone, I.G., 1987. Geology of the Proterozoic Davenport Province, central Australia. *Bureau of Mineral Resources, Geology and Geophysics, Australia, Bulletin*, 226, 70 pp.

Budd, A.R., Wyborn, L.A.I. & Bastrakova, I.V. 1998. Exploration significance of the Hiltaba Suite, South Australia, *Australian Geological Survey Organisation, Research Newsletter*, 29, 1-4.

Chamberlain, C P, & Sonder, L J, 1990. Heat-producing elements and the thermal and baric patterns of metamorphic belts. *Science*, 250, 763-769.

Champion, D.C., & Heinemann, M.A., 1994. Igneous rocks of North Queensland: 1:500 000 map and explanatory notes. *Australian Geological Survey Organisation, Record*, 1994/11, 82 pp.

Champion, D.C., & Mackenzie, D.E., 1994. Igneous rocks of North Queensland, *Australian Geological Survey Organisation, Metallogenic Atlas Series*, 2, 46 p.

Chappell, B W, 1979. Granites as images of their source rocks. *Geological Society of America, Abstracts with Programs*, 11, 400.

Chappell, B.W., 1984. Source rocks of I- and S-type granites in the Lachlan Fold Belt, southeastern Australia. *Philosophical Transactions of the Royal Society of London*, A310, 693-707.

Chappell, B.W., 1998. The restite model: a revolution in petrogenesis?. *Abstracts for the Bruce Chappell Symposium: Granites, Island Arcs, The Mantle and Ore Deposits. Australian Geological Survey Organisation, Record*, 1998/33, 26-28.

Chappell, B.W., & Stephens, W.E., 1988. Origin of infracrustal (I- type) granite magmas. *Transactions of the Royal Society of Edinburgh, Earth Sciences*, 79, 71-86.

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

Chappell, B.W., & White, A.J.R., 1984. I-type and S-type granites in the Lachlan Fold Belt, southeastern Australia. *In*: Xu Kequin and Tu Guangchi (Editors) *Geology of granites and their Metallogenic relations. Proceedings of the International Symposium, Nanjing University, Nanjing, China. Beijing, Science Press*, pp 87-101.

Chappell, B.W., White, A.J.R. & Wyborn, D., 1987. The importance of residual source material (restite) in granite petrogenesis. *Journal of Petrology*, 28, 1111-1138.

Chappell, B.W., English, P.M., King, P.C., White, A.J.R. & Wyborn, D., 1991. Granites and related rocks of the Lachlan Fold Belt, 1:1 250 000 scale map, *Bureau of Mineral Resources, Geology and Geophysics, Australia: Canberra*.

Collins, W.J., Beams, S.D., White, A.J.R., & Chappell, B.W., 1982. Nature and origin of A-type granites with particular reference to southeastern Australia. *Contributions to Mineralogy and Petrology*, 80, 189-200.

Compston, D.M. & McDougall, I., 1994. ^{40}Ar-^{39}Ar and K-Ar age constraints on the Early Proterozoic Tennant Creek Block, northern Australia, and the age of its gold deposits. *Australian Journal of Earth Sciences*, 41, 609-616.

Compston, D.M. & McDougall, I., 1995. Time constraints on the evolution of the Tennant Creek Block, northern Australia. *Precambrian Research*, 71, 107-129.

Conor, C.H.H., 1996. The Paeleo-Mesoproterozoic geology of Northern Yorke Peninsula, South Australia, Hiltaba Suite-related alteration and mineralisation of the Moonta-Wallaroo Cu-Au district, *Resources 96 Field Excursion, 2-3 December 1996, Mines and Energy, South Australia*.

Cook, N.D.J., Fanning, C.M. & Ashley, P.M., 1994. New geochronological results from the Willyama Supergroup, Olary Block, South Australia. *In: Australian Research on Ore Genesis Symposium, Adelaide, Australian Minerals Foundation*, 19.1-19.5.

Creaser, R.A. & White, A.J.R., 1991. Yardea Dacite - large volume, high-temperature felsic volcanism from the Middle Proterozoic of South Australia. *Geology*, 19, 48-51.

Cull, J., 1982. An appraisal of heat Australian heat-flow data. *BMR Journal of Australian Geology and Geophysics*, 7, 11-21.

Czamanske, G.K., & Wones, D.R., 1973. Oxidation during magmatic differentiation, Finnmarka Complex, Oslo area, Norway: Part 2, the mafic silicates. *Journal of Petrology*, 14, 349-380.

Daly, S.J., 1993a. Earea Dam Goldfield. *In*: Drexel, J.F., Preiss, W.V. and Parker, A.J., (*Editors*). The Geology of South Australia, Volume 1 - the Precambrian. *South Australia Geological Survey, Bulletin* 54, 138.

Daly, S.J., 1993b. Glenloth Goldfield. *In*: Drexel, J.F., Preiss, W.V. and Parker, A.J., (*Editors*). The Geology of South Australia, Volume 1 - the Precambrian. *South Australia Geological Survey, Bulletin* 54,138.

Daly, S.J., Horn, C.M. & Fradd, W.P., 1990. Tarcoola Goldfield. *In*: Hughes, F.E. (*Editor*) Geology of the Mineral Deposits of Australia & Papua New Guinea, *The Australiasian Institute of Mining And Metallurgy: Melbourne*, 1049-1053.

Denaro, T.J., Withnall, I.W. & Bain, J.H.C., 1997. Known mineralisation and resources (of the Georgetown Region, in Chapter 3 of) Bain, J.H.C. & Draper, J.J (*Compilers and Editors*), North Queensland Geology, *Australian Geological Survey Organisation, Bulletin* 240/*Queensland Department of Mines and Energy, Queensland Geology* 9.

Dickenson, M.P. & Hess, P.C., 1986. The structural role and homogeneous redox equilibria of iron in peraluminous, metaluminous and peralkaline silicate melts. *Contributions to Mineralogy and Petrology*, 92, 207-217.

Dickson, W L, White, A J R, Clemens, J D; Holloway, J R; Silver, L T; Chappell, B W; & Wall, V J, 1986. S-type granites and their probable absence in southwestern North America; discussion and reply. *Geology*, 14, 894-895.

Ding, P., 1997. Palaeoproterozoic geological events and gold mineralisation in the Halls Creek-Granites-Tanami Orogenic Domain, Northern Australia. *In*: Rutland, R.W.R., and Drummond, B.J., (*Editors*), Palaeoproterozoic Tectonics and Metallogenesis: comparative analysis of parts of the Australian and Fennoscandian Shields. *Australian Geological Survey Organisation, Record*, 1997/44, 25-29.

Ding, P., & Giles, C., 1993. Geological setting of gold mineralisation in the Tanami Region, Northern Territory, Australia. *Proceedings of the International Symposium on Gold Mining Technology, Beijing*, June 1993, 15-17.

Donnellan, N., Hussey, K.J., & Morrison, R.S., 1995. Flynn 5759 and Tennant Creek 5758 explanatory notes. *Northern Territory Geological Survey, Department of Mines and Energy, 1:100 000 Geological Map series*, 79 pp.

Drexel, J.F., Preiss, W.V, & Parker, A.J., 1993. The Geology of South Australia, Part I the Precambrian. *Geological Survey of South Australia, Bulletin*, 54.

Drummond, B.J., Wyborn, L.A.I., Wyborn, D., & Tarney, J.F., 1988. Temporal changes in continental growth patterns revealed by seismic crustal structure and granite geochemistry. *Geological Society of Australia, Abstracts*, 21, 118-119.

Dunnet, D., & Harding, R.R., 1967. Geology of the Mount Woodcock 1-mile Sheet area, Tennant Creek, N.T. *Bureau of Mineral Resources, Geology and Geophysics, Australia, Report*, 114, 50 pp.

Eby, G.N., 1990. The A-type granitoids: a review of their occurrence and chemical characteristics and speculation on their petrogenesis. *Lithos*, 26, 115-134.

Ellis, D.J., & Wyborn, L.A.I., 1984. Petrology and geochemistry of Proterozoic dolerites from the Mount Isa Inlier. *BMR Journal of Geology and Geophysics*, 9, 19-32.

Etheridge, M.A., Rutland, R.W.R., & Wyborn, L.A.I., 1987. Orogenesis and tectonic processes in the Early to Middle Proterozoic of northern Australia. *American Geophysical Union Geodynamics Series*, 17, 131-147.

Ferenczi, P.A., 1994. Are Tennant Creek style ironstone-related gold-copper-bismuth deposits unique? A review of available data and a comparison with possible analogous deposits. *Australasian Institute of Mining and Metallurgy, Publication Series*, 5/94, 171-177.

Gallagher, R., Wyborn, L.A.I., & Jagodzinski, E.A., 1993. The Mount Isa GIS. *ARC/INFO world book of maps,* 34.

Gardner, C.M., 1978. Precambrian Geology of the Westmoreland region. Part lll the Nicholson Granite Complex and Murphy Metamorphics. *Bureau of Mineral Resources, Geology and Geophysics, Australia, Record*, 1978/32.

Gellatly, D.C., Sofoulis, J., Derrick, G.M., & Morgan, C.M., 1974a. The older Precambrian geology of the Lennard River 1:250 000 Sheet Area, Western Australia. *Bureau of Mineral Resources, Geology and Geophysics, Australia, Report*, 153, 126 pp.

Gellatly, D.C., Derrick, G.M., Halligan, R., & Sofoulis, J., 1974b. The geology of the Charnley 1:250 000 Sheet Area, Western Australia. *Bureau of Mineral Resources, Geology and Geophysics, Australia, Report*, 154, 88 pp.

Goellnicht, N.M. 1992. Late Proterozoic fractionated granitoids and their role in the genesis of gold and base metal mineralisation in the Telfer district, Western Australia, *PhD thesis, University of Western Australia (unpublished).*

Goellnicht, N.M., Groves, D.I., & McNaughton, N.J., 1991. Late Proterozoic fractionated granitoids of the mineralised Telfer area, Paterson Province, Western Australia. *In*: Haapala, I. & Condie, K.C. (*Editors*), Precambrian Granitoids - Petrogenesis, Geochemistry and Metallogeny. *Precambrian Research,* 51, 375-391.

Goellnicht, N.M., Groves, D.I., & McNaughton, N.J., 1993. The role of late Proterozoic fractionated granitoids in the genesis of polymetallic mineralisation in the Telfer District, WA. Specialist Group in Economic Geology, 2nd National Meeting, Armidale, 4-5th February, *Geological Society of Australia, Abstracts*, 34, 22-23.

Goncharov, A., Drummond, B.J., Tripolsky, A., and Wyborn, L.A.I., 1998. Average composition of the crust in the Australian, Fennoscandian, and Ukrainian shields from refraction seismic studies and petrophysical modelling. *Australian Geological Survey Organisation, Research Newsletter*, 28, 20-28.

Gow, P.A., Wall, V.J., Oliver, N.H.S., & Valenta, R.K., 1994. Proterozoic iron oxide (Cu-Au-U-REE) deposits: Further evidence of hydrothermal origins. *Geology*, 22, 633-636.

Griffin, T.J., & Grey, K., 1990. King Leopold and Halls Creek Orogens. *In*: Geology and Mineral Resources of Western Australia. *Western Australia Geological Survey, Memoir*, 3, 232-255.

Griffin, T.J., & Tyler, I.M., 1992. Geology of the southern Halls Creek Orogen - a summary of field work in 1992. *Geological Survey of Western Australia, Record*, 1992/17, 28 pp.

Griffin, T.J., Tyler, I.M. & Playford, P.E., 1993. Lennard River, Western Australia, Third Edition, 1:250 000 Geological Series. *Geological Survey of Western Australia, Explanatory Notes, SE/51-08*, 56 pp.

Henderson, G.A.M., 1989. Notes on Croydon, north Queensland, fieldwork July/August 1988 and results of K/Ar dating of sericitic alteration. *Bureau of Mineral Resources, Geology and Geophysics, Australia, Record* 1989/46.

Henley, R.W. and Hoffman, C.F., 1987. Gold: Sources to Resources, in Pacfic Rim Congress 87, pp 159-168 (The Australasian Institute of Mining and Metallurgy: Melbourne)

Hoatson, D.M. & Cruickshank, B.I., 1985. A stream sediment geochemical orientation survey of the Davenport Province, Northern Territory. *Bureau of Mineral Resources, Geology and Geophysics, Australia, Record* 1985/44, 61 pp.

Hobbs, B.E., Ord, A., & Walshe, J.L., 1998. The concept of coupled geodynamic modelling with special reference to the Yilgarn. *In*: Abstracts for 'Geodynamics and gold exploration in the Yilgarn', *Australian Geodynamics Cooperative Research Centre, Nedlands*, 36-39.

Holcombe, R.J., Pearson, P.J., & Oliver, N.H.S., 1992. Structure of the Mary Kathleen Fold Belt. *Bureau of Mineral Resources, Geology and Geophysics, Bulletin*, 243, 257-287.

Hutchinson, R.W., 1981. Mineral Deposits as Guides to Supracrustal Evolution. *In*: O'Connel, R.J., & Fyfe, W.S. (*Editors*), Evolution of the Earth. *American Geophysical Union Monograph*, 5.

Ishihara, S., 1977. The magnetite-series and ilmenite-series in granitic rocks. *Mining Geology*, 27, 293-305.

Jagodzinski, E.A., 1991. Stratigraphy of the Pul Pul Rhyolite, South Alligator Valley Mineral Field. *BMR Research Newsletter*, 14, 4-5.

Jagodzinski, E.A., 1992. A study of the felsic volcanic succession south-east of Coronation Hill: Palaeovolcanology-geochemistry-geochronology. *Bureau of Mineral Resources, Geology and Geophysics, Record*, 1992/9, 147 pp.

Jagodzinski, E.A., Wyborn, L.A.I., & Gallagher, R., 1993. Mount Isa Metallogenic Atlas, Volume 1, Geology, *Australian Geological Survey Organisation, Metallogenic Atlas Series*, 1, 21p.

Jaques, A.L., Blake, D.H., & Donchak, P.J.T., 1982. Regional metamorphism in the Slewing Range area, northwest Queensland. *BMR Journal of Australian Geology and Geophysics*, 71, 181-196.

Johannes, W., & Holtz., F., 1996. *Petrogenesis and Experimental Petrology of Granitic Rocks. Springer-Verlag: Berlin, Heidleberg.*

Johnson, J.P. & Cross, K.C. 1995. U-Pb geochronological constraints on the genesis of the Olympic Dam Cu-U-Au-Ag deposit, South Australia. *Economic Geology*, 90, 1046-1063.

Johnson, R.W., 1977. Distribution and major-element chemistry of Late Cenozoic volcanoes at the southern end of the Bismark Sea, Papua New Guinea. *Bureau of Mineral Resources, Geology and Geophysics, Australia, Report*, 188, 162 pp.

Jones, F.H., 1938. The Mount Amherst gold and silver-lead deposits, East Kimberley District. *Aerial, Geological and Geophysical Survey of Northern Australia, Report*, 31, 4 pp.

Keough, D., 1993. The Osborne Deposit - its discovery, geology and development. Carpentaria and Mount Isa Regional Development Forum, August, 1993, *Northwest Queensland Branch of the Australasian Institute of Mining and Metallurgy*, 69-70.

Large, R.R., 1974. Zonation of the hydrothermal minerals at the Juno Mine, Tennant Creek goldfield, central Australia. *Economic Geology*, 70, 1387-1413.

Lawrie, K.C., Jaireth, S., A-Izzeddin, D., & Grace, J., 1998. Gold localisation in a lateral ramp within a reactivated mylonite: the Golden Butterfly deposit, Croydon Goldfield, N.Q., *14th AGC Geological Convention, Townsville, July, Geological Society of Australia, Abstracts*, 49, 261.

Ludwig, K.R. & Cooper, J.A., 1984. Geochronology of Precambrian granites and associated U-Ti-Th mineralisation, northern Olary Province, South Australia. *Contributions to Mineralogy and Petrology*, 86, 298-308.

Madigan, T., Rawlings, D.J., Haines, P., & Pietsch, B.A. *in press*. Arnhem Bay- Gove data record. *Northern Territory Geological Survey, Report* GS95/8.

Magoon, L.B., & Dow, W.G., 1991. The petroleum system - from source to trap, *American Association of Petroleum Geologists*, 75 (3):627.

Mahood, G.A., 1991. Evidence for ascent of differentiated liquids in silicic magma chamber found in granitic pluton. Abstracts for the Second Hutton Symposium on Granites and Related Rocks, Canberra, 1991. *Bureau of Mineral Resources, Geology and Geophysics, Australia, Record*, 1991/25: 66.

Manning, D.A.C., 1981. The effect of fluorine on liquidus phase relationships in the system Qz-Ab-Or with water. *Contributions to Mineralogy and Petrology*, 76, 206-215.

Martin, A.R., 1996. Gold mineralisation at the Tunkilla prospect (Yarlbrinda Shear Zone), Lake Everard, *In*: Preiss, W.V., (*Editor*) Convention Abstracts, Resources 96, Adelaide, 4-5 December 1996, *Mines and Energy, South Australia*, 90-93.

McDonald, G.D., & Collerson, K.D., 1998. Ewen Plutonic Association, northern Mount Isa Block: tectonic and metallogenic significance. *Geological Society of Australia, Abstracts*, 49, 300.

McNaughton, N.J., Sheppard, S. & Goellnicht, N.M., 1993. Understanding the nature of proximal-distal mineralisation in thermal-aureole gold deposits in the Proterozoic of northern Australia using lead isotopes. Specialist Group in Economic Geology, 2nd National Meeting, Armidale, 4-5th February, *Geological Society of Australia, Abstracts*, 34, 22-23.

Meyer, C., 1981. Ore-forming processes in geologic History. *Economic Geology, 75th Anniversary Volume*, 6-41.

Miller, C.F., White, A.J.R., Clemens, J.D., Holloway, J.R., Silver, L.T., Chappell, B.W., & Wall, V.J., 1986. S-type granites and their probable absence in southwestern North America; discussion and reply. *Geology*, 14, 804-806.

Morrison, G.W. & Beams, S.D., 1995. Geological setting and mineralisation style of ore deopsits of northeast Queensland. In Beams, S.D. (*Editor*) Exploring the tropics - mineral deposits of northeast Queensland: geology aand geochemistry. *James Cook University, Economic Geology Research Unit, Contributions*, 52, 1-32.

Needham R.S., 1982. Nabarlek Region, N.T., 1:100 000 scale. *Bureau of Mineral Resources, Australia, Geology and Geophysics, Australia, Map Commentary*, 472.

Nutman, A.P. & Ehlers, K. 1998. Evidence for multiple Palaeoproterozoic thermal events and magmatism adjacent to the Broken Hill Pb-Zn-Ag orebody, Australia. *Precambrian Research*, 90, 203-238.

Oreskes, N., & Einaudi, M.T., 1990. Origin of rare earth element-enriched hematite breccias at the Olympic Dam Cu-U-Au-Ag deposit, Roxby Downs South Australia. *Economic Geology*, 85, 1--28.

Nutman, A.P. & Ehlers, K. 1998. Evidence for multiple Palaeoproterozoic thermal events and magmatism adjacent to the Broken Hill Pb-Zn-Ag orebody, Australia. *Precambrian Research,* 90, 203-238.

Page, R.W. & Laing, W.P. 1992. Felsic metavolcanic rocks related to the Broken Hill Pb-Zn-Ag orebody, Australia: geology, depositional age and timing of high grade metamorphism. *Economic Geology*, 87, 2138-2168.

Page, R.W., Compston, W., & Needham, R.S., 1980. Geochronology and evolution of the Late-Archaean basement and Proterozoic rocks in the Alligator Rivers Uranium Field, Northern Territory, Australia. *In*: Ferguson, J., & Goleby, A.B. (*Editors*), Uranium in the Pine Creek Geosyncline. Proceedings of an International Symposium on the Pine Creek Geosyncline, *International Atomic Energy Agency, Vienna*, 39-68.

Passchier, C.W., 1986. Evidence for early extensional tectonics in the Proterozoic Mount Isa Inlier, Australia. *Geology*, 14,1008-1011.

Patino Douce, A.E., & Beard, J.S., 1995. Dehydration-melting of biotite gneiss and quartz amphibolite from 3 to 15 kbar. *Journal of Petrology,* 36, 707-738.

Patino Douce, A.E., 1997. Generation of metaluminous A-type granites by low pressure melting of calc-alkaine granitoids. *Geology,* 25, 743-746.

Pearce, J., A., Harris, M.B.W. & Tindle, A.G., 1984. Trace element discrimination diagrams for the tectonic interpretation of granitic rocks. *Journal of Petrology,* 25, 956-983.

Pearson, P.J., Holcombe, R.J., & Page, R.W., 1992. Synkinematic emplacement of the Middle Proterozoic Wonga Batholith into a mid-crustal extensional shear zone, Mount Isa Inlier, Queensland, Australia. *Bureau of Mineral Resources, Geology and Geophysics, Bulletin,* 243, 289-328.

Picahavant, M., & Manning, D.,1984. Petrogenesis of tourmaline granites and topaz granites; the contribution of experimental data. *Physics of the Earth and Planetary Interiors,* 35, 31-50.

Pirajno, F., Rugless, C.R., Griffin, T., & Tyler, I., 1994. Hydrothermal vein gold and base metal deposits in the Halls Creek Province, East Kimberley, Western Australia. *Geological Society of Australia, Abstracts*, 37, 347.

Pitcher, W.S., 1982. Granite type and tectonic environment. *In*: Hsu, K.J. (*Editor*) *Mountain Building Processes*, 19-40. London, Academic Press.

Pryce, W., 1778. *Mineralogia Cornubiensis; a treatise on minerals, mines, and mining. James Phillips, London*.

Rawlings, D.J., 1994. Characterisation and correlation of volcanism in the McArthur Basin and transitional domain, NT. *In*: Hallenstein, C.P. (*Editor*), Australian Mining Looks North - the Challenges and Choices, Technical Program Proceedings. *The Australasian Institute of Mining and Metallurgy Publication Series,* 5/94, 157-160.

Sanidford, M., & Hand, M., 1998. Australian Proterozoic high-temperature, low-pressure metamorphism in the conductive limit. *In*: Treloar, P.J. and O'Brien, P.J. (*Editors*) What Drives Metamorphism and Metamorphic Reactions? *Geological Society of London, Special Publications*, 138, 109-120.

Sandiford, M., Hand, M., & McLaren, S., *in press*. High Geothermal Gradient metamorphism during thermal subsidence. *Earth and Planetary Science Letters*.

Sheppard, S., 1996. Mafic-felsic magma mingling in the Bow River Batholith of the Halls Creek Orogen. *Geological Survey of Western Australia*, *1995-1996 Annual Review*, 56-60.

Sheppard, S., Griffin, T.J., & Tyler, I.M., 1995. Geochemistry of the felsic igneous rocks of the southern Halls Creek Orogen. *Geological Survey of Western Australia, Record*, 1995/4, 81 pp.

Sheppard, S., Tyler, I.M., & Hoatson, D.M., *in prep*. Explanatory notes on the Mount Remarkable 1:100000 Geological Sheet, Western Australia. *Geological Survey of Western Australia, 1:100000 geological map commentary*.

Sheraton, J.W. & Labonne, B., 1978. Petrology and geochemistry of acid igneous rocks of northeast Queensland, *Bureau of Mineral Resources, Geology and Geophysics, Australia, Bulletin* 169.

Singh, J., & Johannes, W., 1996a. Dehydration melting of tonalites. Part 1. Beginning of melting. *Contributions to Mineralogy and Petrology*, 125, 16-25.

Singh, J., & Johannes, W., 1996b. Dehydration melting of tonalites. Part 11. *Composition of melts and solids. Contributions to Mineralogy and Petrology*, 125, 26-44.

Skirrow, R.G., & Ashley, P.M., 1998. Copper-Gold mineral systems and regional alteration, Curnamona Craton. *In*: Gibson, G.M. (*Compiler*), Broken Hill Exploration Initiative: Abstracts of papers presented at the fourth annual meeting in Broken Hill, October 19-21, 1998. *Australian Geological Survey Organisation, Record* 1998/25, 104-108.

Solomon, M., & Heinrich, C.A., 1992. Are heat producing granites essential to the origin of giant lead-zinc deposits at Mount Isa and McArthur River, Australia, *Exploration and Mining Geology*, 1, 85-91.

Sparks, R.S.J., Hupert, H.E., & Turner, J.S., 1984. The fluid dynamics of evolving magma chambers. *Philosophical Transactions of the Royal Society of London*, A310, 511-534.

Stewart, K.P., 1992. High temperature felsic volcanism and the role of mantle magmas in Proterozoic crustal growth: The Gawler Range Volcanic Province. *The University of Adelaide, PhD thesis (unpublished)*.

Stolz, A.J., & Morrison, R.S., 1994. Proterozoic igneous activity in the Tennant Creek region, Northern Territory, Australia, and its relationship to Cu-Au-Bi mineralisation. *Mineralium Deposita*, 29, 261-274.

Streckeisen, A.L., 1973. Plutonic rocks. Classification and nomenclature recommended by the IUGS Subcommission on the sys-tematics of igneous rocks. *Geotimes*, 18 (10): 26-30.

Stuart-Smith, P.G., Needham, R.S., Page, R.W., & Wyborn, L.A.I., 1993. Geology and Mineral Deposits of the Cullen Mineral Field, Northern Territory. *Australian Geological Survey Organisation, Bulletin*, 229, 145 pp.

Stuart-Smith, P.G., & Needham, R.S., 1984. Hydrothermal mineral deposits and their association with granitoids in the Cullen Mineral Field, Northern Territory. Darwin Conference, *Australasian Institute of Mining and Metallurgy*, pp 329-338.

Sun, S-S., & Eadington, P.J., 1987. Oxygen isotope evidence for the mixing of magmatic and meteoric waters during tin mineralisation in the Mole Granite, New South Wales, Australia. *Economic Geology*, 82, 43-52.

Sun, S.-S., & McDonough, W.F., 1989. Chemical and isotopic systematics of oceanic basalts: implications for mantle composi-tion and processes. *In*: Saunders, A.D., and Norry, M.J. (*Editors*), Magmatism in the Ocean Basins. *Geological Society of London, Special Publication*, 42: 313-345.

Tunks, A.J., 1996. Geology of the Tanami Gold Mine. *Ph.D. Thesis, University of Tasmania (unpublished).*

Tuttle, O.F., & Bowen, N.L., 1958. Origin of granite in the light of experimental studies in the system $NaAlSi_3O_8$-$KAlSi_3O_8$-SiO_2-H_2O. *Geological Society of America, Memoir* 74.

Tyler, I.M., Griffin, T.J., Page, R.W., & Shaw, R.D., 1995 . Are there terranes within the Lamboo Complex of the Halls Creek Orogen?. *Geological Survey of Western Australia, Annual Review*, 1993-1994, 37-46.

Valenta, R., & Wall, V., 1996. Controls on mineralisation at the Granites, Tanami Desert, Northern Territory. *Geological Society of Australia, Abstracts*, 41, 451.

Wall, V.J., 1989. Fluids and metamorphism. *Ph.D. Thesis, Monash University, (unpublished)*.

Walshe, J.L., Heithersay, P.S., & Morrison, G., *in press*. Toward an understanding of the metallogeny of the Tasman Fold Belt System. *Economic Geology*.

Warren, R.G., 1994a. Gold mineralisation in the northern East Kimberley Gold District, Western Australia. *The Australasian Institute of Mining and Metallurgy, Publication Series*, 5/94, 117-121.

Warren, R.G., 1994b. Role of early extensional faults in the Grants Patch District, East Kimberley, *Western Australia. Geological Society of Australia, Abstracts*, 37, 453.

Warren, R.G., Stewart, A.J. and Shaw, R.D. 1974. Summary of information on mineral deposits of the Arunta Complex, Alice Springs area, Northern Territory. *Bureau of Mineral Resources, Geology and Geophysics, Australia, Record* 1974/117, 44 pp.

Wedekind, R.M. & Love, M.R., 1990. Warrego Gold-Copper-Bismuth Deposit. *In*: F.E. Hughes (*Editor*), Geology and Mineral Deposits of Australia and Papua New Guinea. *Australasian Institute of Mining and Metallurgy, Monograph*, 14, 839-843.

Whalen, J.B., 1985. Geochemistry of and island-arc plutonic suite: the Uasilau-Yau Yau Intrusive Complex, New Britain, P.N.G. *Journal of Petrology*, 26, 603-632.

Whalen, J.B., Britten, R.M., & McDougall, I., 1982. Geochronology and geochemistry of the Frieda River prospect area, Papua New Guinea. *Economic Geology*, 77, 592-616.

White, A.J.R., & Chappell, B.W., 1977. Ultrametamorphism and granitoid genesis. *Tectonophysics*, 43: 7-22.

White, A.J.R., & Chappell, B.W., 1983. Granitoid types and their distribution in the Lachlan Fold Belt, south east Australia. *In*: Roddick, J.A., (*Editor*), Circum-Pacific Plutonic terranes. *Geological Society of America, Memoir*, 159, 21-34.

White, A.J.R., Clemens, J.D., Holloway, J.R., Silver, L.T., Chappell, B.W., & Wall, V.J., 1986. S-type granites and their probable absence in southwestern North America. *Geology*, 14, 115-118.

White, A.J.R., Wyborn, D., & Chappell, B.W., 1991. A granite classification for the economic geologist. *Geological Society of Australia, Abstracts*, 29, 57.

Williams, P.J., & Heinemann, M., 1993. Maramungee: a Proterozoic Zn skarn in the Cloncurry District, Mount Isa Inlier, Queensland, Australia. *Economic Geology*, 88, 1114-1134.

Withnall, I.W., Bain, J.H.C., Draper, J.J., Mackenzie, D.E. & Oversby, B.S., 1988, Proterozoic stratigraphy and tectonic history of the Georgetown Inlier, northeastern Queensland, *Precambrian Research*, 40/41, 429-446.

Witt, W.K., & Sanders, T., 1966. Magmatic-hydrothermal breccia dykes and hydrothermal alteration in the McHale Granodiorite, Halls Creek Orogen: a possibly porphyry system. *Geological Survey of Western Australia*, 1995-1996 Annual Review, 104-110.

Wyborn, D., 1983. Fractionation Processes in the Boggy Plain Zoned Pluton. *Ph.D Thesis, Australian National University (unpublished)*.

Wyborn, D., 1993. A granite classification for the economic geologist. Workshop on Magmatismo Gran¡tico e Mineralisa?es Associadas, *Academia Brasileira de Cîncias, Rio de Janerio,* September 1993, Abstracts, 55-57.

Wyborn, D., & Chappell, B.W., 1986. The petrogenetic significance of chemically related plutonic and volcanic rock units. *Geological Magazine*, 123, 619-628.

Wyborn, D., Turner, B.S., & Chappell, B.W., 1987. The Boggy Plain Supersuite: a distinctive belt of I-type igneous rocks of potential economic significance in the Lachlan Fold Belt. *Australian Journal of Earth Sciences,* 34: 21-43.

Wyborn, L.A.I., 1988. Petrology, geochemistry and origin of a major Australian 1880-1840 Ma felsic volcano-plutonic suite: a model for intracontinental felsic magma generation. *Precambrian Research*, 40/41, 37-60.

Wyborn, L.A.I., 1990. Localisation of mineralisation in the Coronation Hill and related deposits, South Alligator Mineral Field, NT. *BMR Research Newsletter*, 12, 1-2.

Wyborn, L.A.I., 1992. The Williams and Naraku Batholiths, Mount Isa Inlier: an analogue of the Olympic Dam Granites? *BMR Research Newsletter*, 16: 13-16.

Wyborn, L.A.I., 1993. Constraints on interpretations of lower crustal structure, tectonic setting and metallogeny of the Eastern Goldfields and Southern Cross Provinces provided by granite geochemistry. *Ore Geology Reviews,* 8, 125-140.

Wyborn, L.A.I., & Heinrich, C.A., 1993. Empirical observations on granite-associated gold + base-metal mineral deposits in the Proterozoic of Australia: delineating exploration criteria, *AGSO Research Newsletter,* 19:3-4.

Wyborn, L.A.I., Bastrakova, I.V., & Budd, A.R., 1998. Australian Proterozoic Granites - characteristics, sources and possible mechanisms for derivation and emplacement. *In*: Abstracts for the Bruce Chappell Symposium: Granites, Island Arcs, The Mantle and Ore Deposits. *Australian Geological Survey Organisation, Record*, 1998/33, 47-49.

Wyborn, L.A.I., Page, R.W., & Parker, A.J., 1987. Geochemical and geochronological signatures in Australian Proterozoic igneous rocks. *In*: Pharaoh, T.C., Beckinsale, R.D. and Rickard, D.T. (*Editors*), Geochemistry and Mineralisation of Proterozoic Volcanic suites. *Geological Society Special Publication* 33, 377-394.

Wyborn, L.A.I., Wyborn, D, Chappell, B.W., Sheraton, J., Tarney, J.F., Collins, W.J., & Drummond, B.J., 1988a. Geological evolution of granite compositions with time in the Australian continent - implications for tectonic and mantle processes. *Geological Society of Australia, Abstracts*, 21: 434-435.

Wyborn, L.A.I., Page, R.W., & McCulloch, M.T., 1988b. Petrology, geochronology, and isotope geochemistry of the post-1820 Ma granites of the Mount Isa Inlier: mechanisms for the generation of Proterozoic anorogenic granites. *In*: Wyborn, L.A.I, and Etheridge, M.A., (*Editors*), The early to middle Proterozoic of Australia. *Precambrian Research,* 40/41: 509-541.

Wyborn, L.A.I., Wyborn, D., Warren, R.G., & Drummond, B.J., 1992. Proterozoic granite types in Australia: implications for lower crust composition, structure and evolution. *Transactions of the Royal Society of Edinburgh, Earth Sciences,* 83, 201-209.

Wyborn, L.A.I., Heinrich, C.A., & Jaques, A.L., 1994a. Australian Proterozoic Mineral Systems: essential ingredients and mappable criteria. *The Australasian Institute of Mining and Metallurgy, Publication Series,* 5/94, 109-115.

Wyborn, L.A.I., Gallagher, R., Jaques, A.L., Jagodzinski, E.A., Thost, D., & Ahmad, M., 1994b. Developing metallogenic Geographic Information Systems: examples from Mount Isa, Kakadu, and Pine Creek. *The Australasian Institute of Mining and Metallurgy, Publication Series,* 5/94, 129-133.

Wyborn, L.A.I., Ord, A., Hobbs, B., & Idnurm, I., 1997. Episodic crustal magmatism in the Proterozoic of Northern Australia - a continuum crustal heating model for magma generation. *Australian Geological Survey Organisation, Record* 1997/44, 131-134.

Wyborn, L.A.I, Bastrakova, I.V., & Budd, A.R., 1998a. Using GIS is a data-driven, mineral systems approach to asses the mineral potential of Australia Proterozoic Granites. *Geological Society of Australia, Abstracts*, 49, 480.

Wyborn, L.A.I, Budd, A.R., & Bastrakova, I.V., 1998b. Australian Proterozoic Granite-related Ore-Systems. *Geological Society of Australia, Abstracts*, 49, 481.

Wyborn, L.A.I, Idnurm, M., Budd, A.R., Bastrakova, I.V., Hazell, M.S., & Edgecombe, S.M., 1998c. What do ~10 000 whole rock geochemical analyses tell us about Australian Proterozoic Intraplate Igneous Activity. *Geological Society of Australia, Abstracts*, 49, 484.

Wyborn, L.A.I, Budd, A.R., Stevens, B.P.J., Ashley, P.M., Conor, C.H.H., & Bastrakova, I.V., 1998d. Major felsic igneous units of the Broken Hill-Olary region and their metallogenic potential. *In*: Gibson, G.M. (*Compiler*), Broken Hill Exploration Initiative: Abstracts of papers presented at the fourth annual meeting in Broken Hill, October 19-21, 1998. *Australian Geological Survey Organisation, Record* 1998/25, 123-126.

Wyborn, L.A.I., Bastrakova, I.V., & Budd, A.R., 1998e. Australian Proterozoic Granites - characteristics, sources and possible mechanisms for derivation and emplacement. In: Abstracts for the Bruce Chappell Symposium: Granites, Island Arcs, The Mantle and Ore Deposits. *Australian Geological Survey Organisation, Record*, 1998/33, 47-49.

Wyborn, L.A.I., Hazell, M., Page, R.W., Idnurm, M., & Sun, S-.S., 1998. A newly discovered major Proterozoic granite-alteration system in the Mount Webb region, central Australia, and implications for Cu-Au mineralisation. *AGSO Research Newsletter*, 28, 1-6.

Zen, E-an, 1986. Aluminium enrichment in silicate melts by fractional crystallisation: some mineralogical and petrographic constraints, *Journal of Petrology*, 27, 1095-1117.

2 ALBANY-FRASER PROVINCE

Compiled by Anthony Budd

2.1 Executive Summary - Geology

The Albany-Fraser province extends along the southern and southwestern margin of the Yilgarn Craton. It consists mainly of orthogneiss and granite but also includes large sheets of metagabbro (including the Fraser Complex), remnants of mafic dykes and widespread metasedimentary rocks. The orthogneisses are derived from Late Archaean and Palaeo- and Mesoproterozoic granitic rocks that were deformed and metamorphosed during Mesoproterozoic orogenic activity.

The province is comprised of Archaean and Proterozoic rocks. Proterozoic intrusive activity was accompanied by metamorphism and deformation, and occurred in at least two events. The Biranup Supersuite probably intruded at around 1700 - 1600 Ma, and is mostly comprised of heterogeneous orthogneisses. The Nornalup Supersuite appears to include granites intruded at two ages, approximately 1300 Ma and 1190 Ma. It is dominated by heterogeneous ortho- and paragneisses. There is insufficient detailed information to divide the Nornalup Supersuite into two suites as is indicated by these two distinct ages.

Nelson *et al.*, (1995) present a summary of the geological history of the Esperance region (eastern part of the Albany-Fraser province). Widespread granite emplacement in the Yilgarn Craton occurred at 2620 Ma, followed by emplacement of granitic rocks in the Albany-Fraser province at 1700-1600 Ma. Arenaceous sediments were deposited at < *ca* 1560 Ma. Widespread intrusion of gabbro (Fraser Complex) and granite into thickened crust at a high metamorphic grade occurred between 1300-1280 Ma. Widespread granites were intruded into the southeastern part of the orogen between 1190-1130 Ma.

Geochronological studies in the western part of the province have not found any evidence of the *ca* 1700-1600 Ma granitic rocks. The post-1300 Ma geological histories of both eastern and western parts of the Albany-Fraser province appear to be broadly similar.

Granites of both the Biranup and Nornalup Supersuites show similar geochemical trends. Analyses of the Nornalup Supersuite include mafic enclaves (Clarke, 1995). The granites show little alkali alteration, have a spread of Th/U ratios, and are mostly reduced, becoming oxidised in the most felsic samples. They are metaluminous, have increasing K/Rb (showing that the granites are not K-feldspar fractionated), and only the most felsic samples show any increase in Rb/Sr. Compositions range from tonalite to granite, and all samples are Sr-depleted, Y-undepleted. Some samples show moderately high HFSE.

2.2 Executive Summary - Metallogenic Potential

These granites are restite-dominated, as shown by the lack of fractionation and the presence of mafic enclaves in granites of the Nornalup Supersuite. None of the Proterozoic granites of the Albany-Fraser province are concluded to have any significant metallogenic potential.

2.3 Future Work

Further granite geochemistry, petrology and dating will undoubtedly refine the subdivision of the granites in this Block, and will possibly alter the understanding of their metallogenic potential. This is not a high priority given the lack of fractionation and the restitic nature of the granites.

2.4 Methodology

Information Sources: The geochronological framework of the Albany-Fraser province is now quite well constrained, with SHRIMP dating carried out on granites of all ages (Black *et al.*, 1992; Clark, 1995; Nelson *et al*, 1995; Nelson, 1995), however the tectonic framework is still debated. There are difficulties in relating dated rocks back to the 1:250 000 geological mapsheets used as a base for this project's GIS. In some instances, a single map unit has two very different age determinations, meaning that it is difficult to assign all polygons with the one map symbol to one Supersuite. For this reason, and because of limited geochemical data, the Supersuites to which some map units have been assigned here will possibly be changed with further work.

Geochemical samples are mostly from Curtin University Honours theses and Nelson *et al* (1995). References to other literature used are given below. 1:250 000 geological maps and commentaries were also used. Much of the work carried out in the Albany-Fraser province has been aimed at understanding the tectonic setting (Nelson *et al.*, 1995; Myers and Barley, 1992; Myers, 1990). As part of this, mafic xenolith-bearing granites are likely to have been over-represented in the sample group, and samples of the most felsic endmembers may be under-represented.

Classification of Granites: In this synthesis, the granites were tentatively grouped using only limited geochemistry, brief literature articles, good geochronology coverage, and information from regional-scale mapping (published 1:250 000 mapsheets).

Host Rocks: The metasediments which the granites are presumed to intrude are not well described in the literature: the data available for this are limited, and possibly incomplete.

Relating Mineralisation: None of Proterozoic age.

2.5 References

Black, L.P., Harris, L.B., and Delor, C.P., 1992. Reworking of Archaean and Early Proterozoic components during a progressive, Middle Proterozoic tectonothermal event in the Albany Mobile Belt, Western Australia, *Precambrian Research,* 59, 95-123.

Blockley, J.G. and Myers, J.S., 1990. Proterozoic rocks of the Western Australian shield - geology and mineralisation, in Hughes, F.E. *(Ed.), Geology of the Mineral Deposits of Australia and Papua New Guinea, pp 607-615, The Australian Institute of Mining and Metallurgy: Melbourne.*

Clark, W.C., 1995. Granite petrogenesis, metamorphism and geochronology of the Western Albany-Fraser Orogen, Albany, Western Australia, *BSc (Honours) thesis, Curtin University of Technology, Perth, WA - unpublished.*

Myers, J.S., 1990. Albany-Fraser Orogen, pp 255-263, in *Geology and Mineral Resources of Western Australia: Western Australia Geological Survey, Memoir* 3.

Myers, J.S., 1993. Precambrian history of the West Australian Craton and adjacent orogenies, *Annual Review of Earth and Planetary Science*, 21, 453-485.

Myers, J.S. and Barley, M.E., 1992. Proterozoic tectonic framework and metal deposits of southwestern Australia, *Precambrian Research,* 58, 345-354.

Nelson, D.R., 1995. Compilation of SHRIMP U-Pb zircon geochronology data, 1994, *Geological Survey of Western Australia, Record* 1995/3.

Nelson, D.R., Myers, J.S., and Nutman, A.P. 1995. Chronology and evolution of the Middle Proterozoic Albany-Fraser Orogen, Western Australia, *Australian Journal of Earth Sciences,* 42, 481-495.

2.6 Table 2.1

Chpt #	Grouping (Type)	Age (Ma)	Potential					Confid Level	Pluton
			Cu	Au	Pb/Zn	Sn	Mo/W		
2	Biranup (Kalkadoon)	1700	Low	Low	Low	Low	Low	110	Undivided
3	Nornalup (Kalkadoon)	1300 - 1180	Low	Low	Low	Low	Low	110	Undivided

3 ARNHEM BLOCK/McARTHUR BASIN

Compiled by Lesley Wyborn

3.1 Executive Summary - Geology

The Arnhem Block/McArthur Basin is best know for its world class sediment hosted HYC Pb/Zn deposit. It is certainly not noted for granite-related Cu-Au deposits. Some Cu mineralisation occurs in the southern McArthur Basin area, and although hosted by mafic volcanics, is more probably derived from copper- and sulphate-rich basinal brines (Wall and Heinrich, 1990) than from magmatic fluids (c.f. Knutson *et al.*, 1979).

The regional geology is well summarised by Jackson *et al.* (1987), Plumb and Roberts (1992), Plumb *et al.* (1990), Madigan and Rawlings (1994) and Pietsch *et al.* (1994). The Arnhem Block occurs in northeast Arnhem Land and consists of high grade metamorphics which were intruded by a suite of restite-rich S-type garnet- and cordierite-bearing granites at around ~1850 Ma (Bradshaw Suite). A suite of I-type younger fayalite bearing granites (Giddy Suite) intruded the basement at ~1835 Ma. Somewhat similar in composition, the Bickerton Suite of felsic volcanics were extruded at around 1814 Ma.

A series of sedimentary packages belonging to the McArthur Basin was then deposited unconformably on these basement rocks. Throughout the basin five main stratigraphic sequences were deposited: each are generally separated by regional unconformities. The lowermost sequence, the Tawallah Group contains most of the igneous suites. The suites are either bimodal, dominantly felsic or dominantly mafic. The volcanics are mostly related to rift phase sedimentation. Some granite plutons are coeval with these volcanic units, but all plutons are relatively small in size and have a limited SiO_2 range. Most of the granites are high level intrusives which grade into their own coeval volcanic ejecta.

3.2 Executive Summary - Metallogenic Potential

There is no known mineralisation associated with the basement suites in Arnhem Land (Bradshaw or Giddy Suites). Heavy mineral sand fractions from Cato River and Wonga Creek were reported as containing 0.25% and 0.27% Sn. Petrological examination indicated the presence of ilmenite, rutile, and minor cassiterite. The actual location of the samples is not known and the Bukudal Granite, Bradshaw Granite and Latram Granite are all exposed in the general area (Masood Ahmad, *pers. comm*; Chestnut *et al.*, 1966).

The suites of igneous rocks related to the McArthur Basin are also not considered to have any economic potential. The suites are all too felsic and have high concentrations of high field strength elements, suggesting A-type affinities.

3.3 Future Work

In view of the limited potential of the granites in the Arnhem Block/McArthur Basin no further work is recommended. The only potential could lie in the Bukudal Granite with Sn, however, this is considered unlikely to produce significant mineralisation.

3.4 Methodology

Information Sources: 1:250 000 maps and commentaries, 1:100 000 maps and notes where available, published ages, AGSO ROCKCHEM database supplemented with data from NTGS, BRS/AGSO Minloc database, AGSO magnetics and gravity.

Classification of Granites: In this report the granites have been divided into suites based on the age, geographic location, and geochemistry of each pluton. Using this method, approximately 3 main suites are recognised (Table 1.1).

Host Rocks: The country rocks which are thought to be intruded by each suite have been summarised, and classified according to mineralogical characteristics thought to be important in determining the metallogenic potential of a granite intrusive event.

Relating Mineralisation: There are virtually no deposits within 5 kms of any of the granite suites from the Arnhem Block or McArthur Basin.

3.5 Acknowledgements

This section was prepared with much assistance from Ken Plumb and Ian Sweet (AGSO) and Masood Ahmad and Tanya Madigan (NTGS).

3.6 References

Chestnut, W., Blayden, I., Edyvean, M., and Gee, C., 1966. Report on exploration within Prospecting Authority 1138, Eastern Arnhem Land. Broken Hill Proprietary Company Limited. *Northern Territory Department of Mines and Energy Company Report CR* 66/8.

Jackson, M.J., Muir, M.D., and Plumb, K.A., 1987. Geology of the southern McArthur Basin, Northern Territory. *Bureau of Mineral Resources, Geology and Geophysics, Australia, Bulletin*, 220, 173 pp.

Knutson, J., Ferguson, J., Roberts, W.M.B., Donnelly, T.H., and Lambert, I.B., 1979. Petrogenesis of the Copper-bearing breccia pipes, Redbank, Northern Territory, Australia. *Economic Geology,* 74, 814-826.

Madigan, T. L. A., and Rawlings, D. J. 1994. Lower pressure regional metamorphism in the Bradshaw Complex, Northern Arnhem Land, Northern Territory, Australia. *Geological Society of Australia, Abstracts,* 37, 260.

Pietsch, B.A., Plumb, K.A., Page, R.W., Haines, P.W., Rawlings, D.J., and Sweet, I.P., 1994. A revised stratigraphic framework for the McArthur Basin, N.T. In: Hallenstein, C.P. (Editor), Australian Mining Looks North - the Challenges and Choices, Technical Program Proceedings. *The Australasian Institute of Mining and Metallurgy, Publication Series*, 5/94, 135-138.

Plumb, K.A., 1994. Structural Evolution of the McArthur Basin, NT. In: Hallenstein, C.P. (Editor), Australian Mining Looks North - the Challenges and Choices, Technical Program Proceedings. *The Australasian Institute of Mining and Metallurgy, Publication Series,* 5/94, 139-145.

Plumb, K.A., and Roberts, H.G., 1992. The geology of Arnhem Land, Northern Territory. *Bureau of Mineral Resources, Geology and Geophysics, Australia, Record,* 1992/55, 193 pp.

Plumb, K.A., Ahmad, M., and Wygralak, A.S., 1990. Mid-Proterozoic basins of the Northern Australian Craton - regional geology and mineralisation. In: F.E. Hughes (Editor) Geology of the Mineral Deposits of Australia and Papua New Guinea. *Australasian Institute of Mining and Metallurgy, Monograph*, 14, 881-902.

Rawlings, D.J., Madigan, T., Haines, P., Pietsch, I.P., Sweet, I. P., Plumb, K.A and Krassay, A., in prep. Arnhem Bay-Gove special, Northern Territory, SD53-03, SD53-04 1:250 000 Geological Sheet. *Northern Territory Geological Survey - Australian Geological Survey Organisation, Explanatory Notes.*

Wall, V.J., and Heinrich, C.A., 1990. Breccia pipes at Redbank, southern McArthur Basin: copper mineralisation by fluid mixing. *Mount Isa Inlier Geology Conference Abstracts, Monash University 27-30 November 1990, Victorian Institute of Earth and Planetary Sciences,* 47-49.

3.7 Table 3.1

Ch pt #	Grouping (Type)	Age (Ma)	Potential					Confid Level	Pluton
			Cu	Au	Pb/Zn	Sn	Mo/W		
2	Bradshaw (Forsayth)	1850	None	None	None	None	None	320	Mirarrmina Complex
									Bradshaw Granite
									Drimmie Head Granite
3	Giddy (Sybella)	1835	None	None	None	Low	Low	320	Bukudal Granite
									Giddy Granite
									Garrthalala Granite
									Dhalinbuy Granite
4	Fagan (Sybella)	1710	None	None	None	None	None	320	Hobblechain Rhyolite
									Cato Volcanics
									Tanumbirini Rhyolite
									West Branch Volcanics
									Fagan Volcanics
									Latram Granite
									Gadabara Volcanics
									Jimbu Granite
									Packsaddle Microgranite
									Yanungbi Volcanics

4 ARUNTA INLIER

Compiled by Anthony Budd

4.1 Executive Summary - Geology

The Arunta Inlier has a very limited history of mining and exploration, and although several mines have been operated, total production is low. The deposits mined include gold, copper, lead and zinc, tin-tungsten-tantalum, fluorite and mica. Exploration has been limited, partly due to poor outcrop, isolation, and a perception that the Inlier is too highly metamorphosed to host significant deposits.

The regional geology of the Arunta Inlier was reviewed in terms of its tectonic setting in two papers: Stewart, Shaw and Black, 1984; and Shaw, Stewart and Black, 1984. In these works, the Arunta Block was seen to be made up of a partly fault bounded Central Tectonic Province of high grade metamorphic rocks and a few granites, flanked by the Northern and Southern provinces, which contain low grade metamorphic rocks and numerous granite intrusions. The stratigraphy was broken up into three major divisions. Division 1 was inferred to be the oldest, and was made up of mafic and felsic granulites, that in part represented a bimodal metavolcanic assemblage interlayered with minor metasediments. This was most common in the central province, but also occurred in the northern province. Division 2 rocks are mainly immature metasediments of turbiditic origin, which cover extensive areas of the northern province. Division 3 rocks are platform-style sediments comprising quartzite-shale-carbonate successions that locally unconformably overlie the two other divisions. More recent work by Collins and Shaw (1995), suggests that no major structural discontinuity exists between the northern and central tectonic provinces, but that the Redbank Thrust Zone is, at least in part, a province boundary. Also, these authors state that rocks originally assigned to divisions are better grouped into a larger number of lithological assemblages until better stratigraphic and isotopic correlations can be made. These authors propose a tectonic history nomenclature consisting of several chronologically constrained tectonic events, orogenies and uplift phases.

Granites were intruded mostly syntectonically during the history of the Arunta Inlier. The earliest known granites are dated at ~1880 Ma, and the youngest at ~1140 Ma. The largest granite intrusive event is dated at about 1770 Ma. The two most mineralised granite events are dated at 1713 Ma, and 1570 Ma. Generally, the granites in the Arunta Inlier were emplaced at deep crustal levels, and show little sign of extensive alteration. Most are Sr-depleted, Y-undepleted, indicating a plagioclase-residual source, and an ensialic rifting environment during emplacement. Most are I-type, with few S-types.

4.2 Executive Summary - Metallogenic Potential

This compilation has assessed the potential of each granite suite based on the criteria set out in the Project Proposal. Suites which have been identified as having high potential for granite-related mineralisation are:

The <u>Atnarpa Suite</u> at 1880 Ma has unknown potential, due to the difficulty in determining the extent of fractionation in this suite. It shares some similarities with Phanerozoic magma systems associated with porphyry-style deposits, although it is more felsic. 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. On this basis, the suite may have a high potential for further gold occurrences.

The <u>Napperby Suite</u> at 1770 Ma is one of the most extensive suites in the Inlier. It shows fractionation and evidence of the activity of a fluid phase, however, it was crystallised over a very narrow silica range, and there are very few known mineral occurrences nearby this suite. This suite therefore has only moderate potential for copper, gold and tungsten-molybdenum.

The Jinka Suite 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.

The Alarinjela Suite, thought to be intruded at 1713 Ma, is fractionated, coloured red to pink, oxidised, shows evidence of a fluid phase, intrudes suitable host rocks, and is possibly associated with mineralisation. It is assigned high potential for copper, lead and zinc, and moderate potential for gold.

The Barrow Creek Suite at 1713 Ma, is one of only a few S-type granites in the Inlier. It is fractionated, has abundant pegmatites, is host to many small occurrences of tin-tantalum-tungsten and molybdenum, and its oxidation state increases with fractionation. It is considered to have a high potential for further mineralisation similar to that already known to be associated with it.

The Ali Curung Suite at 1713 Ma is metaluminous, oxidised, fractionated, has a mapped contact aureole, and is nearby to several known mineral deposits. However, it is volumetrically small, has a short fractionation range, and is not strongly fractionated or enriched in heat-producing elements. It is considered to have moderate potential for copper, gold, lead and zinc mineralisation.

The Mount Webb Suite at 1615 Ma shows evidence of fractionation, brecciation, late stage fluids and hydrothermal alteration. It has probably been emplaced at shallow levels and thus epithermal or vein style mineralisation are a possibility. It has high potential for copper and gold mineralisation. Further, it is apparent that not much exploration has been conducted in the area, therefore this suite may be considered as having ‘greenfields’ potential.

The Ennugan Mountains Suite at 1600 Ma is enriched, abundant in fluorine, and has several tin, tantalum and uranium occurrences associated with it. It has moderate potential for further tin, molybdenum and tantalum occurrences.

The Southwark Suite at 1570 Ma is fractionated, has a broad compositional range, has pegmatite, aplite, microgranite and greisen phases, and is associated with copper, molybdenum and silver deposits. It is similar to the Cullen Batholith granites, and is considered to have moderate to high potential for mineralisation of many types.

The Teapot Suite at 1140 Ma is the youngest Proterozoic granite in the Arunta Inlier. It is fractionated, enriched, oxidised, and ranges from tonalite to granite in composition. It has no known mineralisation nearby, but is considered to have moderate potential for copper and gold.

4.3 Methodology

Information Sources: 1:250 000 maps and commentaries, 1:100 000 maps and notes where available, published ages, AGSO ROCKCHEM database supplemented with data from NTGS and University of Adelaide, BRS/AGSO Minloc database, AGSO magnetics and gravity.

Classification of Granites: In this report the granites have been divided into suites based on the age, geographic location, and geochemistry of each pluton. Using this method, approximately 30 suites are recognised (Table 1.1).

Host Rocks: The country rocks which are thought to be intruded by each suite have been summarised, and classified according to mineralogical characteristics thought to be important in determining the metallogenic potential of a granite intrusive event. This has been a little difficult in the Arunta, due to limited outcrop, and the fact that division of units was based on tectonostratigraphic packages, rather than lithologies.

Relating Mineralisation: One of the greatest problems in this compilation has been attempting to relate known mineralisation with a source, be it granite or otherwise. Very little direct dating of mineralisation is available in the Arunta Inlier. Further, only brief descriptions are available for most deposits. Therefore, the method used has been to exclude all deposits more than 5 km from a known outcropping granite, then for those remaining, to make an assessment of the likelihood that they may be derived from granite intrusive activity (based on deposit style). The existence of known mineralisation thought to be associated with a granite has been a factor in categorising the metallogenic potential of that granite, however, it is only one criteria of several.

4.4 References

Collins, W.J. and Shaw, R.D. 1995. Geochronological constraints on orogenic events in the Arunta Inlier: a review, *Precambrian Research*, 71, 315-346.

Shaw, R.D., Stewart, A.J. and Black, L.P., 1984. The Arunta Inlier: a complex ensialic mobile belt in central Australia. Part 2: tectonic history. *Australia Journal of Earth Science*, 31, 457-484.

Stewart, A.J., Shaw, R.D. and Black, L.P., 1984. The Arunta Inlier: a complex ensialic mobile belt in central Australia. Part 1: stratigraphy, correlations and origin, *Australian Journal of Earth Science,* 31, 445-455.

Warren, R.G., Stewart, A.J. and Shaw, R.D. 1974. Summary of information on mineral deposits of the Arunta Complex, Alice Springs area, Northern Territory. *Bureau of Mineral Resources, Geology and Geophysics, Australia,* Record 1974/117, 44 pp.

4.5 Table 4.1

Chpt #	Grouping (Type)	Age (Ma)	Potential					Confid Level	Pluton
			Cu	Au	Pb/Zn	Sn	Mo/W		
2	Atnarpa (Sally Downs)	1880	?	?	Low	None	None	222	Atnarpa Igneous Complex
26	Ngadarunga (Unclassified)	1880	None	None	None	None	None	110	Ngadarunga Granite
3	Narwietooma (Unclassified)	1880	None	None	None	None	None	310	Bunghara Metamorphics
									Illyabba Metamorphics
									Mt Hay Granulite
									Mt Chapple Metamorphics
									Unnamed unit *Pnx*
4	Harverson (Forsayth)	1820	None	None	None	Low	Low	321	Harverson Granite
									Anmatjira Orthogneiss
									Yaningidjara Orthogneiss
									Mount Airy Orthogneiss
5	Warimbi (Unclassified)	1785	Low	Low	Low	Low	Low	320	Warimbi granite
6	Carrington (Unclassified)	1780	Low	Low	Low	Low	Low	210	Carrington Granitic Suite
									Yulyupunyu Granitic Gneiss
7	Napperby (Cullen)	1775	Mod	Mod	Low	Low	Mod	321	Napperby Gneiss
									Possum Creek Charnockite
									Boothby Orthogneiss
									Ngalurbindi Orthogneiss
									Wangala Granite
									Uldirra Porphyry
									Yakalibadgi Microgranite

Chpt #	Grouping (Type)	Age (Ma)	Potential					Confid Level	Pluton
			Cu	Au	Pb/Zn	Sn	Mo/W		
8	Jennings (Kalkadoon)	1771	Low	Low	Low	None	None	321	Jennings Granitic Gneiss
									Flint Springs gneiss
									Georgina Gap granitic gneiss
									Randall Peak metamorphics
									Oolbra orthogneiss
									Charles River gneiss
									Mulga Creek granite
									Ongeva granulite
									Sliding Rock metamorphics
									Trephina granitic gneiss
									Casey Bore granite
									Unnamed unit *p*Є
9	Jervois (Kalkadoon)	1771	Low	Low	Low	None	None	321	Jervois Granite
									Dneiper Granite
									Copia Granite
									Crooked Hole Granite
									Mount Bleechmore Granulite
									Queenie Flat Granite
10	Entia (Sally Downs)	1767	Low	Low	Low	None	None	210	Entia Gneiss
									Inkamulla Granodiorite
									Huckitta Granodiorite
11	Atneequa (Kalkadoon)	1762	None	None	None	None	None	310	Atneequa Granitic Complex
12	Mount Zeil (Kalkadoon)	1760	None	None	None	None	None	210	Mount Zeil Granite
									Forty Five Augen Gneiss
13	Alice Springs (Sally Downs)	1752	None	None	None	None	None	320	Alice Springs Granite
14	Jessie Gap (Sally Downs)	1747	None	None	None	None	None	220	Jessie Gap Gneiss
26	Wuluma (Unclassified)	1728	?	?	?	?	?	110	Wuluma granite
									Gum Tree Granite
15	**Jinka** (Sybella)	**1713**	Low	Low	Low	None	**High**	321	Jinka Granite
									Mount Swan Granite
									Mount Ida Granite
									Mascotte Gneiss
16	**Alarinjela** (Cullen)	**1713?**	**High**	Mod	**High**	None	Low	322	Alarinjela suite
									Unca Granite
									Marshall Granite
17	**Barrow Creek**	**1713**	None	None	None	**High**	**High**	222	Barrow Creek Granite

Chpt #	Grouping (Type)	Age (Ma)	Potential					Confid Level	Pluton
			Cu	Au	Pb/Zn	Sn	Mo/W		
	(Allia)								Bean Tree Granite
18	Ali Curung (Cullen)	1713	Mod	Mod	Mod	None	None	322	Ali Curung Granite
									Ooralingie Granite
19	Madderns Yard (Cullen)	1680	None	None	None	None	None	110	Glen Helen Metamorphics
									Ellery Granitic Complex
									Boggy Hole Gneiss
									Spears Metamorphic Complex
20	Andrew Young (Kalkadoon)	1635	Low	Mod	Low	None	None	110	Andrew Young Igneous Complex
21	**Mount Webb** (Hiltaba)	**1615**	**High**	**High**	Low	Low	Low	310	Mount Webb Granite
									Polloch Hills Formation
									Unnamed granites
22	Iwupataka (Cullen)	1605	Low	Low	Low	None	None	320	Rungutjirba Gneiss
									Burt Bluff Gneiss
									Ormiston Pound Granite
									Brinkley Bluff Gneiss
									Lovely Hills Schist
									Ryans Gap Metamorphics
23	Ennugan Mts (Sybella)	1600	Low	Low	Low	Low	Low	211	Ennugan Mountains Granite
									Unnamed unit *Pgp*
24	**Southwark** (Cullen)	**1567**	**High**	**High**	Mod	Mod	Mod	322	Yarunganyi Granite
									Southwark Granite Suite
									Wabudali Granite
									Wakurlpa Granite
									Yaloolgarrie Granite
									Yumurrpa Granophyre
25	Teapot (Unclassified)	1140	Mod	Mod	Low	Low	Low	210	Teapot granitoid

5 BROKEN HILL BLOCK

Compiled by Lesley Wyborn

5.1 Executive Summary - Geology

The regional geology of the Broken Hill Block is summarised by Stevens *et al.* (1988), Stevens (1995) and Willis *et al.* (1983). The region is dominated by the Willyama Supergroup which comprises 5 main groups. The lowermost group can be subdivided into the Redan facies which is interpreted as a thick lacustrine clastic-evaporitic sequence interspersed with non-volcanic pelites, whilst the Thorndale facies is interpreted as a sandy to clayey fluvial deltaic system. The overlying Thackaringa Group contains lacustrine sedimentary rocks, felsic metavolcanic rocks, shallow granite sills and several varieties of iron formations. The overlying Broken Hill Group is most likely shallow marine and contains the Hores Gneiss which has been interpreted as a series of volcanics or volcanic mass flows and high Fe tholeiites of the Silver King Formation. The Sundown Group represents shallow marine sedimentation whilst the youngest group, the Paragon Group was organic rich in the initial phases and then progressed to fine-grained turbidites (Stevens, 1995).

In part because of the inference that felsic magmatism had played a major role in the genesis of the main ore body at Broken Hill, and in part because of its high metamorphic grade, the Broken Hill Block has been treated somewhat differently from other provinces in this project. There is reasonable evidence of felsic magmatism throughout the lower part of the Willyama Supergroup, up to the Sundown Group. All quartzofeldspathic units which had been considered in the literature to have been derived from a felsic igneous rock were assessed as outlined in the Project Proposal. Not one of the suites assessed was considered to have any potential for significant granite-related mineralisation. Those suites assessed were either too restite rich for fractionation processes to have occurred, or else had too limited a silica range for any significant mineralisation. Most suites are peraluminous (S-type) and the only I-type suite occurred in the lower most Redan facies.

5.2 Executive Summary - Metallogenic Potential

The Broken Hill Block contains the world class Broken Hill Pb-Zn-Ag deposit which contains 300 million tonnes averaging greater than 15% combined metal (Wright *et al.*, 1993). The main debate in the genesis of this ore body has focused on whether or not felsic magmatism has played any role in the generation of the rich Pb-Zn-Ag lodes. This review would suggest that felsic magmatism (and hence mafic magmatism) is **not** likely to have played any role in the genesis of Pb, Zn, Ag and Cu mineralisation in the Broken Hill Block.

The only possible relationship of felsic igneous rocks to mineralisation occurs in the rocks labeled BG1 (‘Potosi gneiss’ rocks) of the Potosi Supersuite. These rocks were found to have analogous chemical trends to crystal-rich arenites of the El Sherana Group of the Coronation Hill Region Northern Territory (Jagodzinski, 1992; Jagodzinski and Cas, 1992). The chemical trends within the BG1 were considered to have resulted from a winnowing process whereby the ash component was removed by phreatic eruptions generated as the ignimbrite entered water: the resultant sediment was relatively Fe-enriched due to the loss of the high SiO_2, Fe-poor ash component. The resultant sediment had high porosity and may have acted subsequently as an aquifer for highly reduced metalliferous brines along the lines of the model proposed by Haydon and McConachy (1987) and Wright *et al.* (1987, 1993). Some support for this is found in the reduced alteration overprint in the BG1 rocks that have the highest Pb and Zn values.

In summary, there is little evidence to disagree with the view of King and Thomson (1953) that ‘there is no secure basis for a genetic association between the ore (at Broken Hill) and the granite- and pegmatite-producing conditions’ (p. 564).

5.3 Future Work

In terms of felsic igneous rocks, better sampling could be done on rocks of the younger Mundi Mundi Suite to further evaluate their potential relationship to Sn deposits. Using the methodology developed by Jagodzinski (1992) all available analyses of the BG1 rocks could be better assessed to define where the greatest amount of ash winnowing had occurred, as not only will this help to better define the palaeogeographic setting, it may also help to define those parts of the BG1 stratigraphy which had the greatest porosity.

5.4 Methodology

Information Sources: Broken Hill Stratigraphic 1:100 000 scale map (Willis, 1989), published papers, published ages, NSW geological survey Broken Hill whole rock geochemical database, BRS/AGSO Minloc database, AGSO magnetics and gravity.

Classification of Granites: In this report the felsic igneous have been divided into suites based on position within the stratigraphy. Using this method, two suites and one supersuite have been recognised (Table 5.1). All granites from the northern Broken Hill Block have been placed into the Mundi Mundi Batholith. This infers an non-genetic grouping of the granites as there was insufficient geochemistry and geochronology to confidently assign the plutons within this region to suites. A further grouping was made of the pegmatites and leucogneisses: again these were difficult to work with due to a paucity of geochemical and geochronological data.

Host Rocks: Because most of the granites were considered to have little or no potential, the host rocks were not considered in detail.

Relating Mineralisation: As most of the mineralisation is probably related to sedimentary and or metamorphic processes, spatial proximity to a felsic igneous rock does not mean that there is a definite genetic link. Hence, the proximity relationships between the 'felsic' igneous rocks and known occurrences of mineralisation were only considered in general terms.

5.5 Acknowledgements

This section was prepared with tremendous help and assistance from Barney Stevens and Kevin Capnerhurst (NSW Geological Survey) on whose database this whole section is based. David Maidment, George Gibson and Dick Haren (AGSO) also provided assistance.

5.6 References

Haydon, R.C., McConachy, G.W., and Wright, J.V., 1993. Broken Hill Environment - examples of critical guides to ore location. *Australasian Institute of Mining and Metallurgy, International Symposium - World Zinc '93*, 131-149.

Jagodzinski, E.A., 1992. A study of the felsic volcanic succession south-east of Coronation Hill: Palaevolcanology-geochemistry-geochronology. *Bureau of Mineral Resources, Geology and Geophysics, Record,* 1992/9, 147 pp.

Jagodzinski, E.A., and Cas, R.A.F., 1992. The passage of a subaerial pyroclastic flow into water: a Proterozoic example from the Pine Creek Inlier, NT. *Geological Society of Australia, Abstracts, 32,* 136-137.

King, H.F., and Thomson, B.P., 1953. The geology of the Broken Hill District. In: Edwards, A.B. (Editor), Geology of Australian Ore Deposits. *Fifth Empire Mining and Metallurgical Congress, Australia and New Zealand*, 1, 533-577.

Stevens, B.P.J., 1995. A review of Broken Hill Regional Geology. In: Mineral Search in the south-west Pacific Region. *8th Edgeworth David Day Symposium, Sydney University,* 37-50.

Stevens, B.P.J., Barnes, R.G., Brown, R.E., Stroud, W.J, and Willis, I.L., 1988. The Willyama Supergroup in the Broken Hill and Euriowie Blocks, New South Wales. *Precambrian Research,* 40/41, 297-327.

Willis, I.L., 1989. Broken Hill Stratigraphic Map. *New South Wales Geological Survey.*

Willis, I.L., Brown, R.E., Stroud, W.J., and Stevens, B.P.J., 1983. The early Proterozoic Willyama Supergroup: stratigraphic subdivision and interpretation of high to low-grade metamorphic rocks in the Broken Hill Block, New South Wales. *Journal of the Geological Society of Australia,* 30, 195-224.

Wright, J.V., Haydon, R.C., and McConachy, G.W., 1987. Sedimentary model for the giant Broken Hill Pb-Zn deposit, Australia. *Geology,* 15, 598-602.

5.7 Table 5.1

Ch pt #	Grouping (Type)	Age (Ma)	Potential					Confid Level	Pluton
			Cu	Au	Pb/Zn	Sn	Mo/W		
2	Redan (Kalkadoon)	1820	None	None	None	None	None	221	Redan Gneiss - afm
									Redan Gneiss - BT
									Ednas Gneiss - Pl4
									Ednas Gneiss - Pl3
									Mulculca Formation - BT
									Mulculca Formation Pl3
3	Thackaringa (Maramungee)	1710	None	None	None	None	None	221	Lady Brassey Formation - Pl4
									Lady Brassey Formation - Pl
									Cues Formation - Pl
									Himalaya Formation - Pl2
									Himalaya Formation - Pl
4	Potosi (Forsayth)	1690	None	None	None	None	None	321	Parnell Formation - BG1
									Hores Gneiss - BG1
									Cues Formation - BG1
									Rasp Ridge Gneiss - Bm, Bc, BG2
									Alma Gneiss - Bm, Bc, BG2
5	Mundi Mundi (Unclassified)	1600	?	?	?	?	?	110	Brewery Creek Pluton
									Cusin Creek Pluton
									Alberta Pluton
									Champion Suite
6	Pegmatites (Unclassified)	???	None	None	None	None	None	111	Leucogneisses
									Pegmatites
									Green Pegmatites

6 TENNANT CREEK/DAVENPORT

Compiled by Lesley Wyborn

6.1 Executive Summary - Geology

Due to its high economic potential, the geology of the Tennant Creek Province has been the focus of many detailed studies over the years. The most recent summary of the whole province was by Le Messurier *et al.* (1990). The Tennant Creek Province is currently being remapped at 1:100 000 scale by the NTGS (Donnellan *et al.*, 1994, 1995, in prep.). The Davenport Province was remapped in the early 1980's as part of a major 1:100 000 scale geological mapping program by the BMR (Blake *et al.*, 1987). In this report, the Tennant Creek and Davenport Provinces are treated as the one entity.

The oldest unit in the Tennant Creek and Davenport Provinces is the Warramunga Formation, a polydeformed succession consisting of lithic, sublithic, arenite, wacke and siltstone, terrigenous mudstone and hematitic shale. The sediments contain immature volcanic detritus and are regarded as medium grained turbidites of proximal to distal fan facies derived apparently as part of a prograding (coarsening upwards) succession. Magnetite is ubiquitous and locally may form distinct laminae: it is a major component in the hematite shales (Donnellan, 1994; Donnellan *et al.*, 1994; Le Messurier *et al.*, 1990). Carbonaceous shales are not common (N. Donnellan, *pers comm*): one occurrence of hematitic shale with 0.2% C was reported by Reveleigh (1997). The Warramunga Formation was deformed and metamorphosed to greenschist facies and the ironstone hosts to the Au mineralisation appear to have formed early in the deformation history (Ding and Giles, 1993). Felsic volcanics, and volcaniclastic and clastic sediments of the Flynn Subgroup and the Ooradidgee Subgroup were deposited on deformed Warramunga Formation. The Tennant Creek Supersuite was emplaced throughout this part of the geological history as volcanics within the Warramunga Formation (~1870 Ma, mainly in the Davenport Province), as granites (1858-1940 Ma) which are pre-, syn- and post- deformation, and as bimodal volcanics in the lower Flynn and Ooradidgee Subgroups (~1840 Ma) (Hussey *et al.*, 1994). Sedimentation continued through to the Tomkinson Creek, Wauchope and Hanlon Subgroups and was predominantly orogenic terrigenous and stable shelf (Donnellan *et al.*, in prep.). A compositionally distinctly different suite of bimodal volcanics and shallow level intrusions, the Treasure Suite was emplaced at ~1820 Ma. Sedimentation continued after this suite, but all known mineral deposits are hosted by rocks equivalent in age or older than this suite. Post sedimentation a final magmatic episode at about 1700 Ma resulted in the intrusion of the Devils suite, a suite of shoshonitic lamphrophyres and a syenite body.

Synthesis: Sediments of the Tennant Creek and Davenport Provinces are dominated by clastics, felsic and mafic volcanics. The clastic sequences are relatively oxidised, containing magnetite and hematite. Carbonaceous sediments are extremely rare, and carbonate rocks are rare. The lack of carbonate rocks within the sequences mean that skarn mineralisation will be limited (Hoatson and Cruickshank, 1985), and the lack of carbonaceous sediments would imply that reduction of oxidised magmatic fluids by interaction with methane bearing connate brines is unlikely. The best hosts are the secondary ironstone bodies, although fluid mixing may be a viable alternative.

6.2 Executive Summary - Metallogenic Potential

This compilation has assessed the potential of each granite suite based on the criteria set out in the Project Proposal. All three suites have been identified as having potential for granite-related mineralisation, but only the Treasure Suite is considered to be highly significant.

The <u>Tennant Creek Supersuite</u> was emplaced at around 1850 Ma. It is a restite-rich I-(granodiorite) type which shows limited fractionation in the most felsic end members due to restite separation. The supersuite is associated with very minor W mineralisation. Although of a similar age to the proposed timing of the formation of the ironstones, the supersuite is not believed to have played any role in either their formation other than to act as a possible heat source to enhance the circulation of the basinal brines. The supersuite also has no relationship to the Au mineralisation.

The Treasure Suite at ~1820 Ma is mainly expressed as volcanics, intrusive granophyres and porphyries in the Davenport and as diorites to monzodiorites in the Tennant Creek Province. The suite is I-(granodiorite) fractionated, with the more mafic end members preserved in the NW Tennant Creek area and the more felsic fractionated members in the southeast. The suite is believed to be associated with the Au, Bi, Cu mineralisation at Tennant Creek and with W, Cu, Bi, Mo mineralisation in the Hatches Creek area. The more significant Au mineralisation associated with this suite is predominantly hosted by ironstones, but there is potential for quartz vein Au mineralisation independent of the ironstone bodies.

The Devils Suite at 1700 Ma is an extremely fractionated I-(granodiorite) type which is associated with minor vein W-mineralisation. The granite is oxidised and is associated with extensive alteration of the country rocks. However, the granite crystallised over a very narrow and high SiO_2 range and seems to contain high F. Its potential is therefore limited to vein W deposits. Although abundant cassiterite has been recorded in stream sediments from the area, the oxidised nature of the granite means that vein Sn is unlikely to be well developed.

6.3 Future Work

There are two aspects worthy of follow up in the Tennant Creek Province.

1) There is a wealth of alteration data within the AGSO data set. Many of the members of the Tennant Creek Supersuite have either a Na or K alteration overprint, whilst the younger suites have a K overprint only. Much effort has been expended in using geochemistry to distinguish between barren and mineralised ironstones (e.g., McMillan and Debnam, 1961; Dunnet and Harding, 1967; Smith, 1980). Huston and Cozens (1994) documented mineralisation associated K-rich alteration of a post-ironstone porphyry. This alteration is very similar to the K-alteration geochemistry as portrayed in the AGSO data set. Rather than using ironstone geochemistry as a pathfinder to ore, perhaps a more effective methodology would be to look at the alteration compositions of the porphyries, granites and quartzofeldspathic sediments surrounding these ironstones as a means of determining if the mineralisation-related alteration had affected the environs of the ironstone.

2) More geochemical analyses are required of the more mafic end members of the Treasure Suite in the northwestern Tennant Creek Province. This may not be all that easy for, as pointed out by Dunnet and Harding (1967), these more mafic rocks are poorly exposed, strongly lateritised and difficult to distinguish from lateritised Cambrian and Warramunga Formation sediments. They may also be confused with the abundant tholeiitic gabbros and dolerites that are coeval with both the Tennant Creek Supersuite and the Treasure Suite.

6.4 Methodology

Information Sources: 1:250 000 maps and commentaries, 1:100 000 maps and notes where available, published ages, AGSO OZCHRON databases, AGSO ROCKCHEM database supplemented with data from NTGS, BRS/AGSO Minloc database, AGSO magnetics and gravity.

Classification of Granites: In this report the granites have been divided into suites based on the age, geographic location, and geochemistry of each pluton. Using this method, approximately 3 suites are recognised (Table 1.1).

Host Rocks: The country rocks which are thought to be intruded by each suite have been summarised, and classified according to mineralogical characteristics thought to be important in determining the metallogenic potential of a granite intrusive event.

Relating Mineralisation: A combination of geochronology, relative stratigraphic position, and relationship to known structures were used to relate the known mineralisation to the igneous suites. The Tennant Creek and Davenport Provinces were one of the better chronologically controlled provinces examined, with many age determinations available on both the mineralisation and the igneous rock suites.

6.5 Acknowledgements

This section was prepared with assistance from Dave Blake, Dave Huston and Roger Skirrow (AGSO) and Nigel Donnellan, Phil Ferenzi and others from the NTGS.

6.6 References

Blake, D.H., Stewart, A.J., Sweet, I.P., and Hone, I.G., 1987. Geology of the Proterozoic Davenport Province, central Australia. *Bureau of Mineral Resources, Geology and Geophysics, Australia, Bulletin,* 226, 70 pp.

Ding, P., and Giles, C., 1993. Timing of deformation events with respect to gold mineralisation in the Tennant Creek Goldfield, Northern Territory, Australia. *Proceeding of the International Symposium on Gold Mining Technology, Beijing,* 1993, 100.

Donnellan, 1994. The Palaeoproterozoic Warramunga Formation, Tennant Creek Block, Central Australia: sedimentology, geochemistry and provenance. *The Australasian Institute of Mining and Metallurgy, Publication Series,* 5/94,179-184.

Donnellan, N., Morrison, R.S. and Hussey, K.J., 1994. A brief summary of stratigraphy and structure of the Tennant Creek Block, Central Australia. *The Australasian Institute of Mining and Metallurgy, Publication Series,* 5/94, 161-164.

Donnellan, N., Hussey, K.J., and Morrison, R.S., 1995. Flynn 5759 and Tennant Creek 5758 explanatory notes. *Northern Territory Geological Survey, Department of Mines and Energy, 1:100 000 Geological Map series,* 79 pp.

Donnellan, N., Morrison, R.S., Hussey, K.J., Kruse, P.D., and Ferenzci, P., in prep. Tennant Creek, Northern Territory - 1:250 000 Geological Map Series. *Northern Territory Geological Survey, Explanatory notes, SE/53-14.*

Dunnet, D., and Harding, R.R., 1967. Geology of the Mount Woodcock 1-mile Sheet area, Tennant Creek, N.T. *Bureau of Mineral Resources, Geology and Geophysics, Australia, Report*, 114, 50 pp.

Hoatson, D.M. and Cruickshank, B.I., 1985. A stream sediment geochemical orientation survey of the Davenport Province, Northern Territory. *Bureau of Mineral Resources, Geology and Geophysics, Australia, Record 1985/44,* 61 pp.

Hussey, K.J., Morrison, R.S., and Donnellan, N., 1994. Stratigraphy and geochemistry of the Flynn Subgroup Volcanic Rocks. *The Australasian Institute of Mining and Metallurgy, Publication Series,* 5/94, 165-169.

Huston, D.L. and Cozens, G., 1994. The geochemistry and alteration of the White Devil porphyry; implications to intrusion timing. *Mineralium Deposita,* 29, 275-287.

Le Messurier, P., Williams, B.T., and Blake, D.H., 1990. Tennant Creek Inlier - regional geology and mineralisation. In: Hughes, F.T. (Editor), The geology and mineral deposits of Australia and Papua New Guinea, *Australasian Institute of Mining and Metallurgy, Monograph,* 14, 829-838.

McMillan, N.J., and Debnam, A.H., 1961. Geochemical prospecting for copper in the Tennant Creek Goldfield. *Bureau of Mineral Resources, Geology and Geophysics, Australia, Record* 1961/101.

Mendum, J.R., and Tonkin, P.C., 1976. Geology of the Tennant Creek 1:250 000 Sheet area, Northern Territory. *Bureau of Mineral Resources, Geology and Geophysics, Australia, Record* 1976/68; Microfilm MF96.

Reveleigh, G.C., 1977. Geology and genesis of Nobles Nob and Golden Forty ore deposits, Tennant Creek, N.T. *M.Sc thesis, James Cook University of North Queensland* (unpublished).

Smith, S.E, 1980. Trace metal content of ironstones, Tennant Creek Au-Bi mineralisation. *Journal of Geochemical Exploration*, 12, 207-211.

6.7 Table 6.1

Chpt #	Grouping (Type)	Age (Ma)	Potential					Confid Level	Pluton
			Cu	Au	Pb/Zn	Sn	Mo/W		
2	Tennant Creek (Kalkadoon)	1850	None	None	None	Low	Low	321	Tennant Creek Granite
									Red Bluff Granite
									Mumbilla Granodiorite
									Unnamed intrusive porphyries
									Channingum Granite
									Hill of Leaders Granite
									Gosse River North Granite
3	**Treasure** (Cullen)	**1820**	**High**	**High**	Low	Mod	**High**	323	unnamed granophyres
									unnamed porphyries
									unnamed diorites
4	Devils (Sybella)	1710	None	None	None	Low	Mod	321	Warrego Granite
									Devils Marbles Granite
									Elkedra Granite
5	Lamprophyres (Unclassified)	1690	Low	Low	Low	Low	Low	320	Unnamed lamprophyres
5	Gosse River East (Unclassified)	1712	Low	Low	Low	Low	Low	210	Gosse River East syenite

7 GASCOYNE PROVINCE

Compiled by Lesley Wyborn and Carole Hensley

7.1 Executive Summary - Geology

The Gascoyne Province has a very limited history of mining and exploration, and there have been no significant mineral discoveries made within it in recent years, although there are numerous occurrences of gold, copper, lead and zinc, uranium and silver. Like the Arunta Inlier, exploration has been very limited, partly due to poor outcrop, as well as a perception that the province is too highly metamorphosed to host significant deposits. Given its potential, the Gascoyne Province has been one of the most difficult to evaluate in the whole project: there is only one report on the regional geology of the Gascoyne Province (Williams, 1986) and a review paper by Myers (1990): there are also not many detailed descriptions of the granites of the province.

The Gascoyne Province is highly deformed and metamorphosed and comprises voluminous granite intrusions, mantled gneiss domes, metamorphosed and migmatised sedimentary rocks and reworked Archaean gneisses. The alteration plots on all units show unusually high Th/U values and may reflect as yet unrecognised regional-scale alteration, which could be associated with the formation of numerous small U deposits.

Granites were intruded throughout the province. Although one of the scenarios presented by Williams (1986) considered the possibility that these granites could be generated during subduction, the majority of the granites considered to be Proterozoic are all Sr-depleted, Y-undepleted, which is the dominant granite type in the Australian Proterozoic and the type that is atypical of modern subduction zones. Some intrusives that are Sr-undepleted, Y-depleted clearly have Archaean model ages (Fletcher *et al.*, 1983).

The publicly available age determinations are all either Rb-Sr total rock or mineral isochrons. As the initial $^{87}Sr/^{86}Sr$ ratios are very high for the total rock isochrons (mostly >0.7100), most of the Rb-Sr ages are believed to be reset. The main age of granite intrusion is believed to be ~1800 Ma (Libby *et al.*, 1986), although there are intrusives at 1670 Ma (Pearson, 1996) and possibly 2000 Ma. Because of the uncertainty of the ages and the paucity of descriptive mineralogical information available the granites have been divided into three supersuites. It is to be emphasised that these supersuites are broad classifications and that each one is very likely to contain several different types of granite compositions. Each set of descriptions refer to what is considered to be the dominant granite type in each supersuite.

7.2 Executive Summary - Metallogenic Potential

An attempt was made to assess the potential of each Supersuite based on the criteria set out in the Project Proposal. The dominant granite type is a fractionated I-(granodiorite) type which shows strong similarities to the ~1800-1820 Ma granites of the Pine Creek, Tanami and Tennant Creek areas, *i.e.*, the Cullen type. Some granites are clearly S-types and are probably derived by melting of Morrissey Metamorphics: distinguishing these genuine S-types from the peraluminous, muscovite-bearing plutons which are derived by fractionation from the abundant I-(granodiorite) type intrusions is difficult. There is also a small group of ~1600-1670 Ma HFSE granites which show similarities to the Sybella-type (Pearson, 1996).

The greatest potential is with I-(granodiorite) type Minnie Creek Supersuite which is one of the most extensive suites in the Province. By the project definition it incorporates parts of the Aurilla Creek, Minnie Creek, Landor and Mount Marquis Batholiths and the Yinnetharra, Conndoondoo, and Dalgety Gneiss domes of Williams (1986, Figure 23). It may also incorporate parts of the Chararoo and Boolaloo Supersuites, but the data are not good enough to differentiate this type in these areas. The Minnie Creek Supersuite is both oxidised and fractionated and is associated with a few small Au and Cu prospects in the southeast, although nothing significant has been located in recent years. Although speculative, the limitation to the success of locating major deposits may be because the country rock appears to be a predominantly oxidising environment, and hence the closest exploration analogy will be the highly localised, difficult to find, Tennant Creek-style of deposit. Another factor may be the high metamorphic grade of the country rocks, many of which are migmatites. This provides a limitation for a least two reasons. The first is because the high metamorphic grade restricts porosity and permeability. Secondly, the high metamorphic temperatures would burn off any organic matter within the host sedimentary sequence, reducing the chances of finding an organic-rich reductant (fluid and/or rock) for the fluids emanating from the oxidised fractionating plutons of the Minnie Creek Supersuite (*c.f.*, Mathai *et al.*, 1996).

7.3 Future Work

Given that there may be some potential, without doubt the database on the granites of the Gascoyne Province is one of the weakest in the Proterozoic of Australia in terms of petrographic descriptions, geochemical analyses and U-Pb zircon dates. Likewise data on the mineralogical compositions of the host rocks is also lacking. The granites of this whole province need systematic sampling and U-Pb zircon dating. In view of the interesting chemistry that clearly hints there could be some metallogenic potential associated with these granites, sampling of this province should be a high priority.

7.4 Methodology

Information Sources: 1:250 000 maps and commentaries, published ages, AGSO ROCKCHEM database, BRS/AGSO Minloc database, AGSO magnetics and gravity.

Classification of Granites: In this report the granites have been divided into 3 Supersuites (Table 1.1).

Host Rocks: An attempt was made to classify the rocks according to mineralogical characteristics thought to be important in determining the metallogenic potential of a granite intrusive event. This has been almost impossible in the Gascoyne region, due to limited outcrop, and lack of adequate descriptive data.

Relating Mineralisation: One of the greatest problems in this compilation has been attempting to relate known mineralisation with a source, be it granite or otherwise. Very little direct dating of the granites or the mineralisation is available in the Gascoyne Province. There is almost no data on the prospects and occurrences in the Province and therefore, the method used has been to exclude all deposits more than 5 km from a known outcropping granite, then for those remaining, to make an assessment of the likelihood that they may be derived from granite intrusive activity.

7.5 Acknowledgements

This section is indebted to Peter Dunn (formerly GSWA) who located the only paper copy in existence of the geochemical data base on granites of the Gascoyne Province. This data set had been collected by the late Steve Williams (GSWA) who died tragically in the 1980's before he could complete his Ph.D on the petrogenesis of these rocks. Although we could not do all that much with the granites of this province, without the efforts of both Peter and Steve, we would have done even less. Discussions with Johanna Pearson and David Nelson are also gratefully acknowledged.

7.6 References

Daniels, J.L., 1965. Proterozoic granites of the Ashburton Region, North-west Division. *Geological Survey of Western Australia, Annual Report for the Year 1964,* 31-34.

Daniels, J.L., 1970. Wyloo, Western Australia, Sheet SF50-10. *Geological Survey of Western Australia, 1:250 000 Geological Series Explanatory Notes,* 20 pp.

Elias, M., and Williams, S.J., 1980. Robinson Range, Western Australia, Sheet SG50-7. *Geological Survey of Western Australia, 1:250 000 Geological Series Explanatory Notes,* 32 pp.

Fletcher, I.R., Williams, S.J., Gee, R.D., and Rosman, K.J.R., 1983. Sm-Nd model ages across the margins of the Archaean Yilgarn Block, Western Australia: northwest transect into the Proterozoic Gascoyne Province. *Journal of the Geological Society of Australia,* 30, 168-174.

Hocking, R.M., Williams, S.J., Lavaring, I.H., and Moore, P.S., 1985. Winning Pool-Minilya, Western Australia, Sheets SF49-16 and SF50-13. *Geological Survey of Western Australia, 1:250 000 Geological Series Explanatory Notes*, 36 pp.

Libby, W.G., de Laeter, J.R., and Myers, J.S., 1986. Geochronology of the Gascoyne Province. *Geological Survey of Western Australia, Report*, 20, 31 pp.

Myers, J.S., 1990. Gascoyne Complex. In: *Geology and Mineral Resources of Western Australia: Geological Survey of Western Australia, Memoir*, 3, 77-119.

Muhling, P.C., Brakel, A.T., and Davidson, A.W., 1978. Mount Egerton, Western Australia, Sheet SG50-3. *Geological Survey of Western Australia, 1:250 000 Geological Series Explanatory Notes*, 28 pp.

Pearson, J.M., 1996. Alkaline rocks of the Gifford Creek Complex, Gascoyne Province, Western Australia: their petrogenetic and tectonic significance. *Ph.D. Thesis, University of Western Australia*, 286 pp.

Van de Graaff, Denman, P.D., Hocking, R.M., and Baxter, J.L., 1980. Yanrey-Ningaloo, Western Australia, Sheets SF49-12, SF50-9. *Geological Survey of Western Australia, 1:250 000 Geological Series Explanatory Notes*, 24 pp.

Williams, S.J., 1986. The Geology of the Gascoyne Province, Western Australia. *Geological Survey of Western Australia, Report*, 15, 85 pp.

Williams, S.J., Williams, I.R., Chin, R.J., Muhling, P.C., and Hocking, R.M., 1983a. Mount Phillips, Western Australia, Sheet SG50-2. *Geological Survey of Western Australia, 1:250 000 Geological Series Explanatory Notes*, 29 pp.

Williams, S.J., Williams, I.R., and Hocking, R.M., 1983b. Glenburgh, Western Australia, Sheet SG50-6. *Geological Survey of Western Australia, 1:250 000 Geological Series Explanatory Notes*, 25 pp.

7.7 Table 7.1

NB These ratings are extremely tentative.

Chpt #	Grouping (Type)	Age* (Ma)	Potential					Confid Level	Pluton
			Cu	Au	Pb/Zn	Sn	Mo/W		
2	Boolaloo (Cullen)	1800	Mod	Mod	Low	Mod	Mod	111	Boolaloo Granodiorite
									Jundelaya Hill Granodiorite
									Kilba Granite
									Mount Danvers Granodiorite
									Hooley Granite
3	Chararoo (Forsayth?)	1800	Low	Low	Low	Low	Low	111	Chararoo Granite
									Pimbyana Granite
									Nyang Granite
									Joy Helen Granite
									Peringee Bore Granite
4	**Minnie Creek** (Cullen)	**1800**	Mod	**High**	Low	Mod	Mod	111	Minnie Creek Granodiorite
									Mount Marquis Granite
									Yabbat Granite
									Lyndon River Granite
									Yinnietharra Granite
									Yabbat Granite
									Landor Granite

*Note: these ages are approximate and believed to date the main granite intrusive event: components of ~2000 Ma and ~1600 Ma suites are also known to be present, but are not considered to be in the majority of these intrusive groupings

8 GAWLER AND CURNAMONA CRATONS

Compiled by Anthony Budd

8.1 Executive Summary - Geology

The Gawler Craton underlies the greater part of South Australia. It is defined as that region of crystalline basement of Archaean to Mesoproterozoic age that has undergone no substantial deformation except for minor brittle faulting since 1450 Ma. The Gawler Craton is subdivided into a number of discrete tectonic subdomains based on structural, metamorphic and stratigraphic character. These include the Christie and Coulta Subdomains which contain most of the exposed Archaean rocks; the Cleve Subdomain which is a Palaeoproterozoic fold belt on eastern Eyre Peninsula; the Moonta Subdomain which, although considered an extension of the Cleve Subdomain, includes stratigraphically younger rocks; the Mesoproterozoic Gawler Ranges Volcanic Province; and the Wilgena, Nuyts and Nawa Subdomains of mixed or complex character.

The Christie and Coulta Subdomains are composed predominantly of Archaean or earliest Palaeoproterozoic rocks representing the original protolith on which subsequent tectonic units were superimposed. The Fowler Suture Zone in the southern part of the Christie Subdomain contains voluminous Proterozoic intrusives, whereas there are no Palaeoproterozoic intrusives known in the Coulta Subdomain. Both were deformed to some extent during later Palaeoproterozoic events, and neither contains substantial components of younger Proterozoic metasediments, volcanics or intrusives.

At ~2000 Ma, along what is now its eastern margin, the Gawler Craton underwent substantial extension to form a major elongate basin into which a ~1950-1845 Ma mixed clastic shallow water and chemical sedimentary succession (including iron formation, carbonates) was deposited. Subsequent deformation of this basin during the Kimban Orogeny (1845-1700 Ma), accompanied by intrusion of large volumes of granite, led to the formation of a broad fold belt or orogen known as the Cleve Subdomain. The Moonta Subdomain is approximately parallel to and east of the Cleve Subdomain, and consists of syn-Kimban orogeny acid volcanics, chemical and clastic sediments, and earliest Mesoproterozoic granitoids.

Unlike older subdomains of the Gawler Craton, the Gawler Ranges Volcanic Province is relatively undeformed and more irregular in its distribution. It overlies and intrudes the older Cleve and Coulta Subdomains. The Province is composed of the Gawler Range Volcanics (GRV) and very restricted contemporaneous sediments (such as the Corunna Conglomerate and the Labyrinth Formation), and the Hiltaba Supersuite.

The Stuart Shelf is not strictly a tectonic unit of the Gawler Craton but defines the region of Neoproterozoic to Cambrian platformal sedimentation developed upon the existing craton (ie underlain by Gawler Craton including GRV and Hiltaba granites).

The Curnamona Craton crops out in the Willyama, Mount Painter and Mount Babbage Inliers, and is located on the eastern and northeastern margins of the Adelaide Geosyncline. The remainder of the Curnamona Craton is poorly known as it is largely mantled by platformal sediments. Drill hole data indicates that the composition of the Craton is similar to the eastern edge of the Gawler Craton. The Willyama Inliers include the Olary and Broken Hill Blocks which are separated by the Mundi Mundi Fault zone.

Three major episodes of granite emplacement occurred during the Proterozoic in the Gawler and Curnamona Cratons, with several smaller events. Granites emplaced syntectonically during the Kimban Orogeny have been divided into two supersuites - those of the Donington Granitoid Supersuite at ~1840-1820, and those emplaced around 1750-1700 Ma. The Gawler Range Volcano-Plutonic event at ~1590 Ma is one of the biggest magmatic events in Australia, and is divided into two geochemical suites, each suite related to a particular style(s) of mineralisation. Possible correlatives of the GRV magmatic event exist in the Curnaomona Province (including Olary Block and Mount Painter & Mount Babbage Inliers). Minor but locally important magmatism also occurred at ~2000 Ma, ~1800 Ma, 1740 Ma, 1700 Ma, ~1625 Ma, 1560 Ma, and ~1530 Ma.

8.2 Executive Summary - Metallogenic Potential

This compilation has assessed the potential of each granite suite within the limitations of the existing data sets based on the criteria set out in the Project Proposal. Suites which have been identified as having high potential for granite-related mineralisation are set out below.

This project has identified the key differences between two suites of granites of the Hiltaba Suite at 1592 Ma, emplaced during the Gawler Ranges volcano-plutonic event, and the implications of these differences on the mineralisation potential for each suite. The Roxby Downs type is host to the giant Olympic Dam deposit, and several other Fe-oxide style prospects. The Kokatha type is probably host to Au-Sn-Ag deposits such as those of the Glenloth Goldfield. The Roxby Downs type is more fractionated and more oxidised, and was emplaced at a shallower level, than the Kokatha type. Both suites have high potential for further discoveries. It is most likely that granites of the Hiltaba Suite extend into the Curnamona Province.

8.3 Methodology

Information Sources: Special mention must be made of the Volume 1: The Precambrian, The Geology of South Australia, Bulletin 54 (Drexel *et al*, 1993), which is an excellent summary of the geology of the Gawler and Curnamona Cratons. In addition, two CD-ROM packages by the Department of Mines and Energy Resources of South Australia were also used: the SA State GIS (March, 1995), and the Olary Region, prepared as part of the Broken Hill Exploration Initiative. The granites map prepared by this project used the 1:1,000,000 map of Flint (1986) as a base map. Published ages are derived predominantly from Bulletin 54 and much of the goechemistry was sourced from MESA database supplemented with data from AGSO and the University of Adelaide. The BRS/AGSO Minloc database, and AGSO magnetics and gravity were also used.

Classification of Granites: In this report the granites have been divided into suites based on the age, geographic location, and geochemistry of each pluton. Using this method, approximately 15 suites are recognised (Table 1.1).

Host Rocks: The country rocks which are thought to be intruded by each suite have been summarised, and classified according to mineralogical characteristics thought to be important in determining the metallogenic potential of a granite intrusive event.

Relating Mineralisation: Quite good descriptions have been found for most of the deposits thought to be related to Proterozoic granites in the Gawler Craton.

8.4 References

Daly, S.J., Fanning, C.M., Fairclough, M.C., 1998, Tectonic evolution and exploration potential of the Gawler Craton, *Australian Geological Survey Organisation Journal of Australian Geology and Geophysics.*, 17(3), 145-168.

Drexel, J.F., Preiss, W.V., and Parker, A.J., (*Editors*) 1993. The Geology of South Australia, Volume 1, the Precambrian, *Geological Survey of South Australia, Bulletin* 54, 242 pp.

Flint, R.B., 1986, Geological Map, Gawler Craton, 1:1,000,000 scale, *Australian Journal of Earth Science*, 33.

8.5 Table 8.1

Ch pt#	Grouping (Type)	Age (Ma)	Potential					Confid Level	Pluton
			Cu	Au	Pb/Zn	Sn	Mo/W		
2	Miltalie (Forsayth)	2015	None	None	None	None	None	120	Miltalie Gneiss
3	Donington (Kalkadoon)	1840	Mod	Mod	None	Mod	None	220	Donington Granitoid Suite
									Memory Cove Charnockite
	Colbert (Unclassified)	?	?	?	?	?	?	110	Cape Colbert hornblende granite
4	Minbrie (Unclassified)	>1800	None	None	None	None	None	120	Minbrie Gneiss
5	Younger Lincoln (Nicholson)	1750~ 1700	Mod	Mod	None	Mod	Low	220	McGregor Volcanics
									Middle Camp Granite
									Carpa Granite
									Moody Tank granite
									Burkitt Granite
									Bungalow Granodiorite
									Engenina Adamellite
									Symons Granite
									Carappee Granite
									Ifould Lake granite gneiss
									Yunta Well Leucogranite
									Uranno Microgranite
									Wertigo Granite
6	Olary A-type (Sybella)	1703	Low	Low	None	None	None	111	Undivided metagranitoid, inc. Ameroo Hill granitoid
7	St Peter Hiltaba?	1625	?	?	?	?	?	220	St Peter Suite
									Nuyts Volcanics
									St Francis Granite
8	**Hiltaba**	**1592**	**High**	**High**	Low	None	Mod	323	**Roxby Downs type**
									Roxby Downs Granite
									Charleston Granite
									Cultana granophyre
									Moonta adamellite
									Hiltaba granite
									Nuyts granite
									Tickera Granite

Chpt #	Grouping (Type)	Age (Ma)	Potential					Confid Level	Pluton
			Cu	Au	Pb/Zn	Sn	Mo/W		
			Mod	**High**	**High**	Mod	Mod	323	**Kokatha suite**
									Kokatha granite
									Kychering granite
									Kingoonya granite
									Tarcoola granite
									Minnipa granite
									Wudinna granite
									Buckleboo granite
			?	?	?	?	?		Balta Granite
									Calca Granite
9	Olary 1590 Ma (Hiltaba)	1590	Mod	Mod	Low	Low	Low	212	'Regional suite'
									'Gb suite'
10	**Babbage** (Hiltaba)	**1560**	**High**	Mod	Mod	Mod	Mod	212	Mount Neill Granite
									Terrapina Granite
									Wattleowie Granite
									Yerila Granite
									Camel Pad Granite
									Radium Creek granite
									Old Camp Granite
									Prospect Hill Granite
									White Well Granite
									Box Bore Granite
									Golden Pole Granite
									Con Bore Granite
									Lookout Granodiorite
11	Myola (Sybella)	1791	?	?	?	?	?	210	Myola Volcanics
11	Olary 1640Ma I-type (Hiltaba?)	1640	?	?	?	?	?	110	Granodiorites and tonalites in the Poodal Hill-Tonga Hill-Alconie Hill-Antro Woolshed-Bimbowrie region
11	Spilsby (Hiltaba)	1530	?	?	?	?	?	110	Porphyritic monzograite to granodiorite on Spilsby and Sir Joseph Banks Group islands
11	Tidnamurkuna (Sybella)	1806	?	?	?	?	?	100	Tidnamurkuna Volcanics
11	Wirriecurrie (Hiltaba)	1793	?	?	?	?	?	110	Wirriecurrie Granite

9 GEORGETOWN INLIER

Compiled by Anthony Budd

9.1 Executive Summary - Geology

The Georgetown Inlier in north Queensland occupies about 50 000 km^2 of the Cairns-Townsville hinterland. It consists largely of variably metamorphosed and deformed sedimentary and volcanic rocks of Palaeo- to Mesoproterozoic age, intruded by Mesoproterozoic granitoids. The eastern margin is in faulted contact with the Meso- to Neoproterozoic Hodgkinson and Broken River provinces of the Tasman Orogen. The western and central parts are variably overlain by scattered remants of Mesozoic sedimentary rocks, and the east by Cainozoic basalt (Bain *et al.,* 1990; Bain and Draper, 1997).

Withnall (1997) has recognised several structural units in the Georgetown 'Region', including the Etheridge Province and the Croydon Province:

The Palaeoproterozoic *Etheridge Province* has been divided into the Forsayth and Yambo Subprovinces (Bain and Draper, 1997). The *Forsayth Subprovince* includes the Etheridge and Langlovale Groups, McDevitt Metamorphics, various mafic intrusives rocks and Mesoproterozoic granites of the Forsayth and Forest Home Supersuites. The metasedimentary sequence was deposited in an intracratonic rift setting between about 1700 Ma and at least as young as 1650 Ma. It underwent a major metamorphism and deformational event at about 1550 Ma, at which time most of the S-type granites were emplaced (Forsayth, Forest Home, Lighthouse suites). The Palaeoproterozoic *Yambo Subprovince* represented by the Dargalong Metamorphic Group occurs in the northern part of the region. The rocks there may be slightly younger than at least the lower part of the Etheridge Group, and were possibly deposited after 1640 Ma. Isotopic dating indicates major granite emplacement at about 1580 Ma, and metamorphism at about 1575 Ma.

A Mesoproterozoic 'cover sequence' in the west, assigned to *Croydon Province*, and comprising the Croydon Volcanic Group and related granites of the Esmeralda Supersuite. They were emplaced at about 1550 Ma, probably at the close of the main deformation event in the Etheridge Province. They are overlain by the Inorunie Group. All of these rocks were previously assigned to the Croydon subprovince of the Georgetown Province (Withnall *et al.,* 1980).

Four suites or supersuites of Proterozoic granites and several ungrouped granites are known in the Georgetown Inlier (Bain and Draper, 1997). They are the Forest Home Supersuite, Esmeralda Supersuite, Forsayth Supersuite, the Lighthouse Suite, and ungrouped granites in the Yambo Subprovince.

The Forest Home 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. Granites of this type are rare in the Australian Proterozoic, as they are the only ones that show evidence of garnet in the source region in the mantle.

The Esmeralda Supersuite comprises the Esmeralda, Nonda, Mooremount, Little Bird, Macartneys, Olsens, Dregger and Bimba Granites, and is comagmatic with the Croydon Volcanic Group (CVG). These granitoids comprise granites and adamellites with lesser granodiorites. A feature of the granites is the presence of locally abundant graphitic inclusions. The supersuite is felsic, fractionated, reduced to oxidised, weakly peraluminous to peraluminous, and hydrothermally altered in parts. Traditionally, this supersuite have been classified as a S-type granite, mostly because of its high Aluminium Saturation Index (ASI), but also because of the presence of garnet and muscovite. This project questions the traditional view that this is a S-type, and suggests that it is an I-type with genetic associations with the Croydon Goldfields. The factors in contention are outlined below:

- Quite a few of the samples have ASI between 1 and 1.1 (ie 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 suite of the Hiltaba Supersuite).
- Hornblende was found in two samples of the Esmeralda Granite by Sheraton and 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. Further evidence of the oxidised nature of the Supersuite is the relatively high magnetic remnance and susceptibility (Idnurm, *pers comm*), which indicates the presence of magnetite.

The Forsayth Supersuite 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. Black and McCulloch (1990) U-Pb zircon dated the Mistletoe and Forsayth Granites at 1550±6 Ma and 1544±7 Ma respectively. This is the ‘type Australian’ restite S-type suite.

The Lighthouse Suite is relatively small, outcropping along the eastern margin of the Forsayth Granite near Georgetown. It is felsic, and veins and pegmatites are common suggesting that the granite may be fractionated (despite the narrow silica range). This granite shows an affinity to the Silurian ‘I-type’ granites in the region (Champion, 1991). It has not been dated, and may be younger than Proterozoic.

9.2 Executive Summary - Metallogenic Potential

Of all of the suites in the Georgetown Inlier, the Esmeralda Supersuite is considered to have the greatest potential. This suite 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 and Beams (1995).

In contrast, some workers have interpreted these deposits as Palaeozoic 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.

Disseminated replacement gold deposits (Carlin-style) occur within thick predominantly pelitic units containing highly pyritic, carbonaceous and locally calcareous mudstone, siltstone and sandstone (Candlow and Lane Creek Formations of the Etheridge Group) (Denaro *et al*., 1997) within 3 km of the Illewana, Dregger and Bimba Granites.

Numerous tin deposits are thought to be definitely associated with the Esmeralda Supersuite, including the Stanhills, Comet and Mount Cassiterite deposits (Denaro *et al*., 1997). The Comet deposit has been Pb-dated at ~1530 Ma (Carr, *pers comm*).

If the Au mineralisation is shown to be Palaeozoic then a possible model is that significant Au was disseminated in the pyrite-bearing members of the Esmeralsa Supersuite during crystallisation and was then remobilised in a later hydrothermal event. During crystallisation of the pyrite-bearing phases of the Esmeralda Supersuite, Au was possibly incorporated into an *iss* (intermediate solid solution - Cygan and Candela, 1995) forming a protore, which may then have been remobilised during the Palaeozoic hydrothermal event. This model may be tested by microprobing the gold content of pyrite in the gold-bearing granites and volcanics.

The Forsayth, Lighthouse and Forest Home Suites/Supersuites are not considered to have any significant mineralisation potential.

9.3 Methodology

Information Sources: Data was sourced mainly from David Champion's 1991 PhD thesis, and work by GSQ and AGSO geologists. Geochemical data is from ROCKCHEM; geochronology is sourced from OZCHRON and published literature. The digital map base was provided by the North Queensland NGMA project.

Classification of Granites: Champion (1991) and Bain & Draper (1997) a pluton-suite-supersuite hierarchical classification based on geochemistry, field relations, and limited geochronology. This classification has been followed here.

Host Rocks: Hosts to the Proterozoic granites of the Georgetown Inlier include the Etheridge, Langlovale, and Croydon Groups. The Palaeo- to Mesoproterozoic Etheridge Group consists of shallow-water, fine-grained, clastic metasedimentary rocks, and minor basaltic lavas and related dolerite intrusions. The Langlovale Group is a fluviatile to marine, pro-deltaic facies. The Croydon Volcanic Group is dominated by subaerial felsic ignimbrites.

Relating Mineralisation: Information on mineralisation was sourced from Bain *et al.*, 1990.

9.4 References

Bain, J.H.C. and Draper, J.J (*Compilers and Editors*), 1997. North Queensland Geology, *Australian Geological Survey Organisation, Bulletin* 240/*Queensland Department of Mines and Energy, Queensland Geology* 9.

Bain, J.H.C., Withnall, I.W., Oversby, B.S. and Mackenzie, D.E., 1990. North Queensland Proterozoic inliers and Palaeozoic igneous provinces - regional geology and mineral deposits, Hughes, F.E., (*Ed*) *Geology of the Mineral Deposits of Australia and Papua New Guinea, Australian Institute of Mining and Metallurgy,* 963-978.

Black, L.P. and McCulloch, M.T. 1990. Isotopic evidence for the dependence of recurrent felsic magmatism on new crust formation: An example from the Georgetown region of Northeastern Australia, *Geochimica et Cosmochimica Acta,* 54, 183-196.

Carr, G., *pers comm* to S.S-Sun, from Pb-dating 6/7/87.

Champion, D.C., 1991. The felsic granites of far north Queensland, *PhD thesis, Australian National University (unpublished).*

Cygan, G.L. and Candela, P.A., 1995. Preliminary study of gold partitioning among pyrrhotite, pyrite, magnetite and chalcopyrite in gold-saturated chloride solutions at 600 to 700 °C, 140 MPa (1400 bars), in Thompson, J.F.H. (*Ed*) Magmas, Fluids and Ore Deposits, *Mineralogical Association of Canada Short Course Series,* 23, 129 - 137.

Denaro, T.J., Withnall, I.W. and Bain, J.H.C., 1997. Known mineralisation and resources (of the Georgetown Region, in Chapter 3 of) Bain, J.H.C. and Draper, J.J (*Compilers and Editors*), North Queensland Geology, *Australian Geological Survey Organisation, Bulletin* 240/*Queensland Department of Mines and Energy, Queensland Geology* 9.

Henderson, G.A.M., 1989. Notes on Croydon, north Queensland, fieldwork July/August 1988 and results of K/Ar dating of sericitic alteration. *Bureau of Mineral Resources, Geology and Geophysics, Australia, Record* 1989/46.

Idnurm, M., *pers comm,* NRM Intensities and Susceptibilities of Croydon Volcanics, 27/6/97.

Lawrie, K.C., Jaireth, S., A-Izzeddin, D., and Grace, J., 1998. Gold localisation in a lateral ramp within a reactivated mylonite: the Golden Butterfly deposit, Croydon Goldfield, N.Q., *14th AGC Geological Convention, Townsville, July, Geological Society of Australia, Abstracts*, 49, 261.

Morrison, G.W. & Beams, S.D., 1995. Geological setting and mineralisation style of ore deposits of northeast Queensland. *In* Beams, S.D. (*Editor*): Exploring the tropics -- mineral deposits of northeast Queensland: geology and geochemistry. *James Cook University of North Queensland, Economic Geology Research Unit, Contribution* 52, 1--32.

Sheraton, J.W. and Labonne, B., 1978. Petrology and geochemistry of acid igneous rocks of northeast Queensland, *Bureau of Mineral Resources, Geology and Geophysics, Australia, Bulletin* 169.

Withnall, I.W., 1997. Geological Framework (of the Georgetown Region, in Chapter 3 of) Bain, J.H.C. and Draper, J.J (*Compilers and Editors*), North Queensland Geology, *Australian Geological Survey Organisation, Bulletin* 240/*Queensland Department of Mines and Energy, Queensland Geology* 9.

Withnall, I.W., Bain, J.H.C. and Rubenach, M.J. 1980. The Precambrian geology of Northeastern Queensland, *in* Henderson, R.A. and Stephenson, P.J. *(Eds)*, The Geology and Geophysics of Northeastern Australia, *Geological Society of Australia, Queensland Division, Brisbane*, 109-128.

Withnall, I.W., Bain, J.H.C., Draper, J.J., Mackenzie, D.E. and Oversby, B.S., 1988, Proterozoic stratigraphy and tectonic history of the Georgetown Inlier, northeastern Queensland, *Precambrian Research*, 40/41, 429-446.

9.5 Future Work

- Test background value of Au in pyrite in Esmeralda Granite, to see if the Au has been taken into pyrite as the granite becomes sulphur-saturated when being reduced.
- Get fresh samples of hornblende from Esmeralda Granite: this will help determine whether the granite is I- or S-type.

9.6 Table 9.1

Chpt #	Grouping (Type)	Age (Ma)	Potential					Confid Level	Pluton
			Cu	Au	Pb/Zn	Sn	Mo/W		
2	Forsayth (Forsayth)	1550	None	None	None	Low	Low	321	Forsayth Granite
									Aurora Granite
									Delany Granite
									Goldsmiths Granite
									Mistletoe Granite
									Ropewalk Granite
									Welfern Granite
									Mywyn Granite
									Mount Hogan Granite
									Fig Tree Hill Complex?
									parts of Digger Creek Granite
3	**Esmeralda** (Hiltaba)	**1550**	Low	**High**	Low	**High**	Mod	322	Esmeralda Granite
									Nonda Granite
									Mooremount Granite
									Little Bird Granite
									Macartneys Granite

Chpt #	Grouping (Type)	Age (Ma)	Potential					Confid Level	Pluton
			Cu	Au	Pb/Zn	Sn	Mo/W		
									Olsens Granite
									Dregger Granite
									Bimba Granite
4	Forest Home (Maramungee)	1550	Low	Low	Low	Low	Low	321	Forest Home Trondhjemite
									Talbot Creek Trondhjemite
5	Lighthouse (Unclassified)	1550	Low	Low	Low	Low	Low	320	Lighthouse Granite

10 GRANITES-TANAMI BLOCK

Compiled by Lesley Wyborn

10.1 Executive Summary - Geology

Gold was first discovered in The Granites-Tanami Block in 1900 and was mined intermittently between 1904 and 1961. More recently it has been the focus of significant exploration efforts with several major new mines operating since 1986. The area as a whole is poorly exposed and is mostly covered by thick regolith. The regional geology of the Granites-Tanami Block was described by Blake *et al.* (1979) and very little has been published on the regional geology since. More detailed geological descriptions are available in papers on the gold deposits in the region (*e.g.*, Ireland and Mayer, 1984; Mayer, 1990; Ireland, 1995) and new structural interpretations are available in Ding (1996, 1997) and Ding and Giles (1996).

Traditionally, the Granites-Tanami Block was believed to consist of 2 major subdivisions separated by a major unconformity (Blake *et al.*, 1979). The lower subdivision, the Tanami Complex, was deformed and metamorphosed prior to the eruption of the volcanics of the Mount Winnecke Formation and deposition of the overlying Supplejack Sandstone. The lowermost Tanami Complex rocks are believed to rest unconformably on Archaean basement (Page and Sun, 1994; Page *et al.*, 1995). The Tanami Complex comprises the Killi Killi Beds, Mount Charles Beds, Nanny Goat Creek Beds, Nongra Beds and the Helena Creek Beds. These units consist of greywacke, siltstone, arenite, chloritic and sericitic shale, as well as carbonaceous shale, banded iron formation, and mafic and felsic volcanics. Most of the mineralisation is hosted by the Mount Charles Beds which contains some of the more reactive rock types of the Tanami Complex including banded iron formations and carbonaceous shales.

Recently Ding (1997) in an abstract has provided a reinterpretation of the Granites-Tanami Block in which he identifies 5 major stratigraphic packages ranging in age from at least 2450 Ma (Tanami Group) to 1815 Ma. Each package is separated by a major unconformity, and the basal group lies unconformably on basement that is ~2500 Ma (Ding, 1997).

Ding (1997) reports a single crystal zircon age of 2450 Ma on a granite sill which intrudes the Tanami Group. The earliest known Proterozoic ‘granites’ dated by conventional means occur at ~1880 Ma. These are partial melts of late Archaean gneisses which occur in the Browns Range Dome. Some felsic volcanics have been identified within the Tanami Complex, but only one has been dated at around ~1800 Ma. The dated rock is presumed not to come from the Tanami Complex, but from volcanics belonging to the Granites Supersuite which are dated from about 1825 Ma to 1795 Ma. The members of this suite were intruded mostly after the deformation that affected rocks of the Tanami Complex.

Most felsic igneous rocks in The Granites-Tanami Block are Sr-depleted and Y-undepleted, indicating a plagioclase-residual source.

10.2 Executive Summary - Metallogenic Potential

The only suite with recognised metallogenic potential is the Granites Supersuite which 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 and 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 (e.g., Tunks, 1995, Valenta and 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 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. The limiting factor in this model may be that the magmas in this northern area are also the most fractionated and may have already lost metals such as Au or Cu.

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 and 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.

10.3 Future work

The felsic igneous rocks of The Granites-Tanami Block are poorly defined both in terms of their chemistry and their ages. The single crystal ages reported by Ding (1987) need to be confirmed by more conventional SHRIMP analyses to determine just how representative these individual zircon ages are not only of the samples dated, but also of the intrusions that each individual sample is taken from.

A systematic granite sampling program also needs to be carried out, firstly to better define the metallogenic characteristics of this suite, but secondly and more importantly, to try to classify the numerous unnamed granite outcrops scattered throughout the area and to try to define whether they are part of the Granites Supersuite or belong to the 1880 Ma or the Archaean suites.

10.4 Methodology

Information Sources: 1:250 000 maps and commentaries, 1:100 000 maps and notes where available, published ages, AGSO ROCKCHEM database, BRS/AGSO Minloc database, AGSO magnetics and gravity.

Classification of Granites: In this report the granites have been divided into suites based on the age, geographic location, and geochemistry of each pluton. Only one major suite was recognised (Table 1.1).

Host Rocks: The country rocks which are thought to be intruded by each suite have been summarised, and classified according to mineralogical characteristics thought to be important in determining the metallogenic potential of a granite intrusive event.

Relating Mineralisation: As the granites occur only as scattered outcrops, it has been difficult to relate mineralisation to known outcrops of granites, particularly as so few had been sampled.

10.5 Acknowledgements

This study has benefited greatly from the input of Dave Blake.

10.6 References

Blake, D.H., 1978. The Proterozoic and Palaeozoic rocks of The Granites-Tanami region, Western Australia and Northern Territory, and interregional correlations. *Bureau of Mineral Resources, Journal of Australian Geology and Geophysics,* 3, 35-42.

Blake, D.H., Hodgson, I.M., and Muhling, P.C., 1973. The geology of the Granites-Tanami Region, Northern Territory and Western Australia. *Bureau of Mineral Resources, Geology and Geophysics, Bulletin,* 197, 91 pp.

Czamanske, G.K., and Wones, D.R., 1973. Oxidation during magmatic differentiation, Finnmarka Complex, Oslo area, Norway: Part 2, the mafic silicates. *Journal of Petrology* 14, 349-380.

Ding, P., 1996. Extensional tectonism: pre-orogenic deformational history and its associated metamorphism, magmatism and hydrothermal activity within the early Proterozoic Tanami Group in the Granites-Tanami Block, N.T., Australia. *Abstracts for the Beijing International Geological Congress.*

Ding, P., 1997. Palaeoproterozoic geological events and gold mineralisation in the Halls Creek-Granites-Tanami Orogenic Domain, Northern Australia. In: Rutland, R.W.R., and Drummond, B.J., (*Editors*), Palaeoproterozoic Tectonics and Metallogenesis: comparative analysis of parts of the Australian and Fennoscandian Shields. *Australian Geological Survey Organisation, Record,* 1997/44, 25-29.

Ding, P., and Giles, C., 1993. Geological setting of gold mineralisation in the Tanami Region, Northern Territory, Australia. *Proceedings of the International Symposium on Gold Mining Technology, Beijing,* June 1993, 15-17.

Ireland, T.J., 1995. The discovery of the Callie Gold Deposit in the Tanami Region, Northern Territory, Australia. *AMF conference on New Generation Gold Mines: case histories of discovery,* 6.1-6.10.

Ireland, T.J., and Mayer, T.E., 1984. The geology and mineralisation of the Granites Gold Deposits, Northern Territory. *The Australasian Institute of Mining and Metallurgy, Centenary Conference,* August 1984, 397-405.

Lovett, D.R., Giles, C.W., Edmonds, W., Gum, J.C., and Webb, R.J., 1993. The geology and exploration history of the Dead Bullock Soak Gold Deposits, The Granites-Tanami Goldfield, NT. *The Australasian Institute of Mining and Metallurgy, Centenary Conference, Adelaide,* 73-79.

Mayer, T.E., 1990. The Granites Gold Field. In: F.E. Hughes (Editor), The geology and mineral deposits of Australia and Papua New Guinea. *The Australasian Institute of Mining and Metallurgy,* 14, 719-724.

Page, R.W., and Sun, S-S., 1994. Evolution of the Kimberley Region, W.A., and adjacent Proterozoic Inliers - New Geochronological constraints. *Geological Society of Australia, Abstracts,* 37, 332-333.

Page, R.W., Sun, S-S, and Blake, D.H., 1995. Geochronology of an exposed late Archaean basement terrane in the Granites-Tanami region. *Australian Geological Survey Organisation Research Newsletter,* 22, 19-20.

Valenta, R., and Wall, V., 1996. Controls on mineralisation at the Granites, Tanami Desert, Northern Territory. *Geological Society of Australia, Abstracts,* 41, 451.

Tunks, A.J., 1996. Geology of the Tanami Gold Mine. *Ph.D. Thesis, University of Tasmania.*

Wall, V.J., 1989. Fluids and metamorphism. *Ph.D. Thesis, Monash University*.

Wyborn, D., 1983. Fractionation Processes in the Boggy Plain Zoned Pluton. *Ph.D Thesis, Australian National University.*

10.7 Table 10.1

Ch pt #	Grouping (Type)	Age (Ma)	Potential					Confid Level	Pluton
			Cu	Au	Pb/Zn	Sn	Mo/W		
3	Billabong (Unclassified)	2514	None	None	None	None	None	000	unnamed gneisses east of The Granites Gold mine
3	Browns Range (Unclassified)	1882	None	None	None	None	None	000	unnamed gneisses from the Browns Range Dome
2	**Granites** (Cullen)	**1810**	Mod	**High**	Low	Mod	Low	323	Lewis Granite
									The Granites Granite
									Slatey Creek Granite
									Winnecke Granophyre
									Mount Winnecke Formation

11 KIMBERLEY PROVINCE SYNTHESIS

Compiled by Lesley Wyborn

11.1 Executive Summary - Geology

Although the Kimberley Province (including the King Leopold and Halls Creek Orogens) has many geological elements common to other Proterozoic provinces in Australia, it is probably the most poorly endowed with respect to significant economic deposits of Au, base metals, Sn and W. The only world class deposit within the province is the Mesoproterozoic Argyle diamond mine. There are some Ni, Cr and PGE prospects within the layered mafic-ultramafic intrusives (Hoatson, 1993a; 1995; Hoatson and Tyler, 1993; Trudo and Hoatson, 1996) and a suite of alkaline igneous rocks hosts a Nb and rare earth elements prospect (Chalmers, 1990): there are also some VHMS base metal prospects in the Koongie Park area (Rea, 1997; Hoatson, 1993b). The regional geology of the Kimberley Province has been summarised by Griffin and Grey (1990), Tyler *et al*. (1995) and by Plumb (1990). The region has also been the focus of detailed mapping as part of a revision of the West Kimberleys by GSWA and the East Kimberleys as part of the NGMA program by both AGSO and GSWA.

Like many Palaeoproterozoic provinces, the earliest sediments were deposited between ~1920-1840 Ma and consisted of several packages that include mafic and felsic volcanics, clastic sediments, carbonaceous and calcareous sediments, and some banded iron formations. Some high level granites were also intruded early into the sequence at ~ 1910 Ma. These rocks were all deformed and metamorphosed, some to granulite facies, before or during the intrusion of most of the granite suites (Tyler *et al*., 1995).

Most of the granites in the Kimberley Province were intruded from about 1865 Ma to 1818 Ma and there is a gradual shift in the age of the granites during this period from the west-northwest to the east-southeast. At least eight suites occur in the whole Kimberley region: all suites are I-(granodiorite) type, with the exception of the alkaline Butchers Gully Suite. Most granite suites are also interpreted to be predominately restite-rich with the exception of the Koongie Park Suite. Most of the major granite events are coeval with the intrusion of layered mafic-ultramafic complexes (Hoatson, 1993a, 1995).

From a metallogenic point of view, there appears to be only minor evidence of fractionation processes operating within the major 1865 to 1818 Ma granite suites of the Kimberley Province, unlike the Gawler Craton or the Pine Creek Inlier. Compared with granites from these two areas, those of the Kimberleys are relatively homogeneous over wide areas and there are few major distinctive leucocratic plutons developed. The felsic Whitewater Volcanics are phenocryst rich (up to 50% crystals (Gellatly *et al.*, 1974a)) 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.

In all other Australian provinces dealt with in the Metallogeny of Australian Proterozoic Igneous Rocks Project, we have not discussed the tectonic setting. Because of the metallogenic implications, the Kimberley Province will be an exception as the regional tectonic setting of this has been contentious for many years with one interpretation considering that the province developed in an intracontinental setting (e.g. Hancock and Rutland, 1984), whilst others have drawn analogies to modern continental margins, with the formation of the felsic igneous rocks being directly related to modern-style subduction processes (e.g., Ogasawara, 1988; Tyler *et al.*, 1995). Although the chemistry of the felsic melts is interpreted by many (e.g., Ogasawara, 1988; Tyler *et al.*, 1995; Sheppard *et al.*, 1995) to indicate derivation from contemporaneous subduction, there are some arguments inconsistent with this model.

The first is that within the comagmatic volcanics in the Kimberley region andesites, common in regions of subduction-related magmatism, are very rare and second, the granites are generally more felsic than those found in continental margins. Thirdly, each magmatic event is bimodal and there is a distinct gap in the SiO_2 content between 54 and 58 wt. % within the coeval but not comagmatic compositions. Such a gap, common in extensional regimes, is not usually found in most continental margin regions where instead the suites progress from gabbros through diorite to quartz diorite to tonalite to granodiorite to granite, with rocks of tonalitic to granodioritic compositions being dominant. The presence of coeval, but not comagmatic, layered mafic/ultramafic intrusions is also considered by some to be indicative of extensional conditions (von Gruenewaldt and Harmer, 1992).

An alternative interpretation to the contemporaneous subduction model is that mafic to intermediate igneous material was underplated in the lower crust in the late Archaean to earliest Proterozoic (Wyborn *et al.*, 1992), and that this material subsequently became the source for the felsic melts emplaced into the Kimberley Province from about 1880 to 1780 Ma. This source was emplaced at around 2.3 to 2.5 Ga based on Nd-Sm data (S.-S. Sun, personal communication, OZCHRON). This underplated source material was of two distinct compositions: the first composition, derived by melting of a plagioclase stable region, was emplaced into the lower crust in the West Kimberleys and in the western part of the East Kimberleys. In contrast, in the eastern part of the East Kimberleys the material underplated was derived from a garnet-stable source region. It is calculated that this underplated material would be very similar in composition to igneous rocks of modern subduction zones. Both types of underplated material were subsequently remelted during various extensional episodes between 1860 to 1818 Ma to give the two different granite types. Because both are restite dominated, their chemistry now simply ‘images their source region’ (Chappell, 1979), rather than the tectonic setting at the time of emplacement of the granite suites.

The argument for contemporaneous subduction versus extension processes during the emplacement of the granites has little relevance to determining the economic potential of the granite suites. However, it is worth stressing that, based on the compilation of magmas associated with modern porphyry systems in both island arc and continental margins done by this project, there are some significant major element and mineralogical differences between these and the granites of the Kimberley Province and those of modern subduction zones. These differences may explain the apparent absence of major porphyry systems within the Kimberley Province felsic igneous rocks themselves.

A final granite event at around 1800 Ma produced high SiO_2 granites which are more typical of the Sybella-type. These intrusions appear to be chemically different from granites of similar age in the Granites-Tanami Province, although data are limited.

11.2 Executive Summary - Metallogenic Potential

This compilation has assessed the potential of each granite suite based on the criteria set out in the Project Proposal. Eight suites were recognised and only one, the volumetrically small Koongie Suite, is considered to have major mineral potential (Table 1.1). 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. This study argues that the potential of the granites of the Kimberley Province is limited by the abundance of restite in the granite suites. Some 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 this could has occurred in the East Kimberleys but more analyses are required of rocks of high SiO_2 contents (>75 wt %) to confirm this. Volcanics of the Koongie Park Formation were deposited in a subaqueous environment, which may explain their spatial association with small VHMS prospects. Again, there are insufficient analysed samples, particularly at the high SiO_2 end to determine if these volcanics are fractionated, although the comagmatic felsic volcanics are predominantly aphyric, indicating that the magma was predominantly liquid. The granites of the youngest suite, the Sans Sou Suite, being a Sybella type, may have some potential for minor Sn and perhaps Mo/W.

11.3 Future work

Because the majority of the granites in the Kimberley Province are interpreted as being restite-rich and unfractionated, they are not considered to have potential for significant mineralisation. However, before completely dismissing their metallogenic potential outright, further sampling of the more fractionated phases identified from the radiometric data is required. Some sampling of the altered phases also visible in both the magnetic and radiometric data is also warranted. However, it is to be noted that given the extent of geochemical sampling in this region so far, combined with the lack of significant discoveries, the outlook does not seem to be all that promising.

11.4 Methodology

Information Sources: 1:250 000 maps and commentaries, preliminary 1:100 000 maps and notes, published ages, the GSWA whole rock geochemical data, supplemented with data from AGSO ROCKCHEM data base, BRS/AGSO Minloc database, AGSO magnetics and gravity.

Classification of Granites: In this report the granites have been divided into suites essentially as defined by Sheppard *et al*. (1995) with some modifications (Table 1.1). Because of the large aerial extent of the Paperbark Supersuite in the Kimberley region, for the purpose of this project, the Supersuite has been subdivided into the west and east Kimberleys and dealt with in two separate chapters so that readers can more easily relate to the individual granite plutons of the two areas.

Host Rocks: The country rocks which are thought to be intruded by each suite have been summarised, and classified according to mineralogical characteristics thought to be important in determining the metallogenic potential of a granite intrusive event.

Relating Mineralisation: The method used has been to exclude all deposits more than 5 km from a known outcropping granite, then for those remaining, to make an assessment of the likelihood that they may be derived from granite intrusive activity (based on deposit style).

11.5 Acknowledgements

This section has benefited greatly by help from I. Tyler, S. Sheppard, T. Griffin, D.H. Blake, D. Hoatson and S-S Sun.

11.6 References

Chalmers, D.I., 1990. Brockman multi-element and rare earth deposit. In: Hughes, F.E., (Editor), The Geology and Mineral Deposits of Australia and Papua New Guinea. *The Australasian Institute of Mining and Metallurgy, Monograph*, 14, 707-709.

Chappell, B.W., 1979. Granites as images of their source rocks. *Geological Society of America, Abstracts with Programs,* 11, 400.

Dow, D.B., and Gemuts, I., 1969. Geology of the Kimberley Region, Western Australia: The East Kimberley. *Bureau of Mineral Resources, Geology and Geophysics, Australia, Bulletin,* 106, 135 pp.

Gellatly, D.C., Sofoulis, J., Derrick, G.M., and Morgan, C.M., 1974a. The older Precambrian geology of the Lennard River 1:250 000 Sheet Area, *Western Australia. Bureau of Mineral Resources, Geology and Geophysics, Australia, Report,* 153, 126 pp.

Gellatly, D.C., Derrick, G.M., Halligan, R., and Sofoulis, J., 1974b. The geology of the Charnley 1:250 000 Sheet Area, Western Australia. *Bureau of Mineral Resources, Geology and Geophysics, Australia, Report*, 154, 88 pp.

Gellatly, D.C., Derrick, G.M., and Plumb, K.A., 1975. The geology of the Lansdowne 1:250 000 Sheet Area, Western Australia. *Bureau of Mineral Resources, Geology and Geophysics, Australia, Report*, 152, 100 pp.

Gemuts, I., 1971. Metamorphic and igneous rocks of the Lamboo Complex, East Kimberley Region, Western Australia. *Bureau of Mineral Resources, Geology and Geophysics, Australia, Bulletin,* 107, 71 pp.

Griffin, T.J., and Grey, K., 1990. King Leopold and Halls Creek Orogens. In: Geology and Mineral Resources of Western Australia. *Western Australia Geological Survey, Memoir,* 3, 232-255.

Griffin, T.J., Tyler, I.M., and Playford, P.E., 1993. Lennard River, Western Australia, 3rd edition, Sheet SE51-8. *Geological Survey of Western Australia 1:250 000 geological series - Explanatory notes*, 56 pp.

Hancock, S.L., and Rutland, R.W.R., 1984. Tectonics of an Early Proterozoic geosuture - The Halls Creek orogenic subprovince, northern Australia. *Journal of Geodynamics,* 1, 387-432.

Hoatson, D.M., 1993a. Summary of geoscientific information for the East Kimberley, Western Australia, with specific reference to the Dixon Range 1:250 000 Sheet (SE/52-6) and Gordon Downs 1:250 000 Sheet (SE/52-10). *Australian Geological Survey Organisation, Record,* 1993/32, 76 pp.

Hoatson, D.M., 1993b. Correlation of structurally disrupted layered ultramafic-mafic intrusions in the East Kimberley. *Australian Geological Survey Organisation, Research Newsletter,* 19, 9-10.

Hoatson, D.M., 1995. New mineral discoveries on the East Kimberley. *Australian Geological Survey Organisation, Research Newsletter*, 22, 9-11.

Hoatson, D.M., and Tyler, I.M., 1993. Prospective layered mafic-ultramafic intrusions in the East Kimberley. *Australian Geological Survey Organisation, Research Newsletter*, 18, 8-9.

Hoatson, D.M., Blake, D.H., Warren, R.G., Orth, K., Tyler, I.M., 1995. Recent NGMA mapping highlights the metallogenic potential of the East Kimberley. *Australian Geological Survey Organisation, Research Newsletter,* 22, 1-2.

Ogasawara, M., 1988. Geochemistry of the Early Proterozoic granitoids in the Halls Creek orogenic subprovince, northern Australia. *Precambrian Research,* 40/41, 469-486.

Page, R.W., Hoatson, D.H., Sun, S-S, and Foudoulis, C., 1995. High-precision geochronology of Palaeoproterozoic layered mafic-ultramafic intrusions of the East Kimberley. *Australian Geological Survey Organisation, Research Newsletter*, 22, 7-8.

Plumb, K.A., 1990. Halls Creek Province and Granites-Tanami Inlier. *The Australasian Institute of Mining and Metallurgy, Monograph,* 14, 681-695.

Rea, P.S., 1997. Aspects of the geology and mineralisation of Proterozoic VHMS systems in Koongie Park, Western Australia. *Geological Society of Australia, Abstracts,* 44, 61

Sheppard, S., Griffin, T.J., and Tyler, I.M., 1995. Geochemistry of the felsic igneous rocks of the southern Halls Creek Orogen. *Geological Survey of Western Australia, Record,* 1995/4, 81 pp.

Sheppard, S., Tyler, I.M., and Hoatson, D.M., in prep. Explanatory notes on the Mount Remarkable 1:100 000 Geological Sheet, Western Australia. *Geological Survey of Western Australia, 1:100 000 geological map commentary*.

Tyler, I.M., Griffin, T.J., Page, R.W., and Shaw, R.D., 1995. Are there terranes within the Lamboo Complex of the Halls Creek Orogen. *Geological Survey of Western Australia, Annual Review,* 1993-1994, 37-46.

Trudo, A., and Hoatson, D.M., 1996. Depths of emplacement of Precambrian layered intrusions in the East Kimberley. *Australian Geological Survey Organisation, Research Newsletter,* 25, 10-12.

von Gruenewaldt, G., and Harmer, R.E., 1992. Tectonic setting of Proterozoic layered intrusions with special reference to the Bushveld Complex. In: K.C. Condie (Editor), Proterozoic Crustal Evolution. *Developments on Precambrian Geology,* 10, 181-213.

Wyborn, L.A.I., Wyborn, D., Warren, R.G., and Drummond, B.J., 1992. Proterozoic granite types in Australia: implications for lower crust composition, structure and evolution. *Transactions of the Royal Society of Edinburgh, Earth Sciences,* 83, 201-209.

11.7 Table 11.1

Chpt #	Grouping (Type)	Age (Ma)	Potential					Confid Level	Pluton
			Cu	Au	Pb/Zn	Sn	Mo/W		
2	Paperbark *(West Kimberley)* (Kalkadoon)	1860	Low	Low	None	Low	None	321	Mount Amy Granite
									Barker Monzogranite
									Bickleys Porphyry
									Black Rock Granodiorite
									Cone Hill Granite
									Lerida Granite
									Mount Disaster Porphyry
									Cascade Bay Monzogranite
									Long Hole Granite
									Little Gold River Microgranodiorite
									Louisa Monzogranite
									Kongrow Granite
									King Granodiorite
									Lennard Granite
									Mondooma Granite
									McSherrys Granodiorite
									Nellie Tonalite
									Pillara Monzogranite
									Square Top Microgranite
									Richenda Microgranodiorite
									Scrutons Monzogranite
									Tarraji Microgranite
									Mulkerrins Granite
									Swift Monzogranite
									Dyasons Granite
									Chaneys Granite
									Secure Bay Monzogranite
									Whitewater Volcanics
3	Paperbark *(East Kimberley)* (Nicholson)	1850	Low	Low	None	Low	None	321	Neville Granodiorite
									Gnewing Granodiorite
									Mussell Creek Granite
									Sandy Dam Monzogranite
									Togo Monzogranite
									Top Water Tonalite
									Airfield Granodiorite
									Paperbark Granite

Chpt #	Grouping (Type)	Age (Ma)	Potential					Confid Level	Pluton
			Cu	Au	Pb/Zn	Sn	Mo/W		
									Pandanus Yard Monzogranite
									Tumagee Granite
									Mad Gap Monzogranite
									Castlereagh Hill Porphyry
									Greenvale Porphyry
									Beefwood Yard Granite
									Crooked Creek Granite
									Dinner Creek Tonalite
									Gordons Gorge Granite
									Matchbox Granite
									Mount Nulasy Granite
									Neil Creek Monzogranite
									Whitewater Volcanics
4	Sally Downs (Nicholson)	1825	Low	Low/ Mod	None	Low	None	321	Grimpy Monzogranite
									Loadstone Monzogranite
									Violet Valley Tonalite
									Dillinger Monzogranite
									Mount Christine Granitoid
									Mabel Downs Tonalite
									Corrara Granite
									Sally Downs Tonalite
									Mount Fairbairn Monzogranite
									McHale Granodiorite
									Kevins Dam Monzogranite
									Koondooloo Monzogranite
									Magotty Springs Monzogranite
									Shepherds Bore Granite
									Wesley Yard Granite
5	**Koongie Park** (Unclassified)	**1840**	**High**	Low	**High**	Low	Low	221	Koongie Park Formation
									Angelo Microgranite
5	San Sou (Sybella)	1800	None	None	None	Low	Low	221	San Sou Monzogranite
									Eastman Granite
5	Sophie Downs (Unclassified)	1910	None	None	None	None	None	221	Sophie Downs Granite
									Esaw Monzogranite
									Junda Microgranite
									Ding Dong Downs Volcanics
5	Dougalls (Sally Downs)	1850	None	None	None	Low	None	221	Dougalls Tonalite
									Monkey Yard Tonalite

Chpt #	Grouping (Type)	Age (Ma)	Potential					Confid Level	Pluton
			Cu	Au	Pb/Zn	Sn	Mo/W		
									Corkwood Tonalite
									Dead Fish Tonalite
									Reedy Creek Granodiorite
5	Butchers Gully (Unclassified)	1850	Low	Low	None	None	None	221	Butchers Gully Member
									Maude Headley Member

12 MOUNT ISA INLIER

Compiled by Lesley Wyborn, Irina Bastrakova, Carole Hensley and Anthony Budd.

12.1 Executive Summary - Geology

The Mount Isa Inlier has a very long history of mining and exploration. The Inlier hosts several major Pb-Zn deposits (Mount Isa, Hilton, George Fisher, Century, Cannington) and the Mount Isa Cu deposit. Although the relationship between Au and Cu deposits and plutons of the Williams Supersuite was first postulated by Nye and Rayner (1940) in the eastern Mount Isa Inlier, it is only recently that there has been more general acceptance that granites may be related to mineralisation in this part of Inlier (*e.g.*, Wyborn and Heinrich, 1993a, 1993b) with the discovery of deposits such as Ernest Henry, Osborne, Eloise and Starra.

The regional geology of the Mount Inlier was reviewed by Blake (1987). The Mount Isa Inlier itself can be subdivided into 3 broad tectonic divisions: the Western and Eastern Fold Belts separated by the older Kalkadoon-Leichhardt Fold Belt. The Murphy Inlier to the northwest separates the Mount Isa Inlier cover sequences from the McArthur Basin. The oldest sequence, designated by Blake (1987) as basement, consists of a package of predominantly quartzofeldspathic sediments which were deformed and metamorphosed by about 1875 Ma. A series of cover sequences were then deposited from about 1875 Ma to 1580 Ma in the Western and Eastern Fold Belts. The amount of volcanics within these sequences decreases throughout time, and they can be either dominantly felsic, dominantly mafic or bimodal.

Granites were intruded throughout the history of the Mount Isa Inlier and most are I-type, with a few S-types. The earliest known granites are dated at ~1860 Ma, and the youngest at ~1490 Ma. The larger granite intrusive events are at 1860 Ma, 1760 Ma, 1740 Ma, 1670 Ma and 1510 Ma. The most mineralised granite event is at ~1510 Ma. Most granites are Sr-depleted, Y-undepleted, indicating a plagioclase-residual source.

12.2 Executive Summary - Metallogenic Potential

This compilation has assessed the potential of each granite suite based on the criteria set out in the Project Proposal. Suites which have been identified as having high potential for granite-related mineralisation are:

The Williams Supersuite, comprising the post-D_2 plutons of the Williams and Naraku Batholiths, has the greatest potential for further discoveries of Au and Cu in the surrounding environments. The magma becomes more oxidised with increasing fractionation, and Cu values decrease with increasing SiO_2. The high oxidation state of the late magmatic derivatives means that reduction is the most likely cause for metal precipitation and that suitable host rocks will be either carbonaceous rocks or ironstones. Reduction could also occur by interaction of the magmatically derived fluid with a reduced connate fluid.

The Burstall Suite consists of a series of comparatively small plutons some of which have potential for Cu-Au deposits, and although these are likely to be of low tonnage, they have the potential to be of high grade. With the exception of the Saint Mungo Granite and the Myubee Igneous Complex, members of the Burstall Suite are oxidised and Cu generally decreases with increasing SiO_2. The Saint Mungo Granite, which is relatively reduced, is the closest pluton to the Tick Hill Au deposit. New geochronological information (Page and Sun, 1996; Page *et al.* 1997) would suggest that coeval with this intrusive suite is a series of felsic volcanics which are interbedded with the Ballara Quartzite, Mitakoodi Quartzite and Corella Formation (and may also include volcanics of the Tommy Creek Block). Although speculative, it is possible that epithermal and/or Carlin-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 Sybella Suite has high HFSE contents and is not regarded as having much potential for Au or Cu. It has some potential for Sn, Mo and Be.

The Nicholson Suite is dominated by restite in its more mafic end members. Fractionation has only occurred over a very narrow SiO_2 range at high SiO_2 values. The only metal potential appears to be in areas surrounding these late fractionated derivatives in the central part of the Murphy Inlier, where there is a possibility of small Cu, Sn or even Au deposits.

The Kalkadoon-Leichhardt Suite, being predominantly a restite suite, is regarded in general as having low economic potential. However, in the north near Dobbyn and also near the Ewen Batholith, the suite may have potential for small Cu deposits, as minor fractionation appears to have taken place.

12.3 Future work

Two areas of further research have been identified.
1) Further sampling of the northern part of the Ewen Granite and the Kalkadoon Granodiorite in the Dobbyn and northern Prospector 1:100 000 sheet areas to determine if the granite system has undergone fractionation and if so what are the metallogenic implications.
2) A complete dissection of the 1780-1740 Ma felsic igneous rocks of the Eastern Fold Belt and the Wonga region of the Kalkadoon-Leichhardt Belt. The focus of this research should try to determine which parts of the Wonga Suite are comagmatic with the Argylla Suite and which parts are comagmatic with the Burstall Suite. The geochemical research project should apply to both the intrusives and extrusives given the economic potential of the Burstall Suite.

12.4 Methodology

Information Sources: 1:250 000 maps and commentaries, 1:100 000 maps and notes where available, published ages, AGSO ROCKCHEM database, BRS/AGSO Minloc database, AGSO magnetics and gravity.

Classification of Granites: In this report the granites have been divided into suites based on the age, geographic location, and geochemistry of each pluton. Using this method, approximately 10 suites are recognised (Table 1.1). However, if it can be proven that the older granites of the Wonga Suite are part of the Argylla Suite and that the Burstall Suite is comagmatic with the Tommy Creek Suite then the number of suites is reduced.

Host Rocks: The country rocks which are thought to be intruded by each suite have been summarised, and classified according to mineralogical characteristics thought to be important in determining the metallogenic potential of a granite intrusive event.

Relating Mineralisation: As very little direct dating of mineralisation is available in the Mount Isa Inlier, the method used has been to exclude all deposits more than 5 km from a known outcropping granite, then for those remaining, to make an assessment of the likelihood that they may be derived from granite intrusive activity (based on deposit style). The existence of known mineralisation thought to be associated with a granite has been a factor in categorising the metallogenic potential of that granite, however, it is only one criteria of several.

12.5 Acknowledgements

This section has benefited from helpful discussions with Dave Blake and Shen-Su Sun.

12.6 References

Blake, D.H., 1987. Geology of the Mount Isa Inlier and environs, Queensland and Northern Territory. *Bureau of Mineral Resources, Geology and Geophysics, Bulletin,* 225.

Nye, P.B and Rayner, E.O., 1940. The Cloncurry Copper deposits, with special reference to the Gold-Copper Ratios of the ores. *Aerial, Geological and Geophysical Survey of Northern Australia,* Report Queensland No. 35, 38 pp.

Page, R.W., and Sun, S-S, 1996. Age and provenance of granites and host sequences in the Eastern Fold Belt of the Mount Isa Inlier. MIC'96: New developments in metallogenic research: the McArthur, Mount Isa, Cloncurry Minerals Province, Extended Conference Abstracts, *EGRU Contribution 55*, 95-98.

Page, R.W., Sun, S.-S., and McCready, T., 1997. New geochronological results in the central and eastern Mount Isa Inlier and implications for mineral exploration. *Abstracts, Geodynamics and Ore Deposits Conference, Australian Geodynamics Cooperative Research Centre, Ballarat, Victoria*, 46-48.

Wyborn, L.A.I.1998. Youger *ca* 1500 Ma granites of the Williams and Naraku Batholiths, Cloncurry district, eastern Mt Isa Inlier: geochemistry, origin, metallogenic significance and exploration indicators, *Australian Journal of Earth Sciences*, 45, 397-411.

Wyborn, L.A.I., and Heinrich, C.A., 1993a. The relationship between late-tectonic felsic intrusives and Cu-Au mineralisation in the Eastern Fold Belt, Mount Isa Inlier. *Australian Institute of Geoscientists*, Bulletin, 13, 27-30.

Wyborn, L.A.I., and Heinrich, C.A., 1993b. Empirical observations on granite-associated gold + base-metal mineral deposits in the Proterozoic of Australia: delineating exploration criteria. *AGSO Research Newsletter*, 19, 3-4.

12.7 Table 1.1

Ch pt #	Grouping (Type)	Age (Ma)	Potential					Confid Level	Pluton
			Cu	Au	Pb/Zn	Sn	Mo/W		
2	Kalkadoon (Kalkadoon)	1860	Low	Low	None	Low	None	322	Kalkadoon Granodiorite
									Wills Creek Granite
									Woonigan Granite
									One Tree Granite
									Hardway Granite
									Leichardt Volcanics
									Ewen Granite
3	Nicholson (Nicholson)	1850	Mod	Mod	Low	Mod	Low	322	Nicholson Granite
									Cliffdale Volcanics
4	Argylla (Sybella)	1780	None	None	None	None	None	321	Argylla Formation
									Bottletree Formation
									Bowlers Hole Granite
									Mairindi Creek Granite
5	Wonga (Sybella)	1760	None	None	None	None	None	321	Birds Well Granite
									Bushy Park Gneiss
									Mount Maggie Granite
									Natalie Granite
									Playboy Granite
									Scheelite Granite
									Winston Churchill Granite
6	Burstall (Hiltaba)	1740	Mod	Mod	None	Low	Low	322	Burstall Granite
									Mount Godkin Granite
									Overlander Granite
									Mount Erle Igneous Complex

Chpt #	Grouping (Type)	Age (Ma)	Potential					Confid Level	Pluton
			Cu	Au	Pb/Zn	Sn	Mo/W		
									Revenue Granite
									Saint Mungo Granite
									Myubee Granite
7	Fiery (Sybella)	1710	None	None	None	None	None	321	Peters Creek Volcanics
									Fiery Creek Volcanics
									Weberra Granite
8	Sybella (Sybella)	1670	None	None	None	Low	Low	321	Annable Granite
									Briar Granite
									Dingo Granite
									Easter Egg Granite
									Garden Creek Porphyry
									Giddya Granite
									Guns Knob Granite
									Hay Mill Granite
									Kahko Granodiorite
									Keithys Granite
									Kitty Plain Microgranite (in part)
									Queen Elizabeth Granite
									Steeles Granite
									Widgewarra Granite
									Wonomo Granite
									Carters Bore Rhyolite
9	Maramungee (Maramungee)	1545	None	None	None	None	None	321	Maramungee Granite
10	**Williams** (Hiltaba)	**1510**	**High**	**High**	None	None	Low	323	The Mavis Granodiorite
									Malakoff Granite
									Saxby Granite
									Mount Angelay Granite
									Squirrel Hills Granite
									Yellow Waterhole Granite
									Wimberu Granite
									Mount Cobalt Granite
									Mount Dore Granite
11	Tommy Creek (Hiltaba)	1760	Low	Mod	None	None	None	321	Tommy Creek Microgranite
									Lalor beds
									Milo beds(?)
11	Little Toby (Sybella)	?	?	?	?	?	?	210	Little Toby Granite

Ch pt #	Grouping (Type)	Age (Ma)	Potential					Confid Level	Pluton
			Cu	Au	Pb/Zn	Sn	Mo/W		
11	Monaghans (Forsayth)	1804	None	None	None	None	None	320	Monaghans Granite
11	Yeldham (Forsayth)	1820	None	None	None	None	None	220	Yeldham Granite
11	Cowie (Unclassified)	?	?	?	?	?	?	220	Cowie Granite Blackeye Granite
11	Levian (Unclassified)	1746	?	?	?	?	?	321	Levian Granite
11	Mount Maragret (Unclassified)	1530	?	?	?	?	?	100	Mount Margaret Granite
11	Gin Creek (Forsayth)	1740	?	?	?	?	?	311	Gin Creek Granite (muscovite-tourmaline phase)

13 MUSGRAVE BLOCK SYNTHESIS

Compiled by Anthony Budd

13.1 Executive Summary - Geology

The Musgrave Block is a Palaeo-Mesoproterozoic crystalline basement domain extending across the common borders of South Australia, Western Australia, and the Northern Territory. Exposures are excellent in the main ranges (Birksgate, Tomkinson, Mann, Musgrave and Everard Ranges) but other areas are mostly veneered by sand dunes and sheets of the Great Victoria Desert. The Musgrave Block is flanked by Neoproterozoic and Palaeozoic sedimentary basins: Canning Basin to the northwest, Amadeus Basin to the north, Officer Basin to the south and west, and Warburton Basin to the east. The Mesozoic Eromanga Basin oversteps the latter two from the east onto the Musgrave Block.

The Musgrave Block is subdivided into two tectonic subdomains - the area north of, and structurally below, the Woodroffe Thrust is the Mulga Park Subdomain, whereas the region to the south is the Fregon Subdomain, which is structurally above the thrust. A recent compilation by Major and Conor (1993) simplifies the terminology used in the area. The Olia Gneiss refers to the amphibolite-facies gneisses north of the Woodroffe Thrust (Mulga Park Subdomain) (note that recent dating suggests that only gneiss in areas around Mulga Park are pre-Musgravian Orogeny in age, and that the Olia Gneiss in other areas may be deformed equivalents of the Pottoyu Granitic Complex, i.e. part of the Kulgera Supersuite (Nigel Duncan, NTGS *pers comm* 1996)). The Musgravian Orogeny includes a ~1200 Ma metamorphic event which produced the Birksgate Complex which refers to all the metamorphic rocks (ie granulite and amphibolite-facies gneisses) south of the Woodroffe Thrust (Fregon Subdomain). This excludes the Giles Complex, Kulgera Supersuite and basic dykes. The Bentley Supergroup in the western Musgraves overlies earlier gneisses and the Giles Complex. It includes the Tollu Group, which includes the possibly A-type Smoke Hill volcanics at 1080 Ma.

Only three age groupings of granites have been recognised at this stage. They are the regionally extensive 'Kulgera Supersuite' at ~1185 Ma, a suite of granitoids informally named the Winburn suite in the area of the Giles Complex - Tollu Group at ~1050 Ma, and an age of ~1550 Ma has been obtained from some zircons in felsic gneisses. It must be stressed that this division is tentative, as it is based on a limited geochemical and geochronological dataset, and mapping that was done in pockets rather than throughout the Block. Further, literature descriptions are difficult to interpret. Also, Comacho (*pers comm*) and Sheraton (*pers comm*) have indicated that on local scales there is significant variability in the composition of the granites, and that grouping the granites into suites is difficult. It is considered by the author highly likely that further work in the Musgraves Block would substantially change the suites that many of the individual mapunits are assigned to. This must be borne in mind when considering the metallogenic potential of any of these areas.

Camacho and Fanning (1995) dated felsic gneisses from both the Fregon and Mulga Park subdomains containing zircons that were structured with euhedral centres overgrown by round elongate rims. SHRIMP analyses of the cores gave ages of 1557 ± 24 and 1554 ± 28 Ma respectively, and were interpreted to represent the time of igneous crystallisation. Maboko *et al*. (1992) dated a metagranitoid by the SHRIMP method at 1502 ± 14 Ma. Although this is clear evidence for an old granite event, there is no other data to make an analyses of these granites possible. It is not even clear where these particular granite samples are located, which units they belong to, or how extensive they are. They may represent samples of the Birksgate Complex (see later), or may predate or intrude this Complex. No geochemical analyses are available for these samples, so the granites of this age unfortunately cannot be considered in any more detail.

The Kulgera Supersuite was emplaced during and after high-grade metamorphism of the Musgravian Orogeny, at ~1185 Ma. It is composed of widespread felsic, mainly mmonzogranitic and charnockitic plutons emplaced predominantly in the Fregon Subdomain. They range in composition from alkali granite to diorite, and include extensive biotite granite gneiss. The hydrous and oxidation states vary so that orthopyroxene, clinopyroxene, hornblende or biotite may be locally dominant. Texturally, the granitoids are commonly porphyritic and vary from foliated to massive. The Kulgera Supersuite includes granites of the Kulgera Suite in the northeastern part of the Musgraves Block. It also includes the Pottoyu Granitic Complex and the Olia Gneiss in the northwestern (Petermann Ranges) part of the Block. Granites in the southern part of the Block are thought to be part of the Supersuite, and have been informally grouped as the Southern granites.

The Winburn suite intruded contemporaneously with the Giles Complex and the Smoke Hill Volcanics at 1080 Ma (Sun *et al.*, 1996). It is restricted in occurrence to the western Musgraves, in the broad area of the Tomkinson Ranges - Hinkley Ranges. It is composed of charnockites, rapakivi granites, megacrystic granites, and biotite granites. Some of the granites are I-types, typical of intracrustal melts, and they have marked Y depletion. Other granites are fluorite-bearing (which is consistent with rapakivi and megacrystic textures), and are suggested to be the intrusive equivalents of the Smoke Hill Volcanics. Some of the granites of this age have back intrusion relationships with the Giles Complex, and it is suggested that the Winburn Suite and Giles Complex are derived during a single magmatic episode.

The Kulgera Supersuite and Winburn Suite intrude the Birksgate Complex. The only named unit of the complex is the Wataru Gneiss in the Birksgate Range. The Birksgate Complex is comprised of more than 90% acid lithologies, with the remainder including pelitic, quartzitic, calcsilicate and intermediate paragneisses, and intermediate, basic and ultrabasic orthogneisses (note that these are common lithologies throughout the Block, meaning that lithological mapping alone cannot provide a stratigraphy). It is granulitic with hornblende, biotite ± orthopyroxene ± clinopyroxene. The bulk of the metamorphic rocks of the Birksgate Complex are suggested to have volcanic precursors, being dominantly felsic orthogneisses, but also including mafic and ultramafic bodies. The presence of peraluminous gneiss, magnetite-rich quartzite and calcsilicate indicate that clastic and chemical sedimentary components are widespread.

There appears to be a broad regional pattern in the distribution of metamorphic grade within the Fregon Subdomain, with the Tomkinson, Mann and Musgrave Ranges forming a core characterised by granulite-facies rocks. These possibly pass southwards and eastwards into lower grade amphibolite-facies rocks. Hornblende-bearing granulites are distributed across the central and southern portions of the subdomain.

13.2 Executive Summary - Metallogenic Potential

The Kulgera Supersuite is strongly oxidised to oxidised, moderately fractionated, has a wide composition range, is strongly metaluminous, and is Sr-depleted, Y-undepleted. Potential hosts which the suite intrude include mafic and ultramafic units of the Birksgate Complex, which have Fe^{2+}-rich mineralogy (pyroxene, hornblende), and magnetite-rich quartzites. The Kulgera Suite is thought to have moderate potential for gold and possibly copper mineralisation.

The Winburn suite is not considered to have any significant mineralisation potential, because of its A-type character.

13.3 Methodology

Information Sources: Major and Conor (1993) contains a useful summary of the part of the Musgrave Block occurring in South Australia. The NGMA mapping carried out in the western part of the Block has also provided useful information and geochemical data and geochronology (Glikson *et al.*, 1995; Sheraton and Sun, 1995; Sun *et al.*, 1996; Glikson *et al.*, 1996). However, a large part of the focus of this work was on the mafic and ultramafic units of the Giles Complex, with less information available on the felsic intrusives in the area. Geochemical data is sourced from AGSO's ROCKCHEM database, and data for the Northern Territory granites was provided by the NTGS.

Classification of Granites: In this synthesis, the granites were tentatively grouped using only limited geochemistry, very brief literature articles, and information from relatively small-scale mapping.

Host Rocks: The country rocks which are thought to be intruded by each suite have been summarised, and classified according to mineralogical characteristics thought to be important in determining the metallogenic potential of a granite intrusive event. Again, the data available for this is limited, and possibly incomplete.

Relating Mineralisation: Very little mineralisation (none of it economic to date) has been found in the Musgrave Block. Minor primary uranium, copper and gold mineralisation has been identified within gneiss and granulite of the Fregon Subdomain.

13.4 References

Camacho, A. and Fanning, C.M. 1995. Some isotopic constraints on the evolution of the granulite and upper amphibolite facies terranes in the eastern Musgrave Block, central Australia, *Precambrian Research,* 71, 155-181.

Glikson, A.Y., Ballhaus, C.G., Clarke, G.L., Sheraton, J.W., Stewart, A.J. and S.-S. Sun, 1995. Geological framework and crustal evolution of the Giles mafic-ultramafic complex and environs, western Musgrave Block, central Australia, *Australian Geological Survey Organisation, Journal of Australian Geology and Geophysics,* 16, 1/2, 41-67.

Glikson, A.Y., Stewart, A.J., Ballhaus, C.G., Clarke, G.L., Feeken, E.H.J., Leven, J.H., Sheraton, J.W., S.-S. Sun, 1996. Geology of the western Musgrave Block, central Australia, with particular reference to the mafic-ultramafic Giles Complex, *Australian Geological Survey Organisation, Bulletin* 239.

Maboko, M.A.H., McDougall, I., Zeitler, P.K. and Williams, I.S., 1992. Geochronological evidence for ~530-550 Ma juxtaposition of two Proterozoic metamorphic terranes in the Musgrave Ranges, central Australia, *Australian Journal of Earth Sciences,* 39, 457-471.

Major, R.B. and Conor, C.H.H., 1993. Musgrave Block, pp 156-167, *in* Drexel, J.F., Preiss, W.V., and Parker, A.J., (*Editors*). The Geology of South Australia, Volume 1, the Precambrian, *Geological Survey of South Australia, Bulletin* 54, 242 pp.

Sheraton, J.W. and S.-S. Sun, 1995. Geochemistry and origin of felsic igneous rocks of the western Musgrave Block, *Australian Geological Survey Organisation, Journal of Australian Geology and Geophysics,* 16, 1/2, 107-125.

S.-S. Sun, Sheraton, J.W., Glikson, A.Y., and Stewart, A.J., 1996. A major magmatic event during 1050-1080 Ma in central Australia, and an emplacement age for the Giles Complex, *Australian Geological Survey Organisation, Research Newsletter,* 24.

13.5 Table 13.1

Chpt #	Grouping (Type)	Age (Ma)	Potential					Confid Level	Pluton
			Cu	Au	Pb/Zn	Sn	Mo/W		
	Unnamed	1550	?	?	?	?	?	???	???
2	Kulgera (Cullen)	1190	Mod	Mod	None	None	None	110	Undivided
3	Winburn (Sybella)	1080	None	None	None	None	None	110	Undivided

14 PATERSON OROGEN SYNTHESIS

Compiled by Lesley Wyborn

14.1 Executive Summary - Geology

The Paterson Orogen contains Telfer, one of Australia's largest Au deposits hosted by Proterozoic sediments, as well as the Kintyre U deposit and the Nifty Cu deposit. The regional geology of the Paterson Orogen was recently reviewed by Hickman *et al*. (1994) and substantially modified by Bagas *et al*. (1995).

The Paterson Orogen consists of 2 major packages of rocks. The older package comprises the Rudall Complex, which contains two distinguishable units: older banded orthogneiss (50% of outcrop) and paragneiss, and younger quartzite and schist. The Rudall Complex contains some highly reactive rock types including graphitic schists and quartz + magnetite rocks. The Rudall Complex has been highly deformed and metamorphosed, in some areas up to granulite facies.

The younger package, formerly called the Yeneena Group, has been subdivided into three groups (Bagas *et al*., 1995): the Lamil Group in the north, the Throssell Group and the overlying much younger Tarcunyah Group in the west to southwest. The Lamil Group occurs mainly in the Telfer area and contains what has been informally called the 'Telfer Succession'. The Telfer Succession contains highly reactive dolomites and calcareous rocks, with quartzites and some carbonaceous and pyritic shales. The Throssell Group contains the Broadhurst Formation, host to the Nifty Cu mineralisation.

The earliest know granites were emplaced at around 1910 Ma. Although an older age has been documented at ~ 2015 Ma, this is thought to be an inherited age (Bagas and Smithies, *in prep*). A major period of granite intrusion, the Kalkan Supersuite, occurred at around ~ 1780 Ma. A suite of poorly known granites on the Tabletop and western Rudall 1:250 000 sheet areas was possibly emplaced at between 1490 and 1310 Ma (Smithies and Bagas, *in prep.*). The most metallogenically important suite, the O'Callaghans Supersuite was emplaced at ~ 625 Ma and is thought by some (but not all!) to be related to the Telfer Au deposit.

14.2 Executive Summary - Metallogenic Potential

The assessment of the potential of each granite suite in the Paterson Orogen based on the criteria set out in the Project Proposal has been hindered by the limited data available, particularly for the granites in the southern part. Suites identified as having some potential for granite-related mineralisation are:

The <u>Kalkan Supersuite</u> at ~1780 Ma which shows some indications of fractionation. It cannot be dismissed outright, but the potential on current information is equivocal and hence the areas surrounding this suite may be worth some follow-up exploration.

The <u>Krackatinny Supersuite</u> at ~ 1310 Ma (?) which crops out in the far eastern part of the Orogen, mainly on the Tabletop 1:250 000 Sheet area. Data on this suite are very limited, and the rocks appear to intrude rocks of the Rudall Complex. Exposures are scattered amongst sand dunes. 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.

The <u>O'Callaghans Supersuite</u> at ~ 625 Ma has a proven spatial relationship with mineralisation. The Supersuite shows fractionation and evidence for the activity of a fluid phase. It can be divided into two suites: the oxidised Mount Crofton Suite, which contains magnetite, but very little mineralisation, and the reduced O'Callaghans Suite which is ilmenite stable. Any fluids which came off the O'Callaghans Suite would be reduced and have potential to carry gold, copper, tungsten and molybdenum. Exploration to date has focused on targets similar in composition to the hosts of the mineralisation at Telfer. However, some mineralisation may be associated with the more oxidised Mount Crofton Suite. If so then the host rocks could have a different composition, and the resultant mineralisation may be more Cu-rich.

14.3 Future Work

More sampling is required on the granites, particularly on the Tabletop 1:250 000 area. The orthogneisses of the Rudall Complex have barely been touched chemically and need more chemical work to fully assess their potential.

14.4 Methodology

Information Sources: Ph.D theses, 1:250 000 maps and commentaries, 1:100 000 maps and notes where available, published ages, AGSO ROCKCHEM database supplemented with data from the GSWA, BRS/AGSO Minloc database, AGSO magnetics and gravity.

Classification of Granites: In this report the granites have been divided into suites based on the age, geographic location, and geochemistry of each pluton. Using this method, three supersuites have been defined. (Table 1.1). They have been given ‘supersuite’ status as there is insufficient geochemical and geochronological information available to define these units as suites within the strict definition.

Host Rocks: The country rocks which are thought to be intruded by each suite have been summarised, and classified according to mineralogical characteristics thought to be important in determining the metallogenic potential of a granite intrusive event. This has been a little difficult in the southern Paterson Orogen, particularly in the Rudall Complex where identifying potentially reactive host rocks within the vicinity of the granites has proven difficult due to high metamorphic grade in some areas combined with limited outcrops.

Relating Mineralisation: Again this has been a little difficult in the southern Paterson Orogen, particularly in the Rudall Complex. Known occurrences of mineralisation are not in the vicinity of areas where geochemical and petrological data are available.

14.5 Acknowledgements

This section has benefited greatly from help provided by Hugh Smithies and Leon Bagas of the GSWA who provided data, preliminary notes and much assistance on the telephone. Anyone interested in following up data on this area should contact these two people. Thanks also to discussions held over the years to Nicky Netherway (nee Goellnicht) on the granites of the Telfer region and special thanks to Newcrest who flew me over to the Telfer area to enable me to see what these granites actually look like in their field context.

14.6 References

Bagas, L., and Smithies, H., *in prep*. Connaughton 1:100 000 Explanatory Notes. *Geological Survey of Western Australia.*

Bagas, L., Grey, K., and Williams, I.R., 1995. Reappraisal of the Paterson Orogen and Savory Basin. *Geological Survey of Western Australia, Annual Review,* 1994-1995, 55-63.

Chin, R.J., Hickman, A.H., and Towner, R.R., 1982. Paterson Range (Second Edition), Western Australia, sheet SF/51-6. *Bureau of Mineral Resources, Geology and Geophysics, Australia and the Geological Survey of Western Australia, 1:250 000 Geological Series, Explanatory Notes,* 29 pp.

Chin, R.J., Williams, I.R., Williams, S.J., and Crowe, R.W.A., 1980. Rudall, Western Australia, sheet SF/51-10. *Geological Survey of Western Australia, 1:250 000 Geological Series, Explanatory Notes,* 22 pp.

Dimo, G., 1990. Telfer Gold Deposits. In: F.E. Hughes (Editor), The geology and mineral deposits of Australia and Papua New Guinea. *The Australasian Institute of Mining and Metallurgy, Monograph*, 14, 643-651.

Goellnicht, N.M., 1992. Late Proterozoic fractionated granitoids and their role in the genesis of gold and base-metal mineralisation in the Telfer district, Western Australia. *Ph.D. Thesis, University of Western Australia*.

Goellnicht, N.M., Groves, D.I., McNaughton, N.J., and Dimo, G., 1989. An epigenetic origin for the Telfer gold deposit. In: Keays, R.R., Ramsay, W.R.H., and Groves, D.I., (Editors). The Geology of Gold Deposits: The Perspective in 1988. *Economic Geology Monograph,* 6, 151-167.

Goellnicht, N.M., Groves, D.I., and McNaughton, N.J., 1991. Late Proterozoic fractionated granitoids of the mineralised Telfer area, Paterson Province, Western Australia. *Precambrian Research*, 51, 375-391.

Hickman, A.H., and Bagas, L., 1995. Tectonic evolution and economic geology of the Paterson Orogen - a major reinterpretation based on detailed geological mapping. *Geological Survey of Western Australia, Annual Review*, 1993-1994, 67-76.

Hickman, A.H., Williams, I.W., and Bagas, L. 1994. Proterozoic geology and mineralisation of the Telfer-Rudall Region. *Geological Society of Australia (WA division) Excursion Guide*, 5, 60 pp.

Nelson, D.R., 1995. Compilation of SHRIMP U-Pb zircon geochronology data, 1994. *Geological Survey of Western Australia, Record*, 1995/3.

Nelson, D.R., 1996. Compilation of SHRIMP U-Pb zircon geochronology data, 1995. *Geological Survey of Western Australia, Record*, 1996/5.

Rowins, S.M., Groves, D.I., McNaughton, N.J., Brown, P.E., McLeod, R.L., and Hall, D., 1993. Evidence of unusually carbonic and reduced ore fluids in the late Proterozoic Seventeen Mile Hill porphyry copper-style deposit, Telfer District, Western Australia. *Geological Society of Australia, Abstracts*, 34, 68-69.

Sexton, M.A., 1994. Geophysical characteristics of the Telfer Gold Deposits, Western Australia. In: 'Geophysical Signatures of Western Australian Mineral Deposits', *Geology and Geophysics Department (Key Centre) and UWA Extension, The University of Western Australia, Publication*, 26, 199-212.

Turner, C.C., 1982. The Telfer Gold deposits, Western Australia: stratigraphy, sedimentology and gold mineralisation of the Proterozoic Yeneena Group. *Ph.D. Thesis, University of New England.*

14.7 Table 14.1

Ch pt #	Grouping (Type)	Age (Ma)	Potential					Confid Level	Pluton
			Cu	Au	Pb/Zn	Sn	Mo/W		
2	Kalkan (Unclassified)	1780	Mod	Mod	Low	Low	Mod	111	PRga
									PRgh
3	Krackatinny (Sally Downs)	1310-1490	Mod	Mod	Low	Low	Mod	110	Krackatinny Tonalite
									Kutakuta Tonalite
									Harbutt Leucogranite
									Runton Adamellite
4	**O'Callaghans** (Cullen)	**625**	**High**	**High**	Low	Low	Mod	323	Mount Crofton Granite
									Hansens Folly Gneiss
									Desert's Revenge Granite
									O'Callaghans Granite
									Tyama Granite
									Minyari Granite
									Koolyu Granite

15 PINE CREEK INLIER

Compiled by Lesley Wyborn, Elizabeth Jagodzinski, Irina Bastrakova and Anthony Budd.

15.1 Executive Summary - Geology

The Pine Creek Inlier is one of the major mineral provinces of Australia. The Inlier hosts 30% of the world's known uranium resources (Ranger, Koongarra, Jabiluka and Nabarlek) and is a major gold producer with deposits such as Cosmo Howley, Enterprise, and Mount Todd. Historically, substantial amounts of base metals, silver, iron, tin and tungsten have also been mined.

The regional geology of the Pine Creek Inlier was reviewed by Needham and de Ross (1990) and Needham (1988). The main components of the Pine Creek Inlier are a series of late Archaean basement domes overlain by a Palaeoproterozoic sedimentary sequence deposited in a shallow intracontinental rift. This predominantly clastic sequence also contains some highly reactive rock units including carbonaceous shales, banded iron formations, evaporites, carbonates, mafic and felsic volcanics. These units were deformed, metamorphosed and intruded by granite at around ~1875 Ma. A sequence of predominantly rift-related felsic volcanics were extruded unconformably over the deformed basement at around 1860-1830 Ma. These volcanics were overlain by platform sandstones of the Katherine River Group.

There are two main episodes of granite intrusion in the Pine Creek Inlier. The first major event was syn or post the major deformation event and occurred between 1865 and 1850 Ma (Nimbuwah Suite, Allia Suite, Wagait Suite). The next major event was the intrusion of the Cullen Supersuite and the Jim Jim Suite from about 1830-1810 Ma. Both events were associated with felsic volcanism. All suites are Sr-depleted, Y-undepleted, indicating a plagioclase-residual source. Most suites are I-(granodiorite) type, although there is a reasonable proportion of S-types in the Litchfield Block (the Allia Suite).

15.2 Executive Summary - Metallogenic Potential

This compilation has assessed the potential of each granite suite based on the criteria set out in the Project Proposal. Suites which have been identified as having potential for granite-related mineralisation are:

The <u>Allia Creek Suite</u> at ~1845 Ma is a felsic fractionated S-type suite with potential for Sn. The suite contains pegmatites and greisens.

The <u>Cullen Supersuite</u> at 1825 Ma is a felsic fractionated I-(granodioritic) type suite which has proven Au, Sn and W potential and has some minor Cu and base metal occurrences.

The <u>Jim Jim Suite</u> at 1825 Ma is a fractionated I-(granodioritic) suite which may have some potential for Sn and Au.

15.3 Future Work

In view of the abundance of data in the Pine Creek Inlier in comparison to some of the more poorly known Proterozoic Provinces, further sampling in this province is not regarded as a high priority. Some more focused research could be carried out with respect to the Pb isotopes to resolve the issue as to whether the source of the Au is from the granites or whether the Au is leached from the adjacent country rocks by interaction with magmatic fluids.

15.4 Methodology

Information Sources: 1:250 000 maps and commentaries, 1:100 000 maps and notes where available, published ages, AGSO ROCKCHEM database supplemented with data from NTGS, BRS/AGSO Minloc database, AGSO magnetics and gravity.

Classification of Granites: In this report the granites have been divided into suites based on the age, geographic location, and geochemistry of each pluton. Using this method, 4 major and 3 minor suites are recognised (Table 15.1).

Host Rocks: The country rocks which are thought to be intruded by each suite have been summarised, and classified according to mineralogical characteristics thought to be important in determining the metallogenic potential of a granite intrusive event.

Relating Mineralisation: Very little direct dating of mineralisation is available in the Pine Creek Inlier, particularly for Au. Therefore, the method used has been to exclude all deposits more than 5 km from a known outcropping granite, then for those remaining, to make an assessment of the likelihood that they may be derived from granite intrusive activity (based on deposit style). The existence of known mineralisation thought to be associated with a granite has been a factor in categorising the metallogenic potential of that granite, however, it is only one criteria of several.

15.5 Acknowledgements

This section has benefited greatly from the help provided by Zia Bajwah and Masood Ahmad of the NTGS.

15.6 References

Ahmad, M., Wygralak, A., Ferenczi, P.F., and Bajwah, Z.U., 1993. Pine Creek, Northern Territory - 1:250 000 Metallogenic Map Series. *Northern Territory Geological Survey Explanatory Notes* SD52-8.

Bajwah, Z.U., 1991. Geochemical evolution of the Proterozoic Granitoids, related hydrothermal activity responsible for mineralisation, Pine Creek Geosyncline, Northern Territory, Australia. Abstracts for the inaugural national meeting of the Specialist Group in Economic Geology of the Geological Society of Australia on “Ore Fluids - their origin, flow paths, effects and products”, *Bureau of Mineral Resources, Geology and Geophysics, Australia, Record,* 1990/95, 1-2.

Bajwah, Z.U., 1994. Mineralogy and magnetic susceptibility of the Proterozoic granites, related to gold mineralisation, Pine Creek Geosyncline, Northern Territory Australia. In: C.P. Hallenstein (editor), Australian Mining Looks North - The Challenges and Choices. *Australasian Institute of Mining and Metallurgy, Publication Series,* 5/94, 57-67.

Klominsky, J., Partington. G.A., McNaughton, N.J., Ho, S.E., and Groves, D.I., 1996. Radiothermal granites of the Cullen Batholith and associated mineralisation (Australia). *Czech Geological Survey Special Papers,* 5, 44 pp.

Needham, R.S., 1988. Geology of the Alligator Rivers Uranium Field, Northern Territory. *Bureau of Mineral Resources, Geology and Geophysics, Australia, Bulletin,* 224, 96 pp.

Needham, R.S., and de Ross, G.J., 1990. Pine Creek Inlier - regional geology and mineralisation. In: Hughes, F.E. (Editor), Geology and Mineral Deposits of Australia and Papua New Guinea. *Australasian Institute of Mining and Metallurgy, Monograph,* 14, 727-737.

Needham, R.S., and Stuart-Smith, P.G., 1985. Stratigraphy and tectonics of the Early to Mid Proterozoic transition, Katherine- El Sherana area, Northern Territory. *Australian Journal of Earth Sciences,* 32, 219-230.

Needham, R.S., Stuart-Smith, P.G., and Page, R.W., 1988. Tectonic Evolution of the Pine Creek Inlier, Northern Territory. *Precambrian Research,* 40/41, 543-564.

Stuart-Smith, P.G., Needham, R.S., Page, R.W., and Wyborn, L.A.I., 1993. Geology and Mineral Deposits of the Cullen Mineral Field, Northern Territory. *Australian Geological Survey Organisation, Bulletin,* 229, 145 pp.

Walpole, B.P., Crohn, P.W., Dunn, P.R., & Randal, M.A., 1968. Geology of the Katherine-Darwin region, Northern Territory. *Bureau of Mineral Resources, Australia, Geology and Geophysics, Bulletin,* 82.

Wyborn, L.A.I., and Stuart-Smith, P.G., 1993. The relationship between granite composition, host rock types, and Au + base-metal mineralisation in the Cullen Mineral Field, Pine Creek Inlier. *Australian Geological Survey Organisation Research Newsletter,* 19, 5-8.

15.7 Table 15.1

Chpt #	Grouping (Type)	Age (Ma)	Potential					Confid Level	Pluton
			Cu	Au	Pb/Zn	Sn	Mo/W		
6	Gerowie (Kalkadoon)	1885	None	None	None	None	None	321	Geworie Tuff
									Mount Bonnie Formation
									Tollis Formation
									Berinka Volcanics
									Warr's Volcanic Member
									Mulluk Mulluk Volcanic Member
									Burrell Creek Formation
									Yarrawonga Volcanic Member
									Meeway Volcanics
2	Nimbuwah (Kalkadoon)	1865	None	None	None	None	None	210	Nimbuwah Complex intrusives
3	**Allia Creek** (Allia)	**1845**	None	Low	None	**High**	Low	322	Allia Creek Granite
									Two Sisters Granite
									Marra-Kamangee Granite
									Jammine Granite
									Fish Billabong Adamellite
									Mount Litchfield Granite
									Soldiers Creek Granite
									Turnbull Bay Granite
6	El Sherana (Kalkadoon)	1865	None	None	None	None	None	221	El Sherana Group
									Pul Pul Rhyolite
									Coronation Sandstone
6	Wagait (Kalkadoon)	1850	None	None	None	None	None	320	Wagait Granite
									Peppimenarti Granite
									Reynolds River Granite
									Koolendong Granite
4	**Cullen** (Cullen)	**1825**	Mod	**High**	Low	**High**	Mod	323	Allamber Springs Granite
									Bonrook Granite
									McKinlay Granite
									Mount Porter Granite
									Burnside Granite
									Douglas Leucogranite
									Frances Creek Leucogranite
									Mount Davis Granite
									Driffield Granite
									Fingerpost Granodiorite

Chpt #	Grouping (Type)	Age (Ma)	Potential					Confid Level	Pluton
			Cu	Au	Pb/Zn	Sn	Mo/W		
									Fenton Granite
									Tennysons Leucogranite
									Umbrawarra Leucogranite
									Wandie Granite
									Wolfram Hill Granite
									Yenberrie Leucogranite
									Foelsche Leucogranite
									Saunders Leucogranite
									Mount Bundey Granite
									Margaret Granite
									McMinns Bluff Granite
									Prices Springs Granite
									McCarthys Granite
									Minglo Granite
									Shoobridge Granite
									Tabletop Granite
5	Jim Jim (Nicholson)	1825	None	Mod	None	Low	Low	322	Nabarlek Granite
									Tin Camp Granite
									Jim Jim Granite
									Malone Creek Granite
									Grace Creek Granite
									Eva Valley Granite
									Yeuralba Granite
									Edith River Volcanics
									Plum Tree Creek Volcanics
									Big Sunday Formation
									Gimbat Formation

16 OTHER PROVINCES

Compiled by Anthony Budd

Proterozoic granites of Cape Leeuwin, the Northampton Complex and King Island are included in this chapter mostly because of their small sizes and lack of data. No data at all is available for the Northampton Complex, some age data is available for Cape Leeuwin, and geochemical and gechronological data is available for King Island. The metallogenic potential of each province cannot be adequately quantified with the available data.

16.1 King Island

Proterozoic granites on King Island have been called the 'West Coast granite' (Gresham, 1972). It occupies roughly one quarter of the island, mostly on the western and northern parts of the island. It is a composite body, ranging in composition from adamellite to granodiorite and is predominantly fine to medium grained with minor phases of porphyritic granite. The granite consists essentially of quartz, plagioclase, microcline perthite, orthoclase perthite, with minor biotite, muscovite and chlorite, and accessory zircon, apatite, sericite, zoisite and opaques. Xenoliths of basic material up to 30 cm in diameter are common throughout the granite mass.

Typical West Coast granite is granodiorite in composition. At the northern end of the island two distinct types of granite have been noted, including an orthoclase-porphyritic phase and a medium- to fine-grained phase. Most of the West Coast granite is deformed in some way, being either strongly sheared and foliated, or having cataclastic texture.

The contacts of the granite with the west coast metasediments are highly variable and intermixed. The contact near Cape Wickham displays development of migmatitic type rocks and a variety of quartzose-feldspathic rocks. However, the contacts display a general conformability between the west coast metasediments and the West Coast granite and it is considered the granite is only locally intrusive and largely generated *in situ*. However, Blackney (1982) concludes that the granite is not of minimum melt composition. A contact between the East Coast metasediments and the granite is revealed, and appears to be fairly abrupt with some degree of silicification of the metasediments.

Potassium-argon dating of the micas within the West Coast granites by McDougall and Leggo (1965) give an age of 715 Ma. More recent dating by Black (1993) gave a SHRIMP age of 767±10 Ma, with inheritance of between 1400-1800 Ma and ~2900 Ma. Other dating by Cox (1993) yields dates of 763±12 Ma and 748±2 Ma.

Sixteen samples have been analysed, 15 by Streit (1994) and 1 by Black (the same sample as was SHRIMP dated). The granites sampled are mostly felsic, although there is evidence in at least two of the samples of silicification. Some sodic alteration is present, and the one sample that was analysed for its stoichiometry is reduced and may be weathered. The Proterozoic granites appear to form one suite, which is mildly fractionated, Sr-depleted/Y-undepleted, and is metaluminous to peraluminous and therefore is an I-(granodiorite) type. Geochemically, it has compositions ranging from granodiorite to granite, consistent with field descriptions.

<u>Further Work:</u> It is considered that these granites have low to moderate potential for Cu-Au mineralisation. In order to quantify the exact potential, further sampling of felsic, possibly fractionated granites is needed. The small size of the suite is probably a limiting factor in the mineral potential of this suite. However, given the global (and Australian) importance of late Neoproterozoic granite mineralisation, further work on the Proterozoic granites of King Island may be warranted.

16.2 Leeuwin Complex

The Leeuwin Complex consists of intensely deformed plutonic igneous rocks, mainly granite, metamorphosed to granulite facies (Myers, 1990). The granite is composed of quartz, feldspar, biotite and clinopyroxene with or without hornblende and garnet. It has a granoblastic texture and contains thin pegmatite veins. Small garnets are generally abundant, but in some places they are absent. The gneiss is intensely deformed and subsequently recrystallised in granulite facies with granoblastic textures and blebby partial-melt patches overprinting and replacing older tectonite fabrics.

Porphyritic granite is also abundant, and it is strongly deformed along with the granite gneiss (above) and remnants of layered-basic intrusions, and is recrystallised in amphibolite or granulite facies. It is generally less intensely deformed than the other rocks and has thus preserved either porphyritic or even-grained relict igneous textures.

Although no geochemical samples are available of the Leeuwin Complex granites, several SHRIMP analyses have been made (Nelson, 1996).

Hornblende granite gneiss at Cape Leeuwin is described as medium- to coarse-grained, granoblastic gneiss consisting of perthite/microcline, quartz, and plagioclase with lesser dark-green hastingsitic hornblende, minor biotite, and accessory opaques, titanite, apatite, and zircon. Distinctive features are the relatively low quartz content for a granite, abundant accessory zircons, and abundant accessory titanite. The original rock was an iron-rich granite, metamorphosed to medium grade or lowest high grade. The interpreted age of crystallisation is 688 ± 7 Ma.

Granite gneiss at Cosy Corner is a coarse-grained, strongly foliated granoblastic granite gneiss, containing indistinct melt patches and intruded by coarse-grained pegmatite dykes that post-date the main phase of deformation. The principal minerals in this sample are perthite, quartz, and albite, with minor opaque oxides and altered amphibole, and accessory titanite, zircon, calcite and chlorite. The age of granite crystallisation is interpreted to be 779 ± 23 Ma, with peak metamorphism at 605 ± 36 Ma.

Another sample of hornblende granite gneiss from Cape Leeuwin contains a coarse-grained, moderately oriented granoblastic assemblage of perthite/microcline, quartz and oligoclase, with lesser hornblende, minor biotite, and accessory opaques, apatite and zircon. A single small grain of garnet was noted. The original rock was an iron-rich granite, metamorphosed to medium grade or lowest high grade. The granite crystallisation age is interpreted as 681 ± 10 Ma.

Hornblende-biotite monzogranite gneiss at Canal Rocks north consists of medium- to coarse-grained, moderately foliated, granoblastic gneiss containing perthite, quartz, hornblende and plagioclase with accessory biotite, opaques, apatite, and zircon. The original rock was a granite that has since undergone medium-grade metamorphism. 702 ± 7 Ma is considered to be the age of crystallisation.

<u>Further Work:</u> Given the importance of ~700 Ma granites, further work is warranted on these granites. Geochemical sampling of the granites should be carried out, as should some mapping of the units they intrude.

16.3 Northampton Complex

Three main rock units have been distinguished in the Northampton Complex: granulite, granite and migmatite (Myers, 1990). They form large scale open folds with north to northwest axes that plunge steeply towards the southwest. Most rocks are metamorphosed in granulite facies, or are retrograde from granulite facies. A thick sheet of porphyritic granite was emplaced into the granulites, and a contact zone of migmatite developed in rafts of granulite are abundant in garnet-bearing granite. The main body of granite is a foliated quartz-microcline-plagioclase-biotite rock, and this is enclosed by a contaminated marginal zone characterised by garnet, and locally by cordierite.

<u>Further Work:</u> Very little work has apparently been done on these granites. At least some sampling for geochemistry, geochronology and petrology should be done.

16.4 Bridget Suite

The Bridget Suite includes small stocks of granite ranging in composition from hornblende monzogranite to quartz monzonite, and associated hornblende porphyry dykes (Hickman 1978, Hickman and Lipple 1975, Hickman 1983, Hickman *et al*. 1983, Collins *et al*. 1988). The suite forms a north-northwest trending belt in the Bamboo Creek area of the Archaean Pilbara Block of Western Australia. It intrudes the Mosquito Creek Formation, Mount Bruce Supergroup, Warrawoona and Gorge Creek Groups. It is the only known Proterozoic granite suite in the Pilbara Block, and has been dated by the Rb-Sr method at 1731 ± 14 Ma by Collins *et al*. (1988).

The Bridget Suite is named after the Bridget Adamellite, and includes the Parnell Quartz Monzonite and several other unnamed plutons.

The suite is Sr-undepleted, Y-depleted (which is rare for Australian Proterozoic granites), fractionated, and shows minor alteration. It has a well-developed contact aureole, and dykes of aplite, granophyre and pegmatite are common. It intrudes Archaean sediments and mafic to intermediate volcanics, some of which are potential hosts to mineralisation.

Geochemcially the suite appears to have some potential, but it must be noted that this is based on a small (possibly unrepresentative) sample set. The suite also intrudes host rocks with some potential for being reactive to an oxidised fluid. There are numerous quartz-vein gold deposits within the vicinity of the suite, but these appear to be syn-deformational (and earlier than the Bridget granites) and are also more widespread than exposures of the granite, suggesting that these granites are not the cause of the mineralisation.

Further Work: Sampling and analysis is required on both the granites and the nearby gold deposits; the low potential assigned to the suite is based on inadequate data.

16.5 References

Black, L.P., 1993. SHRIMP date on sample 93220008 contained in AGSO's OZCHRON database.

Blackney, P.C.J., 1982. The petrology and conditions of metamorphism of the Fitzmaurice Bay to Stokes Point area, King Island. *BSc Honours thesis, University of Tasmania (unpublished).*

Collins, W.J., Gray, C.M. and Goode, A.D.T. 1988. The Parnell Quartz Monzonite: A Proterozoic zoned pluton in the Archaean Pilbara Block, Western Australia, *Australian Journal of Earth Sciences,* 35, 535-547.

Cox, S.F., 1993. SHRIMP dates on samples 93220010 and 93220011 contained in AGSO's OZCHRON database.

Gresham, J.J., 1972. The regional geology of King Island, Geopeko Ltd, King Island, *Tasmania Mines Department company report* TCR 72-867.

Hickman, A.H. 1978. Nullagine , Western Australia, 1:250 000 Geological Series, *Geological Survey of Western Australia, Explanatory Notes,* SF/51-05, 22pp.

Hickman, A.H. 1983. Geology of the Pilbara Block and its environs, *Geological Survey of Western Australia, Bulletin* 127.

Hickman, A.H. and Lipple, S.L. 1975. Explanatory notes on the Marble Bar 1:250 000 sheet, Western Australia, *Geological Survey of Western Australia, Record* 1974/20 *(unpublished).*

Hickman, A.H., Chin, R.J. and Gibson, D.L. 1983. Yarrie, Western Australia, 1:250 000 Geological Series, *Geological Survey of Western Australia, Explantory Notes,* SF/51-01, 33pp.

Jennings, D.J., Cox, S.F., 1978. King Island - Flinders island, 1:250 000 geological map, *Geological Survey of Tasmania.*

McDougall, I. and Leggo, P.J., 1965. Isotopic age determination on granitic rocks from Tasmania, *Journal of the Geological Society of Australia,* 12, 295-332.

Myers, J.S., 1990. Pinjarra Orogen, in *Geology and Mineral Resources of Western Australia, Western Australia Geological Survey, Memoir* 3, 265-274.

Nelson, D.R., 1996. Compilation of SHRIMP U-Pb zircon geochronology data, 1995, *Geological Survey of Western Australia, Record* 1996/5.

Streit, J.E., 1994. Effects of fluid-rock interaction on shear zone evolution in Proterozoic granites on King Island, Tasmania, *unpublished PhD Thesis, Australian National University.*

17 ORIGINAL PROPOSAL, 1995

This is an abbreviated copy of the original project proposal of 1995. The following chapter on methods shows how we adapted the project as it evolved.

EXECUTIVE SUMMARY

Granites are increasingly being seen as important in the development of Australian Proterozoic hydrothermal Au ± base metal deposits. This project will provide sponsors with a synthesis of publicly available data on major Australian Proterozoic granite suites and their associated host rocks. By combining these two data sets, new areas of potential granite-related Au ± base metal and also VMS mineralisation may be targeted.

Each major Proterozoic pluton will be assigned to a granite suite, and each suite will be attributed according to geological and geochemical parameters considered important indicators of mineral potential. Each granite suite will also be divided into a broad classification scheme on the basis of its similarities to eight major Australian Proterozoic granite suites, particularly those known to be associated with mineralisation. A classification based on the level of heat production will also be applied. Using GIS, a qualitative assessment will be made of the rock types (e.g., age, environment of deposition and the mineralogical content) and of the mineral deposits or occurrences that occur within 5 km of each granite suite.

The results will be presented as:

- an integrated GIS package and hard-copy atlas based on the new digital 1:2 500 000 geological map of Australia.
- a series of spreadsheets that classify the granites and their host rocks.
- a synthesis report summarising the dominant features of the granites of each province and their metallogenic potential.

The program will be undertaken by a small team led by Dr Lesley Wyborn supported by graduate scientists and technical officers. The project will be carried out in collaboration with the State and Territory Geological Surveys.

THE METALLOGENIC POTENTIAL OF AUSTRALIAN PROTEROZOIC GRANITES

OBJECTIVES

- To classify major Australian Proterozoic granite[1] suites according to their similarities to major mineralised and unmineralised granite suites.
- To identify compositionally and temporally suitable host rocks adjacent to granite suites considered to have potential for Au (base metal mineralisation.
- To identify areas which have the combination of appropriate granites and host rocks which may host potential mineralisation.

SIGNIFICANCE OF RESEARCH

As more exploration in the Proterozoic is focussing on known areas of hydrothermal Au ± base metal mineralisation, granites are increasingly seen by many to be an important component of the mineralising system in areas such as Pine Creek, Telfer, Granites-Tanami, the eastern Mount Isa Inlier and Olympic Dam. As this style of mineralisation can occur up to 3 km from the granite body, it is also now recognised

1 For this proposal the term granite includes diorites, tonalites, granodiorites, monzogranites (adamellites), and granites (*sensu stricto*).

that the mineralogical composition of the country rock plays an important role in controlling metal precipitation, as most deposits are hosted by rocks rich in reductants such as magnetite, graphite and/or sulphide. This Proterozoic style of mineralisation contrasts considerably with normal conceptual models of granite-related mineralisation, e.g., porphyry copper deposits, where mineralisation is either hosted by, or lies above, the associated intrusive; or skarn-style mineralisation, where the ore is usually hosted by carbonate-rich rocks immediately adjacent to the granite.

The Australian Geological Survey Organisation (AGSO) has built up significant expertise on Australian Proterozoic granite systems, both mineralised and unmineralised, in several major provinces. AGSO has been approached by two companies to further develop this work and extend it into some poorly known provinces. This project proposes to undertake a one-year review not only of major Proterozoic granites suites, but also of the major mineralogical compositions of the adjacent country rocks to identify potential new areas for Au ± base metal mineralisation in Proterozoic provinces of Australia. This project will also target areas of interest which may require more detailed follow-up work.

The research program outlined in this proposal will be led by Dr Lesley Wyborn, in collaboration with the State and Territory Geological Surveys. Participating companies will be invited to send staff to be part of the research team.

BACKGROUND TO THIS PROPOSAL

RATIONALE

Reviews of geological and geochemical data in several Proterozoic provinces by AGSO (Wyborn, 1994a, b, c, *in prep.*) have shown that Proterozoic granite suites which have hydrothermal ± base metal mineralisation within 2 to 3 km of the contact have many easily determined field, petrographic and geochemical characteristics in common; whilst unmineralised granite suites also have distinctive features. The mineralogical composition of the host rock is also considered an important factor controlling precipitation (Stuart-Smith *et al*. 1993; Wyborn and Heinrich, 1993; Wyborn *et al*. 1994a).

Therefore a combined analysis not only of the geological and chemical features of the major granite suites, but also of their host rocks, may target new potential areas of Proterozoic granite-related Au ± base metal mineralisation. The same information gathered by this project can also be used to target potential areas for VMS deposits and locate high heat-producing granites

PROJECT SCOPE AND TIMING

The proposal involves a one-year review of all easily available AGSO and State/Territory Proterozoic felsic igneous geochemical and relevant associated geological data to determine other areas which may have potential for granite-related Au ± base metal mineralisation.

Sponsors must appreciate that this proposal is for a o-year review of existing publicly available data. The proposal scope and content will also be limited by the number of sponsors.

The project will access AGSO, State and Territory digital databases, the Australian Register of Stratigraphic Names (of which AGSO is custodian), map commentaries and reports, explanatory notes and the 1:2 500 000 digital geological map of Australia.

At the end of one year, a review will be undertaken of the project to consider possible extensions such as a sampling program on granites from poorly known areas or expanding the documentation of the mineralogical content of Australian Proterozoic stratigraphic units.

PROPOSED RESEARCH PLAN

STAFFING

The research project will be funded jointly by AGSO and industry sponsors. It is envisaged that the project will be led by Dr Lesley Wyborn and include at least one graduate scientist and one technical officer. Companies are invited to send staff to participate so that they can enhance their expertise in granite classification and in GIS development.

A MODULAR APPROACH

The project will have four modules: Granites, Country Rock, Mineral Deposits and Synthesis.

THE GRANITES MODULE will utilise the fact that Australian Proterozoic granite suites are often uniform over many thousands of kilometres (Wyborn, D., 1988; Wyborn *et al*. 1992; Griffin *et al*. 1994), and hence are more than suitable for classification within a regional GIS system. The granites module will be approached in three steps:

Step 1 will identify individual plutons and tag each with the relevant 'number' from the Australian Register of Stratigraphic Names.

Step 2 will amalgamate the individual granite plutons in each province into suites. A suite is defined as a group of plutons of similar petrographic, chemical and isotopic composition which have similar source-rock composition (Chappell 1984). A suite is the most useful unit in metallogenic analysis, for if one pluton is shown to have a relationship to mineralisation, then all members must be considered to have potential.

Each Proterozoic granite suite will be tagged within an EXCEL spreadsheet (as developed by Jagodzinski *et al*. 1993a, b, c; Wyborn *et al*. 1994b) according to the following field and geochemical criteria:

A) Field Criteria

- The relative size of the suite.
- Presence/absence of pegmatite, aplite, greisen, miarolitic cavities.
- Is it a restite or non-restite suite?
- Is the suite magnetite-bearing (oxidised and usually metaluminous i.e., I-type and Au/Cu bearing) or is it ilmenite only-bearing (reduced and usually peraluminous, i.e., S-type and Sn bearing)?
- Is fluorite abundant throughout?
- Is there a significant contact aureole?
- Is there alteration visible within the granite and/or country rock?
- Are there any significant breccia zones within the granite and/or country rock?
- Age (either relative or absolute; if absolute, by which method?)

B) Chemical Criteria

- At low SiO_2 contents does the suite have ASI > 1.1 or < 1.1 (i.e., metaluminous or peraluminous)?
- Minimum SiO_2.
- Maximum SiO_2.
- Average K_2O content of the pluton.
- Average Th content of the pluton.
- Average U content of the pluton.
- Does P_2O_5 increase/decrease with increasing SiO_2?
- Does Y increase/decrease with increasing SiO_2?
- Does Rb increase/decrease with increasing SiO_2?
- Does U increase/decrease with increasing SiO_2?
- Does Th increase/decrease with increasing SiO_2?

- Does K/Rb increase/decrease with increasing SiO_2?
- What are the Ba and Sr contents at low SiO_2?
- Granite type (I, A or S) (Chappell & White 1974; White & Chappell 1983).
- Granite subtype (I-granodiorite, I-tonalite, M-type) (Chappell & Stephens 1988).

Step 3: Each suite will then be tagged according to similarities to the following major Australian Proterozoic granite suites already identified (Wyborn 1992; Wyborn *et al*. 1992; Wyborn 1994b, c):

- Cullen type - metaluminous, moderate-temperature, fractionated, Au-dominant.
- Olympic Dam type - metaluminous, very high-temperature, fractionated, Au + Cu (± U).
- Kalkadoon type - metaluminous, restite-dominated, unmineralised.
- Sybella type - metaluminous, high F, limited SiO_2 range, unmineralised.
- Argylla type - metaluminous, A-type, unmineralised.
- Maramungee type - trondhjemitic, high Na, association with mineralisation uncertain.
- Allia Creek type - peraluminous, fractionated, Sn-bearing.
- Big Toby type - peraluminous, restite-dominated, unmineralised.

In addition, searches will be made to identify metallogenically important granite types of other ages which have not as yet been identified in the Australian Proterozoic including:

- High temperature silicic andesitic suites associated with some porphyry Cu, Mo (White *et al*., 1991; Wyborn, 1993).
- Shoshonite suites such as those associated with Au in the Ordovician of the Lachlan Fold Belt and Cainozoic volcanic rocks at Lihir, Papua New Guinea (Wyborn, D., 1988).
- Continental margin granites (e.g., Peninsular Ranges Batholith, plus mineralised suites if data available).

From the average Th, U and K contents, an additional classification will also be applied to enable sponsors to identify high heat-producing granites, believed by some (e.g., Solomon and Heinrich 1992) to be an essential ingredient for the generation of giant sediment-hosted Pb-Zn deposits.

The **COUNTRY ROCK MODULE** will focus on the mineralogy of the host rock, as this has been shown to exert an important control on the type of commodity precipitated. In the Proterozoic, empirical compilations have shown that carbonate-rich, but carbon-poor rocks, commonly host Pb and Zn mineralisation; rarely, if ever, do they host Au or Cu mineralisation. Au mineralisation is predominantly hosted by reduced (carbon- or Fe^{2+}-rich) rocks, including banded iron formations, mafic volcanics, magnetite-bearing felsic volcanics, earlier more mafic magnetite-bearing phases of the granite itself (rare), carbon-bearing rocks, sulphide-bearing shales and magnetite-bearing skarns which replace silicate, but not carbonate rocks. The cause of this preference for a particular host rock is possibly related to vapour/brine separation, with Au and Cu carried in a S-enriched vapour phase which precipitates in reductant-bearing units; Pb and Zn are carried in a Cl-enriched brine, which preferentially interacts with carbonate hosts (Heinrich *et al*. 1992a,b, 1993).

Based on information from sources such as the Australian Register of Stratigraphic Names, geological map commentaries and explanatory notes, this module will compile a second EXCEL spread sheet which will note the relative abundance of carbonate, graphite, sulphide and magnetite in units within 5 km of the granite outcrops and where easily recognisable, their subsurface boundaries from regional geophysical data sets. In this module, each sedimentary unit will also be tagged according to its age (where available), and for sediments, the environment of deposition will be broadly classified into subaerial, shallow and deep water. This latter attribute will enable sponsors to locate areas of coincident fractionated magmas and deep water sedimentation, believed to be an important combination for localising VMS deposits (e.g., Cas 1992; Large *et al*. 1994).

The **MINERAL DEPOSIT MODULE** will briefly assess mineral deposits within 5 km of granites of interest. The module will access digital mineral deposit data bases such as MINLOC (owned by AGSO) and the more detailed, recently released OZMIN (developed by AGSO).

The **SYNTHESIS MODULE** will capitalise on recent techniques developed by AGSO in data integration and analysis of geological and metallogenic data within GIS (e.g., Jagodzinski *et al*. 1993a, b, c; Wyborn *et al*. 1994b, Champion and Mackenzie 1994). This module will synthesise all of the available data from the other three modules into a GIS package, a hard copy atlas and a synthesis report. The GIS will be based on the new 1:2 500 000 scale Geological Map of Australia as it progressively becomes available. The base will be prepared at this scale, as it is the only available digital geological map covering the continent. However, the attribute tables will be developed within EXCEL, and each unit will be tagged with the code number from the Australian Register of Stratigraphic Names. This will give a unique index number to every geological unit on a continent-wide scale, and will enable clients to merge the EXCEL spread sheet data with any digital geological map of any scale which has the stratigraphic units also coded with the same number.

SOFTWARE

- The GIS will utilise ARC/INFO and ARCVIEW2.
- Databases will be developed in MS EXCEL version 5 spread sheets on IBM-compatible PC's.
- Geochemical data will use GDA, AGSO's data processing package.
- All reports will be written in Microsoft WORD 6 for WINDOWS on IBM-compatible PC's.

OUTPUTS

The results will be presented as:

- an integrated GIS package and hard copy atlas based on the digital 1:2 500 000 geological map of Australia.
- EXCEL spread sheets classifying the granites and their host rocks.
- a synthesis report summarising the dominant features of the granites of each province and their metallogenic potential.

The digital GIS data will be available for either workstation or PC versions of ARC/INFO and ARCVIEW2. On request the GIS will be converted into MAP/INFO or DXF formats, although potential sponsors are warned that in the translation, some functionality may be lost.

Note: Because most of the raw data to be utilised in this project are sold as part of separate commercial data packages, the project will provide only syntheses of data. To obtain raw data, sponsors will be referred to the survey from which the data originated, unless the data are available by prior arrangement through AGSO.

REFERENCES

Cas, R.F., 1992. Submarine Volcanism: eruption styles, products, and relevance to understanding the host rock successions to volcanic-hosted massive sulphide deposits. *Economic Geology,* 87, 511-541.

Champion, D. C. and Mackenzie, D. E., 1994. Igneous rocks of North Queensland, *Australian Geological Survey Organisation, Metallogenic Atlas Series,* 2, 46 pp.

Chappell, B.W., 1984. Source rocks of I- and S-type granites in the Lachlan Fold Belt, southeastern Australia. *Philosophical Transactions of the Royal Society of London,* A310, 693-707.

Chappell, B.W. and Stephens, W.E., 1988. Origin of infracrustal (I- type) granite magmas. *Transactions of the Royal Society of Edinburgh: Earth Sciences,* 79, 71-86.

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

Griffin, T.J., Sheppard, S. and Tyler, I.M., 1994. Geochemical constraints on the tectonic evolution of the early Proterozoic orogens in the Kimberley Region of Western Australia. *Geological Society of Australia, Abstracts,* 37, 151-152.

Jagodzinski, E.A., Wyborn, L.A.I. and Gallagher, R., 1993a. Mount Isa Metallogenic Atlas, Volume 1, Geology. *Australian Geological Survey Organisation, Metallogenic Atlas Series*, 1, 21 pp.

Jagodzinski, E.A., Wyborn, L.A.I. and Gallagher, R., 1993b. Mount Isa Metallogenic Atlas, Volume 2, Geochemistry. *Australian Geological Survey Organisation, Metallogenic Atlas Series*, 1, 49 pp.

Jagodzinski, E.A., Wyborn, L.A.I., Gallagher, R., Whitaker, A., Morse, M.P., Tarlowski, C. and Simonis, F., 1993c. Mount Isa Metallogenic Atlas, Volume 3, Geophysics. *Australian Geological Survey Organisation, Metallogenic Atlas Series,* 1, 10 pp.

Heinrich, C.A., Mernagh, T.P. and Ryan, C.G., 1992a. Metal segregation by magmatic gases — first results from new fluid inclusion technique. *BMR Research Newsletter,* 16 , 12-13.

Heinrich, C.A., Ryan, C.G., Mernagh, T.P. and Eadington, P.J., 1992b. Segregation of pore metals between magmatic brine and vapor: a fluid inclusion study using PIXE microanalysis. *Economic Geology,* 87, 1566-1583.

Heinrich, C.A., Ryan, C.G. and Mernagh, T.P., 1993. Ore metals in magmatic brine and vapour: new evidence from PIXE microanalysis of fluid inclusions. *Geological Society of Australia, Abstracts,* 34, 28-29.

Large, R.R., Doyle, M., Cooke, D. and Raymond, O., 1994. Evaluation of the role of Cambrian granites in the genesis of world-class volcanogenic-hosted massive sulphide deposits in Tasmania. *Geological Society of Australia, Abstracts,* 37, 236-237.

Solomon, M. and Heinrich, C.A., 1992. Are heat-producing granites essential to the origin of giant lead-zinc deposits at Mount Isa and McArthur River, Australia? *Exploration and Mining Geology,* 1, 85-91.

Stuart-Smith, P.G., Needham, R.S., Page, R.W. and Wyborn, L.A.I., 1993. The geology and mineral deposits of the Cullen Mineral Field. *Australian Geological Survey Organisation, Bulletin,* 229.

White, A.J.R. and Chappell, B.W., 1983. Granitoid types and their distribution in the Lachlan Fold Belt, south east Australia. *In* Roddick, J.A. (*editor*), *Circum-Pacific Plutonic Terranes. Geological Society of America, Memoir,* 159, 21-34.

White, A.J.R., Wyborn, D., and Chappell, B.W., 1991. A granite classification for the economic geologist. *Geological Society of Australia, Abstracts,* 29, 57.

Wyborn, D., 1988. Ordovician magmatism, gold mineralisation, and an integrated tectonic model for the Ordovician and Silurian history of the Lachlan Fold Belt in NSW. *BMR Research Newsletter,* 8, 13-14.

Wyborn, D., 1993. A granite classification for the economic geologist. Workshop on Magmatismo Granitico e Mineralisaes Associadas. *Academia Brasileira de Cincias, Rio de Janerio, September 1993, Abstracts,* 55-57.

Wyborn, L.A.I., 1992. The Williams and Naraku Batholiths, Mount Isa Inlier: an analogue of the Olympic Dam Granites? *BMR Research Newsletter,* 16, 13-16.

Wyborn, L.A.I., 1994a. Granites in the Proterozoic. *Centre for Ore Deposit and Exploration Studies, University of Tasmania, Master of Economic Geology Course notes on Ore Deposit Studies and Exploration Models, July 1994, Volume* 2, 93-130.

Wyborn, L.A.I., 1994b. Exploration criteria to determine which Australian Proterozoic granites may be associated with gold + base metal mineralisation. *Geological Society of Australia, Abstracts,* 37, 471-472.

Wyborn, L.A.I., 1994c. Granites of the Mount Isa Region - which ones have potential and for what? *Australian Mineral Foundation, Mount Isa Inlier One Day Seminar,* 30-35.

Wyborn, L.A.I., in prep. Factors controlling mineralisation in Australian Proterozoic granites and resultant exploration criteria. *(Invited paper for the Australian Journal of Earth Sciences).*

Wyborn, L.A.I. and Heinrich, C.A., 1993. The relationship between late-tectonic felsic intrusives and Cu-Au mineralisation in the Eastern Fold Belt, Mount Isa Inlier. *Australian Institute of Geoscientists, Bulletin,* 13, 27-30.

Wyborn, L.A.I., Heinrich, C.A. and Jaques, A.L., 1994a. Australian Proterozoic Mineral Systems: essential ingredients and mappable criteria. *Australasian Institute of Mining and Metallurgy, Publication Series,* 5/94, 109-115.

Wyborn, L.A.I., Gallagher, R., Jaques, A.L., Jagodzinski, E.A., Thost, D. and Ahmad, M., 1994b. Developing metallogenic Geographic Information Systems: examples from Mount Isa, Kakadu, and Pine Creek. *The Australasian Institute of Mining and Metallurgy, Publication Series,* 5/94, 129-133.

Wyborn, L.A.I., Wyborn, D., Warren, R.G. and Drummond, B.J., 1992. Proterozoic granite types in Australia: implications for lower crust composition, structure and evolution. *Transactions of the Royal Society of Edinburgh, Earth Sciences,* 83, 201-209.

18 METHODS

Overview

The main premise on which this project is based is that the combination of specific granite types and distinctive host rocks tends to be associated with certain types of Au, Cu, Zn, Pb, Sn and W mineralisation. Rarely is Proterozoic mineralisation hosted by granites themselves, and for the most part it is hosted in the country rock, often 3 km or more from the nearest known granite. There is an apparent host rock control on the deposition of metals; this can be both compositional and also controlled by the competence of the host rocks. This compostional host rock control has been documented by Stuart-Smith *et al.* (1993) for the Pine Creek Inlier and noted in the eastern Mount Isa Inlier by Wyborn and Heinrich (1993).

This project collated data on the Proterozoic granites and their comagmatic volcanics, the mineralogical composition of the rocks that they intrude, and briefly assessed the style and type of mineralisation present within 5 km of an outcrop of granite. All data collated in the reports are built into the accompanying GIS, and essentially each item listed in the report is converted into a searchable item within the GIS.

This project has aimed to provide the data and interpretations to show the following:

1) Which Proterozoic granites have metallogenic potential.

2) What commodities they are likely to be associated with, and

3) Where the better host rocks are located that are likely to host potential mineralisation.

The 'Audit Trail' approach

The data have been systematically collated using the 'Information Life Cycle Approach' (Williamson *et al.*1996) as outlined in the Data ⇒ Information Cycle (Fig. 17.1). The main data bases accessed were ROCKCHEM (AGSO's whole-rock geochemical data base), MINLOC (AGSO's data base of the locations and commodities of Australian mineral deposits, prospects and occurrences) and OZCHRON (AGSO's geochronological data base). All State and Territory Geological Surveys contributed relevant available geochemical and geochronological data.

Much of the descriptive data came from reports, map commentaries, data records and bulletins. As a rule we often found the older literature the most suitable as the descriptions were more relevant and often more factual, rather than interpretative. All State and Territory Geological Surveys contributed available data, often in the form of very early draft manuscripts.

In the data reports, all features considered significant in differentiating the metallogenically interesting suites are compiled for each individual pluton, and then synthesised for the whole suite at the start of each section heading. The data from each suite are then synthesised at the start of the relevant chapter. The important data from each suite are then synthesised into an overall province summary. This approach essentially leaves an 'audit trail,' so that any part of the synthesis can be traced back to the raw information.

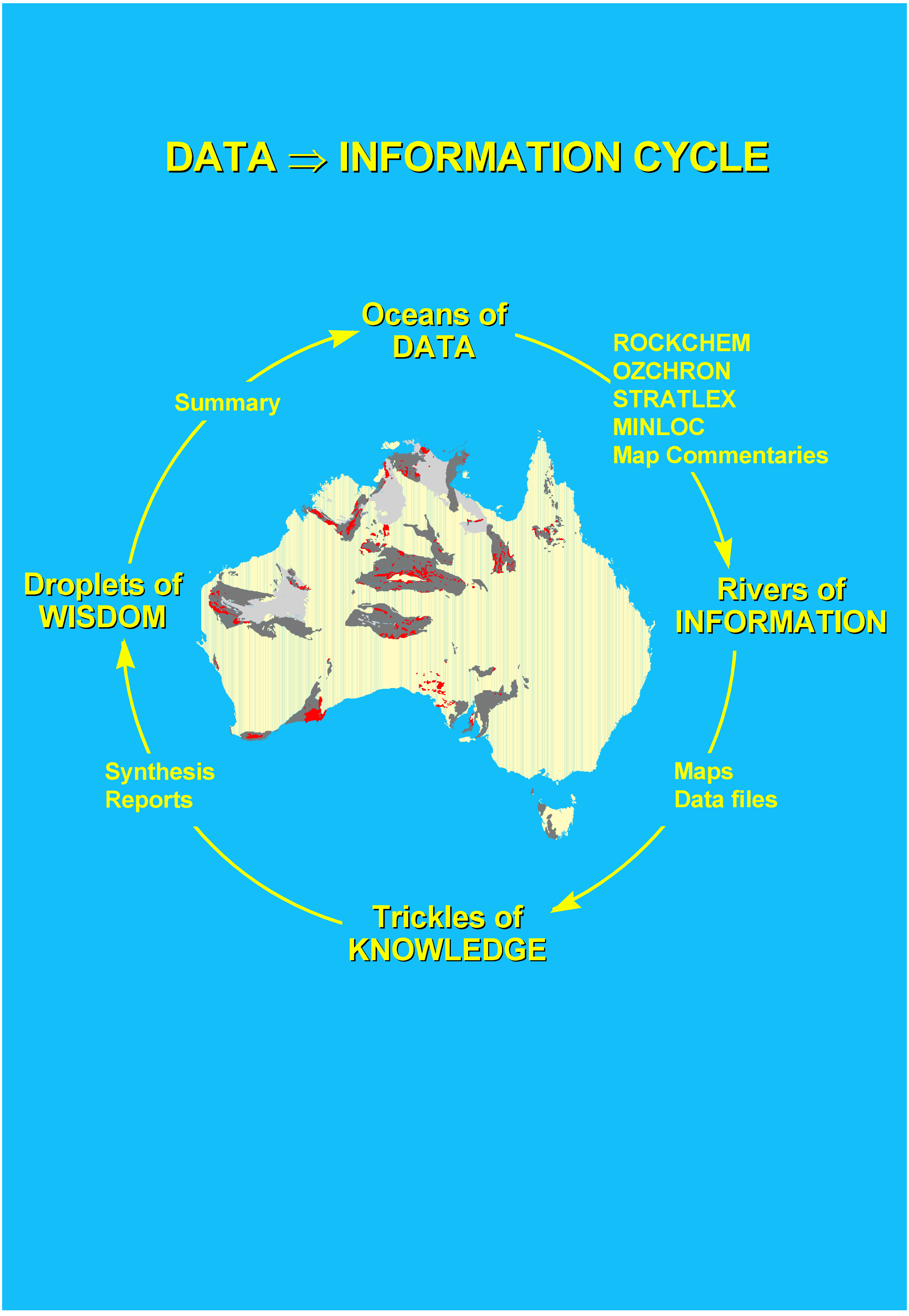
The Data Report Format

The following gives a detailed description of the 'questions' asked in each section and the reasons why these questions can give insights into the mineral potential of any Proterozoic granite. The numbering is the same as for all of the data reports.

18.1 Timing

This is the average or more common age of the suite as a whole.

Figure 18.1


DATA ⇒ INFORMATION CYCLE
Oceans of DATA
ROCKCHEM
OZCHRON
STRATLEX
MINLOC
Map Commentaries
Rivers of INFORMATION
Maps
Data files
Trickles of KNOWLEDGE
Synthesis Reports
Droplets of WISDOM
Summary

18.2 Individual Ages

Primary Ages: This section lists all of the known absolute ages, e.g.:

1. Unit — 1745 ± 9 Ma, U-Pb

Sources: This lists the source of all ages listed in the document.

18.3 Regional Setting

This section describes the regional setting of the associated province when the felsic magma was derived. Is the granite suite one of several that were emplaced during a major tectonic event? Was it extensional? Was the granite generation coeval with a major metamorphic event? Were the volcanics part of a major sedimentary sequence, were they subaerial? If they were subaerial were they coeval with adjacent sedimentary basins?

18.4 Summary

This section describes the summary of the main magmatic features of the suite, and notes any potential host rocks.

18.5 Potential

This section summarises the style and type of mineralisation expected. For each commodity type we have used a four-fold qualitative subdivision: none, low, moderate and high. These categories are defined as: none - none of the criteria considered important for ore formation are met (*e.g.*, wrong granite type, and unreactive hosts, and no known mineralisation); low - few of the criteria are met (*e.g.*, granite type is favourable, but host rocks are not reactive and no mineralisation is known nearby, or other combinations); moderate - several but not all of the criteria are met (*e.g.*, favourable granites and host types, but little known mineralisation); and high - all conditions are met (*i.e.*, favourable granites and hosts, with several known deposits associated).

Cu:
Au:
Pb/Zn:
Sn:
Mo/W:
Confidence level:

Confidence Level

The confidence level is a rating given in the summary table of the granite grouping in the introductory chapter of each province. It has been added to give a quick view of how confident the authors are in their interpretations given the amount and quality of the data that were available to them. The numbers represent *Granite*, *Host* and *Mineralisation*, respectively. Three factors are quantified for *granite*: sufficiency of data for chemistry, mineral descriptions, and field descriptions. A well defined granite grouping has a value of 3 meaning that data on all 3 factors were available; 2 means one factor was not well defined (usually geochemistry); 1 means that (generally) only field data were available. Two factors are quantified for *host*: sufficiency of mineral descriptions, and field descriptions. A well defined host has a value of 2; whereas 1 usually means that only field data were available. One factor is quantified for *mineralisation*: amount of known mineralisation near the particular granite. A value of 3 means world-class ore deposits occur associated with the granite; 2 means mines (of any size except those in 3); 1 means prospects or occurrences; and zero means no known mineralisation.

The Williams Suite in Mount Isa is an example of a granite suite for which we are confident in providing a high potential rating for Au and Cu. The granite grouping is well defined (many geochemical samples, good field and mineralogical data), the host rocks are well defined (good field and mineralogical descriptions), and several large ore deposits are (*e.g.*, Ernest Henry, Osborne, Eloise and Starra). We give this suite a **Confidence Level** of **321**.

The granites in the Albany-Fraser province are a good example of groupings that we cannot be confident about rating, because of poor data. Only limited geochemical, geochronological, field and mineralogical data are available for the granites; only field descriptions are available for the host rocks; and there is no known mineralisation. We have assigned a low potential rating for all metals for these granites, but have given this rating a **Confidence Level** of **110**.

18.6 Descriptive Data

Field petrographic descriptions are considered vital, particularly if the criteria that are used to distinguish granite types are to be observed by the average company field geologist. The particular questions asked are as follows:

Location**:** A brief summary of where the suite is and the relevant 1:250 000 map sheets.

Dimensions and area: This section lists the length and breadth of the suite, and its area as calculated from the GIS. How large is the suite? Larger suites have the potential to concentrate more metals than smaller ones, larger ones could also generate a larger volume of hydrothermal fluid.

18.7 Intrusives

Component plutons: What are the names of the component plutons?

Form: What is the shape of the pluton(s)? Are they elliptical to circular plutons? Are they ‘amorphous masses’ - most of the restite-rich suites do not form regular pluton shapes. Are they elongate?

Metamorphism and Deformation: Has the suite been affected by later metamorphism and deformation? This may affect the whole-rock geochemistry.

Dominant intrusive rock types: What are the dominant intrusive rock types (e.g., tonalite, porphyritic granite, etc.)?

Colour: What is the colour? This is important, as most highly oxidised suites are pink to red; reduced granites are grey. The pink colour is related to hematite substitution in the lattice of K-feldspar. This was often the hardest attribute to get as most modern reports do not describe colour.

Veins, Pegmatites, Aplites, Greisens: Are there veins, pegmatites, aplites and greisens? (These can indicate evolution of a late magmatic phase.) Are there miarolitic cavities or vugs which could indicate shallow levels of emplacement?

Distinctive mineralogical characteristics: Are there any distinctive mineralogical characteristics such as the presence of hornblende, cordierite and garnet, is fluorite ubiquitous, are there rapakivi textures?

Breccias: Are there breccias within the granite? This is common in the Williams type at Mount Isa.

Alteration in the granite: Is there alteration within the granite? This is not often all that common, and is more prevalent in the Hiltaba types where it is expressed as K-feldspar-hematite-albite alteration. In contrast, in the Cullen type it is more subtle chemically and is expressed as ‘sericite’ alteration.

18.8 Extrusives

The next series of questions relates to comagmatic extrusives. These are often the best method to determine if the granite is a restite-rich and non-fractionating suite. Phenocryst-rich lavas and ignimbrites are more common with the restite-rich suites; crystal-poor flow-banded rhyolites are more common in the non-restite suites. Volcanics in close proximity to the intrusives can also indicate shallow levels of emplacement.

18.9 Country Rock

Contact metamorphism: The width of the contact aureole can sometimes indicate whether a suite has been emplaced in thermal disequilibrium with its host. Although the development of a contact aureole can be depth-dependent, a wide contact aureole can indicate a large temperature difference between the granite and the host rocks and involve greater meteoric circulation.

Reaction with country rock: Is the country rock chemically altered, is there tourmalinisation or other indicators of country rock interaction with the granite?

Units the granite intrudes: Which stratigraphic units does the suite intrude?

Dominant rock types: What are the dominant country rock types?

Potential hosts: Within the country rocks are there any reactive rock types present *e.g.*, carbonate-rich rocks, banded iron formations, mafic volcanics, magnetite-bearing felsic volcanics, carbon-bearing rocks, sulphide-bearing shales and magentite-bearing skarns? What is the connate fluid likely to have consisted of?

18.10 Mineralisation

If present, what are the commodities, what are they hosted in? What type of minerals are present?

18.11 Geochemical Data

For each set of geochemical data we ask the following questions before starting to process the data. ***Note: all plots throughout all data reports are drawn on an identical scale, unless otherwise stated. This enables a broad relative comparison to be made between all suites on a national scale.***

Data source: Who collected the data, and was the collection part of a specialist or regional program?

Data quality: Which laboratory analysed the samples? Were the samples all analysed in one laboratory? What is the analytical quality?

Are the data representative? Are the data biased towards any particular SiO_2 values? For example, samples collected for Rb-Sr data tend to be biased towards felsic end members, whilst samples collected for tectonic studies tend to be biased towards realtively mafic end members.

Are the data adequate? This is a summary question which gives an overall assessment as to whether the data are good enough for an effective evaluation of the metallogenic potential.

SiO_2 range: A simple SiO_2 histogram is drawn for each suite. The questions asked are: is the suite relatively restricted in SiO_2 range or has it a wide range of SiO_2 values? Mineralisation was thought to be associated with suites which fractionate over a wide range of SiO_2 values so as to enhance the capacity to fractionate more important elements (White *et al.* 1991). However this was definitely not always the case, *e.g.*, granites at Telfer have a restricted silica range.

Alteration (Fig. #.2): This section assesses the degree of alteration of the suite and also consideres the possibility that the alteration may be related to a younger metallogenic event.

- ***SiO_2:*** Is there any evidence of desilicification or silicification: remembering that most unaltered granite systems cannot be more felsic than 77 wt.% SiO_2.
- ***K_2O/Na_2O:*** Alteration is common in some Proterozoic suites. The alteration can either be high in Na_2O (albitisation) or K_2O. K alteration associated with K-feldspar-hematite-barite tends to have higher K_2O values (8-14 wt.%) than that associated with sericite (5-7 wt.% K_2O). Sericite alteration is characterised by low Na_2O values.
- ***Th/U:*** Most granites have a Th/U ratio of 2 to 6. Values outside this may indicate alteration, metamorphism or weathering.
- ***$Fe_2O_3/(FeO+Fe_2O_3)$:*** Alteration in Proterozoic granites can involve extremes of oxidation. Granites which have either no FeO or no Fe_2O_3 must be altered. High Fe_2O_3 contents can also indicate weathering.

Fractionation Plots (Fig. #.3): Granites which have undergone feldspar fractionation have several key changes in element concentrations with increasing SiO_2. This section seeks to determine what the style of fractionation was with increasing SiO_2. Please note that these fractionation plots distinguish fractionation only in highly silicic end members (i.e., usually >70 wt.% SiO_2) and are not suitable for mafic or intermediate suites.

- ***Rb:*** Fractionated I or S-type granites have exponentially increasing values for this element with increasing SiO_2. In restite granites, the increase is more linear.
- ***U:*** Fractionated I or S-type granites have exponentially increasing values for this element with increasing SiO_2. In restite granites, the increase is more linear.
- ***Y:*** Relatively reduced fractionated I-types can have exponentially increasing values for this element with increasing SiO_2.
- ***P_2O_5:*** Fractionated S-types can have exponentially increasing values for this element with increasing SiO_2, and I-types have decreasing values with SiO_2.
- ***Th:*** Th and Th/U will decrease in fractionated S-types with increasing SiO_2.

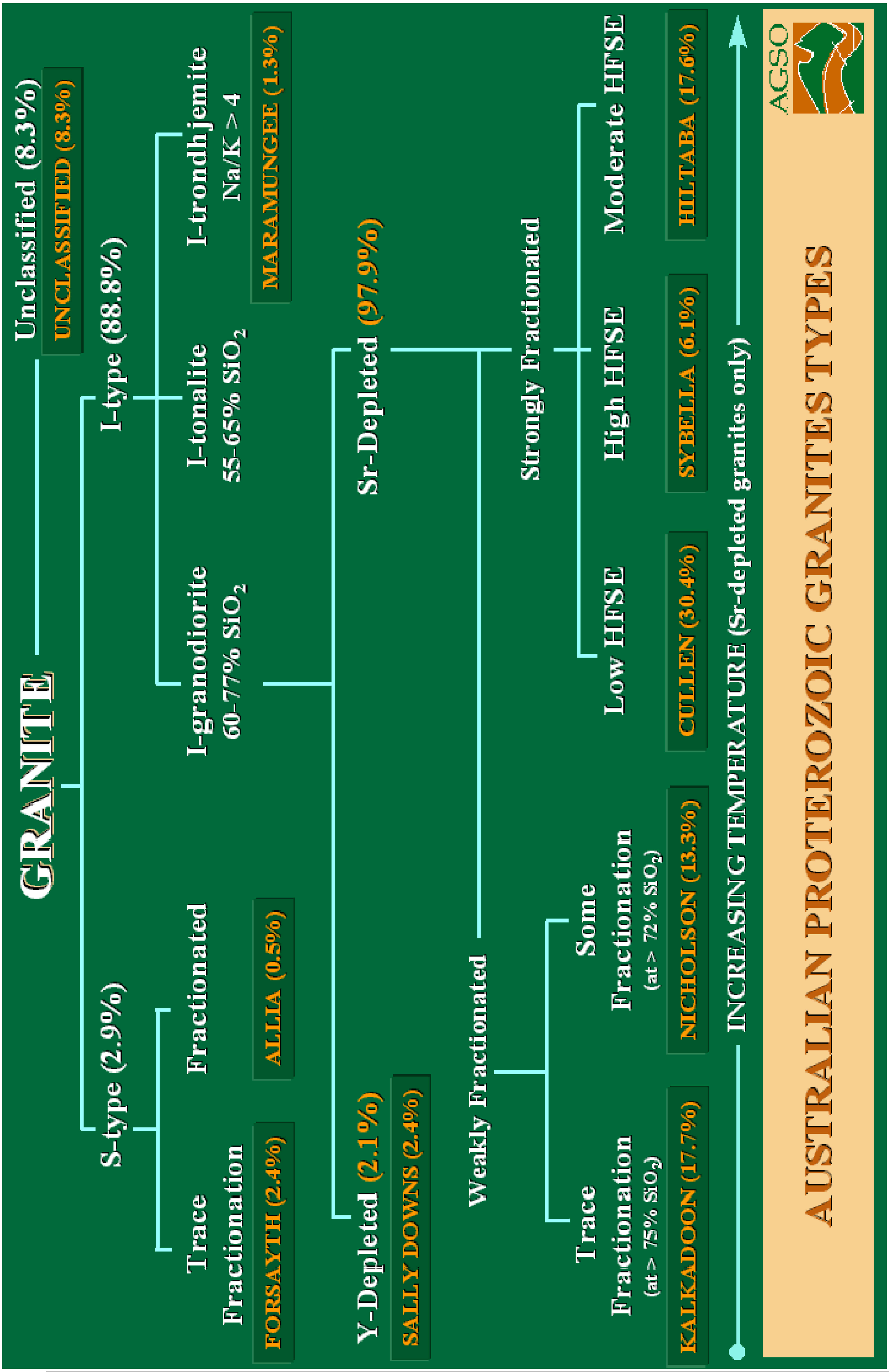

GRANITE
S-type (2.9%)
I-type (88.8%)
Unclassified (8.3%)
UNCLASSIFIED (8.3%)
Trace Fractionation
FORSAYTH (2.4%)
Fractionated
ALLIA (0.5%)
I-granodiorite
60-77% SiO2
I-tonalite
55-65% SiO2
I-trondhjemite
Na/K > 4
MARAMUNGEE (1.3%)
Y-Depleted (2.1%)
SALLY DOWNS (2.4%)
Sr-Depleted (97.9%)
Weakly Fractionated
Strongly Fractionated
Trace Fractionation
(at > 75% SiO2)
Some Fractionation
(at > 72% SiO2)
Low HFSE
High HFSE
Moderate HFSE
KALKADOON (17.7%)
NICHOLSON (13.3%)
CULLEN (30.4%)
SYBELLA (6.1%)
HILTABA (17.6%)
INCREASING TEMPERATURE (Sr-depleted granites only)
AUSTRALIAN PROTEROZOIC GRANITES TYPES
AGSO

Figure 18.2

- ***K/Rb:*** Fractionatied I or S-type granites have decreasing values for this element with increasing SiO_2. In restite granites, the trend is usually flat.
- ***Rb-Ba-Sr:*** Using the fields in the triangular Rb-Ba-Sr diagram of El Bouseily and El Sokkary (1975) can also help to distinguish fractionated suites.
- ***Sr:*** Usually decreases with increasing SiO_2.
- ***Rb/Sr:*** Fractionated I or S-type granites have exponentially increasing values for this element with increasing SiO_2. This ratio is more sensitive than the K/Rb ratio.
- ***Ba:*** In a fractionated suite, Ba initially increases and then decreases with increasing SiO_2.
- ***F:*** F increases with increasing SiO_2 in most fractionated granites. However, in some granites although F still shows an increase with increasing SiO_2, F is high throughout all SiO_2 values relative to other members. Most of these high-F granites are unmineralised with respect to Au and Cu, although some have Mo and W with them. Values of 0.07 to 1.7 wt % are considered typical of Palaeozoic A-type granites (Eby 1990). Most analyses did not have any F values. The presence of rapakivi textures (albite rims around K-feldspars) can also indicate high F. High F interrupts the ability of the melt to partition off a Cl-rich phase; if this happens then the suite is unlikely to concentrate base metals.

Metals (Fig. #.4):

- ***Cu:*** This is assessed qualitatively for the whole data set.
- ***Pb:*** As for Cu.
- ***Zn:*** As for Cu
- ***Sn:*** As for Cu.

High field strength elements (Fig. #.5): These elements tend to be higher in the A-type rocks.

- ***Zr:*** This is assessed qualitatively for the whole data set. In a convective fractionation suite Zr, can initially increase and then decrease with increasing SiO_2.
- ***Nb:*** As above.
- ***Ce:*** As above.

Classification (Fig. #.6):

- ***The CaO/Na$_2$O/K$_2$O plot of White, quoted in Sheraton and Simons (1992):*** This plot enables a relative assessment to be made of the rock types present. Unfortunately as most Proterozoic granites have high K_2O contents relative to their Palaeozoic counterparts, the estimates are not always accurate. For example true tonalites can plot as granodiorites because the amount of K_2O in K-feldspar is over estimated when much of it is in biotite or hornblende.
- ***Zr/Y vs Sr/Sr*:*** This gives a measure of the amount of Sr depletion in a 'spidergram plot'. Most of the samples from island arcs or continental margins plot above the value of 1 for Sr/Sr*, whilst most Proterozoic rocks plot below 1 as they are inherently Sr-depleted.
- ***Spidergram:*** These are used as outlined by Wyborn *et al.* (1992).
- ***Oxidation plot of Champion and Heinemann (1994):*** This plot gives an indication of the initial and final oxidation state of the granite. Most granite suites related to Cu-Au mineralisation are more oxidised than the Au-dominated suites.
- ***ASI:*** Values above 1.1 are considered S-type, values below 1.1 are I-type.
- ***A-type plot of Eby (1990):*** At the end of the project most samples were found to plot in the A-type field of Eby (1990).

Granite type (Chappell and White, 1974; Chappell and Stephens, 1988): Granite type (I, A or S; Chappell and White, 1974; White and Chappell, 1983). Granite subtype (I-granodiorite, I-tonalite, M-type; Chappell and Stephens, 1988).

Australian Proterozoic granite type: Each suite was tagged according to similarities to the following major Australian Proterozoic granite suites already identified (Wyborn, 1992; Wyborn *et al.* 1992; Wyborn, 1994a, b). Note that these have been revised from the original project proposal listings. The types are shown in Figure 17.2.

I-types:

- ***Kalkadoon type:*** I-(granodiorite) type, restite-dominated, unmineralised.
- ***Nicholson type:*** I-(granodiorite) type, restite-dominated for much of the crystallisation history with some fractionation taking place late in the history due to restite separation.

They are usually weakly mineralised with small vein-style Sn and W deposits, with some Cu and Au.

- ***Cullen type:*** I-(granodiorite) type, moderate-temperature, fractionated, low HFSE, Au-dominant.
- ***Sybella type:*** I-(granodiorite) type, high temperature, fractionated, limited SiO_2 range, high HFSE, W-Mo mineralised.
- ***Hiltaba type:*** I-(granodiorite) type, very high-temperature, fractionated, moderate HFSE, Au + Cu (± U).
- ***Sally Downs type:*** I-(granodiorite) type, Y-depleted.
- ***Maramungee type:*** I-(trondhjemitic) type, high Na/K, association with mineralisation uncertain.

S-types:

- ***Allia type:*** S-type (peraluminous), fractionated, Sn associated.
- ***Forsayth type:*** S-type, trace fractionation only.

18.12 Geophysical Signature

Radiometrics (Fig. #.7): From the database, the average K_2O, Th and U values were calculated for all rock types in the Pine Creek and Mount Isa Inliers. Each pluton within a suite is then assessed as to whether it plots above or below this regional median. The method gives approximate relative values for K_2O, Th and U, and can help determine how the pluton and its fractionated or altered members will ‘appear’ in an RGB image. The method is fully explained in Wyborn (1992b).

Gravity: Each suite was assessed against the AGSO regional gravity data base to qualitatively assess its regional gravity signature.

Magnetics: Each suite was assessed against the AGSO regional magnetic data base to qualitatively assess its regional magnetic signature.

18.13 References

Champion, D.C. and Heinemann, M.A. 1994. Igneous rocks of northern Queensland: 1:500 000 map and GIS explanatory notes. *Bureau of Mineral Resources, Record* 1994/11, 82 pp.

Chappell, B.W. and Stephens, W.E. 1988. Origin of infracrustal (I- type) granite magmas. *Transactions of the Royal Society of Edinburgh: Earth Sciences*, 79, 71-86.

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

Eby, G.N. 1990. The A-type granitoids: a review of their occurrence and chemical characteristics and speculations on their petrogenesis, *Lithos*, 26, 115-134.

El Bouseily, A.M., and El Sokkary. 1975. The relationship between Rb, Ba and Sr in granitic rocks. *Chemical Geology*, 16, 207-216.

Sheraton, J.W. and Simons, L. 1992. Geochemical data analysis system (GDA) reference manual, *Bureau of Mineral Resources, Geology and Geophysics, Record* 1992/1.

Stuart-Smith, P.G., Needham, R.S., Page, R.W. and Wyborn, L.A.I. 1993. Geology and mineral deposits of the Cullen Mineral Field, Northern Territory, *Australian Geological Survey Organisation, Bulletin,*229, 145 pp.

White, A.J.R. and Chappell, B.W. 1983. Granitoid types and their distribution in the Lachlan Fold Belt, south east Australia. In Roddick, J.A. (editor), Circum-Pacific Plutonic Terranes. *Geological Society of America, Memoir,* 159, 21-34.

White, A.J.R., Wyborn, D. and Chappell, B.W. 1991. A granite classification for the economic geologist. *Geological Society of Australia, Abstracts,* 29, 57.

Williamson, P.E., Petrie, E. and Radke, S. 1996. Getting the most from Public Seismic field data - BRS Petroleum data management project. Preview, February 1996, 31-35.

Wyborn, L.A.I. 1992. The Williams and Naraku Batholiths, Mount Isa Inlier: an analogue of the Olympic Dam Granites? *Bureau of Minerals and Resources, Geology and Geophysics, Research Newsletter,* 16, 13-16.

Wyborn, L.A.I., 1994a. Exploration criteria to determine which Australian Proterozoic granites may be associated with gold ± base metal mineralisation, *Geological Society of Australia, Abstracts,* 37, 471-472.

Wyborn, L.A.I., 1994b. Granites of the Mount Isa Region - which ones have potential and for what? *Australian Mineral Foundation, Mount Isa Inlier One Day Seminar,* 30-35.

Wyborn, L.A.I., and Heinrich, C.A., 1993. The relationship between late-tectonic felsic intrusives and Cu-Au mineralisation in the Eastern Fold Belt, Mount Isa Inlier. *Australian Institute of Geoscientists, Bulletin,* 13, 27-30.

Wyborn, L.A.I., Wyborn, D., Warren, R.G., and Drummond, B.J., 1992. Proterozoic granite types in Australia: implications for lower crust composition, structure and evolution. *Transactions of the Royal Society of Edinburgh, Earth Sciences,* 83, 201-209.

18.14 Metadata for GIS tables

The GIS includes granite and sediment polygon layers, and the tables Granite.PAT, Sediment.PAT, Granite.LUT and Sediment.LUT contain the data for each of these. The two .PAT tables have the same structure, so are described together. A description of these tables follows:

Granite.LUT Metadata

Field	Field Description
Stratno	Stratigraphic index number
Map_symb	Map symbol unique within each province
Province	Name of geological province
Colcode	Colour code number for granite age
Unit_area	Calculated area of unit
Med_age	Median absolute age for the unit in Ma
Min_age	Minimum absolute age for the unit in Ma
Error	Error associated with min_age in Ma
Age_method	Description of the geochronological method used to determine age of the unit
Ig_type	Igenous geochemical type: I, S, A or M
Ig_subtype	Igneous (granite) subtype: granodiorite or tonalite
Classification	Australian Proterozoic granite type
Au	Potential for gold: High (H), Medium (M), Low (L) or None (N)
Cu	Potential for copper: High (H), Medium (M), Low (L) or None (N)
Pb_zn	Potential for lead and zinc: High (H), Medium (M), Low (L) or None (N)
Mo_w	Potential for molybdenum and tungsten: High (H), Medium (M), Low (L) or None (N)
Sn	Potential for tin: High (H), Medium (M), Low (L) or None (N)
Pegmatite	Abundance of pegmatites: High (H), Medium (M), Low (L) or None (N)
Aplite	Abundance of aplites: High (H), Medium (M), Low (L) or None (N)
Greisen	Abundance of greisens: High (H), Medium (M), Low (L) or None (N)
Vein	Abundance of veins: High (H), Medium (M), Low (L) or None (N)
Miarolite	Abundance of miarolites: High (H), Medium (M), Low (L) or None (N)
Restite	Restite-dominated (D) or not restite-dominated (N)
Fr_unit	Extent of fractionation: Strongly (S), Moderately (M), Weakly (W), Unfractionated (U)
Comagmatic	Presence (Y) or absence (N) of comagmatic volcanics
Aureole	Extent of aureole created by intrusion of granite: High (H), Medium (M), Low (L) or None (N)
Grn_alt	Extent of alteration in the granite itself: High (H), Medium (M), Low (L) or None (N)
Grn_brecc	Extent of brecciation within the granite: High (H), Medium (M), Low (L) or None (N)
Grn_def	Extent of deformation of the granite: High (H), Medium (M), Low (L) or None (N)
Sed_alt	Extent of alteration in the host sediments (caused by the granite): High (H), Medium (M), Low (L) or None (N)
Sed_brecc	Extent of brecciation within the host sediments: High (H), Medium (M), Low (L) or None (N)

Field	Field Description
Redox	Dominantly Strongly Reduced (HR), Reduced (R) Oxidised (O), Strongly Oxidised (HO)
Fluorite	Slope of plot (Figure 17.3)
Asi	Metaluminous trend or peraluminous trend (Figure 17.4)
Rb	Slope of plot (Figure 17.3)
U	Slope of plot (Figure 17.3)
Y	Slope of plot (Figure 17.3)
P2o5	Slope of plot (Figure 17.3)
Th	Slope of plot (Figure 17.3)
K/Rb	Slope of plot (Figure 17.3)
Rb/Sr	Slope of plot (Figure 17.3)
Ba	Slope of plot (Figure 17.3)
Min_SiO2	Minimum silica value of samples for **unit** (%)
Max_SiO2	Maximum silica value of samples for **unit** (%)
Av_K2O	Average K2O for **unit** (%)
Av_Th	Average Th for **unit** (ppm)
Av_U	Average U for **unit** (ppm)
K	Average K for **unit** (ppm)
HGU	Calculated Heat Generation Units [HGU] = 0.317r (0.718c_U + 0.913c_{Th} + .262c_K; where r is the density of the rock [g.cm^{-3}]; c_U and c_{Th} are in weight ppm; c_K is in weight per cent
Carb	Abundance of carbonate in host units: High (H), Medium (M), Low (L) or None (N)
Carbon	Abundance of carbon in host units: High (H), Medium (M), Low (L) or None (N)
Hem	Abundance of hematite in host units: High (H), Medium (M), Low (L) or None (N)
Mgt	Abundance of magnetite in host units: High (H), Medium (M), Low (L) or None (N)
Slph	Abundance of sulphides in host units: High (H), Medium (M), Low (L) or None (N)
Grn_volc	Granite (g) or Volcanic (v) unit

Sediment.LUT Metadata

Items of the PAT file	Comments
Label_no	Unique number for Unit (system use)
Stratno	Stratindex number
Map_symb	Map_symbol, used on 250K map
Map_names	A list of the map where the unit (group, subgroup) appears.
Med_age	Median absolute age for the unit in Ma
Min_age	Minimum absolute age for the unit in Ma
Error1	Error associated with min_age in Ma
Max_age	Maximum absolute age for the unit in Ma
Error2	Error associated with max_age in Ma
Age_method	Description of the geochronological method used to determine age of the unit
Env_of_dep	Environment at the time of unit (group, subgroup) deposition
Bif	Abundance of BIF in the unit: High (H), Medium (M), Low (L) or None (N)
Carbon	Abundance of carbonate in the unit: High (H), Medium (M), Low (L) or None (N)
Feld	Abundance of feldspar in the unit: High (H), Medium (M), Low (L) or None (N)
Gr	Abundance of graphite in the unit: High (H), Medium (M), Low (L) or None (N)
Hem	Abundance of hematite in the unit: High (H), Medium (M), Low (L) or None (N)
Mgt	Abundance of magnetite in the unit: High (H), Medium (M), Low (L) or None (N)
Serc_ms	Abundance of sericite-muscovite in the unit: High (H), Medium (M), Low (L) or None (N)
Slph	Abundance of sulphide in the unit: High (H), Medium (M), Low (L) or None (N)
Ag	Silver (Y or N)

Au	Gold	(Y or N)
Cor	Corundum	(Y or N)
Cu	Copper	(Y or N)
Ep	Epidote	(Y or N)
Fe	Iron	(Y or N)
Gs	Gemstones	(Y or N)
Mica	Mica	(Y or N)
Mn	Manganese	(Y or N)
Mo	Molybdenum	(Y or N)
Nb	Niobium	(Y or N)
Pb	Lead	(Y or N)
Sn	Tin	(Y or N)
Tlc	Talc	(Y or N)
U	Uranium	(Y or N)
W	Tungsten	(Y or N)
Zn	Zinc	(Y or N)
Remark	Remarks	
Info_from	References	

Sediment/Granite.PAT Metadata

Items	Description
Feature	Feature type
Ufi	Unique feature identifier
Map_symb	Map text identifying the lithology of the rook unit
Stratno	Stratigraphic index number
Unitname	The name of a stratigraphic unit including rank items that are part of a name
Supergroup/supersuite	An assemblage of related groups, or of formations and groups, having significant lithological features in common
Group/suite	The formal lithostratigraphic unit which includes two or more contiguous or associated formations with significant lithological features in common
Subgroup	A formally differentiated assemblage of formations within a group
Formation	A body of rock strata which is unified with respect to adjacent strata by consisting dominantly of a certain lithological type or combination of types or by possessing other unifying lithological features
Member	A lithostratigraphic unit of subordinate rank comprising some specially developed part of a formation
Unitage	A most precise and known geological time period during which the unit is formed
Agerank	A geological age rank
Rocktype	Dominant lithological grouping
Lith_desc	A description of the lithology of the rock unit

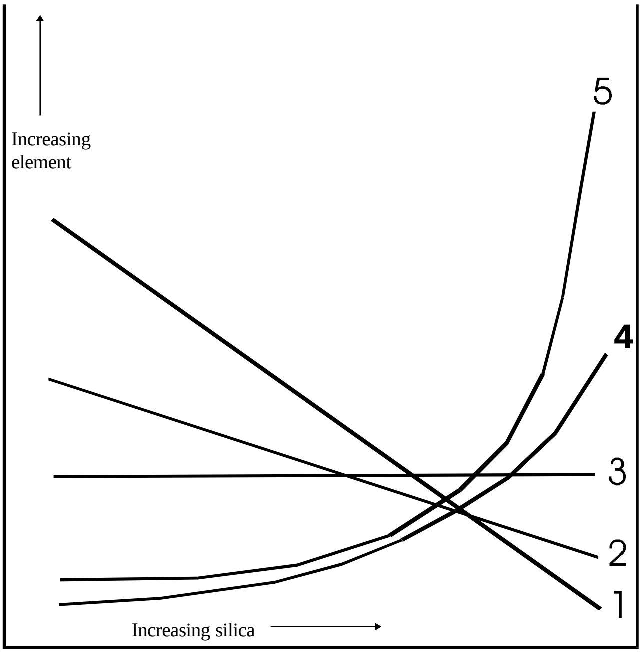


Figure 18.3: Explanation of trends for certain elements (see Granite.PAT metadata table above).

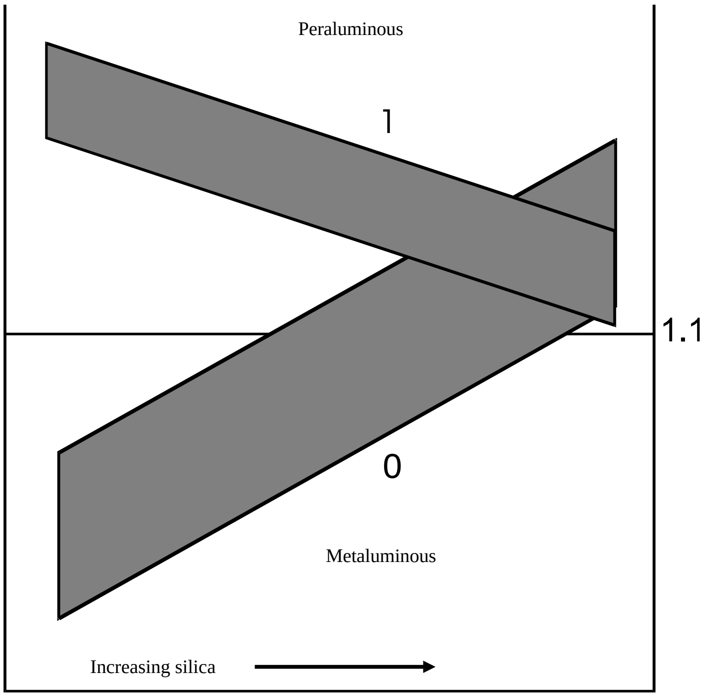


Figure 18.4: Explanation of coding for Aluminium Saturation Index field. A value of zero shows that the granite suite has a metaluminous to peraluminous trend with increasing SiO_2. A value of 1 shows that the granite suite has a peraluminous to less peraluminous trend with increasing SiO_2. Note that at high SiO_2 levels it is not possible to differentiate I-types from S-types using this criterion alone.

19 ABSTRACT 1 - Crustal Heating

EPISODIC CRUSTAL MAGMATISM IN THE PROTEROZOIC OF NORTHERN AUSTRALIA - A CONTINUUM CRUSTAL HEATING MODEL FOR MAGMA GENERATION.

Lesley A.I. Wyborn[1], Alison Ord[2], Bruce Hobbs[2] and Mart Idnurm[1]

[1]Australian Geological Survey Organisation, GPO Box 378, Canberra, ACT, 2601
[2]Australian Geodynamics Cooperative Research Centre, Nedlands, WA, 6009

Australian Geological Survey Organisation, Record 1997/44, 131-134.

Summary: A proposed conductive heating model of the crust provides an explanation of the enigma that in Proterozoic provinces of Australia the temperature of formation of the granitic magmas increases with time whilst that of the mafic magmas appears to decrease. In this model an initial heat pulse applied to the base of the crust in the early Proterozoic creates a thermal anomaly that can last for at least 80 million years, depending on the initial thickness and the thermal conductivity of the crust, the presence of an underplated layer, the thickness of sediment overburden and the time constant for heat input from the mantle. The migration and emplacement of magmas generated by this heating is controlled by intraplate rather than interplate events. Major mineralisation episodes associated with granites are predictable, and metamorphic deposits are expected to occur only late in the thermal history of a province.

The field and laboratory observations:

The Proterozoic shield of Australia can be subdivided into major magmatic provinces each of which occurs within major fold belts or orogenic domains. In each of these provinces magmatic events have been synchronous with basin formation (occurring either contemporaneously with the early rift phase of sedimentation or just prior to turbidite sedimentation), or they may immediately follow a major compressional event. On the basis of outcrop characteristics, thin section petrography, SiO_2 distribution and multi-element, primordial-mantle-normalised trace-element patterns, Wyborn *et al.* (1992) divided the Australian Proterozoic granites into 5 main groups. Group 1, which is usually the oldest, comprises restite-rich I-(granodioritic) types that are Sr-depleted and Y-undepleted. Typical examples are the Tennant Creek Granite of the Tennant Creek Block, the Kalkadoon Granodiorite of the Mount Isa Inlier, and the granites of the King Leopold Inlier, all of which are in the age range of between 1870 to 1850 Ma. Group 2 comprises I-(granodioritic) types which, like Group 1, are Sr-depleted and Y-undepleted but, unlike the latter, show strong evidence of magmatic fractionation: they generally have low concentrations of Ca, Sr, and the incompatible elements. Examples include the granites of The Granites-Tanami region and the Cullen Suite of the Pine Creek Inlier. Group 2 granite ages are mostly around 1850-1800 Ma. Group 3 contains I-(granodioritic) types that are Sr-depleted, Y-undepleted and enriched in incompatible elements. Granites of this group are widely referred to as 'anorogenic'. Wyborn *et al.* (1992) divided Group 3 into three subgroups. Subgroup 3_1 has very high levels of Zr, Nb and Y and includes felsic volanics of the Argylla Formation of Mount Isa and the Myola Volcanics of the Gawler Craton, both emplaced at around 1800-1780 Ma. Subgroup 3_2 is enriched in F, but the levels of incompatible elements such as Y, Zr, and Nb vary from high in some members to low in others. This group is characterised by a narrow SiO_2 range. Examples include the Sybella Granite of the Mount Isa Inlier and the Mount Swan and Ennugan Mountains Granites of the Arunta Block, which range in age from 1760 Ma to 1640 Ma. Subgroup 3_3 is not as enriched in F as Subgroup 3_2 and has a high $Fe_2O_3/(FeO + Fe_2O_3)$ and a wide SiO_2 range. Granites of the two other groups identified by Wyborn *et al.* (1992) are rare in the Proterozoic of Australia. Group 4 is the rarest of the groups and consists of I-(granodioritic) types, but is distinctly Sr-undepleted and Y-depleted - a signature which is most commonly found in granites associated with subduction in island arc or continental margin settings. Group 5 comprises the S-type granites. It is significant that Groups 1, 2 and 3 are all I-(granodioritic) type and are dominated by the Sr-depleted, Y-undepleted magmas.

What is the significance of the dominance of I-(granodioritic) types in the Australian Proterozoic?

As pointed out by Wyborn *et al.* (1987), igneous events in the Proterozoic are either predominantly mafic or felsic, or consist of both types: igneous events dominated by intermediate rocks do not exist. Histograms of the igneous rocks of each province are bimodal and contrast the more unimodal plots of subduction-related terrains in which the SiO_2 maxima are at either 52 wt % (island arcs) or ~65 wt % (continental margins). In a global review of I-type granites, Chappell and Stephens (1988) classified them into three types: (1) M-type derived from partial melting of subducted oceanic crust or of mantle material overlying oceanic slabs in island arc terrains; (2) I-(tonalitic) type, which is characteristic of the Cordillera of South America, and is probably derived from M-type rocks of basaltic to andesitic composition; and (3) I-(granodioritic) type which is believed to be formed from I-(tonalitic) type. Proterozoic granites are predominantly I-(granodioritic) type which, by inference, are derived in at least one if not two stages of melting. Further, in view of the silica distribution, the I-(granodioritic) types must be derived by melting of pre-existing crust, rather than from a mantle source. This is supported by Sm-Nd data which give Nd T_{DM} model source ages that are predominantly in the range 2.1 to 2.8 Ga. However, there are no significant amounts of I-(tonalitic) type material in the exposed rocks of this age in Australia, it has been postulated that the source(s) of the voluminous Proterozoic I-(granodioritic) types was underplated as a result of Archaean to earliest Proterozoic mantle events (Wyborn *et al*. 1992).

What is the significance of the Sr-depleted, Y-undepleted signature ?

The multi-element, primordial-mantle-normalised abundance diagrams contain two distinct patterns. These are either Sr-depleted and Y-undepleted or are Sr-undepleted and Y-depleted, implying that the source has equilibrated with plagioclase and garnet respectively. As I-(granodioritic) type granites have a multistage history then those that are Sr-depleted and Y-undepleted could never have equilibrated with garnet during the melting event(s). Given that Proterozoic crustal thicknesses range from 30 to 50 Kms (Drummond and Collins, 1986), the geothermal gradients must have been extremely high during these melting event(s), otherwise a garnet residue would be expected. Those I-(granodioritic) types with a Y-depleted signature must have equilibrated with garnet at some stage in their history. However, this signature may not necessarily relate to the contemporaneous melting event: it could well be the signature of the event that formed the source for that magma. The Y-depletion signature is often taken to imply that the magmatism occurred in a contemporaneous subduction zone. Alternatively, it could also signify a lower geothermal gradient or other differences in the conditions that operated at the time of forming the source(s).

What do the changes in composition with time tell us ?

Within each of these major Australian magmatic provinces the inferred crustal temperatures in the source regions of the granites increase with time. The restite-rich granites of Group 1 are inferred to form early by the break-down of quartz, albite, K-feldspar and water at the source: biotite and hornblende are restite within these melts and there are abundant xenoliths. Group 2 consists of the fractionated granites that are low in incompatible elements. These granites have rare restitic amphiboles and it is possible that in their source regions dehydration melting of biotite has occurred. The Subgroup 3_1 granites are probably formed by dehydration melting of F-enriched biotites, whilst Subgroups 3_2 and 3_3 may involve dehydration melting of amphibole. Temperatures of formation of some of the Group 3 granites have been inferred to be as high as 1000°C. The systematic progression through these groupings indicates that the source region temperature has increased progressively with time.

In contrast there appears to be a general decrease in the temperature of formation of the mafic igneous rocks with time, with the mafic igneous rocks from 2000 to 1870 Ma being dominated by high Mg-tholeiites (Woodward Dolerite of the Kimberleys and the Zamu Dolerite of the Pine Creek Inlier) whilst continental tholeiites dominate after 1870 Ma (Hart Dolerite of the Kimberleys, Oenpelli Dolerite of the Pine Creek Inlier and the Eastern Creek Volcanics of the Mount Isa Inlier). The exceptions are the ~1700-1650 Ma high Fe-tholeiites of Broken Hill and the Soldiers Cap Group of the Mount Isa Inlier.

What are the durations of the individual magmatic events ?

Australia-wide Palaeoproterozoic to Mesoproterozoic magmatic events have an episodic distribution with time. There is a period of quiescence from about 2400 Ma to 1880 Ma, followed by a series of major magmatic events from about 1880 Ma to 1500 Ma, which are in turn followed by a period of inactivity until about 1350 Ma. Although within any one province the period of magmatism is 70 Ma to 360 Ma, individual magmatic events are episodic. Each episode is of relatively short duration, generally less than 20 Ma and some episodes with tight age control are less than 10 Ma.

What role do tectonic processes play in triggering the emplacement of magmas ?

Magmatism is commonly regarded as being caused by major interplate events such as subduction of a cold oceanic crust in either a continental margin or island arc environment, or impingement of a mantle plume on the lower crust. Other cited causes are extension (either within a continent or at oceanic ridges) and continent/continent collision. A significant feature of the Australian Proterozoic is the continent-wide abundance of magmatic activity. If all of the magmatism occurred at interplate boundaries then the sheer number of magmatic events would require a large number of small plates. Alternatively many of the magmatic events may be the products of intraplate activity.

Intraplate events may be caused by changes in the direction or rate of plate motion (Loutit *et al.* 1994) rather than by plate collisions or within-plate extensional episodes. Intraplate events are regarded as the key in the evolution of sedimentary basin development and deformation (Green *et al*. 1992) , and have been held responsible for major episodes of mineralisation and fluid migration. For example, in northern Australia, a significant intraplate event at 1640 Ma has been suggested to have been responsible for major movements of basinal brines which produced regionally extensive alteration and resulted in the formation of the world class HYC Pb-Zn deposit (Idnurm *et al., 1993; Loutit et al*. 1994). Although this event resulted in large-scale fluid migration, it did not produce regionally extensive angular unconformities. Similarly, intraplate events may provide the clue to the abundance of magmatic episodes in the Proterozoic of Australia.

Palaeomagnetic data have proved useful for determining the time of the major intraplate events. The apparent polar wander path (APWP) for northern Australia displays two modes of absolute plate motion. The first is characterised by periods of relative kinematic stability, represented by straight or nearly straight segments on the APWP. The second mode is characterised by instabilities that reflect geologically rapid changes in plate motion. This mode is represented on the APWP by hairpin bends and points of inflection. A detailed APWP is not available for Australia from ~2000 Ma to 1720 Ma, but the APWP from ~1720 Ma to ~1500 Ma indicates a series of relatively long periods when the direction of plate motion remained constant, separated by intervals of changes of direction. As noted by Loutit *et al*. (1994), most major magnetic overprints due to alteration, several major Pb-Zn deposits, and major magmatic events coincided in time with the hairpin bends and inflection points on the APWP for Northern Australia. For example, the HYC 1640 Ma event described above coincides with a major 180° bend in the APWP. Loutit *et al.*(1994) and Green *et al.* (1992) have argued that the periods of greatest migration of basinal fluids coincide in time with these bends. By the same argument, significant volumes of magmas could have also escaped to the surface at such times. Thus magmatic events may not necessarily result directly from major interplate interactions, but rather from intraplate tectonism. These intraplate events may reflect forces acting a large distance from the major plate boundaries. Palaeomagnetism provides insights also into the episodic nature of magmatism. It appears from the shape of the APWP that magma emplacement coincided in time with the hairpin bends or inflection points. However, the melting of the lower crust/mantle did not necessarily result from the same tectonic processes as the emplacement of the magmas, as that would not allow sufficient time to heat the crust to the melting temperature. Instead subsequent intraplate tectonism may have allowed already existing melts to migrate into the upper crust. Intraplate tectonism may have also enhanced melting by causing decompression.

What alternative causes are there for the melting events ?

Recent thermal modelling may provide new insights into the mechanism of generating melts within the lower crust. If heat is applied to the base of the crust as a result of a major mantle heating event, then the crust will heat up by conduction. The thermal time constants for crust 25, 30, 40 and 50 km thick are 19, 27, 48 and 76 Ma (Upton *et al*. 1997) and hence, the time lag between early mantle magmatic activity and then crustal metamorphism and major crustal melting is of the order of a minimum of 25 Ma and given Proterozoic crustal thicknesses could be at least 70 Ma if not longer. Modelling has also shown that the addition of sediments and thickening of the crust will cause further rises in temperature.

The proposed model shows that it takes considerable time for sufficient heat to be conducted to the crust to generate the types of magma consistently observed in the Proterozoic of Australia. Thus the tectonic processes that helped generate the melt are not necessarily the same as those that allowed for its migration into the upper crust. Intraplate forces acting on the crust can facilitate the escape of magmas to the surface, with the composition of the melt being simply dependant on the temperatures existing in the lower crust at the time of the 'escape' rather than on the contemporaneous tectonic setting.

What are the metallogenic implications ?

A consequence of the present model is that, in any province it is predictable that mineralisation derived from plutonic fluids will be associated with Group 2 and Group 3_3. Group 1 granites being restite-rich, cannot give a greater concentration of any element than that contained in the initial melt or restite and hence are rarely mineralised. Similarly the fluorine-rich granites (Groups 3_1 and 3_2) are rarely mineralised. In contrast Groups 2 and 3_3 that have been formed by dehydration melting of biotite and hornblende respectively appear to have the greatest metallogenic potential. Granites of type 3_3 are rare in the Proterozoic of Australia having only been documented in the Gawler and Mount Isa provinces where they are associated with significant Cu+Au±U mineralisation. The rarity of the granite-types may reflect the difficulty in actually attaining these high temperatures in the lower crust. Further, the conductive model predicts that as the thermal anomaly will only reach mid-crustal and higher levels late in the history of the province, metamorphic deposits will occur late in the history of any province.

Conclusions

The present model, which is preliminary, goes a long way to explaining the observation that in any Proterozoic province, granites are emplaced at progressively higher temperatures with increasing time. The model does not require subduction and implies instead that much of the Proterozoic magmatism may result from intraplate activity. Further modelling will be carried out to more fully determine the actual length of time that the thermal anomalies can exist in the crust, and what influence variables such as the original crustal thickness, the thickness of the sedimentary overburden, the composition of these sediments (viz. conductivity contrast between black shale vs pure quartz sand), and the thickness of the mafic underplated layer can have on the process.

References

Chappell, B.W. and Stephens, W.E. 1988. Origin of infracrustal (I-type) granite magmas. *Transactions of the Royal Society of Edinburgh, Earth Sciences,* 79, 71-86.

Drummond, B.J., and Collins, C.D.N. 1986. Seismic evidence for the underplating of the lower continental crust of Australia. *Earth and Planetary Science Letters,* 79, 361-372.

Green, A.R., May, S.R., and Loutit, T.S. 1992. The origin and evolution of sedimentary basins. *Geological Society of Australia, Abstracts*, 32, 12-13.

Idnurm, M., Giddings, J.W., and Plumb, K.A. 1993. Palaeomagnetism of the southeastern McArthur Basin: poles, overprints and reversals. *Exploration Geophysics,* 24, 227-230.

Loutit, T.S., Wyborn, L.A.I., Hinman, M.C., and Idnurm, M. 1994. Palaeomagnetic, tectonic, magmatic and mineralisation events in the Proterozoic of Northern Australia. *The Australasian Institute of Mining and Metallurgy, Publication Series*, 5/94, 123-128.

Upton, P., Hobbs, B., Ord, A., Zhang, Y., Zhao, C., Drummond, B. and Archibald, N. 1997. Thermal and deformation modelling of the Yilgarn Deep Seismic transect. *Abstracts, Geodynamics and Ore Deposits Conference, Australian Geodynamics Cooperative Research Centre, Ballarat,* 22-25.

Wyborn, L.A.I., Page, R.W., and Parker, A.J. 1987. Geochemical and geological signatures in Australian Proterozoic igneous rocks. In: Pharaoh, T.C., Beckinsale, R.D., and Rickard, D., (editors), Geochemistry and mineralisation of Proterozoic volcanic suites. *Geological Society of London, Special Publication,* 33, 377-394.

Wyborn, L.A.I., Wyborn, D., Warren, R.G., and Drummond, B.J. 1992. Proterozoic granite types in Australia: implications for lower crust composition, structure and evolution. *Transactions of the Royal Society of Edinburgh, Earth Sciences*, 83, 201-209. Also Published as *Geological Society of America, Special Paper,* 272, 201-209.

20 ABSTRACT 2 - Granite-related Ore Systems

AUSTRALIAN PROTEROZOIC GRANITE-RELATED ORE SYSTEMS

Lesley A.I. Wyborn[1], Anthony R. Budd[1], and Irina V. Bastrakova[1]

[1]Australian Geological Survey Organisation, GPO Box 378, Canberra, ACT, 2601

14 th AGC, Townsville, July 1998, GSA Abstracts, 49, 481

AGSO, in collaboration with Commonwealth, State and Territory Geoscience organisations, has completed a project on the 'Metallogeny of Australian Proterozoic Granites' (which was sponsored by 20 mineral companies). 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. Data were collated on the mineralogy, geochemistry (~7500 analyses), and age of Proterozoic granites and felsic volcanics, as well as the age and mineralogical composition of sediments within 5 kms of granite boundaries for 20 provinces.

KEY RESULTS BY GRANITE TYPE

Overall although there is a strong spatial relationship with specific granite types for many commodities, much of the mineralisation is hosted in the country rocks and particularly for Au, up to 5 kms from the nearest granite contact. I-(granodioritic) compositions dominate and these are inevitably Sr-depleted and Y-undepleted which contrasts with igneous rocks normally found associated with porphyry-style mineralisation. Some significant differences were found between Proterozoic granites and their Archaean and Phanerozoic counterparts (*e.g.*, Proterozoic granites have elevated K, Th U, and High Field Strength Elements contents). Hence classifications for A- and S-types, and some metallogenic indicators developed from Palaeozoic granites were not meaningful. 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. More specific relationships are as follows:

- I or S-type granites designated as unfractionated were restite-rich and consistently unmineralised.
- Fractionated I-type granites can be divided into 2 groups: those that were either F-poor or F-rich throughout most of their fractionation history. The F-rich granites are often the true rapakivi types and have little mineralisation presumably because Cl had been partitioned into the granite melt early.
- Fractionated F-poor I-type granites can be further divided into 2 classes: Oxidised and Reduced. The Oxidised granites are most commonly associated with Cu-Au deposits and crystallised at higher temperatures than the Reduced class. Although it is commonly stated that Au mineralisation is only associated with oxidised granites, an unequivocal spatial association occurs between the Reduced class and Au-dominant mineralisation which also has variable amounts of Cu, Sn, W, and Bi. Reduction is due to several causes including increasing ASI, interaction with country rock and perhaps magma cooling.
- Rare fractionated S-types are commonly associated with Sn mineralisation.

KEY RESULTS BY REGION

Mount Isa: The most prospective areas for Cu-Au are those surrounding the Williams Supersuite. The Burstall Suite in the eastern Wonga Belt has some Cu-Au potential including potential epithermal style deposits.

Georgetown: The Esmeralda Supersuite has strong similarities to the Hiltaba Supersuite of the Gawler Craton.

Pine Creek: The Allia Suite and Cullen Supersuite have proven potential: other suites are not highly rated.

Kimberleys: Major suites are essentially unfractionated (restite-rich?) and are not considered prospective. The small Koongie Park Suite (related to the Koongie Park VHMS mineralisation) shows evidence of fractionation.

Granites-Tanami: Although data are limited, many granites are reduced, but some become oxidised at shallower level of emplacement: the two contrasting types may require different conditions for precipitation.

Tennant Creek/Davenport: Au is most likely to be related to the 1820 Ma Treasure Suite.

Gawler Craton: The Hiltaba Supersuite comprises the oxidised Roxby Downs Suite which has Cu-Au-U potential and the more widespread, reduced Kokatha Suite which is associated with Au _ Sn mineralisation.

Paterson: Granites closest to the Telfer deposit are reduced, in contrast to the oxidised Mount Crofton Granite.

Gascoyne: 1800 Ma granite suites are fractionated, although the metal potential may be limited by the high metamorphic grade of many hosts. Prospective targets are likely to be small and focussed as at Tennant Creek.

Arunta: Many suites present: the most prospective are the 1710 Ma Alarinjela and Barrow Creek Suites, the 1640 Ma Mount Webb Suite, and the 1567 Ma Southwark Suite. High metamorphic grade may be a limitation.

Broken Hill: Dominated by restite-S-types that are unlikely to be related to the Broken Hill Pb-Zn-Ag deposit.

Olary: If the 1590 Ma suites are true analogues of the Hiltaba Supersuite, then the potential for Cu/Au is high, although by analogy with the Cloncurry district the presence of calc-silicate rocks may cause limitations.

Northhampton, Rocky Cape, Albany Fraser, Leewin, Musgrave: Insufficient data available for confident predictions of metallogenic potential.

21 ABSTRACT 3 - Interactions Between Crust & Mantle

INTERACTIONS BETWEEN CRUST AND MANTLE THROUGH TIME AND THE RELATIONSHIP TO THE EVOLUTION OF AUSTRALIAN ORE DEPOSIT TYPES

Lesley A.I. Wyborn[1], Murray S. Hazell[1], Laigee M. Bell[1] & Suzanne M. Edgecombe[1].

[1]Australian Geological Survey Organisation, GPO Box 378, Canberra, ACT, 2601

14 th AGC, Townsville, July 1998, GSA Abstracts, 49, 482

Compilations of the distribution of ore deposits types in time clearly show them to form three broad groups that are coincident with the Archaean, Proterozoic and Phanerozoic eons (*e.g.*, Meyer 1981). As many deposits are related to the intrusion/ extrusion of igneous rocks, the changes in dominant ore deposit types appear to parallel temporal changes in the dominant type of igneous rocks in response to mantle cooling. Some examples are:

- The Archaean mantle was at least 100°C hotter than the present mantle as is reflected in the abundance of komatiites derived from deeper parts of the mantle. Hence the Archaean dominance of komatiite-hosted Ni.
- The Archaean lacks the significant volumes of the high-T, oxidised I-(granodioritic) types that are usually associated with Cu/Au mineralisation in the Proterozoic. Thus ironstone hosted Cu-Au deposits are absent.
- Some early Palaeoproterozoic mafic igneous rocks are Mg and Si-enriched, suggesting that mantle melts remained hotter than at present and were derived from shallower levels than in the Archaean. These compositions would promote the formation of layered intrusions within the crust (with associated deposits of Ni, Cr, Pt) and would also result in underplating of the crust which is so prevalent in the Proterozoic.
- Late Archaean/Palaeoproterozoic granites have higher K, Th and U values than granites of other ages. (However, an oxygenated atmosphere is required to free U allowing unconformity-style U deposits to form.)
- Widespread underplating in the Proterozoic could result in more effective conductive heating of the lower crust, whilst the high K, Th and U values would increase radiogenic heat outputs. Both factors would cause higher crustal geothermal gradients, and therefore high temperatures at shallow crustal levels, which in turn would facilitate the generation of the large size of some Proterozoic hydrothermal deposits.
- The physical size of igneous suites is generally larger in the Precambrian than in the Phanerozoic, suggesting also that the related thermal anomalies that influenced basin formation were vast. In the Palaeoproterozoic some basin formation resulted in extensive sag phases characterised by evaporitic sequences that were an important source of ligands (such as Cl^-) for transport of U and base metals.
- Australian Proterozoic VMS are rare as fractionated volcanics rarely coincide with subaqueous sediments.
- I-(granodioritic) types dominate Australian Proterozoic/early Palaeozoic felsic melts and the majority are Sr-depleted, Y-undepleted, possibly signifying high crustal geothermal gradients. Related deposits are mostly hosted in country rock, possibly because the granites are too felsic and/or intrusions are too deep.
- S-type granites or I-types that fractionate to more peraluminous compositions are more prominent in the Palaeozoic, this may explain the greater abundance of Sn mineralisation during this era in Australia.
- Magma types change notably in the Phanerozoic and more are clearly related to activity at plate margins.

- Genuine shoshonites with associated Cu/Au mineralisation made their first appearance in the Ordovician.
- Porphyry-style mineralisation is more common in the Phanerozoic, where it is hosted within I-(tonalitic) or M-types above subduction zones. Most melts are Sr-undepleted signifying lower geothermal gradients.
- Ophiolite-related deposits (Cu-pyrite deposits, podiform Cr deposits) are more common in the Phanerozoic.

Thus the changing thermal regime of the crust and mantle through time exerts a significant control on the dominance of different magma and ore deposit types through time. Although the Archaean was characterised by highest mantle temperatures, crustal geothermal gradients were probably lower possibly due to a thicker lithosphere. Mantle temperatures were intermediate in the Proterozoic, whereas crustal geothermal gradients may have been higher perhaps due to lithospheric thinning, thus allowing mantle melting at shallower levels than in the Archaean. Because of the hotter thermal structure of the continental lithosphere in the Precambrian, deformation was substantially less partitioned into narrowly defined plate boundaries than at present (Etheridge and Wall 1994). Hence in the Precambrian intraplate deformation was more widespread resulting in more opportunities for fluid migration (and hence some larger ore deposits!). The Phanerozoic represents a transition to a dominance of igneous activity and deformation at plate margins driven by a cooler mantle, explaining the increase of ore deposits that characterise the plate margins, viz., porphyry Au/Cu and ophiolite-related deposits.

REFERENCES

Etheridge, M.A. and Wall, V.J. 1994. Tectonic and structural evolution of the Australian Proterozoic. *Geological Society of Australia, Abstracts*, 37, 102-103.

Meyer, C. 1981. Ore-forming processes in geologic history. *Economic Geology, 75th Anniversary Volume*, 6-41.

22 ABSTRACT 4 - Australian Proterozoic Intraplate Igneous Activity

WHAT DO ~10 000 WHOLE ROCK GEOCHEMICAL ANALYSES TELL US ABOUT AUSTRALIAN PROTEROZOIC INTRAPLATE IGNEOUS ACTIVITY?

Lesley A.I. Wyborn[1], Mart Idnurm[1], Anthony R. Budd[1], Irina Bastrakova[1], Murray S. Hazell[1], and Suzanne M. Edgecombe[1].

[1]Australian Geological Survey Organisation, GPO Box 378, Canberra, ACT, 2601

14 th AGC, Townsville, July 1998, GSA Abstracts, 49, 484

A major compilation of Australian Proterozoic Igneous rocks reveals broad patterns which provide major constraints on geodynamic reconstructions in the Proterozoic. The key results show that the Australian Proterozoic can be subdivided into major magmatic provinces each of which is coincident with one or several major recognised fold belts/orogenic domains and contains magmatism that is clearly episodic. The majority of Australian Proterozoic granites are I-(granodioritic) type derived by melting of pre-existing crust. Proterozoic granites are also dominantly Sr-depleted and Y-undepleted, signifying high geothermal gradients and sources dominated by plagioclase. Genuine S-type granites with visible cordierite and garnet in the more mafic compositions are rare, as are intermediate or felsic types that are distinctly Sr-undepleted, Y-depleted: a signature which is most commonly found in granites associated with subduction in island arc or continental margin settings, and infers the presence of garnet in the source and lower geothermal gradients.

Wyborn *et al*. (1997) have shown that in most major Proterozoic magmatic provinces the dominant Sr-depleted, Y-undepleted I-(granodioritic) types can be divided into three groups which show a time progression in geochemistry. The oldest group (Group 1) at 1870-1850 Ma comprises restite-rich suites. Group 2, emplaced at 1840-1800 Ma is a low-Ca type that shows evidence of magmatic fractionation. The youngest group (Group 3) is enriched in incompatible elements and comprises three subgroups: Subgroup 3_1, dated at around 1800-1780 Ma, has very high values of Zr, Nb and Y; Subgroup 3_2, usually emplaced between 1760 and 1650 Ma, is enriched in F and has variable amounts of Y, Zr, and Nb; and Subgroup 3_3, emplaced from 1640 to 1500 Ma, is more oxidised with a wide range in SiO_2 values. A simple explanation for the geochemical evolution from Groups 1 to 3 is that as the temperature in the source region increases, the magma is dominated first by minimum melt, then by biotite breakdown and finally by amphibole breakdown, with evidence of source temperatures of up to 1000°C during the latter phase. The temperature increase of granite melts contrasts with a general decrease in the temperature of the mafic melts with time, 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 Mt. Isa).

It is difficult from the geochemical viewpoint to relate these consistent, continent-wide changes in composition to magmatism at the plate boundaries. Further, given the abundance of continent-wide magmatic activity, this would require an unlikely large number of small plates. Likewise. an explanation for melt emplacement in terms of tectonism, related to coeval mantle heating events is difficult to reconcile with time constants for heat transfer from the mantle to the crust. For crustal thicknesses of 25, 30, 40 and 50 kms the time lags have been calculated as 19, 27, 48, and 76 Ma respectively (Upton *et al*. 1997). Given the likely Proterozoic crustal thicknesses of at least 30 kms, the time lag between mantle magmatic activity and crustal melting is at

least 25 Ma and may exceed 70 Ma, suggesting that melting of the lower crust and the emplacement of granitic magmas were due to different tectonic events. The clue to solving these problems may be in the shape of the apparent polar wander path (APWP) which, for those parts of the Australian Proterozoic where it is defined, confirms plate mobility and also shows that magma emplacement was coincident in time with inflection points on the APWP. The latter are recognised as significant *interplate* tectonic events with associated *intraplate* effects that cause major episodic migration of basinal fluids. Similar intraplate tectonic responses to later plate boundary tectonic events may have also allowed granitic melts to migrate into the upper crust, with the composition of the melt being simply dependant on the temperatures in the lower crust at the time of 'escape'. This hypothesis is consistent with (1) the increase in temperature of the felsic melts with decreasing age, (2) the progressive change in chemical compositions with time in each province, and (3) the related decrease in the temperature of the mantle melts. Finally, the hypothesis implies that major magma emplacement in the Proterozoic of Australia may have occurred in the interior of the plate rather than along numerous plate boundaries.

REFERENCES

Upton, P., Hobbs, B., Ord, A., Zhang, Y., Zhao, C., Drummond, B. and Archibald, N. 1997. Thermal and deformation modelling of the Yilgarn Deep Seismic transect. *Abstracts, Geodynamics and Ore Deposits Conference, Australian Geodynamics Cooperative Research Centre*, Ballarat, 22-25.

Wyborn, L., Ord, A., Hobbs, B., and Idnurm, M. 1997. Episodic crustal magmatism in the Proterozoic of Northern Australia - a continuum crustal heating model for magma generation. *AGSO Record*, 1997/44, 131-134.

23 ABSTRACT 5 - Mount Webb Granite Alteration System

A NEWLY DISCOVERED MAJOR PROTEROZOIC GRANITE-ALTERATION SYSTEM IN THE MOUNT WEBB REGION, CENTRAL AUSTRALIA, AND IMPLICATIONS FOR CU–AU MINERALISATION

Lesley Wyborn[1], Murray Hazell[1], Rod Page[1], Mart Idnurm[1], & Shen-su Sun[1]

[1]Australian Geological Survey Organisation, GPO Box 378, Canberra, ACT, 2601

AGSO Research Newsletter, May 1998, 28, 1-6.

The presence of a major granite-related alteration system has been confirmed in the western Arunta Block - in the remote Mount Webb region (WA/NT border; Fig. 1). According to new petrological, geochemical, and geochronological data from the Mount Webb Granite and its comagmatic felsic volcanics in the Pollock Hills Formation, this magmatic system has many similarities to granites in other Australian Proterozoic regions where hydrothermal Cu and or Au deposits have been linked to magmatic sources (e.g., eastern Mount Isa Inlier, Gawler Craton). Key criteria that establish this region as prospective are:

- fractionation trends in the granite, clearly evident in the geochemical data;
- magmatic alteration effects (including sodic-calcic, sericitic, and hematite-K-feldspar) in the granite and country rock; and
- evidence of metallogenically significant hydrothermal interaction with the country rock.

A preliminary interpretation of the results of 12 analyses recorded in AGSO’s ROCKCHEM database and in Blake *et al.* (1977: BMR Bulletin 197) suggested that the Mount Webb Granite and felsic volcanics of the adjacent Pollock Hills Formation potentially had primary and alteration characteristics similar to granites of the

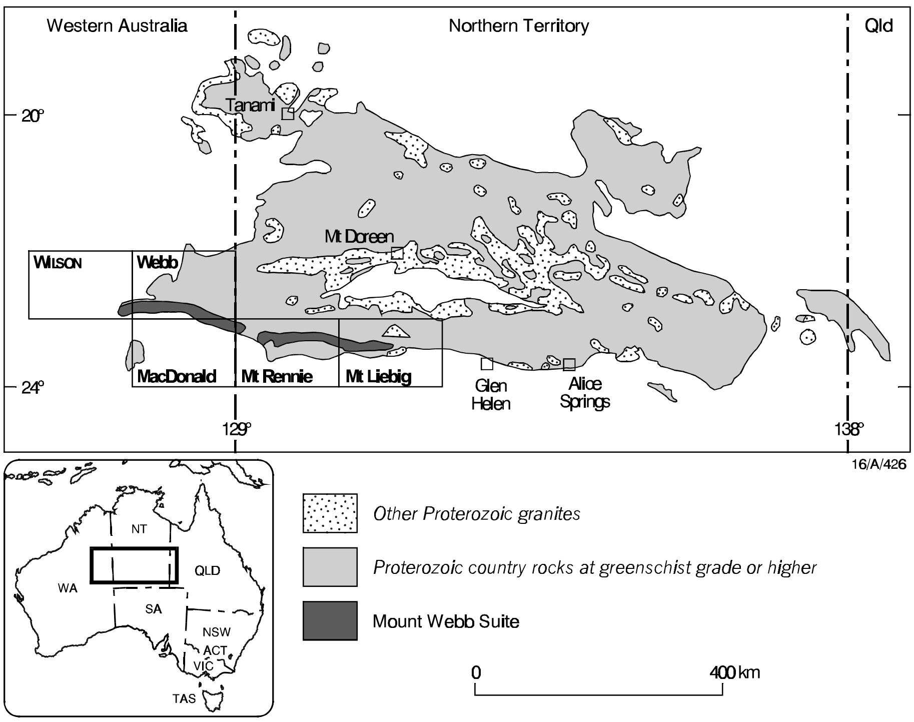


Fig. 1. Location of the Mount Webb region, western Arunta Block

metallogenically important Williams Batholith (eastern Mount Isa Inlier) and Hiltaba Suite (Gawler Craton), both of which are closely associated with Cu–Au mineralisation (Wyborn 1994: Centre for Ore Deposit & Exploration Studies, University of Tasmania, Master of Economic Geology Course, Manual 2). Reference to '... thicker quartz veins cutting highly altered and brecciated granite west of Pollock Hills' (Blake & Towner 1974: BMR Record 1974/53) further heightened the intrigue. In May 1996, AGSO staff visited the Mount Webb region to collect a suite of samples (Fig. 2) for magma typing, age determination, and alteration mapping and evaluation.

The results described here focus on the Webb 1:250 000 Sheet area, but the granite system extends westward into the Wilson Sheet area, and eastward into the Macdonald, Mount Rennie, and possibly Mount Liebig Sheet areas (Fig. 1). Both the granite system and the alteration are large by Australian Proterozoic granite standards.

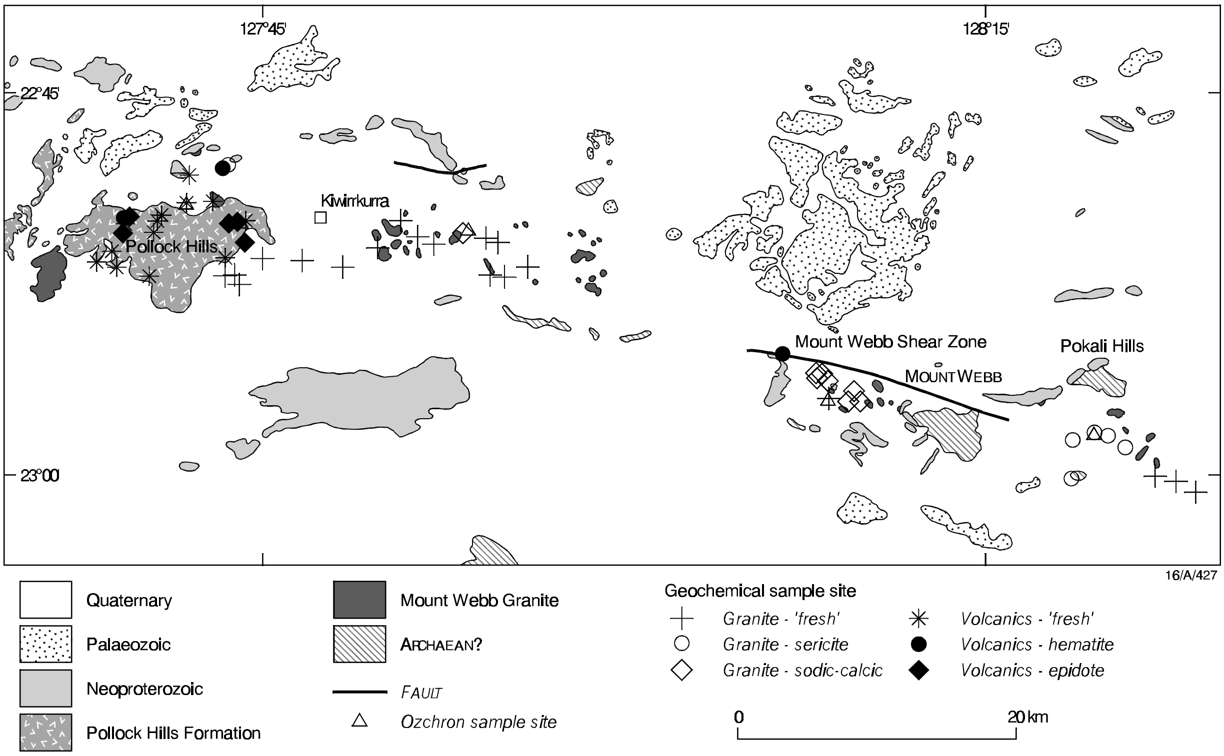


Fig. 2. Geology of the Mount Webb region (based on Blake 1977: op. cit.).

Petrological data

Country rock

In the Webb Sheet area (Blake & Towner 1974: op. cit.; Blake 1977: Webb 1:250 000 Geological Series —explanatory notes, BMR/AGSO), the Mount Webb Granite intrudes 'unnamed Archaean?' rocks (mainly interbedded quartzite and mica schist, and some amphibolite). Near the inferred contact between granite and amphibolite at the southernmost part of one Archaean? outcrop at Pokali Hills (20 km east of Mount Webb), quartz veins and minor ironstones are prominent, and so too is an overprint (metasomatic?) of quartz, biotite, and magnetite replacing all the primary minerals. Away from the inferred contact, constituents of the country rock in this outcrop are mainly amphibole and plagioclase in the central part, and chlorite, actinolite, and minor greenish biotite in the north, suggesting that the granite has both contact-metamorphosed and metasomatically altered the country rock. The country rock elsewhere in the Sheet area is dominated by quartzite and mica schist; late-stage quartz and quartz–tourmaline veins are abundant, and the rock is locally brecciated (Blake & Towner 1974: op. cit.).

Mount Webb Granite The Mount Webb Granite is heterogeneous, comprising several types of unaltered granite, sodic–calcic-altered granite, sericite-altered granite, and aplite. Most altered samples are from near the Mount Webb Shear Zone (Fig. 2). All samples are recrystallised, and most have a distinct foliation, suggesting that the granite has been affected by a post-intrusion metamorphic event.

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). This alteration type is prominent in a linear shear zone trending 310° both to the northwest and southeast of Mount Webb. Few quartz veins bisect the rocks affected by this alteration type, and open spaces were not observed. Most samples contain titanite, and have albite/oligoclase as their only feldspar. 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. In thin section, the sericite consists mainly of fine grains concentrated in veins aligned parallel to the foliation. Opaque phases are rare: some samples have magnetite or small pyrite grains; one has chalcopyrite. Two weathered samples containing visible malachite have Cu concentrations of 348 and 278 ppm; thin sections show that they consist mainly of goethite, which was probably formed as a weathering product of primary sulphides.

Quartz veins carrying sulphides are more prominent in the areas of sericitic alteration, where the granite also tends to be more brecciated and bears tourmaline and fluorite. The sulphides are mainly pyrite, though galena was observed in one sample with 1800 ppm Pb, and another sample has 145 ppm Mo.

Aplite veins, common in the more felsic granite, are probably the products of late-stage magmatic processes.

Pollock Hills Formation The felsic volcanics of the Pollock Hills Formation consist mainly of black porphyritic dacite and rhyodacite overlain by tuffaceous and non-tuffaceous sedimentary rocks (Blake & Towner 1974: op. cit). Alteration is less pervasive in the volcanics than in the Mount Webb Granite, and two alteration types are evident: hematite and epidote. Overall, even the least altered volcanic samples have a markedly recrystallised texture in thin section, suggesting that they are metamorphosed.

The ***least altered volcanics*** are mainly porphyritic ignimbrites with phenocrysts of plagioclase, magnetite, and quartz in decreasing order of abundance. Phenocrysts of ferromagnesian silicate minerals (altered to epidote and/or biotite) are rare. The ignimbrites comprise two broad types: those with abundant lithic fragments and crystals, and those with a lower crystal and lithic content. The lithic-poor ignimbrites contain flattened pumice clasts and abundant spherulites in the matrix; the spherulites indicate that the matrix comprises devitrified volcanic ash. Lapilli tuffs were observed at one locality. Fine-grained magnetite is scattered throughout the groundmass, which is commonly recrystallised. Although, small grains of pyrite/chalcopyrite occur in the spherulite-bearing volcanics, most of the volcanics have magnetite as the dominant opaque mineral; primary sulphides are rare, reflecting the high oxidation state of the magma.

Hematite alteration in the volcanics is possibly related to two events. Firstly, as noted by Blake & Towner (1974: op. cit.), hematite alteration is more prominent at the top of the volcanics, near their contact with the sedimentary rocks of the Pollock Hills Formation. Red hematite-rich layers interspersed with these sedimentary rocks suggest that oxidising atmospheric conditions prevailed during sedimentation and extrusion, so the hematite may be related to meteoric fluids rather than to hydrothermal/magmatic processes. Some of this early hematitic alteration is also cut by late epidote alteration.

Secondly, hematite alteration is evident in highly sheared volcanics sampled away from the sediment/volcanic interface. At one locality, northwest of Kiwirrkurra, a hematite-rich, K-feldspar-altered volcanic rock associated with an ironstone cuts a chlorite/sericite-altered volcanic rock, and is therefore later in the paragenesis. At another, an isolated volcanic outcrop northwest of Mount Webb, hematite alteration is also apparent in a sample of K-feldspar-bearing rock containing anomalously high potassium. Shearing at both localities suggests that this type of hematite alteration is due to another event, distinct from that formed at the sediment/water interface early in the paragenetic history.

Epidote alteration is common in the volcanics. In thin section, it is pervasive and texturally destructive. It progressively destroys any original igneous textures, and produces an end-member assemblage of epidote + quartz. Mineralogically and chemically it closely resembles the sodic–calcic alteration of the Mount Webb Granite, and both are focused in shear zones trending *ca* 310°.

Mafic dykes

Mafic dykes with a prominent north-northwesterly trend are prominent in the area, particularly in the granite outcrops east of the Pollock Hills, but do not intrude the Neoproterozoic and younger sequences (Blake 1977: op. cit.). In thin section, most appear to be pristine, consisting of plagioclase, clinopyroxene, and orthopyroxene; they also contain sulphides (mostly pyrite, but some chalcopyrite). A few of them evince pronounced alteration effects, and are probably older, but they all lack deformational and metamorphic effects, suggesting that they are much younger than the granite.

Geochemistry results

Sixty samples were collected for analysis: 28 granites, nine aplites and quartz veins, 18 volcanic rocks, and five dolerites. The alteration effects in the granites and volcanics are clearly shown in a plot of Na_2O vs K_2O (Fig. 3A). The sodic–calcic-altered samples are depleted in K_2O, whereas the more strongly sericite-altered samples have lost Na_2O. In contrast, the hematite-altered samples show a marked enrichment in K_2O, similar to that in the ~1500-Ma granites in the Cloncurry district (Wyborn in press: Australian Journal of Earth Sciences).

The plots for Rb and Rb/Sr show exponentially increasing values with increasing SiO_2 (Figs. 3B and C). On the Fe_2O_3/FeO vs total Fe as FeO plot (Fig. 3D) of Champion & Heinemann (AGSO Record 1994/11), most samples lie in the oxidised field. The ASI values (molecular $Al_2O_3/[K_2O + \{CaO - 1/3P_2O_5\} + Na_2O]$) are <1.1, indicating that the samples are metaluminous to weakly peraluminous. All these features are characteristic of granites associated with Cu–Au mineralisation in the Proterozoic (see also Wyborn 1994: Geological Society of Australia, Abstracts, 37, 471–472.)

Geophysical data

Parts of the hydrothermal alteration system occur in the Webb and Wilson Sheet areas, for which no airborne geophysical data are in the public domain. We recorded ground magnetic observations on a Geoinstruments susceptibility meter (model JH–8). Susceptibilities range from 200 to 600 SI units x 10^{-5} for the (dominant)

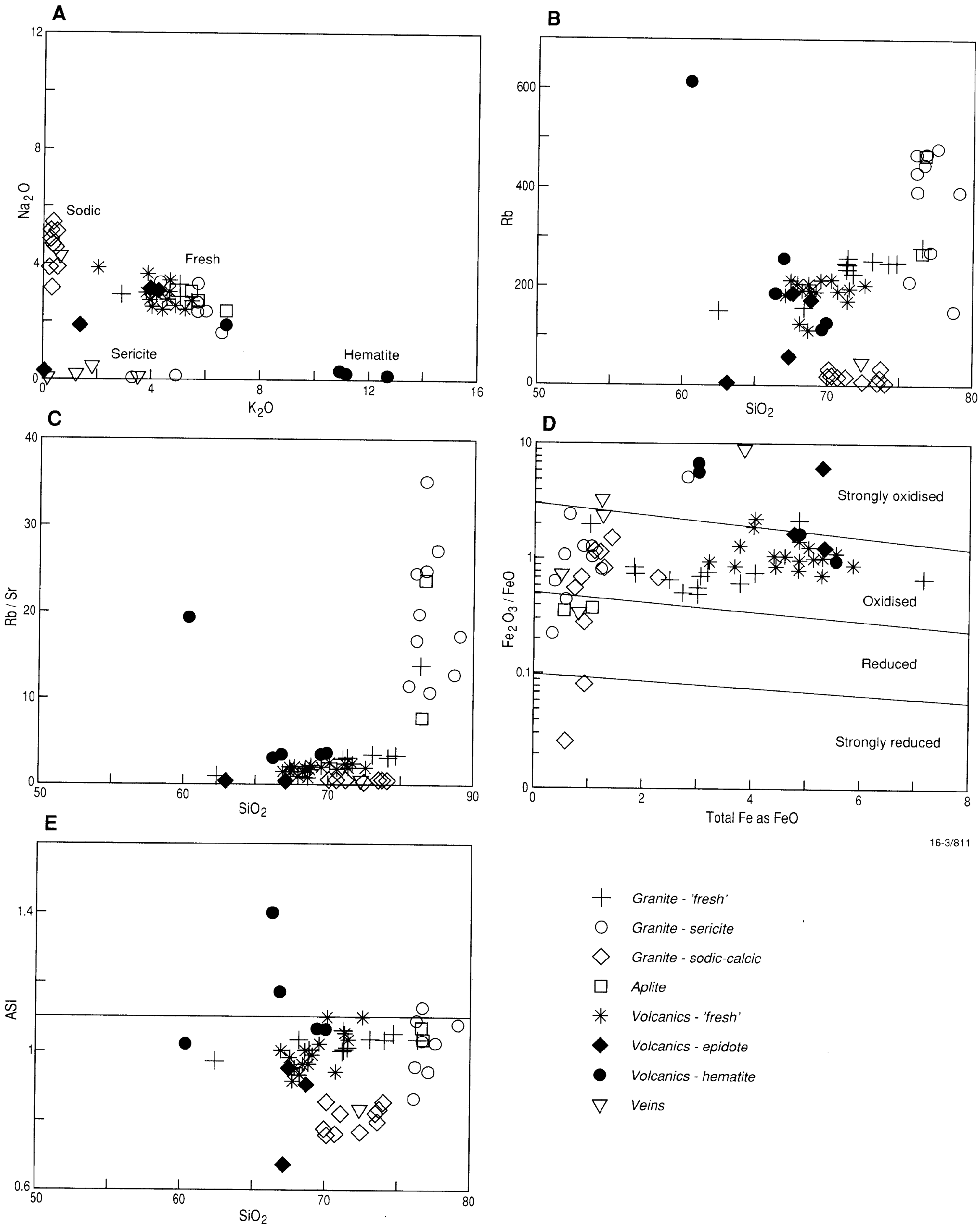


Fig. 3. Geochemical variation diagrams for whole-rock geochemical data from the Mount Webb region.

monzogranite, and 2000–5000 SI units x 10^{-5} for the tonalite/diorite, reflecting increasing modal abundance of magnetite with decreasing SiO_2. The felsic volcanics also have high susceptibilities, generally from 3000–5000 SI units x 10^{-5}, mirroring the abundant magnetite phenocrysts and the ubiquitous fine-grained magnetite in the groundmass.

Alteration zones in both the granite and the volcanics have much lower magnetic susceptibilities (generally <40 SI units x 10^{-5}), reflecting the destruction of magnetite in the areas of sodic–calcic alteration. Although magnetite is generally absent from the sericite-altered areas, some high-susceptibility localities are apparent there.

The country rock generally has low measured susceptibilities, except amphibolite in the Pokali Hills area, where susceptibilities are variable and range from 200–5000 SI units x 10^{-5}. Those rocks with particularly high susceptibilities had metasomatic biotite and magnetite in thin section. The fresh mafic dykes, including the dated sample, have high susceptibilities (<4000 SI units x 10^{-5}): altered dykes have low susceptibilities.

Geochronology results

Page *et al*. (1976: BMR Journal of Australian Geology & Geophysics, 1, 1–13) obtained a combined Rb–Sr isochron age of 1494 ± 25 Ma (recalculated with the 1.42 x 10^{-11} yr^{-1} constant for Rb^{87}) and an initial Sr^{87}/Sr^{86} ratio of 0.7114 ± 0.004 for the Pollock Hills Formation and Mount Webb Granite. Such a high initial ratio for an I-type granite suggests that the Rb–Sr data have been reset, so samples (five) were selected for SHRIMP U–Pb zircon dating (Table 1).

The three granite samples yield ages of 1643 ± 4, 1639 ± 5, and 1639 ± 5 Ma, indicating that they all belong to the one magmatic system. Inherited zircon populations include 1680–1690, 1775–1769, and 1830–1877 Ma. A corollary to these results is that the anomalously young Rb–Sr age might reflect the ubiquitous late metamorphic overprint of both the volcanics and granite.

No satisfactory igneous crystallisation age was obtained for the volcanics of the Pollock Hills Formation, as the zircon populations in the sample studied are exceedingly complex. This sample is dominated by inherited ~1860-Ma zircon; a population at ~1680–1690 Ma is also prominent; older inheritance at ~1970 Ma and 2590 Ma is also apparent. These populations are distinctly older than those of the granite; only one grain analysed from the volcanic sample was close to the age of the granite (~1640 Ma). The dated sample has abundant lithic fragments, and is likely to have xenocrystic zircon populations derived from these fragments. Jagodzinski (1992 AGSO Record 1992/9; 1998 AGSO Research Newsletter 28, 23–25) has reported a similar case in the Coronation Hill region (NT), where an ignimbrite dominated by lithic fragments yielded mainly xenocrystic zircon populations and only a few magmatic grains.

Nd isotopic data from the samples of the Mount Webb Granite and volcanics gave εNd_i values of –1.5 to –2.1 and single-stage T_{DM} model ages of ~2320 Ma (Table 1), similar to those obtained elsewhere in the Arunta Block (Sun *et al*. 1995: Precambrian Research, 71, 301–314). They indicate that the felsic magmas were derived from a pre-existing crustal source.

Table 1. Summary of new U-Pb SHRIMP amd Sm-Nd results from the Mount Webb region.

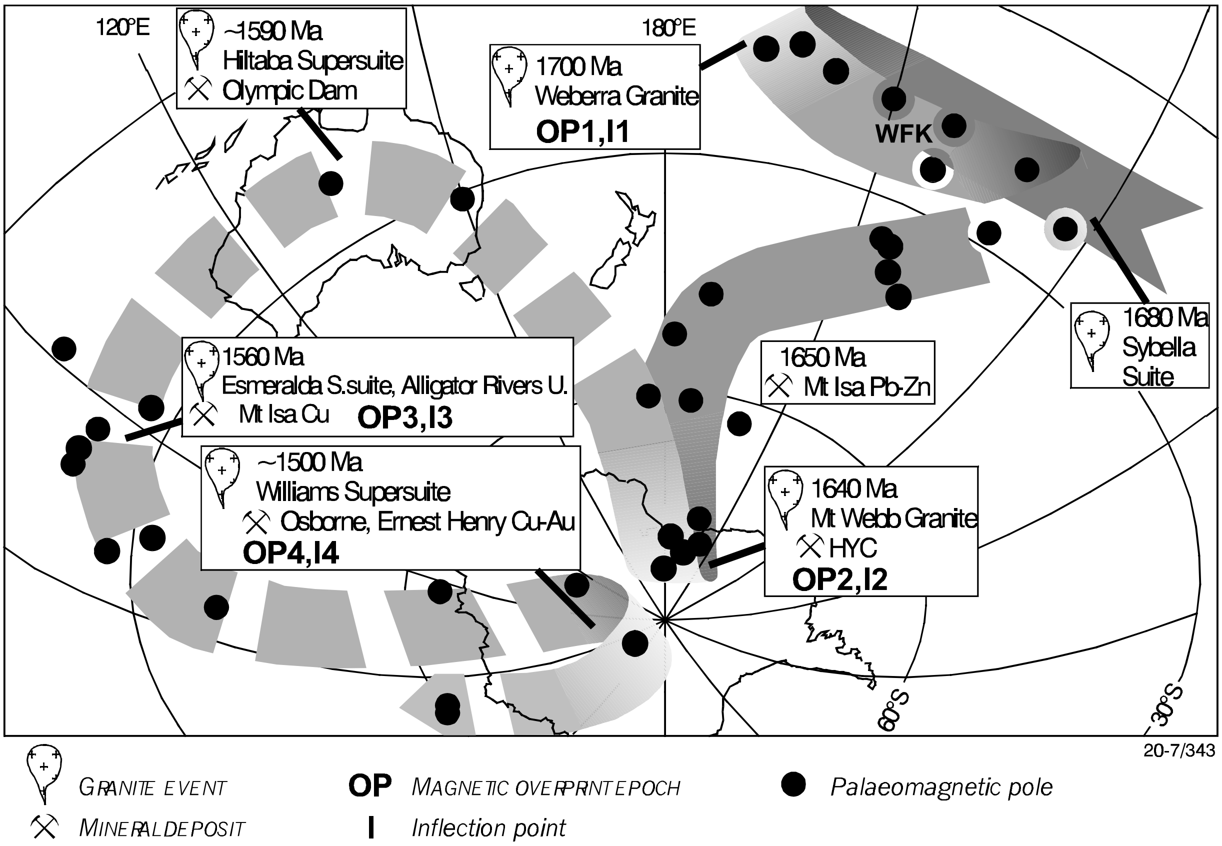
Sample no.	*Rock unit*	*Rock type*	*SiO_2*	*Age (Ma)*	*Xenocrysts*	*εNd_i*	*T_{DM}(Ma)*
96496035	Mount Webb Granite	monzogranite	74 wt %	1643 ± 4	1680–1690 Ma (4 grains), ~1775 Ma (2 grains), 1860–1870 Ma (2 grains)	–2.1	2327
96496028A	Mount Webb Granite	granodiorite	68 wt %	1639 ± 5	1690 Ma (1 grain)	–2.0	2322
96496011	Mount Webb Granite	sericite-altered granite	77 wt %	1639 ± 5	Complex with inheritance patterns at ~1680, ~1760, and 1830–1877 Ma		
96496024	Pollock Hills Formation	lithic-rich ignimbrite	68 wt %	1643 ± 13 (NB: one grain only)	Complex populations 1680–1690, 1862 ± 4 (dominant), single grains at 1966, 2590 Ma	–1.5	2325
96496009	unnamed dolerite	dolerite	48 wt %	976 ± 3 (zircon) 972 ± 8 (baddelyite)	~1630 Ma	2.3	

Both magmatic zircon and baddelyite were dated from an unmetamorphosed dolerite dyke. They recorded Neoproterozoic ages of 976 ± 3 and 972 ± 8 Ma respectively, dispelling the notion of any connection between the dykes and the Mount Webb Granite. These dykes are considerably younger than the Stuart Pass Dolerite, which is abundant throughout the Arunta Inlier and has a well-defined Sm–Nd mineral isochron age of 1076 ± 33 Ma (Zhao & McCulloch 1993: Chemical Geology, 109, 341–354).

Implications of the 1640-Ma age for the Mount Webb Granite

The new age for the Mount Webb Granite is similar to the 1640 ± 7-Ma age of tuffs in the HYC orebody at McArthur River (Page & Sweet in press: Australian Journal of Earth Sciences). Although the similarity may be purely coincidental (not all tuffs in the north Australian Proterozoic sequences have known Australian sources), it does raise the possibility that the HYC tuffs were derived from the Mount Webb region, especially considering the size of the intrusive event.

It is interesting to note that Loutit *et al.* (1994: Australasian Institute of Mining & Metallurgy, Publication Series, 5/94, 123–128) observed that most major granite and major ore-forming events correspond to major inflections in the Australian apparent polar wander path (APWP; Fig. 4). However, no major granite event was then known



to correspond to the major hairpin bend at ~1640 Ma. The new data from the Mount Webb Granite provide evidence for such an event. Loutit *et al.* (1994: op. cit.) asserted that APWP inflections correspond to changes in the direction of crustal plate movement and, therefore, changes in the stress field within the plate. Such changes in stress could allow granitic melts to ascend from the lower crust, explaining the formation of major batholiths at these times.

Mineral potential of the Mount Webb region

Although the present results are preliminary, the primary and alteration geochemistry of the felsic magmas of the Mount Webb region resemble those of other Proterozoic Cu–Au mineralised areas. There is evidence of extensive magmatic alteration (sodic–calcic and sericitic) at some localities, particularly within the more felsic varieties of the granite. Within the sericite-altered granites, fluorite, tourmaline, and sulphides are common accessories, and some of the samples have anomalous F, Cu, and S. Cross-cutting veins also have elevated Mo and Pb values. There is also evidence of metasomatic alteration of the adjacent country rock.

Recent exploration results have confirmed that this truly ‘greenfield’ 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).

Acknowledgments

Lesley Wyborn and Murray Hazell thank Aurora Gold for facilitating their trip to the remote Mount Webb region. The invaluable assistance of Lorna Fitzgerald and Dean Butler of Aurora Gold, and Bobby West and other members of the Kiwirrkurra community during the sampling program is gratefully acknowledged.

24 ABSTRACT 6 - Proterozoic Granites: Characteristics, Sources, Derivation & Emplacement

AUSTRALIAN PROTEROZOIC GRANITES - CHARACTERISTICS, SOURCES AND POSSIBLE MECHANISMS FOR DERIVATION AND EMPLACEMENT.

L.A.I. Wyborn[1], I.V. Bastrakova[1] and Anthony R. Budd[1]

[1]Australian Geological Survey Organisation, GPO Box 378, Canberra, ACT 2601

AGSO Record 1998/33, 47-49.

Granites are a prominent component of almost every Australian Proterozoic orogenic domain. Exposed outcrops of granites and their comagmatic volcanics cover at least 145 000 km^2, and based on gravity and aeromagnetic data, the subsurface extents of granite plutons are likely to be at least 3 times greater. As part of a collaborative project between AGSO and the State and Territory Geological Surveys, and using techniques developed by Bruce Chappell and his coworkers in the Lachlan Fold Belt, some 10 000 chemical analyses were compiled of Proterozoic granites and felsic volcanics, as well as information on their age, mineralogy, host rocks, and associated mineralisation. Using this database and the 'suite' concept (Chappell, 1984), it is possible to identify 9 major types, most of which have analogues in lower Palaeozoic granite suites of the Lachlan Fold Belt.

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 and Stevens (1988).

2) Most Australian Proterozoic granites have high K_2O/Na_2O which manifests itself as ubiquitous K-feldspar phenocrysts commonly up to 4 cm in diameter. 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.

3) Proterozoic mantle normalised trace 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 km and required geothermal gradients of $>30° km^{-1}$. 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 with 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).

Within the period 1880 to 1500 Ma Wyborn *et al*. (1997) have shown the dominant Sr-depleted, Y-undepleted I-(granodioritic) types can be further divided into three groups which show a time progression in geochemistry. The oldest group (Group 1) at 1870-1850 Ma (~ 31%), 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. Group 2, emplaced at 1840-1800 Ma (~ 30%), is a low-Ca type that 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 youngest group, Group 3 (~24%) is the most enriched in incompatible elements and comprises three subgroups: Subgroup 3_1, dated at around 1800-1780 Ma, has very high values of Zr, Nb and Y; Subgroup 3_2, usually emplaced between 1760 and 1650 Ma, is enriched in F and has variable amounts of Y, Zr, and Nb; and Subgroup 3_3, 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 also has the lowest values of Y, Zr and Nb in Group 3.

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 and Stephens 1988). 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 2.0 to 2.6 Ma and 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 (Goncharov *et al.*1998) as is required by the mantle-normalised trace element patterns of the granites. The high K_2O 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 from Groups 1 to 3 is that as the temperature in the source region increases, the magma production is dominated initially by minimum melting of quartz, K-feldspar, albite and some biotite, with calcic plagioclase, amphibole and some biotite being restite phases (*i.e.*, restite-rich Group 1 granites). As the temperature increases in the source region, melting is initially dominated by biotite breakdown and is then followed by amphibole breakdown as source temperatures reach >1000° C, progressively producing Group 2 then Group 3 granites. In reality there is a continuum between the three Groups which simply reflects increasing temperature in the source region.

However, the inferred increase in 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 Group 3_3 granites (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 (*e.g.*, Sandiford *et al.* in press).

Several researchers (*e.g.*, Chamberlain and Sonder 1990; Sandiford and 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 and 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 *e.g.,* 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 Subgroup 33. 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.,* 1998)

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 (*ie.* Cordilleran granites) in Australia from the mid Palaeozoic onwards.

REFERENCES

Chamberlain, C. P. and Sonder, L. J. 1990. Heat-producing elements and the thermal and baric patterns of metamorphic belts. *Science*, 250, 763-769.

Chappell, B. W. 1979. Granites as images of their source rocks. *Geological Society of America, Abstracts with Programs,* 11, 400.

Chappell, B. W. 1984. Source rocks of I- and S-type granites in the Lachlan Fold Belt, southeastern Australia. *Philosophical Transactions of the Royal Society of London, Series A,* 310, 693-707

Chappell, B. W. and Stephens, W. E. 1988. Origin of infracrustal (I-type) granite magmas. *Transactions of the Royal Society of Edinburgh, Earth Sciences,* 79, 71-86.

Cull, J. 1982. An appraisal of heat Australian heat-flow data. *BMR Journal of Australian Geology and Geophysics,* 7, 11-21.

Goncharov, A., Drummond, B. J., Tripolsky, A. and Wyborn, L. A. I. 1998. Average composition of the crust in the Australian, Fennoscandian, and Ukrainian shields from refraction seismic studies and petrophysical modelling. *AGSO Research Newsletter,* 28, 20-28.

Hobbs, B. E., Ord, A. and Walshe, J. L. 1998. The concept of coupled geodynamic modelling with special reference to the Yilgarn. In: Abstracts for 'Geodynamics and gold exploration in the Yilgarn', *Australian Geodynamics Cooperative Research Centre, Nedlands,* 36-39.

Sandiford, M. and Hand, M. 1998. Australian Proterozoic high-temperature, low-pressure metamorphism in the conductive limit. *In:* Treloar, P.J., and O'Brien, P.J., (eds), *What drives metamorphism and Metamorphic reactions? Geological Society of London, Special Publications*, 138, 109-120.

Sandiford, M., Hand, M., and McLaren, S. in press. High Geothermal Gradient metamorphism during thermal subsidence. *Earth and Planetary Science Letters.*

Wyborn, L. A. I. Ord, A., Hobbs, B. and Idnurm, I. 1997. Episodic crustal magmatism in the Proterozoic of Northern Australia - a continuum crustal heating model for magma generation. *Australian Geological Survey Organisation, Record,* 1997/44, 131-134.

Wyborn, L. A. I., Idnurm, M., Budd, A. R., Bastrakova, I. V., Hazell, M. S., and Edgecombe, S. M. 1998. What do ~10 000 whole rock geochemical analyses tell us about Australian Proterozoic Intraplate Igneous Activity. *Geological Society of Australia, Abstracts,* 49, 484.

