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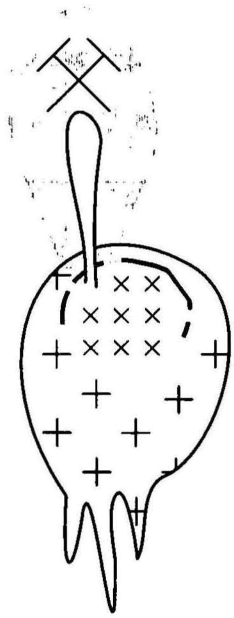

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ISSN: 1448-2177
ISBN: 0 642 46772 2

Recommended forms of reference to this publication are:

a) For reference to an individual paper

CHAMPION, D.C. & BULTITUDE, R.J., 2003, Granites of north Queensland, *in* BLEVIN, P., JONES, M., & CHAPPELL, B., editors, Magmas to Mineralisation: The Ishihara Symposium, Geoscience Australia, Record 2003/14, 19-24.

b) For general reference to the publication

BLEVIN, P., JONES, M. & CHAPPELL, B., editors, 2003, Magmas to Mineralisation: The Ishihara Symposium, Geoscience Australia, Record 2003/14, 155 pp.

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METALLOGENY OF GRANITIC ROCKS

Phillip Blevin
PetroChem Consultants, Canberra ACT Australia

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

Important Metallogenic Parameters

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

Granite type

Classification according to broad compositional character (I, S, A, metaluminous, peraluminous and peralkaline) is important as a guide to the abundance of elements and volatiles in the granites, and their behaviour during fractionation processes. Granophile elements are associated with silica-rich granites while Cu tend to be associated with granite of more intermediate silica contents. Peralkaline granites tend to be strongly compositionally evolved and high in Ta, Nb, Zr and related elements. Provinces with silica distributions skewed to high values are typically associated with Sn, Mo, U and related Au mineralisation, while those skewed to intermediate or lower SiO_2 values are more typically associated with Cu. Potassium and total alkali contents provide useful information on the petrographic character of granite suites.

Degree of Compositional Evolution

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

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

Degree Of Fractionation

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

Oxidation State

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

Classification of oxidation state can be made using petrographic and mineralogical criteria, whole rock Fe_2O_3/FeO ratios, and geophysical methods. Correlation of these parameters has allowed the development of a classification scheme based on whole rock Fe_2O_3/FeO and FeO* (total Fe). An oxidation parameter (ΔOx) has been introduced and can be determined from the following relationship:

$$\Delta Ox = \log_{10}(Fe_2O_3/FeO) + 0.3 + 0.03{*}FeO^*$$

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

Five oxidation classes are recognised (Fig. 2): very strongly, strongly and moderately oxidised; and moderately and strongly reduced. Very felsic granites usually have exaggerated Fe_2O_3/FeO ratios or a susceptible to alteration effects and other methods need to be employed. Peralkaline granites behave differently because of compositional and melt structure considerations that result in high Fe_2O_3/FeO ratios, and need to be treated differently. Rocks belonging to each of these divisions can be characterised by distinctive petrographic and mineralogical features, although *Very Strongly Oxidised* rocks are very rare. *Strongly Oxidised* rocks have abundant magnetite in addition to titanite, and high Mg biotite. Igneous suites associated with economic porphyry Cu-Au systems typically lie in the *Strongly Oxidised* field and have ΔOx values ranging from 0.5 to 0.8.

Metal Zonation and igneous metallogenic provinces.

The combination of the parameters used above, and the areal extent of suites having those features can be used on a district to regional scale to interpret relationships between igneous rocks and ore deposits. Deposit zoning and mineral occurrence data can also be used as a key input in recognising magmatic-hydrothermal "districts". The most intrusion-proximal, high temperature metal association within these districts is defined as the "core metal association" (Fig. 3). Five such core metal associations (Cu-Au, Cu-Mo, Mo, W-Mo-Bi, Sn-W) are recognised and relate back in a systematic way to compositional features of the related igneous suites. Gold is associated with all these core metal associations. The location of economic gold mineralisation within these hydrothermal systems changes from proximal in Cu-Au centred systems (e.g. Cadia, Australia), to the more distal base-metal zone in W-Mo-Bi centred systems (e.g. Kidston, Australia).

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

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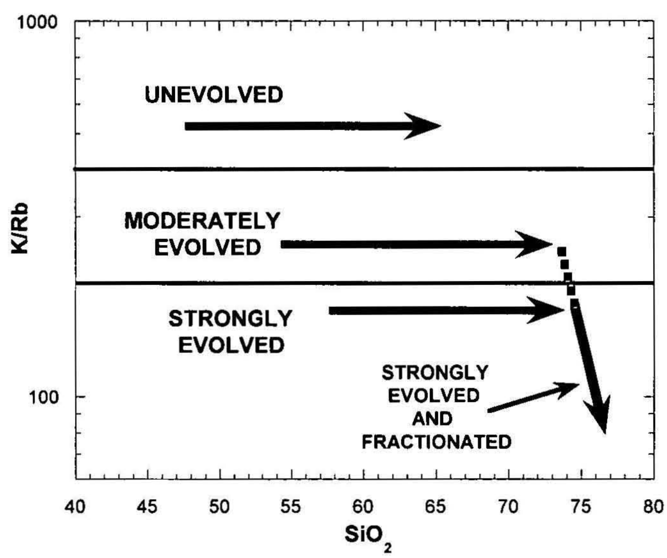

Fig 1 K/Rb classification scheme showing classification fields and typical trends.

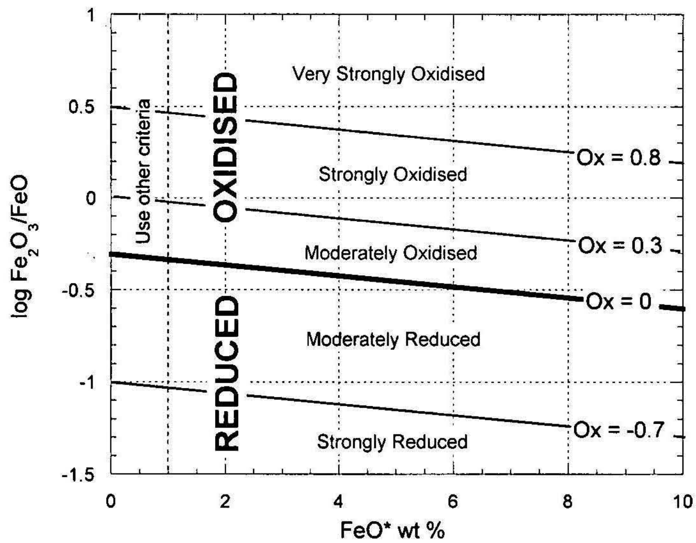

Fig. 2. Redox classification scheme for igneous rocks. FeO* refers to all Fe in the sample reported as FeO. Ox values refer to ΔOx values as defined in the text.

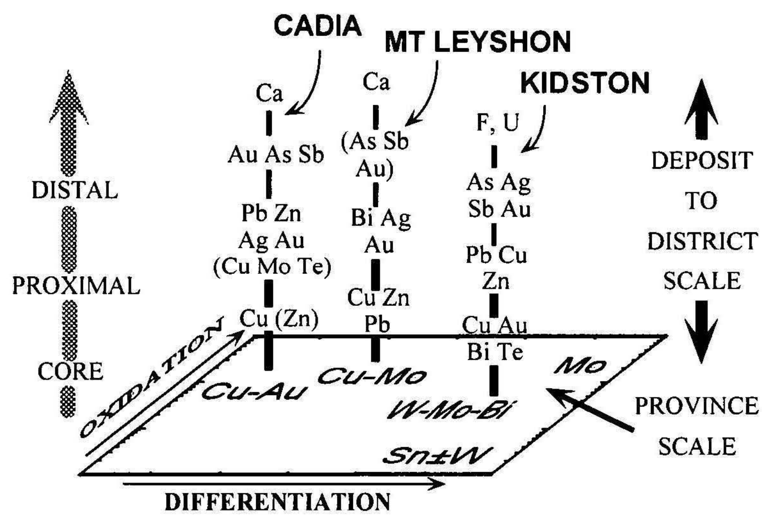

Fig. 3: Conceptual diagram illustrating relationships between metal zonation at the deposit or district scale and how it relates back to higher-temperature proximal igneous-centred systems (Cu-Au, Cu-Mo, W-Mo, Sn-W, Mo). These correspond to the main porphyry deposit types.

PALAEOZOIC GRANITE METALLOGENESIS OF EASTERN AUSTRALIA

P. L. Blevin
PetroChem Consultants, Canberra ACT Australia

Introduction

Granites (s.l.) and related rocks of eastern Australia can be classified according to metallogenic potential using a scheme based on compositional character, degree of compositional evolution, degree of fractionation, and oxidation state. The scheme is based on empirical and theoretical considerations and satisfactorily describes the known distribution of granite-related mineralisation (Figure 1).

Granitic rocks of eastern Australia range from unevolved, mantle compatible compositions to highly evolved and fractionated. They exhibit age- and region-specific variations in silica content, compositional evolution and oxidation state (Blevin et. al., 1996). The most unevolved intrusive igneous rocks comprise those of the Ordovician of the Lachlan Orogen (LO), and the Devonian of the New England Orogen (NEO). Strongly fractionated and evolved I-type granites occur in western Tasmania, the southern NEO, and far north Queensland. Other fractionated suites tend to occur relatively rarely in the LO (eg. the Boggy Plain and Koetong Supersuites) and elsewhere (e.g. Tuckers Supersuite in north Qld).

Oxidation states of granites vary markedly throughout eastern Australia. The most consistently oxidised rocks occur in the Ordovician of the central LO, the Urannah Batholith and Devonian of the northern NEO. The Carboniferous I-types of the northeastern LO are consistently more oxidised than other Siluro-Devonian I-types of the LO. The oxidation states of granites in some areas appear to be influenced by wall rocks.

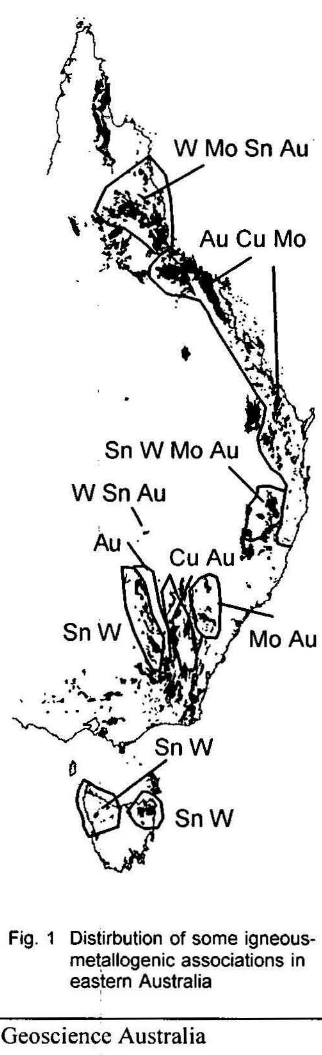

Fig. 1 Distirbution of some igneous-metallogenic associations in eastern Australia

Northern Queensland

Both the Cape York Granites and Coastal Ranges (Georgetown-Herberton) Province are relatively felsic with the majority of granites containing more than 70 % SiO_2. Only the granites of the Coastal Ranges Province have members that are strongly fractionated. The granites of Cape York are very similar in many regards to the similarly aged Siluro-Devonian granites of the LO (and Siluro-Devonian of the Ravenswood Batholith), and their metallogenic potential is considered to be similar. Sn-, W- and Mo-centred systems are widespread in the Carboniferous to Permian Coastal Range and related granites. A significant break in the compositional character of granite magmatism occurs just north of Townsville from more evolved in the north to less evolved and fractionated granites to the south. Cu-Mo-Au centred systems dominate in the oxidised, more unevolved Permian of the Ravenswood Batholith.

Northern New England Orogen

Devonian igneous rocks of the NNEO (Mount Morgan Tonalite Complex) share with the Ordovician of the LO the most unevolved compositions and highest K/Rb ratios of all intrusive igneous units in eastern Australia. The MMTC has trace element and REE signatures indicative of an island arc derivation. The absence of HREE depletion precludes garnet as a residual phase in the source. Sr contents are modest and the low Al_2O_3 nature of the MMTC suggests that plagioclase was a residual phase. The presence of a reasonably continuous compositional range within the MMTC suggests fractionation of basalt as the most likely origin.

Post-Devonian magmatism in the northern NEO comprises moderately evolved compositions (200 < K/Rb < 400). Granites of the Yarrol Province and the Urannah Batholith are on average less compositionally evolved in terms of K/Rb than granites further to the south (i.e. have many units with K/Rb values between 300 and 400). Granites of the Auburn Province (Rawbelle) are clearly less evolved than those of the Moonbi Supersuite of the New England Batholith in the southern NEO with which it is usually compared. Cu-Au mineralisation dominates in the northern NEO from the Devonian to the Cretaceous but tends to be low grade. Intriguingly, oxidation states of most of the intrusive rocks in this region, with the exception of the Urannah Batholith, might not be as high as otherwise expected. More studies are required to establish the veracity of this, but the region retains potential for Au-rich systems, and Ag.

Southern New England Orogen

The granites of the southern NEO fall into two distinct groups in terms of K/Rb. The Clarence River Supersuite (CRSS) has K/Rb ratios around 250 to 350, while all other supersuites have markedly lower K/Rb ratios. In this regard the CRSS granites are more typical of the Yarrol Province and the northern NEO in general than of the south. The Moonbi Supersuite granites are similar in terms of compositional evolution to that of the Carboniferous I-types of the Georgetown-Herberton region of far north Queensland. Marked contrasts between the northern and southern portions of the Moonbi Supersuite are also mirrored in their divergent metallogenic associations. The granites of the southern NEO have a relatively restricted range of oxidation states, with neither strongly oxidised nor strongly reduced examples being present.

The southern NEO remains an enigmatic region of eastern Australia where a very large number of small mines are associated with a large volume of otherwise highly prospective granites. The northern part of the Moonbi Supersuite is highly prospective for Sn and Au deposits. Gold styles like those of Kidston should not be ruled out for systems still buried in Permo-Triassic volcanics or covered by Tertiary basalts. The Clarence River Supersuite is not strongly oxidised, indeed only weakly so, and its prospectivity for porphyry Cu-Au type mineralisation can only be rated as very low. However, these granites should be prospective for Au-Ag associations in both vein and epithermal styles.

Lachlan Orogen: Ordovician

The Ordovician igneous systems of the LO are hosted in four longitudinal belts. More recent petrochemical and geophysical studies have supported a contemporaneous intra-oceanic island arc setting. Ordovician igneous units can be divided into two general compositional types. The majority plot in the trachytic portion of the total alkali-silica (TAS) diagram and fall typically into the very-high-K (shoshonite) field on K_2O-SiO_2 plots. The other group plots along a typical calc-alkaline basalt-andesite-dacite(-rhyolite) (BADR) trend on TAS plots and fall into the medium- to high-K fields on K_2O-SiO_2 plots. Transitional suites between these two trends are not common. Both compositional and isotopic data support an unevolved mantle origin for the Ordovician magmatism. However the mg# of the magmas are relatively evolved and indicate that they represent fusion products of variably enriched mantle materials (Blevin, 2002).

In addition to their unevolved nature, the high relative oxidation state of the Ordovician units clearly distinguishes them from the Siluro-Devonian of the LO (Fig. 2). The major metallogenic association is that of porphyry Cu-Au.

Lachlan Orogen: Siluro-Devonian and Carboniferous

Post-Ordovician granitic magmatism comprises a substantial proportion of the present exposed area of the LO of south-eastern Australia. Although a large number of mineral deposits and occurrences are present, only Sn and W systems are world class in size and these are largely restricted to Tasmania. Numerous metallogenic associations exist however and many have Au present. This provides opportunities for exploration and discovery of new deposits.

The majority of Siluro-Devonian I-type granites are typically too felsic and not strongly oxidised enough for porphyry Cu-Au systems, and not fractionated and oxidised enough for porphyry Mo systems (Fig.2). Sn and Sn-W systems are developed on a world-class scale in reduced and fractionated granites of the central LO and Tasmania.

The granites of the Tasmanian west coast are associated with some of the largest granite-related mineral deposits in south-eastern Australia. These include world-class deposits of Sn (Renison, Cleveland, Mt Bischoff), W (King Island, Kara) and polymetallic zoned systems (Zeehan). These granites are felsic, and mostly highly fractionated and thus are difficult to classify. However, use of chemical, isotopic, and petrographic data enables a satisfactory classification of these granites for the purposes of metallogeny. The granite at Renison is I-type, and long with much of the rest of east Australia, demonstrates that I-type granites have been the major source of Sn in Australia. Taswegian granites are distinct from those of the rest of the LO in that they are generally younger than the main Siluro-Devonian magmatic event and all show the effects of feldspar fractionation (with the exception of the King Island granites). The I-type granites (again with the exception of the Grassy Suite) differ from other LO I-types granites by having higher Zr, Th and U, and being lower in Sr and Pb for any given value of SiO_2 or FeO*. Taswegian Granites are related to intense mineralisation because they are strongly fractionated, fortuitously shallowly exposed and intrude sequences containing reactive carbonates that provide efficient chemical traps for mineralised fluids.
The Carboniferous granites of the northeastern LO have Mo-W, Sn and Au metal associations reminiscent of the Stanthorpe Group of granites within the Moonbi Supersuite (Timbarra); and with the Carboniferous Ootann Supersuite of the far north Queensland (Kidston, Red Dome). While the Carboniferous granites lack the extensive areas of highly fractionated granites as other systems, some strongly fractionated members exist.

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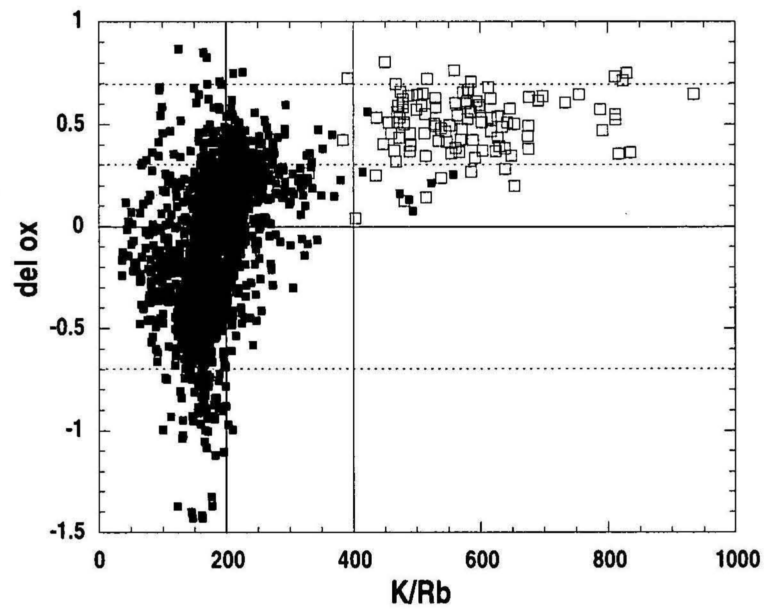

Figure 2. K/Rb ratio versus relative oxidation state for intrusive igneous rocks, Lachlan Orogen. del Ox refers to relative redox states calculated from Blevin (this volume). del Ox > 0 are oxidised. Open squares = Ordovician units, closed squares = Siluro-Devonian units. Ordovician units fall into the field associated with porphyry Cu-Au.

GRANITES OF THE SOUTHERN NEW ENGLAND OROGEN

C.J. Bryant, B.W. Chappell and P.L. Blevin

The New England Orogen (NEO) is easternmost and youngest portion of the Australian continent, generated as a consequence of Devonian to Triassic subduction-related activity. In the southern NEO this subduction-related volcanic and sedimentary assemblage is intruded by Late Carboniferous–Triassic I-, S- and more rarely A-type granites of the New England Batholith (NEB).

S-type Granites

Two temporally and geochemically distinct phases of S-type plutonism are recorded at ~303 Ma (Hillgrove Supersuite) and ~280 Ma (Bundarra Supersuite).

Hillgrove Supersuite

Granites of the Hillgrove Supersuite are commonly intensely foliated. Although they have low CaO, Na_2O and Sr, and are strongly reduced (locally contain graphite), other typical S-type characteristics are poorly developed; (i) they are not particularly peraluminous; ferromagnesian minerals include dominant aluminous russet red biotite, and minor almandine-rich garnet, actinolitic amphibole and cummingtonite, (ii) are comparatively mafic and compositionally diverse (65-75 wt % SiO_2), (iii) P_2O_5 is negatively correlated with SiO_2, as for I-type granites, (iv) isotopically relatively primitive for S-type granites ($^{87}Sr/^{86}Sr$ = 0.705-0.706[1]). Granites of the Hillgrove Supersuite are interpreted to have been derived from young volcano-sedimentary materials[2]. The granites record subtle regional variation is sediment chemistry.

Bundarra Supersuite

The Bundarra Supersuite is almost universally coarse-grained and generally porphyritic, containing large K-feldspar crystals. Although distinct groupings have been identified[3], these granites are chemically very coherent. They are strongly reduced (white K-feldspar; ilmenite; $\delta^{18}O > 12‰$[4]), and are more classically S-type than those of the Hillgrove Supersuite, being more felsic (typically >71 wt % SiO_2), having higher Al_2O_3 and P_2O_5, and containing characteristic alumina-rich minerals (cordierite>muscovite>Fe-rich garnet). The greater peraluminosity of Bundarra granites is consistent with higher degrees of weathering of the sedimentary source materials. However, comparably low $^{87}Sr/^{86}Sr$ ratios indicates rapid reworking of juvenile crustal source components. Subtle, yet significant differences in Th, U, LREE, and Na_2O, indicate that the sediments involved in the genesis of the Bundarra and Hillgrove supersuites were derived from chemically distinct crustal protoliths.

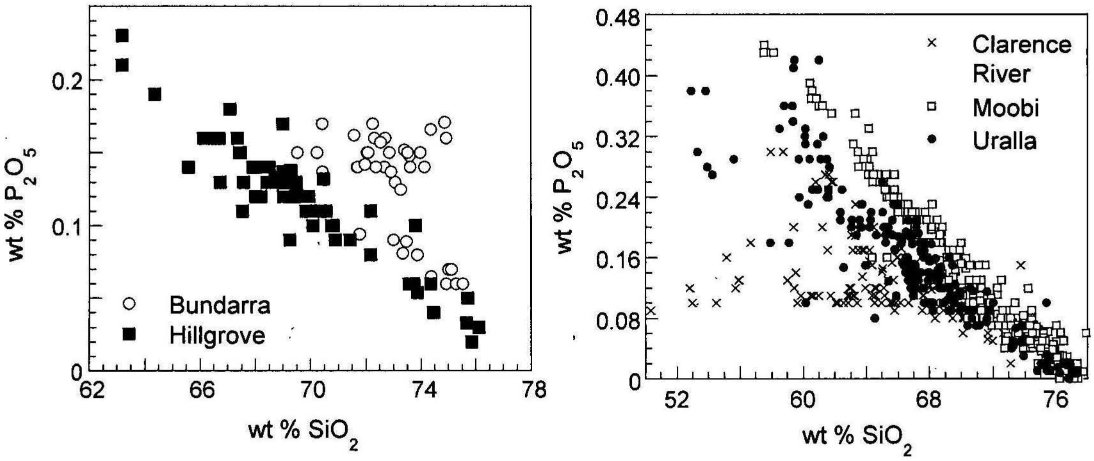

Figure 1: P_2O_5 Harker diagrams for NEB S-type (Bundarra and Hillgrove supersuites) and I-type granites (Clarence River, Moonbi and Uralla).

NEB I-type granites

I-type granites in the NEB are primarily Late Permian–Early Triassic[2] in age. Three major supersuites are recognized.

Moonbi Supersuite

The Moonbi Supersuite (MSS) consists of strongly oxidised, high-K hornblende-biotite (±augite) granites that are characterised by abundant pink K-feldspar megacrysts, titanite and magnetite. Overall, Moonbi granites have high K_2O, Rb, Sr, Ba, Th, U, P_2O_5 and Pb. Nevertheless, geographically significant geochemical variations exist; southern MSS granites have distinctly higher K_2O, Rb, Sr, Ba etc, are more mafic and have lower Y and HREE than the northern MSS intrusions. The latter are dominated by more highly fractionated leucogranites.

Moonbi granites have geochemical similarities with those of the Sierra Nevada batholith and show distinct chemical overlaps with Carboniferous LFB granites[5]. Southern MSS granites are possibly derived partial melting of a garnet-bearing shoshonitic crustal source[3].

Uralla Supersuite

The Uralla Supersuite is compositionally diverse (47–77 wt % SiO_2), consisting of speckled black and white, and typically equigranular granites. Although some overlap exists, they generally have lower K_2O, P_2O_5, Rb, Th, U, light REE (LREE) and Ba and higher Y and HREE than the neighbouring southern MSS intrusions, being more equivalent to the northern MSS in this regard. Although classified as I-type, the Uralla granites have many characteristics that are transitional between NEB S- and I-type granites (*c.f.*, ilmenite-series granites of *Ishihara*[6]), including lower redox states (lower Fe_2O_3/FeO; $\delta^{18}O$ typically > 9[4]), lower normative diopside, higher initial $^{87}Sr/^{86}Sr$ ratios (~0.7046-0.707)[2] and lower δ^7Li[7], indicating the involvement both infracrustal and sedimentary source components. The supersuite can be subdivided into a number of distinct spatially associated geochemical groups.

Clarence River Supersuite

The Clarence River Supersuite consists of calcic and sodic, predominantly dioritic, tonalitic and granodiorite intrusive rocks that are characterized by variable but generally low abundances of K_2O, P_2O_5, Rb, Ba, Nb, Pb, Th, U, LREE, and Sr. They are isotopically juvenile, typically having $^{87}Sr/^{86}Sr_{initial}$ of 0.7032 to 0.7038 and commonly having ε_{Nd} of >+4[8], and δ^7Li of +8 to +2.2‰[7]. They are geochemically and isotopically equivalent to intraoceanic arc lavas. The Clarence River Supersuite is very similar to the Cordilleran granites of the western Peninsular Ranges Batholith, and are likely to have formed either as a direct product of arc magmatism or by partial melting of juvenile arc-derived materials[8].

"Coastal" granites

The granites within the most eastern portion of the NEB incorporate a heterogeneous assortment of I- and more rarely A-type granites. Although distinct geochemical differences are evident, I-type granites from this region share have similarities with those of the Clarence River Supersuite, typically having higher Na_2O, relatively low K_2O, Rb, Th, U, and Pb, and more juvenile isotopic signatures. These features suggest minimal contributions from more enriched and evolved continental crustal materials.

A comparison with the Lachlan Fold Belt

NEB granites differ markedly from the Devonian LFB granites[5]. The NEO clearly has elements that derive recent subduction-related processes, and this is reflected within the chemistry of the granites and in the relative distribution of granite types. Notably, S-types are less common within the NEB, and overall the S-type features are less pronounced. Tonalitic I-type granites (Clarence River Supersuite) are more typical of the younger Cordilleran granite belts. Moonbi granites also have a distinctly arc character, although a direct linkage between with subduction zone magmatism is perhaps more difficult to establish.

NEB granites are demonstrably more heterogeneous over similar distances than their LFB counterparts. Consequently, few suites[9] contain more than one pluton. This heterogeneity is also manifested in the transitional chemistry between the Moonbi and Uralla granites, and the greater overlap observed between S- and I-type granites. These features, combined with the comparably low initial $^{87}Sr/^{86}Sr$ of both S- and I-type granites are consistent with rapid reworking of a young, isotopically juvenile and tectonically complex crustal assemblage. The NEO as a whole perhaps represents a classic example of how we go about building and differentiating continental crust through subduction environment.

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ARCHAEAN GRANITES

D.C. Champion[1] & R.H. Smithies[2]
[1]Geoscience Australia, GPO Box 378, Canberra, ACT, 2601.
[2]Geological Survey of Western Australia, 100 Plain St, East Perth, 6004.

Archaean cratons that formed throughout some 40% of the earth's history (>2500 Ma), now comprise <10% of the continents, but contribute significantly to the world's mineral wealth. Remnant Archaean terrains vary in age from fragments as old as 3.6 to 4.0 Ga (e.g., Isua - Greenland, Acasta – Slave Province), to more common younger cratons (3.6 to 2.5 Ga) of various sizes, the largest being the Superior Province (1,570,000 km^2), which alone constitutes greater than 20% of the total exposed Archaean (Thurston, 1991). Better known Australian examples include the small, but well exposed (<3.6 Ga) Pilbara Craton (45,000 km^2), and the significantly larger, but poorly outcropping Yilgarn Craton (>600,000 km^2), both in Western Australia. Granitic rocks form the main component of most Archaean Cratons (e.g., ~70% of the Yilgarn). They occur as syn-volcanic and younger intrusive units within volcano-sedimentary assemblages (greenstone belts), as intrusive components of batholiths, and as components of high-grade gneissic terrains. Their compositional range is extensive and reflects both short-lived or local tectonic processes as well as longer-term process that relate to regional or global evolution.

Tonalite-Trondhjemite-Granodiorite (TTG) suite

Although ranging from diorite to syenogranite, a large number of Archaean granites are of tonalite, trondhjemite or granodiorite composition, a feature which led early workers to introduce the TTG-suite terminology (Jahn et al., 1981; also called TTD: tonalite-trondhjemite-dacite by some workers). This closely coincided with the recognition, perhaps best encapsulated in a series of papers published within the Trondhjemite volume edited by Barker (1979), that the majority of such rocks are unified by a distinctive geochemistry - they are intermediate to felsic (mostly >65% SiO_2), with high Na_2O/K_2O >1.5), low to moderate LILE contents and with no potassium-enrichment with increasing differentiation (e.g., Barker & Arth, 1976). A result is that TTG-suite nomenclature has become largely synonymous with these geochemical features, with one important modification. Arth, Barker and co-workers (e.g., Barker & Arth, 1976), amongst others, recognised that the sodic rock series can be further subdivided into what they termed high-Al and low-Al subgroups (or end-members), discriminated by the contrary behaviour of elements controlled largely by either plagioclase, garnet and/or hornblende. High-Al types, largely interpreted to reflect melting in the presence of garnet and amphibole, but not plagioclase (or via hornblende/garnet fractionation), are characterised by elevated Sr (Sr-undepleted) and Eu, fractionated REEs, with low HREE (Y- and HREE-depleted), and high Sr/Y ratios. In contrast, low-Al members are characterised by lower Sr (Sr-depleted) and Eu, less fractionated REEs, with higher HREE (Y- and HREE-undepleted), and lower Sr/Y ratios, and reflect control by feldspar (either by residual feldspar during partial melting, or via feldspar fractionation). Many studies have shown that most Archaean TTGs fall into the high-Al subgroup (see review by Martin, 1994), and so, unfortunately, a high-pressure origin has become implicit in the term 'Archaean TTG'. Like Drummond et al. (1996), we prefer to follow the original definition of TTGs, i.e., simply restricted to sodic and felsic igneous rock compositions, with high-Al and low-Al qualifiers used as required. In Australia, true TTGs are largely confined to the Pilbara (Table 1), being poorly represented in the Yilgarn. Pilbara TTGs include both low-Al and high-Al types.

Origins of TTGs

Many early studies (best summarised by Barker & Arth, 1976, Barker, 1979) showed that TTGs were ultimately derived from a source with a broadly (low-K) basaltic composition, either by partial melting or fractional crystallisation at a variety of pressures, consistent with numerous experimental data (e.g., Rapp et al., 1991). The lack of mafic end-members in Archaean TTGs suggest that partial melting was the dominant process. Further, the predominance of high-Al TTGs, in conjunction with the inferred hotter mantle in the Archaean, led a number of authors (e.g., Martin, 1986) to propose that most Archaean TTGs were produced by partial melting of subducting slabs. Supporting evidence for this mechanism was provided by the recognition that mg numbers (45-50 and above), and MgO, Ni and Cr contents, of Archaean TTGs are significantly higher than would be expected by simple partial melting of basaltic material alone, the inference being that an additional component such as interaction with the mantle wedge was required. This appears to be the case for younger TTGs (<3.1 Ga), in particular (Smithies, 2000).

Possible modern analogues? - the adakite connection

Arc magmatism in modern convergent plate margins is thought to be largely derived via partial melting of the mantle wedge in response to volatile fluxing from the slab. In rare circumstances, however, typically in regions undergoing low-angle or flat subduction, silica-enriched (>57% SiO_2) magmas with elevated Al_2O_3, Na_2O, Na_2O/K_2O, LILEs, Sr and HREE/LREE and low HREE are found. These magmas, called adakites (Drummond & Defant, 1990), are inferred to be derived by partial melting of the subducting slab (Kay, 1978). They have many close chemical similarities to high-Al TTGs, including trends to elevated mg#, Ni and Cr, leading workers (Drummond & Defant, 1990; Martin, 1999) to suggest that adakites represent modern-day analogues of what is inferred to have been a much more common process in a hotter Archaean mantle. This analogue best fits with late Archaean (post 3.1 Ga) TTGs; older TTGs do not show high mg numbers, Cr and Ni and appear to either require extreme flat subduction with minimal, or no, mantle wedge interaction (Smithies et al., in press), or perhaps a more non-uniformitarian model.

Transitional 'TTGs'

Our work (e.g., Champion & Smithies, 2001), shows that within many Archaean terranes there exists a subclass of sodic granites (which we call transitional TTGs), largely comprising trondhjemites, granodiorites and granites, that when compared to 'true" TTGs have higher LILE contents, show strong enrichment in LILEs (e.g., K_2O) with increasing differentiation, and tend towards more siliceous compositions (68-77% SiO_2), but still possess a similar characteristic high-Al (more rarely low-Al) signature. Typically, such transitional TTGs are either contemporaneous with, or postdate true TTGs, but may also grade to more mafic compositions that overlap with true TTGs. These transitional TTGs dominate some cratons, the best example being the Yilgarn Craton where they comprise some 60% of the granites (Table 1). Although differences between the two may in part reflect smaller degrees of partial melting coupled with fractionation, Sm-Nd isotopic and inherited zircon data indicate that the petrogenesis of most transitional TTGs requires the involvement of pre-existing crust. The extent to which this crustal component represents input via the subduction process (e.g., subducted sediments) is unclear, however, this process does not explain the presence of inherited zircons. Alternative explanations include a response to thicker pre-existing crust (assimilation-fractional crystallisation processes), or pure crustal melts in thickened Archaean crust.

High-Mg andesites/diorites

The intermediate to felsic (55->62% SiO_2), high-Mg andesites/diorites series, (also called sanukitoids), are characterised by high mg# (typically 60 and above), Cr and Ni, requiring a mantle component, and elevated LILEs (medium- to high-K). These rocks are typically ascribed to subduction-modification of the mantle source with or without some later crustal interaction (e.g., Shirey & Hanson, 1984; Smithies & Champion, 2000). First recognised in Canada (Shirey & Hanson, 1984), they appear to form only a minor component (<5%), of Archaean cratons. They are commonly late in the magmatic cycle and appear to be confined to the late Archaean. High-Mg diorites occur within both the Yilgarn and the Pilbara (Table 1), though are best documented in the central Pilbara (Smithies & Champion, 2000), where they form a ca 2.95 Ga suite inferred to have been derived by partial melting of mantle previously modified by slab-melts. Although compositions of high-Mg diorites tend to converge with TTGs at more felsic compositions, they can commonly be discriminated by a number of factors including their elevated LILEs. Like TTGs, high-Mg diorites have inferred modern analogues, i.e., high-Mg andesites.

Other Archaean granite types

Although TTGs are typically considered the main Archaean granite suite, it is increasingly apparent that a great variety of granite types occur within the Archaean (e.g., Sylvester, 1994). More importantly, it is clear that there is a pronounced secularity with increasing granite diversity through time, particularly within Archaean terranes younger than 3.2 Ga (Champion & Smithies, 2001; Smithies et al., in press; Table 1). The range in granite types, especially the secularity, can be largely attributed to three, clearly interrelated, processes (Champion & Smithies, 2001; Martin & Moyen, 2002; Smithies et al., in press): a) increasing felsic component (and perhaps thickness) of crust, leading to both greater crustal interaction and crustal reworking; b) an increasing variety of crustal diversity, in particular in felsic (TTG) and sedimentary protoliths; and c) increasing operation of convergent margin tectonic processes akin to modern-day subduction environments, with associated mantle metasomatism. By the late Archaean equivalents to all modern day granite types can be found. Non-TTG granites include fractionated (and variously contaminated) tholeiites and plagiogranites, intrusive equivalents of basalt-andesite-dacite-rhyolite series, crustal melts of TTGs, S-type granites, alkaline granites and syenites, and lamprophyres. With the exception of S-type granites, all are found within the Pilbara and Yilgarn cratons (Table 1). The most voluminous of these are those interpreted to result from partial melting of TTGs. These include the Low-Ca granites of Champion & Sheraton (1997), which form ~20% of the Yilgarn Craton, and were emplaced throughout the whole craton almost totally within a 25 Ma period (ca 2.655-2.63 Ga).

Mineralisation

The Late Archaean, especially 2.75 Ga and younger, is a period of extensive mineralisation comprising lode gold and other commodities (e.g., Hagemann & Cassidy, 2000). Although, it is tempting to suggest there is some relationship between this mineralisation and the evidence for convergent margin tectonic processes and associated mantle metasomatism operating in the late Archaean, there is no clear direct link. In contrast, most of the Late Archaean gold not only appears to be late, postdating both greenstone formation and TTG and related magmatism, but as pointed out by Hagemann and Cassidy (2000), is often contemporaneous with late crustal magmatism. This certainly appears to be the case for the Yilgarn Craton, where emplacement of the Low-Ca granites overlap with that of the commonly accepted ages (ca 2.64-2.63 Ga) of the inferred Yilgarn-wide gold mineralisation.

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	East Pilbara	Central Pilbara	Eastern Yilgarn
1. TTG high-Al and low-Al; ± crustal contribution	3.45 Ga high-Al; some isotopic evidence for crustal contribution	3.26-2.95 Ga low-Al	3.3 to 2.8 Ga?? Inferred as the source protolith for Low-Ca group granites
2. "Transitional TTG" LILE-enriched sodic magmatism, includes some TTG magmatism; high-Al and low-Al; chemical (± isotopic) evidence for crustal contribution	3.3-3.25 Ga dominantly high-Al; subgroup of low-Al; isotopic & chemical evidence for crustal contribution	3.26-2.95 Ga Low-Al	(2.76 &) 2.71-2.655 Ga High-Ca group; dominantly high-Al; minor low-Al; strong isotopic signature of crustal input
3. Fe-rich medium- to high-K magmatism characterised by strong low-pressure signature; Fe-rich; often elevated HFSE; clear evidence of crustal component	3.3-3.25 Ga		2.74 to 2.66 Ga High-HFSE group.
4. High-Mg diorite LILE-enriched intermediate to felsic magmatism; clear mantle-derived component. LILE-enrichment interpreted as mantle-wedge subduction enrichment (± crustal contribution).		2.95 Ga	2.67 to 2.65 Ga variable LILE & LREE enrichment
5. Alkaline to sub-alkaline (syenitic) intermediate to felsic; variable LILE contents; elevated HFSE		2.95 Ga Portree Complex	2.665 to 2.64 Ga Syenitic group
6. High-K silicic magmatism often with strongly fractionated end-members; chemical and isotopic signatures indicate dominant crustal component (reworking of TTGs?)	2.93 Ga & 2.85 Ga	2.93 Ga & 2.85 Ga	2.655 to 2.63 Ga Low-Ca group. Across whole Yigarn.

Table 1. Archaean granite types of the central and eastern Pilbara and eastern Yilgarn Craton. Data sources in Champion & Sheraton (1997) and Champion & Smithies (2001).

GRANITES OF NORTH QUEENSLAND

D.C. Champion[1] & R.J. Bultitude[2]
[1]Geoscience Australia, GPO Box 378, Canberra, ACT, 2601.
[2]Geological Survey of Queensland, 80 Meiers Road, Indooroopilly, 4068.

Introduction

North Queensland comprises Palaeoproterozoic to Mesoproterozoic basement (Etheridge, Savannah, Croydon[1]) provinces structurally overlain by successively younger components including Neoproterozoic-Cambrian (Iron Range, Cape River, Barnard), Cambrian-Ordovician (Thalanga) and Ordovician to Carboniferous (Broken River, Hodgkinson) provinces (Figs 1, 2). The region has been the site of long lived, episodic, widespread and voluminous felsic I-, S- and rarer A-type magmatism, spanning some 1200 Ma. Major episodes of granite formation include the Mesoproterozoic (ca 1550 Ma), the Cambrian to Ordovician (ca 480-460 Ma) Macrossan Igneous Province, the Silurian to Devonian (ca 430-380 Ma) Pama Igneous Province, and the Carboniferous to Permian (ca 330-260 Ma) Kennedy Igneous Province (Table 1; Fig. 2).

Mesoproterozoic granites

Proterozoic granites in north Queensland are dominated by the Mesoproterozoic granites of the Georgetown region (Forsayth Subprovince (Etheridge Province) and Croydon Province; Fig. 2). These differ markedly from the majority of Proterozoic granites elsewhere within Australia, being dominated by S-type granites, and also comprising Sr-undepleted, Y-depleted sodic I-type granites. The Georgetown region provides a cross-section through the crust, showing that the S-type granites range from small migmatitic bodies at higher metamorphic grades (middle-upper amphibolite) to large plutons at similar and lower metamorphic grades (Bain et al., 1997). Their potassic, LILE-, LREE-, Th- and U-enriched nature coupled with Nd-Sr isotopic data show that they were largely derived from gneissic metasediments similar to those outcropping in the region. The I-type granites, although locally associated with migmatites, more commonly outcrop as a series of higher level plutons. They are characterised by felsic (>68% SiO_2), low- to medium-K, high Al_2O_3, low LILE, LREE and HREE compositions, consistent with an origin from a basaltic composition source derived at high pressure (garnet stable). All granites give similar ages, within error, of ca 1550 Ma (see Bain et al., 1997).

Late Cambrian-Ordovician granites of the Macrossan province

Granites of the Macrossan Province are largely confined to the Charters Towers region (Hutton et al., 1997; Fig 2; Table 1), though also include units within the Barnard Province (Bultitude et al., 1997) and the Georgetown region (Withnall et al., 1997). The Macrossan Province is dominated by I-types of largely granodioritic to granitic composition, but also includes interpreted S-type granites (Hutton et al., 1997). Ages range from Late Cambrian to Mid Ordovician, with granites of the latter age the most common. Hutton & Crouch (1993) showed that the I-type granites are felsic (>65% SiO_2 mostly), are Sr-depleted, and mostly Y-undepleted, and range from medium- to high-K, with K_2O contents increasing in a systematic regional manner south to north. These workers suggested that the granites were predominantly crustal in origin, though indicated that the Late Cambrian to Early Ordovician members may be (continental) arc-related. The interpreted S-types appear to be spatially and/or temporally associated with high grade metamorphism and migmatites. At least some of the 'S-types' are

[1] All province and region names are as defined by Bain & Draper (1997).

characterised by sodic compositions with high Na_2O/K_2O (1.4-2.0; Hutton & Crouch, 1993), suggesting they are, in part, contaminated I-type granites.

Silurian-Devonian granites of the Pama Igneous Province

Granites of the Pama and the younger Kennedy Igneous Provinces, dominate magmatism in north Queensland. Pama Igneous Province granites outcrop principally in the Georgetown, Coen and Charters Towers regions (Fig. 2, Table 1). Granite geochemistry varies on a regional scale, with each region having its own distinctive signature. The oldest, the largely Silurian granites of the Georgetown region, are dominantly tonalitic & trondhjemitic I-types, but range to locally garnetiferous peraluminous granites. Units are characterised by medium- to high-K, Sr-undepleted Y-depleted compositions, with an expanded silica range (60-75% SiO_2) and, like the Proterozoic I-types of the same area, have a chemistry consistent with the involvement of garnet. In direct contrast, the younger (ca 410-390 Ma) voluminous granites of the Coen region are dominated by felsic potassic peraluminous two-mica granites, interpreted as S-types, and minor (<20%) I-type granites and granodiorites (Blewett et al., 1997). These granites represent the earliest true batholithic S-type granites in north Queensland and are similar in many aspects to S-type granites in the LFB. Granites of the Charters Towers region compositionally and temporally fall between those of the other 2 regions. They are dominated by I-types (largely granodioritic, but ranging from tonalite to granite), with lesser S-type and interpreted S-type peraluminous granites (Hutton et al., 1997). The I-type granites have an expanded silica range (<60% to >75 % SiO_2), mostly range from medium- to high-K, and have a number of similarities to Georgetown region granites, but unlike the latter are largely Sr-depleted and Y-undepleted. Chemical compositions more like Georgetown, however, appear to occur in the western part of the Charter Towers region. This difference is also reflected in the Sm-Nd data. Nd depleted mantle model ages are greatest in the Georgetown and western part of the Charters Towers regions (mostly 2.1 Ga and greater), decreasing eastwards in the central (1.7 to 2.0 Ga) and eastern parts of the Charters Towers region (Black & McCulloch, 1990; Champion, 1991; Hutton et al., 1997b). Model ages for the Coen region granites overlap those of the western and central Charters Towers region (Hutton et al., 1997b). The isotopic and chemical data indicate a significant component of pre-existing crust was involved in the genesis of the majority of Pama Igneous Province granites, either as part of the source or via subsequent contamination.

Carboniferous-Permian granites of the Kennedy Igneous Province

Granites of this age, and the significant associated volcanism, represent the most voluminous magmatic event in north Queensland. Magmatism is particularly concentrated within the Georgetown and Cairns region but is found in all regions (Table 1). Magmatism, ranging in age from ca 340 Ma to ca 260 Ma, is dominated by high-K, high SiO_2 (>70%), I-, S- and lesser A-type granites (Table 1), with common moderately to very strongly fractionated compositions. Although grouped as one province, it is evident that the magmatism can be subdivided into 3 temporal subgroups (Table 1): early Carboniferous (KP1), mid-Carboniferous to Early Permian (KP2), and early to late Permian (KP3). KP1 forms a minor component, characterised by felsic I-type magmatism (intrusive and extrusive) which appears to be localised around the margins of the Broken River Province (and perhaps related to basin formation in some manner). KP2 forms the major component of Kennedy Igneous Province magmatism, particularly concentrated along the southern half of the Palmerville fault and its extension south. Magmatism is both extrusive and intrusive, is largely I-type, dominantly monzogranite and syenogranite (rhyolitic to rhyodacitic) but includes granodiorites and lesser quartz diorite and andesite and local basalt/gabbro. Within the Georgetown and Cairns region, KP2 can be further subdivided into early (ca 325-310 Ma), typically strongly fractionated, high silica (>72% SiO_2) magmatism and younger (ca 305-290 Ma) less siliceous, more compositionally variable magmatism. Both have identical evolved isotopic signatures (depleted mantle model ages of 1.5 Ga and older; Champion & Chappell, 1992). KP3, which may form a continuum with KP2, marks a change from dominantly I-type magmatism to more diverse I-, A- and S-type magmatism in the Permian. S-type granites are concentrated almost solely within the Hodgkinson province. A-types occur either as sub-volcanic intrusions closely associated with volcanics of similar chemistry (Mackenzie, 1993), or as generally high-level intrusions (Bultitude et al., 1997). Temporally associated I-types also typically form a similar distribution, and it is notable that a number of these have A-type affinities. Sm-Nd isotopic data for Kennedy Province granites (Black & McCulloch, 1990; Champion, 1991) shows that all granites have a significant component of older crustal material involved in their genesis. More importantly, Nd depleted mantle model ages appear to broadly correlate with provinces. This is best seen for the I-type granites which show a pronounced broad regional decrease in model ages from 1.5 Ga and older in the Georgetown region to less than 1.2 Ga along the eastern margin of the Cairns region. The S-type granites of the Cairns region also follow this trend, and notably have similar or more primitive isotopic signatures to spatially associated I-types. A-type granites overlap with I-types or extend to younger model ages. The majority of intrusion-related mineralisation in north Queensland is associated with granites of the Kennedy Igneous Province. Significant mineralisation includes: Sn and/or W deposits clearly associated with fractionated and reduced I- and S-type granites (Champion & Mackenzie, 1994); W-Mo-Bi deposits associated with more oxidised I-type granites; and Au, in a variety of settings (breccia-hosted, vein-hosted, lode gold, stockwork, skarn), interpreted to be related to I-type granites in a porphyry environment (Morrison, 1994; Blevin et al., 1996). The A-types appear to be unmineralised.

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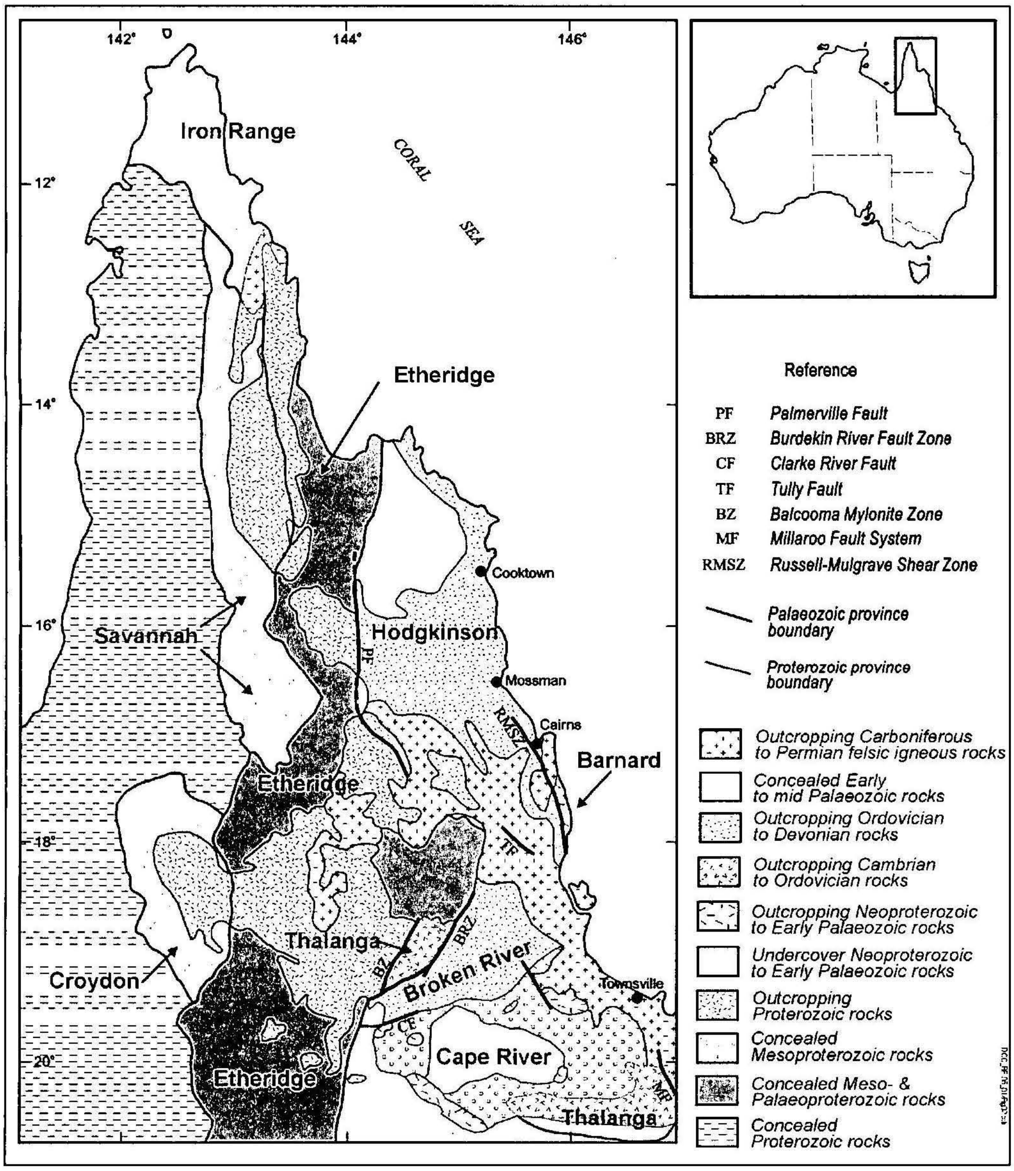

Figure 1. Geological map of the north Queensland region. Province names as defined by Bain & Draper (1997). Geology modified after Bultitude et al. (1995).

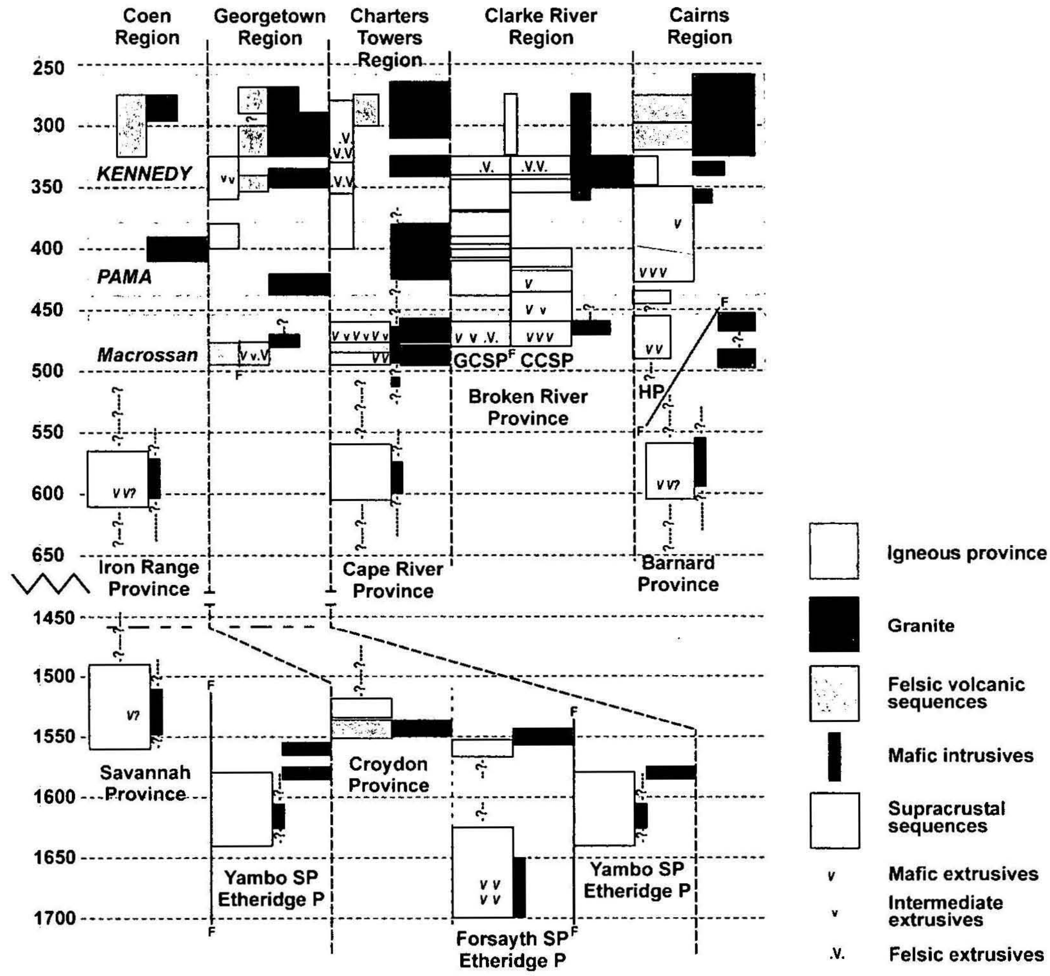

Figure 2. Time space plot for regions and provinces of north Queensland. Compiled from data in Bain & Draper (1977). HP = Hodgkinson province, CCSP = Camel Creek Subprovince, GCSP = Graveyard Creek Subprovince, SP = subprovince, P = province. Igneous province names in italics.

Age	Coen region	Georgetown region	Charters Towers	Hodgkinson region	Clarke River region
Permian	Ig If (M)	If Ig A (M)	If Ig (M)	**S** Ig If A	
Mid Carboniferous - Early Permian	If (Ig)	**If** Ig (It M)	Ig If (M)	**If** Ig (M)	(I?) ((S))
Early Carboniferous		If	**If** (M)	(If, A??)	(If M)
Early – mid Devonian	**S** Ig (M)		**If** S? Ig (M)	?(S)	
Silurian – Early Devonian		**It** Ig (If)	**Ig** If It (M)		((It))
Late Cambrian – Ordovician		(It)	**Ig** If S (It M)	S (I)	
Mesoproterozoic	(Ig S)	**S** It			

Table 1. Granite types for geographic regions of north Queensland. It, Ig & If = dominantly tonalitic, granodioritic, or granitic (monzogranitic & syenogranitic) I-types, respectively. S = S-types, A = A-types, M = mafic rocks (largely gabbros to diorites). Items in bold are dominant granite type for that age period and region; items in single or double parentheses indicate only minor or uncommon component, respectively. Data compiled from information in Bain & Draper (1997).

FROM TUTTLE AND BOWEN ONWARDS

Bruce W. Chappell
GEMOC, Macquarie University, NSW 2010

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

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

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

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

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CAUSES OF VARIATION IN GRANITE SUITES

Bruce Chappell
GEMOC, Macquarie University, NSW 2010

Granite suites each have characteristic compositional features and show regular transitional internal variations in composition. When two elements are plotted against each other the compositional changes reveal themselves as smooth curves, sometimes linear, sometimes curved (White *et al.*, 2001)) Isotopic compositions of suites will normally vary within narrow limits, but may be more variable as a reflection of analogous differences in heterogeneous source rocks. A granite suite will possess characteristic mineralogical features and may also have a distinctive textural character. Single suites may be comagmatic, or else may be cogenetic, both in terms of source and processes. A prime concern in studying granite suites is the process which produced the compositional variation in each case. Following are various possible mechanisms for producing such variation, following Chappell (1996a):

1. Variation inherited from heterogeneous source rocks
2. Varying degrees of partial melting
3. Magma mixing and/or mingling
4. Assimilation or contamination
5. Restite separation, generally restite crystal fractionation
6. Fractional crystallisation (a type of crystal fractionation)
7. Hydrothermal alteration

These processes could operate alone, or sometimes simultaneously (e.g. 4 and 6 in the AFC process), or in some cases sequentially (e.g. 5 followed by 6, or 6 followed by 7). They will be evaluated on the basis of observations that have been made on the granites of eastern Australia.

These different mechanisms will be considered, particularly 3, 5 and 6, those to which a major role has most often been ascribed in producing variation within granite suites.

Magma mixing and/or mingling

This is an extremely popular mechanism for producing compositional variations. A current widely accepted model (e.g. Barbarin, 1991) envisages melt from the mantle partly melting the crust as it crystallises and cools. The two components then mingle to produce a range of rock compositions. Most of the types of evidence cited in support of this model are seen among the granites of the large I-type Bega Batholith (8940 km^2) of the eastern Lachlan Fold Belt (LFB). These include the presence of mafic enclaves that are generally more abundant in the more mafic host rocks, hybrid rocks at Tuross Head, striking examples of linear chemical variations, noting that Wall *et al.* (1987) have stated that "mixing is the classic cause of linear variation in major and trace element Harker diagrams", and variations in isotopic compositions that can readily, although not necessarily correctly, be accounted for on the basis of mixing of various end-member compositions. However, the rocks of this batholith show compositional features that are not consistent with the variation within suites having been produced in that way. When the compositions of pairs of suites are compared, any differences seen at either end of the range in composition are also seen at the other limit, so that both the most mafic and felsic rocks show similar relative abundances of particular elements (Chappell, 1996b). The probability that mafic and felsic end-member components would so consistently choose mixing/mingling partners that share their particular compositional features relative to other mixing pairs is so small that it can be rejected. Furthermore, while the rocks of the Bega Batholith show isotopic compositions that could be produced by mixing of discrete end-members (e.g. Keay *et al.*, 1997), the isotopic variations within suites are relatively small and not of a type that would have been produced by the mixing of more isotopically evolved crust with more primitive mantle-derived components (Chappell & McCulloch, 1990). We are forced to agree with Pitcher (1993, p. 136) who stated that "For all their eye-catching display in outcrop, mingling and mixing in the higher levels of the crust represent but second-order processes in the diversification of the granitic rocks".

These arguments and such a conclusion apply to variations with granite suites of the LFB, but are not directly applicable to the question of the granites having been derived from mixed source rocks, as has been proposed by Gray (1984, 1990), Collins (1996) and Keay *et al.* (1997). Since considerations of such broader scale mixing processes are not relevant to the questions of compositional variations within suites of granites, they are not part of this present discussion.

Assimilation or contamination

Some contamination of granite plutons by components from the country rocks would be expected; it is a question of scale and the amount by which this process contributes significantly to variations within granite suites. Assimilation has been detected in the Boggy Plain pluton (34 km^2), where initial $^{87}Sr/^{86}Sr$ ratios increase from an average of 0.70441 in the marginal diorites and the granodiorites (29% of area), to an average of 0.70479 in the monzogranites (70%), to 0.70554 in one sample from the central aplitic rocks (0.9%) (Wyborn, 1983). Even in this most favourable case of a relatively hot and initially completely molten magma, the amount of assimilation was very small, and did not contribute significantly to the overall compositional variation.

The presence of cordierite in the granites of the LFB that are now called S-type, has long been recognized, most notably by Baker (1940), who favoured an origin resulting from enrichment of the granite magma in Al by assimilation of argillaceous country rock. Snelling (1960) subdivided granites of the Murrumbidgee Batholith of the LFB into "contaminated" and "uncontaminated" types, and suggested that the "contaminated" granites were derived from a parental magma akin to the "uncontaminated" granites in composition by the incorporation of country rocks at depth. Both of Snelling's groups are S-type. With the recognition of the I- and S-type groups by Chappell & White (1974), is has become generally accepted that the cordierite in the S-type granites is either a product of the process that lead to partial melting of the source rocks (e.g. Chappell *et al.*, 1987), or else precipitated from melts that acquired a strongly peraluminous composition during the partial melting of sedimentary source materials (Clemens & Wall, 1981). However, Collins (1996) has stated that "LFB S-type magmas are heavily contaminated I-type magmas".

Fractional crystallisation

This is the process by which the removal of crystals that have precipitated from a melt leads to progressive changes in composition of that melt. This is a mechanism that has been widely used to account for variation in igneous rock suites ever since it was introduced into petrology by Becker (1897). While this process did not operate as widely in the LFB as is sometimes thought, that region does provide some excellent examples. These include the granites and volcanic rocks of the Boggy Plain Supersuite (BPS) (Wyborn *et al.*, 1987), the felsic I-type granites of the Freycinet Peninsular of Tasmania, and felsic S-type granites of the Koetong Suite and Tasmania. Distinctive characteristics of this process are non-linear element abundances on variation diagrams, extreme enrichments or depletions in some trace elements in cases of strong fractionation, the development sometimes of cumulate rocks, the production of the strongly peraluminous "tin granites", and a more common association with mineralisation than for rock suites that evolved in other ways.

Rocks produced by fractional crystallisation will either have the composition of melts from which crystals have been removed, or else will have compositions that reflect the addition to or concentration of crystals in a melt. In the latter case it is useful to distinguish between *cumulate* rocks in which the precipitated crystals formed a framework with the spaces filled with melt, and *cumulative* rocks in which crystals have been concentrated relative to the melt. The latter term can also be used collectively for both processes.

The Koetong Suite and the "tin granites". At SiO_2 contents above about 70%, the granites of the Koetong Suite in the Wagga Batholith provide an excellent and instructive example of fractional crystallisation, with the rock compositions corresponding to Bowen's *liquid line of descent*. The most felsic granites of the Koetong Suite have compositions that project close to those of experimentally determined "minimum-temperature" melts. For the five analysed samples that contain more than 90% of normative $Q + ab + or$ in the system Q-Ab-Or-H_2O (Tuttle & Bowen, 1958), the average proportions of those three components are $Q_{39}ab_{28}or_{33}$. This compares with the experimentally determined H_2O-saturated value of $Q_{40}ab_{29}or_{31}$. It is noteworthy that those five samples from the Koetong Suite are also strongly corundum-normative with an average value of 3.57% *C*. That those rocks represent melt compositions, with at most very little modification by hydrothermal alteration, is firmly established. Unlike many of the relatively felsic granites of other S-type suites of the LFB, those of the Koetong Suite show clear compositional evidence of fractional crystallisation, with abundances of elements such as Rb, Nb and Cs rising, and Sr and Ba falling, in all cases by factors of three or more, as the rocks become more felsic. P_2O_5 contents also rise with increasing fractionation, which is a distinctive feature of fractionated S-type granites (Chappell & White 1998). Those authors also regarded granites that are associated with the Koetong Suite and which contained much higher Sr abundances as cumulative rocks; however isotopic data have since shown that those rocks are not comagmatic and must be assigned to a separate suite. A detailed study of all S-type granite analyses from the LFB has shown that, apart from a very unusual and restricted example from the Blue Tier Batholith, there are no cumulate or cumulative compositions among the analysed S-type granites of the LFB (see below). That such rocks must exist at depth is implied by the occurrence of fractionated melt compositions. Such cumulative S-type granites are known from elsewhere, e.g. in Malaysia and among the European Hercynian granites.

Studies of the evolution of the Koetong Suite have lead to a much better understanding of the origin of the "tin granites". Such rocks were a significant problem in petrogenesis, with their very felsic, fractionated and strongly Al-oversaturated compositions, the very high abundances of several elements such as B, Rb, Sn, Cs, W and U, and generally a lack of associated less felsic rocks. The Koetong Suite shows a complete transition from quite mafic S-type granites to fractionated compositions that match those of "tin granites" such as Cornwall very closely. This has confirmed that fractional crystallisation is the dominant process in producing the "tin granites".

The Boggy Plain Supersuite. In contrast to the evolution of the Koetong Suite along a liquid line of descent, the rocks of the concentrically zoned Boggy Plain pluton correspond to a sequence of cumulate rocks that crystallised at the contracting boundary between melt and previously crystallised material. That process produced a continuous variation in compositions from 50.1% to 74.8% SiO_2, with one break between the outer contact and the aplitic rocks located near the centre of the pluton. Most of these cumulate rocks would not be recognised as such on textural or individual compositional grounds. However, some compositionally distinctive rocks do occur, with high Cr and low Zr and Ba contents, and a positive Eu anomaly in one case. The most mafic rock of the BPS, a plagioclase-rich cumulate from the Yeoval Batholith, has a very distinctive composition and contained very small amounts of melt, with the bulk rock containing 13.6% CaO, 0.06% K_2O, 0.01% P_2O_5 and 13 ppm Zr. The complementary fractionated melts of the BPS occur as felsic volcanic rocks and as plutons (Wyborn *et al.*, 2001).

Fractional crystallisation in haplogranites. Chappell (1999) discussed the process of fractional crystallisation in felsic haplogranites and contrasted the behaviour of strongly fractionated I- and S-type granites. In all of these rocks the contents of the major elements are very similar and do not change with fractionation, being governed by equilibrium between melt and crystals in the Tuttle & Bowen (1958) haplogranite system. However, trace element abundances change markedly with fractionation, and in ways that can differ between the I- and S-types. The I-type granites of the Coles Bay Suite of the Tasmanian east coast and of the S-type Interview Suite of western Tasmania include some strongly fractionated compositions. In all cases the abundances of elements that occur in mafic minerals, and Ca, which have low abundances, decrease further with fractionation, as do Sr and Ba, while Rb and Cs increase. For the Interview Suite the abundances of P increase while elements that occur in P-bearing accessory minerals other than apatite, such as Th, Y and the REE, decrease to low abundances, while for the Coles Bay Suite granites show the opposite trends.

How common are the products of fractional crystallisation in the LFB? There are some granite suites in the LFB that clearly evolved through fractional crystallisation, but they represent a small fraction of the total, certainly less than one quarter. They comprise the high-temperature granite suites (5% of LFB granites) and the fractionated haplogranites of the low-temperature suites. However, the view is commonly held that the variations within rock suites of the LFB and elsewhere are almost universally the result of fractional crystallisation. For example, Clemens (2003, p. 14), in discussing fractional crystallisation, has stated that "it seems safe to say that crystal fractionation (sic) probably plays a major role in the differentiation of very many granite magmas...". He also states that minor mechanisms include magma mixing, wall-rock assimilation and restite unmixing.

Cumulate and cumulative granites in the LFB. Clemens (2003) takes the view that the more mafic granites of the LFB are products of crystal accumulation. While that is the case for mafic rocks of high-temperature granite suites (Chappell *et al.*, 1998), which are always I-type, it does not seem to be the case for the much more abundant low-temperature I-type suites in the LFB, and for the S-type granites, for four reasons. (1) Low-silica rocks closely associated with granites, apart from those of the BPS and the Marulan Batholith, have a very low abundance in the LFB. Among rocks of the BPS, 26% contain less than 59% SiO_2. Excluding the high-temperature granites of the Marulan Batholith and the Carboniferous granites in the east of the LFB, a few of which are possibly the high-temperature type, no other I-type rocks contain less than 55.5% SiO_2 and only 0.8% contain less than 59% SiO_2. For the analysed S-type granites there are no SiO_2 values less than 63%, except for one analysis of a granite with a concentration of garnet, which is distinct from the other most mafic S-type granites of the LFB, which contain abundant quartz, cordierite, biotite and plagioclase. For all other analysed granites, mafic minerals such as biotite (SiO_2 ~ 35%), hornblende (SiO_2 ~ 47%), pyroxenes (SiO_2 ~ 50%) or cordierite (SiO_2 ~ 50%) did not concentrate, at least in rocks at the present levels of exposure, to the exclusion of minerals such as plagioclase (SiO_2 = 66.3% at An_{50}) and quartz. Rocks of the BPS have bimodal SiO_2 contents, with mafic cumulate rocks and the complementary fractionated melt compositions being the most abundant, with only 10.4% of analysed rocks having compositions between 65% and 70% SiO_2. For the other I-type and the S-type granites, 39.8% and 42.3% of the analyses, respectively, lie in that interval. (2) Chemical equivalence of plutonic and volcanic rocks in the low-temperature granite suites of the LFB strongly suggests that none of the former are cumulative. Wyborn *et al.* (1981) pointed out that the general compositions of some plutonic and volcanic suites of the LFB can be matched fairly closely, and that the compositional differences between plutonic suites are also found in the volcanic suites. The volcanic rocks are not more felsic with a greater proportion of melts from which early-formed crystals had been removed, as would be expected if the more mafic granites are cumulative. Wyborn & Chappell (1986) considered the significance of that observation in more detail, and showed that comagmatic plutonic and volcanic rocks of the LFB can be divided into two groups. In the first group, the plutonic and volcanic rocks can be equated in composition, whereas in the second the volcanic rocks are more felsic than the related plutonic rocks. The first instance includes the low-temperature suites and Wyborn & Chappell (1986) argued that those rocks must represent true magma compositions and cannot be cumulative rocks produced during fractional crystallisation (cf. Clemens 1989). In the second case, the more mafic plutonic rocks represent crystal cumulates and the volcanic rocks and the exclusively felsic plutons, the complementary fractionated liquid. This second situation is illustrated by the BPS which includes rhyolitic lavas, the Mountain Creek Volcanics, that are much more felsic than the comagmatic or cogenetic cumulate plutonic rocks. (3) Apart from the granites of the BPS and the Marulan Batholith, the variations for many elements within granite suites of the LFB are not consistent with those rocks having formed progressively as cumulates. In no I-type suites that are referred to as low-temperature do elements such as P, Zr and Ba that may appear as an important component of new liquidus phases during continuing fractional crystallisation, show inflexions on Harker diagrams, e.g. for Ba in the Cobargo Suite which ranges through SiO_2 contents from 59% to 73%. In that and some other suites of the Bega Batholith, Ba increases in abundance as the granites become more, whereas precipitation of the minerals now present in the rocks would have lead to a depletion in the Ba content of the melt, and therefore in subsequently formed rocks, just as is observed for the Boggy Plain pluton at $SiO_2 > 66\%$. Chappell (1996a) has modeled the variations of some trace elements in I-type suites of the Bega Batholith and the S-type Bullenbalong Suite and shown those variations are not consistent with the rocks forming as cumulates by fractional crystallisation. (4) Rock suites that extend from felsic to mafic compositions without compositional discontinuities. If the more mafic members of the low-temperature granite suites of the LFB are cumulative rocks, then the fractionated melts produced by that process should be represented within the felsic rocks of those suites. Furthermore, the compositions of those felsic granites must represent melt rather than cumulative compositions. This is seen in the felsic S-type granites where compositions enriched in the elements contained in monazite such as Th and the light REE, and in the Sr and Ba contained in precipitated feldspars, which are present in cumulative S-type granites in other areas, do not occur. Among the felsic I-type granites, the distinctive high Sr, Ba and heavy REE that are characteristic of such rocks when they are cumulative, are not seen among any of the low-temperature rock suites that extend to more mafic compositions. If the more mafic rocks of those suites, and of the S-type suites, are cumulative, then compositional discontinuities should be widespread for elements, such as Sr, that partition strongly into cumulative rocks, in passing from felsic melt compositions to more mafic cumulative compositions. These are not seen, which confirms that the mafic rocks are not cumulative.

LFB granites as products of fractionated melts. Collins (1996), for example, has proposed that the granite suites of the LFB represent a series of melt compositions produced by fractional crystallisation from a melt with an initial composition matching that of the most mafic rock in a suite. This eliminates some of the difficulties for the cumulative model, but others persist. Three of these will be discussed. (1) The compositional variation within suites is unlikely to be consistent with fractional crystallisation. This argument is analogous to the third argument above, but it is more difficult to make in this case because the crystals that are presumed to have been removed from the melt are not seen. But a strong general argument can be made, which is that the strong "linear" variations that are seen for many elements would not be expected to result from processes in which the precipitating minerals would be continually varying in relative proportions and in compositions. (2) Complementary cumulative batholiths at depth. A general argument against more mafic granite compositions representing melt compositions was made by McCarthy & Groves (1979) who proposed that the granites of the Blue Tier Batholith are cumulate rocks, and pointed out that the alternative scenario in which the granites represent melt compositions, would imply that "each pluton was formed by a vast number of small separate intrusions, analogous to separate lava flows, each one different from the others". Further, they noted that this "demands a second magma chamber at depth where fractional crystallization occurred". On a broader scale, such a mechanism would require that all of the batholiths of the LFB are underlain by extensive cumulative rocks. (3) Occurrence of inherited zircons. The presence of older zircons in many of the more mafic I-type granites, and in all of the more mafic S-type granites of the LFB, shows that those rocks cannot represent melt compositions (Chappell, 2003). The zircon saturation temperatures (Watson & Harrison, 1983) for the most mafic rocks of various suites are all close to 800°C, which within the limits of the method, represents the maximum temperature at which zircon crystals could be present in equilibrium with a melt of those compositions. That is clearly too low a temperature for such a composition to be completely molten, by a very long way, yet the rocks contain old zircons and the variation of Zr in the suite is also consistent with zircon having been present, as a phase in which the magma was saturated. It is clear that the mafic rocks of these suites cannot have been melts, and consequently the compositional variation within those suites cannot correspond to a series of melts produced by fractional crystallisation.

Varying degrees of partial melting

Beyond the point where progressive melting of a granite source rock leads to the removal of one of the components of that melt (Q + ab + or), the temperature of melting will rise and the compositions of the melt will change as the fraction of melt increases. This is a potential mechanism for the generation of variation within rock suites that probably has not received the attention that it merits. It is approximately the reverse of the process of fractional crystallisation for cases in which extreme enrichments or depletions of trace elements have not been produced by that other process. It is possible that variations within the high-temperature granites of the Marulan Suite of the LFB (Carr *et al.*, 1992) were produced in way, but there would not seem to be any other possible cases in the LFB. It has not been favoured as a general mechanism for any of those granites partly because of their distinctive patterns of linear compositional variation, in contrast to Marulan. But in particular, the fact that the variation within single plutons is parallel to that produced by groups of plutons within a suite, would imply that this mechanism can only have operated if every detail of compositional variation within plutons corresponded to different fractions of melt that had been generated by varying degrees of melting. This process seems to be better suited to producing suites that comprise plutons of different but individually relatively uniform compositions.

Restite separation or fractionation

This is a process of crystal fractionation in which the crystals that are separating from the melt were entrained in the melt at its source. This model for compositional variation was first proposed by White & Chappell (1977) to account for observations that had been made on granites of southeastern Australia. A more detailed account of this process was given by Chappell *et al.* (1987).

Many of the granite suites of southeastern Australia show distinctive linear trends for various elements on Harker diagrams. This has been confirmed by Collins (1996) who referred to "the remarkable linear chemical trends" in those granites. Such linear trends are not consistent with a mechanism of crystal fractionation through fractional crystallisation, as has been seen above. Now that extensive magma mingling can be discounted as a mechanism for the production of these variations (Chappell, 1996b), the mechanism of restite fractionation must be considered. In fact it provides an elegant solution to this problem. A mixture of felsic melt and mafic residual material would result from partial melting of the crust, with different degrees of separation of those two components producing linear correlations between elements. This is a process of fractionation of restite crystals from a melt with in which they were initially distributed following partial melting and with which they were in equilibrium. This would be much easier to achieve, at least on a large scale, than the mingling of molten and solid material that would have different physical properties and, at least initially, would not be in equilibrium. It also accounts for the observed correlations in abundances between the mafic and felsic compositions of various suites, since both were derived from the same material.

The veracity of the restite model has received powerful support from the observation of the widespread occurrence of age inheritance in zircon crystals of the granites of the LFB (Williams, 1995), which lead to development of the concept of high- and low-temperature granites by Chappell *et al.* (1998) (see Chappell, 2003).

Hydrothermal alteration

Subsolidus hydrothermal alteration may alter the composition of a granite as feldspars are replaced by sheet silicates and the loss of those elements that cannot be accommodated in the latter, principally Na, Ca and Sr, while K and Rb could be added from circulating solutions. The primary evidence for alteration is generally petrographic; however chemical data generally show that its effects are overrated. Many rocks in which there are clear petrographic signs of alteration plot in a very tight field or array on chemical diagrams, which would not be expected if their compositions were in part the result of low temperature alteration. Also, for most felsic granites of this type, the compositions are generally very close to the minimum-temperature compositions for hydrous melts in equilibrium with quartz and feldspars (Tuttle & Bowen 1958).

Variation inherited from heterogeneous source rocks

Suites of I-type granites in the LFB often show a remarkable compositional coherence, e.g. Sr in the Glenbog Suite shows extremely regular variation throughout 12 plutons that occur over a distance of more than 250 km. While homogeneity in a single pluton could be ascribed to thorough mixing at an early stage, for the Glenbog Suite this implies a relatively homogeneous distribution of Sr in the source rocks that must have contributed separately to the different plutons. The capacity to recognise suites depends on the internal variations within two source materials being small relative to the overall differences between them. A corollary of the very precise suite definitions that can be made in many cases in southeastern Australia, is that either the source materials were very homogeneous, or were mixed thoroughly at an early stage in the production of the suite, that latter situation being unlikely when a suite comprises several dispersed plutons. Because sedimentary source rocks are more heterogeneous than those of I-type granites, S-type suites individually show more scatter in element concentrations about the dominant trend for a suite. Also, when the more mafic members of S-type suites have compositions close to those of their source rocks, it is possible that they might show variations inherited from those source materials.

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HIGH- AND LOW-TEMPERATURE GRANITES

Bruce Chappell
GEMOC, Macquarie University, NSW 2010

I-type granites of the Palaeozoic fold belts of Eastern Australia fall into two groups, formed at high and low magmatic temperatures. The distinction is made on the absence or presence, respectively, of zircon with inherited ages in the more mafic rocks determined using an ion probe (Williams, 1995), and related differences in Zr variation patterns with SiO_2. The high-temperature I-type granites formed from a magma that was completely or largely molten, and in which crystals of zircon were not initially present because the melt was undersaturated in zircon. In contrast with the low-temperature I-type granites, the compositions extend to lower SiO_2 contents and the abundances of Ba, Zr and the rare earth elements initially increase with increasing SiO_2 in the more mafic rocks. While the high-temperature granite magmas were produced by the partial melting of mafic source rocks and represent a comparatively primitive addition to the upper crust, the low-temperature I-type granites resulted from the partial melting of quartzofeldspathic rocks such as older tonalites. In that second case the melt produced was felsic and the more mafic low-temperature granites have that character because of the presence of entrained and magmatically equilibrated restite which includes older zircon crystals. These low-temperature granites may occur in close association with S-type granites since both are products of the magmatic recycling of older crust. There are also broad differences in composition between the I-type groups, with the low-temperature granites being more typically granodiorites and monzogranites. In contrast, tonalites and low-K granodiorites characterise the high-temperature granites, which have inherited that and associated features from their less evolved source materials. S-type granites, at least in the Lachlan Fold Belt, appear to always contain inherited zircon, and are therefore of low-temperature character.

The use of zircon saturation temperatures verifies the restite model for what we term the low-temperature I-type granites, and for the S-type granites (Chappell, 2003a). Those saturation temperatures, the presence of zircon with age inheritance, and the patterns of Zr variation show that the bulk of I-type granites of the Lachlan Fold Belt evolved by restite fractionation, and confirm that some did not, notably the Boggy Plain Supersuite, as we have long advocated (Wyborn, 1983; Chappell *et al.* 1987). Use of zircon saturation based on age-inheritance, and with its distinctive bulk rock chemical fingerprint, at least at more mafic compositions, provides a definitive test of whether a particular suite evolved either by fractionation of restite or in some other way.

Clemens (2003) has challenged the use of zircon saturation temperatures to estimate the temperature of S-type granite melts. He states that the behaviours of zircon and Zr are controlled by disequilibrium and kinetics, so that magma temperatures can rarely be calculated. Clemens (2003) argues that the rate of ascent of magma is far too rapid for equilibrium, which may be so. However the time of partial melting during which the minerals in the source rocks are melting or being transformed to other minerals by melt-forming reactions, would be quite long, so that kinetics should not be a problem. Also, the patterns of Zr variation observed in granite suites, that is Zr generally decreasing with increasing SiO_2 contents throughout low-temperature suites, and increasing towards higher SiO_2 contents in the more mafic rocks of high-temperature suites, must be noted. These variations are consistent only with the former being saturated in zircon, and the latter being undersaturated. Clemens (2001) also argued that it is likely that the more mafic granites are cumulates, rather than former liquids, so the saturation temperature for such a composition is meaningless. Chappell (2003a) has noted that the more mafic S-type granites of the LFB cannot be cumulate or cumulative rocks, and must represent magma compositions.

That I-type granites occur as two distinct types, high- and low-temperature, based on the absence or presence respectively of inherited zircons, has many important implications. To an extent this has previously been discussed, in a different guise, by Chappell (1996) in considering the implications of the restite model. One important implication relates to the potential for association with mineral deposits. Because of both their higher temperatures, and a greater potential to undergo changes in composition, including a progressive increase in both the activity of H_2O and the concentrations of incompatible elements through the process of fractional crystallisation, the high-temperature granite types are more likely to be related to significant mineralisation. This is clearly seen in eastern Australia (Blevin & Chappell, 1992) where, for example, most of the Devonian- and Carboniferous-age I-type granites of the Lachlan Fold Belt, largely of low-temperature origin, are conspicuously lacking in associated mineralisation

Miller *et al.* (2003) have recognised two distinct classes of granite. Their "cold" granites are rich in inherited zircon and formed by melting at temperatures less than 800°C, while the "hot" inheritance-poor granites formed at higher temperatures. This is not precisely the same subdivision as that of Chappell *et al.* (1998), which is based on the presence or absence of inherited zircon determined by ion probe analysis, so the low-temperature granites of that earlier contribution would include the "cold" and some of the "hot" granites of the later authors. Also, in proposing their subdivision, Chappell *et al.* (1998) pointed out that the patterns of Zr variation within low- and high-temperature suites of granites are distinctive and can be used as a secondary criterion. Also, Miller *et al.* (2003) have calculated zircon saturation temperatures for rocks which, in the view of this author, might not represent melt compositions. Miller *et al.* (2003) suggest that their two types must have different mechanisms of melting, whereas Chappell (2003b) considers that the differences are related to source rock compositions, specifically to the fraction of minimum-temperature melt components in the source rocks.

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TOWARDS A UNIFIED MODEL OF GRANITE PETROGENESIS

Bruce W. Chappell
GEMOC, Macquarie University, NSW 2010

Modern granite studies date from the observation by Tuttle & Bowen (1958) that the compositions of the most felsic granites correspond closely with those of hydrous melts produced in equilibrium with quartz and feldspars in the laboratory. This resolved the controversy about whether or not granites are igneous rocks firmly in favour of the magmatic view. These experiments do not tell us whether such haplogranites result from the fractional crystallisation of a more mafic melt, as Bowen (1949) believed, or of partial melting of appropriate material to produce primary granite magmas, which Bowen (1947) conceded could occur. There is now enough evidence to show that haplogranites can form in either way, with uncertainty about the relative amounts and the mechanism of formation in certain cases. However, primary felsic granite magmas, the products of partial melting, are overall the much more abundant type.

Although they are clearly magmatic, details of the origin of the less felsic granites are controversial. Many processes have been proposed to account for the details of formation of such granites and the generation of compositional variation within granite suites. All of these processes probably operate, and can be firmly established in particular examples. The question is on what scale and how frequently a particular process operated. Mechanisms that have been determined in one or a few cases should not necessarily be regarded as general processes. Neither should those processes established in small areas be regarded as necessarily applying to granite bodies of batholithic dimensions.

The key to the resolution of many of these problems has been the observation that granites of very similar bulk compositions have formed over a wide range of magmatic temperatures. *High-temperature granites* were produced under conditions where zircon was soluble when the more mafic rocks were produced, and were defined on that basis by Chappell *et al.* (1998). These rocks formed from complete melts, fractional crystallisation was an important process in their evolution, and they include cumulate rocks. Zircon was saturated in the *low-temperature granites*, even when they have bulk compositions ~ 60% SiO_2, the magmas could never have been completely molten, and the rocks evolved principally by the removal of entrained crystals of restite. Low-temperature granites formed when the source rocks contained sufficient of the quartz, albite, K-feldspar and H_2O components for enough melt to be produced for a magma, that is a fluid comprising melt and crystals, to form at temperatures near 800°C. High-temperature granites generally result from the partial melting of source rocks in which at least one of those components was depleted before the melt could separate from its source materials, with the result that melting continued to higher temperatures. If there is insufficient of these low melting components to produce an extractable melt or magma even at higher temperatures, then the source rock is infertile. Each of those cases will now be considered.

Insufficient minimum-temperature melt forms because the source rocks are deficient in:

1. **Quartz**. Melting continues to higher temperatures with the incorporation of more albite and K-feldspar components in the melt. This leads to the production of quartz monzonites, monzodiorites, etc., as with rocks of the Boggy Plain Supersuite.
2. **Albite**. This is the least common case, but S-type granites that were derived from heavily weathered source rocks may approach this situation. Such pelitic rocks contain low amounts of albite, and perhaps quartz, and may be infertile in terms of producing a granite magma.

3. K-feldspar. Continued melting in the absence of K-feldspar produces melts of tonalitic composition. This is a common situation in production of the large continental margin batholiths such as those of the Cordillera, and in the Clarence River Supersuite, which comprise relatively low-K rocks derived from source rocks sharing that character.

4. H_2O. In this case, the low H_2O-contents leads to melting of the other three components at higher temperatures, producing the A-type granites. The higher temperatures are shown by the high Zr contents and consequent higher zircon saturation temperatures of these rocks. Partitioning of other distinctive trace elements, such as the REE, Y and Ga, into the melt, also occurs at these higher temperatures.

Most granites suites evolve by the removal of crystals from a melt, that is by crystal fractionation. This may be either fractional crystallisation in which the crystals were precipitated from the melt (mainly high-temperature), or restite crystal fractionation where the crystals had been entrained in the melt (low-temperature). Both mechanisms are important, and their operation in a particular case is determined by the composition and hence the physical properties of the melt, which is largely determined by the temperature of partial melting, which in turn is largely a function of the source composition. It is those source rock compositions that basically determine not only the composition of a melt or magma, but also the physical nature of the magmatic response of source rocks to heating, or the fraction of melt in the migma or magma, and the manner in which it fractionates. This dependence on source compositions of both the physical and chemical properties of magmas, and their evolution, provides a unifying basis for further developing our understanding of the origins of granites.

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GRANITES OF THE LACHLAN FOLD BELT

Bruce W. Chappell
GEMOC, Macquarie University, NSW 2010

The Palaeozoic Lachlan Fold Belt (LFB) occupies the southeastern corner of the Australian continent and it has a total area of close to 300,000 km^2. There was very extensive igneous activity in the LFB in Silurian and Devonian times, and during the Carboniferous in the northeastern corner of the belt. Massive quantities of granitic magma were produced and we currently recognise 875 lithological units of granite, the locations of most of which are shown on the map of Chappell *et al.* (1991). Volcanic rocks are also important and most of the 100 such units that are recognised are also shown on that map. With an outcrop area of 61,000 km^2 the granites comprise a little more than 20% of the LFB and they are more abundant in the eastern part, where volcanic rocks are also important. Most of the granites were emplaced into low-grade flysch sediments of Ordovician age, or else into older granites, or volcanic rocks of the same general magmatic episode.

Following are some of the petrogenetic outcomes of granite studies in the LFB in the last forty years:

- The granite plutons can be grouped into suites, which share field, petrographic and compositional features (Hine *et al.*, 1978; Griffin *et al.*, 1978; White *et al.*, 2001). Suites are the basic unit for considering the petrogenesis of the granites.
- The granites form images of their source rocks (Chappell, 1979).
- Characteristics of the distinctive granite provinces were correlated with corresponding differences in their source rocks in the deep crust, or *basement terranes*, by Chappell *et al.* (1988).
- The first-order subdivision of the suites is into the I- and S-types (Chappell & White, 1974, 1992, 2001), derived by the partial melting of older igneous and sedimentary source rocks.
- Compositional variation within most of the suites resulted from varying degrees of separation of crystals entrained from the source from a partial melt, the *restite model* of White & Chappell (1977) and Chappell *et al.* (1987).
- The felsic granites of some suites evolved by fractional crystallisation after mafic restite had been removed (Chappell & White, 1998; Chappell, 1999).
- Some 5% of the granites in the LFB evolved from mafic to felsic composition completely by fractional crystallisation. These are rocks of the Boggy Plain Supersuite (Wyborn, 1983; Wyborn *et al.*, 1987) and the Marulan Batholith (Carr *et al.*, 1992).
- The granites can be subdivided into low- and high-temperature groups, on the basis of the presence or absence of inherited zircon in the more mafic granites on a suite (less than ~ 68% SiO_2). These groups correspond to those that evolved by restite fractionation sometimes followed by low-temperature fractional crystallisation, and those that evolved completely by fractional crystallisation (Chappell *et al.*, 1998, 2000).
- The distinctive A-type granites are the high-temperature felsic granites (Collins *et al.*, 1982; King *et al.*, 1997, King *et al.*, 2001).
- Volcanic rocks can be grouped into suites and into I- and S-types (Owen & Wyborn, 1979; Wyborn *et al.*, 1981).
- For what are now termed the low-temperature granite suites, both the associated volcanic and plutonic rocks have essentially the same range of compositions and the compositions of relatively fresh volcanic rocks can be matched very closely with those of particular granites (Wyborn & Chappell, 1986). In the high-temperature Boggy Plain

Supersuite, the volcanic rocks are felsic rhyolites with compositions that complement those of the more mafic cumulate granites of that supersuite (Wyborn *et al.*, 2001).

- Development of the SHRIMP ion microprobe has facilitated the study of zircon age inheritance and has shown that it is ubiquitous in the S-type granites and widespread in the I-type granites (Williams, 1995, 2001).
- Appreciable economic mineralisation associated with granites of the LFB is limited to those granites whose compositions were modified by fractional crystallisation (Blevin & Chappell, 1992, 1995).
- Debate about the source rocks of the dominant *batholithic* S-type granites (White & Chappell 1988) is unresolved. Chappell *et al.* (2000) favoured a sedimentary source rock that was more feldspathic than those exposed at the surface.
- The formation of the dominant Silurian and Devonian granites of the LFB is not considered to have been related directly to subduction (Chappell, 1998).

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Australia's first hot dry rock geothermal energy extraction project is up and running in granite beneath the Cooper Basin, NE South Australia.

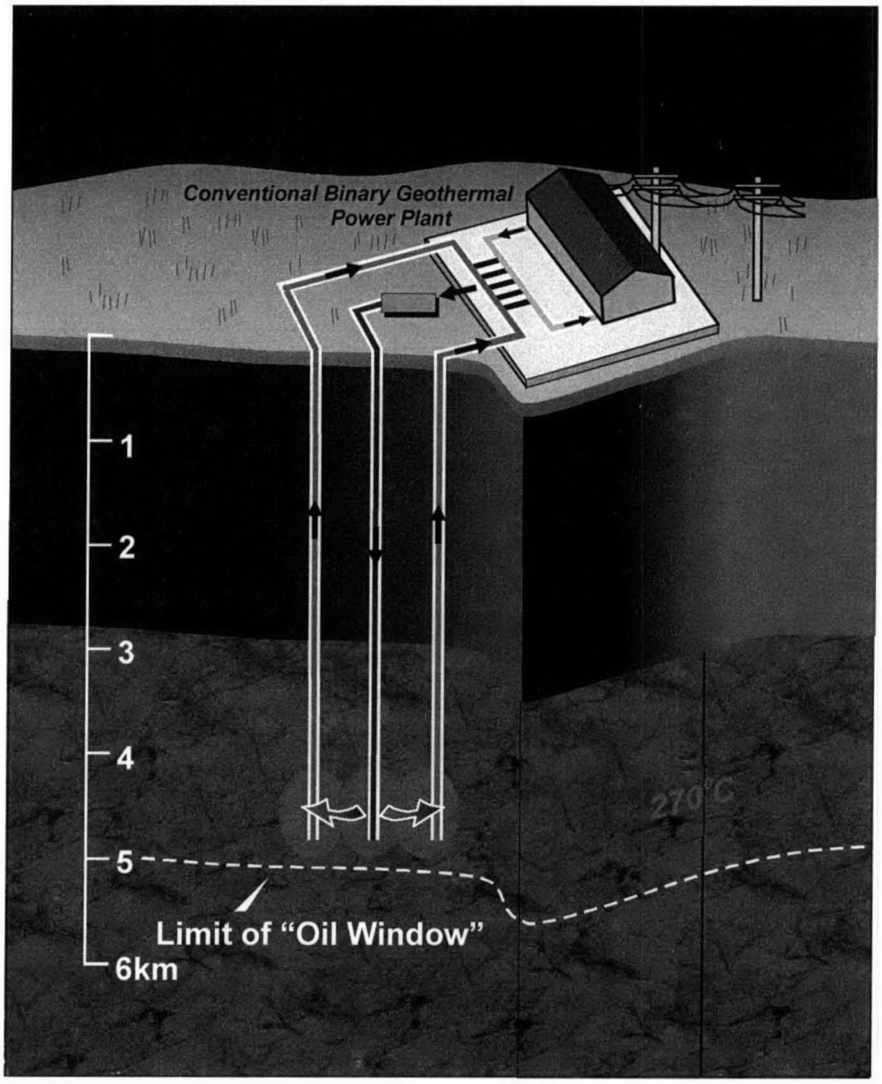
Prame Chopra
Department of Geology, Australian National University, ACT 0200
and
Doone Wyborn
Geodynamics Limited, PO Box 2046, Milton, Qld 4064

Australia's deepest onshore well, Habanero 1, is currently being drilled into hot granite in the basement to the late Carboniferous to Permian Cooper Basin in NE South Australia. The total depth of the well is programmed at 4900m approximately 1200m into the granite. The well is being drilled by Geodynamics Limited to extract heat from the rock to generate renewable electricity without greenhouse gas emissions. Evidence from existing Cooper Basin gas exploration wells that have drilled into the basement in the area, plus seismic and gravity data indicate that granite underlies the deepest part of the Basin over an area of approximately 1000 km^2.

Economic models have been developed based on the cost of developing the project, running costs, amount of energy extracted and efficiency of electricity generation. A demonstration plant consists of a continuously circulating system of one injection well and two production wells spaced 500m apart. For such a system, circulating at 100 litre/second and producing at 245°C, the break-even electricity cost is modeled to be 6.2 cents per kWh, considerably cheaper than current wind power costs and equal to the cost of large scale hydro-power generation. For large-scale production involving drilling 37 wells over an area of 6.25 km^2, and producing 275 MWe, the cost is close to 4 cents per kWh. This is approximately the same cost as current new-entry coal-fired generation. The electricity generated from these developments would attract green incentives known as Renewable Energy Certificates (REC's), which are likely to be valued at around 4 cents per kWh. The 275 MWe plant could effectively generate power at zero cost, and, at a sale price of 4 cents per kWh the plant would generate revenue of $96 million per year. Geodynamics Limited has raised $20 million to prove the energy extraction process based on these attractive economic analyses.

The temperature at the top of the granite, at 3700m depth, is approximately 240°C. The temperature gradient in the granite is expected to increase the rock temperature by ~3°C for every 100m into the granite. The high temperatures at these depths relate to a number of independent geological conditions coinciding in the area:

(1) the presence of low conductivity sediments overlying the granite,
(2) the optimal thickness of these sediments which allows access to hot rock without needing to resort to the expensive drilling equipment required for drilling beyond 5km depth,
(3) a granite chemistry containing relatively high abundances of radiogenic elements giving high heat productivity (high heat production or HHP granite),
(4) the previous unroofing of the Palaeozoic granite which resulted in brittle unloading features, and
(5) the existence of high tectonic stresses in the sediments and granite leading to low fluid permeability, conductive heat flow and minimised heat loss by convection



Heat extraction from granite benefits from the large volumes of relatively homogeneous rock and the presence of interconnected joint sets caused by cooling and unloading.

Evidence from drilling into the granite so far, including information from offset wells, indicates that the granite is a medium to coarse grained, reduced granite with relatively high abundances of radiogenic elements. The heat generation capacity, based on these abundances, is in the range 7-10 watts/m^3, around 3 times higher than typical granite. The granite was originally a two-mica granite with accessory tourmaline, but it has suffered from extensive burial metamorphism since being covered by the sedimentary blanket. Effectively all the biotite has been altered to chlorite, and plagioclase has been altered to albite+calcite+hydrated Ca-silicates. Widespread alaskite dykes and irregular bodies invade the coarser grained normal granite. The granite was previously dated using zircons as Carboniferous, but new monazite dating to be carried out in this project is expected to provide a better age estimate.

Evidence from borehole imaging logs indicate that sub-horizontal joints and fractures dominate the fracture systems in the granite. These fractures are expected to make ideal pathways for fluid flow and heat extraction. In an operation known as hydraulic stimulation the fluid permeability of these fractures is increased by pumping water into the fractures at high pressure. This enhanced fluid pressure causes optimally oriented fractures to exceed the critical state for slip. The resulting micro-earthquakes are mapped with an acoustic monitoring network. For the current project, a network of 4 shallow, 3 moderate depth, and one deep well has been constructed. Mapping of micro-earthquake hypocenters with this network will then provide the basis for positioning the production wells. Similar projects overseas have shown that following slip, the permeability of a granite joint is enhanced by many orders of magnitude.

The hydraulic stimulation of Habanero 1, the positioning and drilling of the Habanero 2 production well, and the conduction of a circulation test between two wells is expected to be carried out over the next 12-18 months as a "Demonstration of Economic Heat Extraction" of Australia's unique geothermal resources.

SOME MODERN CONCEPTS ON LACHLAN GRANITE PETROGENESIS

W.J. Collins, Geology, University of Newcastle, Newcastle, NSW, 2308, Australia

Summary
This presentation will show, based on field, geophysical, geochemical and isotopic studies, that Silurian-Devonian plutonism in the eastern Lachlan Fold Belt (LFB) was intimately involved with mafic magmatism. Most of the granite plutons reflect open-system, disequilibrium processes involving magma mixing. Mixing below and at the base of batholiths generated much of the isotopic diversity observed in LFB granites, and subsequent fractionation processes in the upper crustal magma chambers, including restite unmixing, generated much of the chemical diversity. The dominant stress regime during LFB granite generation and emplacement was extensional and the tectonic environment was interarc to backarc rift, based on the composition of primitive syn-plutonic mafic rocks. Rapid eastward slab retreat is evident from the age distribution of eastern LFB granites, and this retreating or extensional accretionary orogen is ideal for generating vast amounts of mantle-derived magmas, necessary to melt and mix with the crustally derived magmas to produce the voluminous and widespread granites of this region.

Introduction
Detailed field and gravity studies from S-type (Murrumbidgee) and I-type (Bega) batholiths are combined with geochemical/isotopic results to understand the *physical* processes associated with granite generation, emplacement and subsequent fractionation in the eastern LFB. The results require a re-evaluation of models for LFB granite petrogenesis. In particular, it will be shown that the studied plutons are open systems that can often be viewed as sedimentary deposits. They provide stratigraphic sections that record input from various source components and commonly give "way-up" features, allowing the pluton top and bottom to be identified. The plutons are commonly fed by "clean" felsic and mafic dyke material, which can mix and mingle in the ascent conduits or in the magma chamber itself.

Tuross Head pluton: Bega Batholith
The Tuross Head pluton is part of the Moruya Suite from the Bega Batholith. It is well exposed as coastal outcrops at Bingie Point and Tuross Head. Gravity and magnetic surveys have shown that the mafic rocks are km-scale layers concentrically arranged and dipping toward the pluton interior. The arrangement is consistent with inward dipping nature of the mafic layers, which is concordant with a variably developed feldspar foliation and with the orientation of elongate enclaves in the tonalite. The mafic layers are asymmetric, planar on one side and lobate to irregular on the other. The lobate contacts outline m-scale load-cast structures, and asymmetric granitic veining and scarce felsic pipes along these contacts are "way-up" structures that indicate the tops of all mafic layers face towards the interior of the pluton.

Mafic to intermediate enclaves have textures, modes and mineralogy that are similar to those of the mafic sheets. They range from globular and nearly equant bodies with obvious magmatic textures to highly elongate bodies in zones where a magmatic foliation is well developed. They are most concentrated above mafic layers, and local contact relations and textural features suggest they are magma globules ripped off the top of those layers. The field relations demonstrate that these mafic enclaves, which have been called restite by some workers, are derived from mafic magma infusions into the tonalitic magma chamber.

A detailed study of Tuross Head shows that it can be divided into three zones (A,B,C) with a combined thickness of at least 1500 metres. Zone A is lowermost and consists of a silicic tonalite (SiO2 ~65%) with few mafic enclaves and discrete mafic crystals. It is overlain by Zone B, which contains wedge-shaped gabbro/diorite layers and tonalites of generally lower silica contents (61-64%) with abundant mafic enclaves and some mafic clots. The upper layer (Zone C) consists of strongly foliated, very mafic tonalites (57-59% SiO2) and highly dismembered gabbro/diorite layers, which are progressively disaggregated to mineral aggregate-scale clots.

Interpretation. The mafic sheets of Zone B represent replenishment of mafic magma into the Tuross magma chamber and mark various positions of the aggrading floor of that chamber. Since the elongate enclaves and the feldspar foliation in the tonalite are parallel to and intercalated with the mafic sheets, they also define the position of the floor. The intercalation of mafic layers and tonalite strongly suggests that, even though layering is not apparent, the tonalite was also deposited gradually on the chamber floor between episodes of mafic input. Therefore, the Tuross Tonalite probably has a stratigraphic record comparable to that seen in mafic layered intrusions, and the sequence of deposits should provide a time-stratigraphic record of processes in the magma chamber.

Higher up, in Zone C, the coexisting layered mafic and silicic magmas were strongly disrupted during magmatic flow, and the two components mechanically mixed to produce the mafic tonalite. Abundant mafic clots, derived by disaggregation of the mafic layers, characterise this mafic tonalite. They are also seen in Zone B, but are rare in A, and correlate negatively with silica abundance. Incorporation of these clots generates the composition diversity of granites at Tuross Head, with magmas becoming more mafic with time. This reflects open system mixing processes, rather than closed system restite fractionation, where magmas should become more felsic with time.

Kameruka pluton: Bega Batholith

Field and petrographic evidence indicates that the Kameruka suite plutons of the Bega Batholith, eastern Australia, also grew by crystal accumulation on the magma chamber floor. Depositional features in the plutons, including mafic enclave channels, asymmetric enclave pillows and exotic rafts, load casts and flame structures, and graded and trough cross-beds indicate that the pluton built also progressively upward, like the Tuross pluton. Km-scale mafic infusions are also present, and are associated with large enclave swarms, but they are rare. The general eastward dip of depositional features in the Kameruka pluton implies a lower western and upper eastern contact, consistent with a gradational granite-migmatite contact in the west and a sharp, stoped, hornfelsic contact in the east. Mafic, felsic and composite dykes, most common near and below the lower (western) contact, are interpreted as conduits for magma chamber replenishment and imply open-system behaviour during pluton construction.

Textural relations are consistent with an open-system, cumulate origin. Typically, cm-scale grains of quartz, plagioclase and megacrystic alkali feldspar form a touching framework with interstices filled with smaller biotite flakes, normally zoned overgrowths on plagioclase cores, and smaller intercumulus quartz and feldspar crystals. The bulk composition of cumulate mush, represented by the granodiorite, cannot represent the emplaced magma. Chemical variation can be modelled by variable degrees of crystal accumulation from a parental, silica-rich melt represented by the silicic dykes, consistent with isotopic evidence. As dykes periodically fed the magma chamber, crystals accumulated on the floor and more evolved melts probably erupted from its roof. Thus, the average composition of the magma and the cumulus minerals may have remained relatively constant, and the sublinear chemical trends that typify the Kameruka suite simply reflect differing proportions of melt and cumulate material. Chemical and isotopic analysis of the migmatites underlying the Kameruka pluton indicates minimal interaction with the granitic magmas.

The Kameruka pluton is one of a number of elongate, meridional, wedge-shaped bodies that thicken eastward in the Bega Batholith. The E-dipping, primary magmatic accumulation fabric, which becomes steeper to the west in the deeper parts of the pluton, is comparable to sedimentary layers formed by floor depression in syn-rift settings. Syn-rift sediments and co-magmatic volcanics (Long Flat volcanics) directly overlying northern extension of the Bega Batholith suggest that it is the deeper, plutonic expression of a hot, active rift. Displacement along syn-emplacement lateral transfer faults (Burragate and Tantawangelo) suggests up to 25 km of E-W extension during batholith construction The model is not consistent with the restite model, which requires *en mass* diapiric rise of unmelted source and felsic melt, followed by separation of the solid (restite) fragments. This flat-bottomed, laccolithic pluton was fed by silicic (microgranite) dykes that do not contain mafic clots.

Murrumbidgee Batholith

The Murrumbidgee Batholith is typical of other composite S-type granite batholiths in the Lachlan Fold Belt of southeastern Australia, consisting of discrete peraluminous, cogenetic granite suites, although it contains a unique (Murrumbucka) suite at its southern extremity that has chemical and petrological features transitional with metaluminous I-type granites. Detailed structural and metamorphic studies have shown that the batholith is tilted northward, exposing subvolcanic plutons in the north and the root zones in the south, located at depths of ~10 km. A transition from mafic, foliated, sheet-like granites in the south to felsic, generally non-foliated, homogenous granites in the north is consistent with magma ascent via subvertical, structurally controlled sheets to emplacement in an overlying magma chamber.

In the inferred root zones, the Murrumbucka suite hosts migmatitic metasedimentary and gabbroic rocks, both of which have transitional contacts and show evidence for interaction with the host. The migmatites extend southward to become part of the high-T, low-P Cooma Metamorphic Complex, which contains a core of heterogeneous diatexitic granite (Cooma suite), lenses of which also occur throughout the southern (deeper) parts of the Murrumbidgee batholith. The composition of mafic granites from the batholith lie on a chemical tie-line between Cooma suite granites and the gabbros, for almost all elements. This chemical coincidence is interpreted to reflect derivation of parental Murrumbidgee S-type granite magmas by mixing between a felsic (crustal) and mafic (mantle) components, consistent with Sr and Nd isotopic results and field observations. Based on the tie-lines, the Murrumbucka suite is estimated to be a 45:55 mix of mantle and crust, whereas the more peraluminous and widespread Clear Range suite, which is very typical of Lachlan S-type granites, is a 40:60 mix. Chemical variation trends diverge from the mixing lines and suggest that much of the fractionation processes operated after mixing. Mixing occurred within sheets during ascent of the magmas whereas fractionation, including restite separation, was the dominant process generating chemical diversity during emplacement at higher crustal levels.

Tectonic Setting

Silurian-Devonian syn-orogenic basalts and gabbros have oceanic affinities, and are very similar to those formed in the present-day SW Pacific. The compositions indicate generation under lithosphere that was <30 km thick until the Late Devonian. Given normal subcontinental lithospheric thicknesses are >100 km, this evidence strongly favours extensional tectonic models for the eastern LFB during generation and emplacement of LFB granites. Emplacement of Bega Batholith plutons into active half-grabens is consistent with an extensional tectonic model.

The Silurian-Devonian deformation record indicates at least five periods of intermittent contraction, early and late Benambran, Bowning, Bindian, Tabberabberan (390-380 Ma) and Kanimblan. These events were short-lived (~10 Ma), diachronous and complex, resulting in crustal thickening. Nonetheless, these events coincided with the development of widespread rift-basins, and the basalt compositions imply that lithospheric thickening began only in the Middle Devonian (~390 Ma), coinciding with attainment of relative tectonic stability in the LFB. A solution to this paradox involves rapid reversal of prolonged slab retreat by arrival of a buoyant oceanic plateau at the trench, inducing flat subduction and transmission of horizontal compressive stress throughout the orogen. After subduction of the plateau, the ambient mode of slab retreat is re-established and the orogen experiences another phase of regional extension until arrival of the next plateau.

Petrogenetic and Tectonic Implications

1) The analysed I- and S-type granites are crust-mantle mixes, with the dominant crustal component in the Murrumbidgee Batholith being migmatite, derived from directly underlying Ordovician metasediment. I-type magmas of the Bega Batholith did not significantly interact with their underlying migmatites.
2) mafic enclaves and clots in I-types, occasionally interpreted as restite, represent mantle-derived magma that mixed with crustal magmas, either in the ascent zone (Murrumbucka), in dykes below the magma chamber (Kameruka), or in the magma chamber itself (Tuross).
3) The plutons typically reflect open-system processes, mainly associated with magma mixing and deposition of crystal slurries. Stratigraphic sections can be mapped and "way-up" structures identified, from which the top and bottom of plutons can be identified.
4) Mafic (hornblende-biotite) clots in I-type granites are demonstrably disrupted mineral aggregates from coeval mafic magmas, rather than restite. Mafic (cordierite-biotite) inclusions in S-type are demonstrably restite if a gneissic texture is preserved. Similarly, mineral inclusion trails in cordierite cores probably reflect restite, but those crystals without such features cannot be unequivocally regarded as restite.
5) The presence of "clean" feeder dykes in and below I-type plutons suggest that melt segregation and ascent from the source was efficient, involving minimal wall-rock contamination and transport of restite material. On the other hand, S-type magma generation below the Murrumbidgee Batholith involved wholesale breakup of migmatite and transport of solid restitic material, at least initially.
6) basement terranes, an outgrowth of the restite model, do not exist in the eastern LFB.
7) the mantle contribution to LFB petrogenesis was two-fold: as the major supplier of advective heat to the LFB, and a major supplier of material (source component) to the LFB granites.
8) plutons were generally emplaced during extension, as implied by the basalt data and field relations
9) Subduction models are viable and necessary for the LFB. Tectono-stratigraphic data indicate an extensional arc-backarc tectonic setting. Magma migration patterns indicate eastward retreat of a W-dipping slab in a convergent margin, subduction setting.

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Epithermal Au-Ag – The Magmatic Connection Comparisons between East and West Pacific rim

Greg Corbett, Consultant - cgs@speednet.com.au

Introduction

Epithermal Au-Ag deposits are distinguished as high and low sulphidation (HS & LS) on the basis of ore and gangue mineralogy, derived from distinctly different fluid typess, and for the LS deposits there is a further distinction between the group of base metal rich deposits which commonly display a relationship with intrusion source rocks, and the banded adularia-sericite style quartz veins (Figure 1; Corbett 2002, and references therein). Characteristics of the distinctly different fluids which form these variable deposit types result from the relationship to the magmatic source and degree of evolution leading to ore deposition.

Metal distribution

Metal abundance and distribution vary according to tectonic setting, deposit type, crustal level of formation, distance from magma source, and the mechanism of metal deposition.

Crustal composition influences metal contents. Many Western Pacific magmatic arcs are underlain by oceanic crust, whereas those in the eastern Pacific overlie thick continental crustal segments. Consequently, HS deposits (below) in the SW Pacific (Nena & Wafi, PNG; Lepanto, Philippines; Peak Hill & Gidginbung, NSW; Mt Kasi, Fiji) are Ag-poor (generally totally free of Ag), whereas Ag is an important economic component of HS ores in the Americas (La Coipa, Chile;Yanacocha & Pierina, Peru; Veladero, Argentina; Pascua-Lama, Chile-Argentina). Similarly, the LS deposits of varying styles tend to be more Ag rich in the Americas. The polymetallic Au-Ag ores of Mexico, Bolivia and Peru, are important sources of Ag, but may contain very low Au, whereas similar ores in the SW Pacific are commonly Au and not Ag rich (Hadleigh Castle, Qld; Parkers at Mineral Hill, NSW). While, SW Pacific LS quartz-sulphide Au deposits contain low fineness Au, Ag as argentite is a significant part of the ore at the Ocampo district Mexico and taken to be representative of others in the region.

Similarly, porphyry deposits in the SW Pacific occur as Cu-Au porphyry systems, whereas most in the Americas are Cu-Mo bearing, again reflecting the influence of crustal metal content. Some gold rich porphyry systems of the Americas conform to the alkaline intrusion class (below), while others such as some at the Maricunga Belt, Chile, are interpreted by this author to be of the LS quartz-sulphide class (below), formed outside the source intrusion.

Tectonic setting may also play a role in magma composition and hence metal abundances and content. During the Miocene, southward subduction of the Pacific oceanic plate under the Indo-Australian plate was jammed by the thick Otong Java portion of oceanic crust. Consequently, by the Pliocene a new northward facing subduction zone extended from Papua New Guinea and Fiji, to the south of the Miocene north dipping subduction zone. Solomon (1990) proposed that remelting of previously melted oceanic crust has led to the development of the Au-rich alkaline shoshonitic melts, which although occupying only 2% of the igneous rock suite, could account (Sillitoe, 1997) for in 20-30% of the SW Pacific Au content (Lihir & Porgera, PNG; Emperor, Fiji). In each case major crustal structures have acted as conduits to aid the formation of significant magma bodies at high crustal levels. While Porgera crops out as an apophysis to a major magmatic source evident on aeromagnetic data, failure of extrusive volcanic edifices provided the impetus for re formation at Lihir and Emperor ore systems. The quenched LS quartz-sulphide ores at Lihir are As-rich.

Although epithermal Au deposits associated with alkaline magmatism display some distinct metal abundance characteristics, mainly Te enrichment (Emperor, Tavatu Fiji; Cripple Ck, US), they should not be classed as a separate deposit style, but occur as a range of documented deposit types (Corbett and Leach, 1998) derived from a different magma type (Emperor, Porgera, Lihir).

Many alkaline magmatic systems are located more towards back arc portions of the overall magmatic environment; examples include Didipio, Philippines; Bajo de la Alumbrera, Argentina, Porgera and Mt Kare in PNG, and possibly Grasberg in West Papua. The tectonic setting of the Ordovician alkaline complexes of the Lachlan Orogen remains less clearly defined.

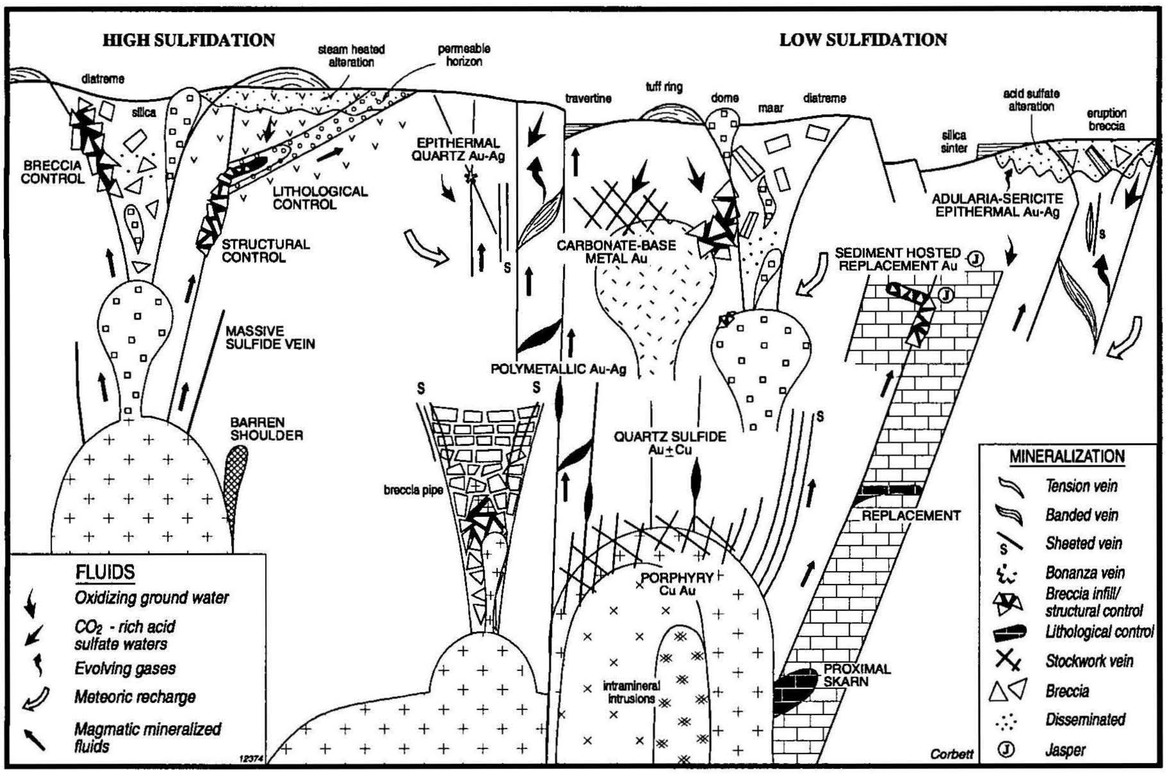

Figure 1. Conceptual model for different styles of magmatic arc Cu-Au-Ag mineralisation (from Corbett 2002).

Deposit Type

Low sulphidation

Low sulphidation Au-Ag deposits develop from cells of circulating dilute meteoric-dominated waters driven by magmatic heat sources within dilational structural settings. These deposits are divided into the group of Arc (ALS) and Rift (RLS) styles, although some transitional relationships are discerned.

The adularia-sericite epithermal Au-Ag deposits (ASED) form banded quartz vein ores common in intra-arc or back-arc rifts and so constitute the Rift LS deposits. These regions are commonly characterised by bimodal volcanism comprising sequences of andesitic flows local basalt and felsic pyroclastic deposits or subvolcanic intrusions. Host rock competency plays an important role in fissure vein formation and so many deposits are more likely to occur within basement shales (Hishikari & Konami, Japan) or andesitic flows (Waihi, Karangahaki, Golden Cross in New Zealand), while andesitic (Chitose, Japan) or felsic (Sado, Japan or Sleeper, US) domes are less common vein hosts. Only rarely (Cerro Vanguardia, Argentina) are felsic volcanic sufficiently brittle to host fissure veins.

While these banded quartz vein ores comprise minerals deposited from rapidly cooling and boiling circulating meteoric waters (chalcedony, adularia, platy calcite replaced by quartz), the metals deposited by fluid mixing (Corbett and Leach, 1998) within black sulphidic ginguro vein portions, may ultimately be derived from distal felsic intrusion source rocks. Felsic domes, dykes and extrusive rocks of similar ages are common in the vicinity of many adularia-sericite deposits (eg, Hishikari).

Furthermore, there are common transitional relationships between (ASED) and the (ALS) deposits, as some RLS deposits become base metal sulphide rich at depth (Waihi) while others contain ore of a LS carbonate-base metal (Karangahake; Misima, PNG) or LS quartz-sulphdie (Rawas, Indonesia) association. Indeed many ASED, particularly in the Jurassic systems of Patagonia, contain early low gold grade quartz-sulphide mineralisation, which is commonly subject to surficial supergene enrichment.

The pattern of Ag significantly greater than Au, is more pronounced in western than eastern Pacific examples, while both display vertical zonation with anomalous Hg, As, Ba in the upper levels.

The Arc Low Sulphidation Au-Ag deposits (Corbett, 2002) are subdivided (Corbett and Leach, 1998) from deeper to higher levels as: quartz-sulphide Au + Cu (QS), carbonate-base metal Au (CBM), and epithermal quartz Au-Ag (EQ). The CBM ores, which are the most prolific gold producers in the SW Pacific, are transitional to the polymetallic Au-Ag fissure veins of the Americas (Arcata, Caylloma, Peru), here Ag-rich, while the CBM deposits also occur as Au>Ag (by value) in the SW Pacific as fissure veins (Acupan, Antamok, Philippines) or fracture/breccia (Kelian, Indonesia; Porgera) ores.

Metals within ALS deposits are derived from intrusion source rocks, entrained within circulating meteoric waters which become progressively more dilute with respect to the magmatic component as they rise to higher crustal levels and mix with more ground waters (eg, QS). Buried magma source rocks are inferred to drive the circulating heat cells. Other gangue minerals such as the carbonate in the CBM deposits is derived from the mixing or ore fluids with evolved bicarbonate waters, inferred to ultimately have been derived from magmatic source rocks. The EQ ores are gangue poor, but contain bonanza gold grades formed by the mixing of ore fluids with condensate (low pH) or oxygenated groundwaters. and occur overprinting CBM (Porgera) or QS (Emperor) and peripheral to porphyry Cu-Au systems (Thames, New Zealand), as an indication of the magmatic derivation.

The magmatic association is most clearly evident in the deeper QS ores some of which are transitional to wall rock porphyry Cu-Au deposits (Cadia, Australia; Maricunga Belt, Chile; La Arena, Peru) while others exploit early structures at higher crustal levels than subjacent porphyry C-Au manifestations (Bilimoia, PNG; Mineral Hill). Many occur within intrusion-related breccia systems (Kidston, Australia; San Cristobal, Chile). These ores are therefore Cu rich at depth and Au rich at higher crustal levels, and where quenched may be anomalous in As (Lihir), and locally Sb and Ba.

CBM Au-Ag deposits occur in association with high level intrusions (Porgera) or diatreme-flow dome complexes developed as clear evidence of felsic magmatism (Kelian, Indonesia; Wau, PNG; Cripple Creek & Montana Tunnels, US). Felsic domes recognised in association with may polymetallic Au-Ag ores in the Americas may be derived from the same magmatic source at depth as the mineralisation.

The more enigmatic sediment hosted replacement Au (SHR) ores, although best developed in the Carlin and Battle Mountain Trends of Nevada, are recognised in other magmatic arcs (Bau, Malaysia; Mesel, Indonesia). These deposits typically form by the replacement of favourable impure limestone in extensional structural settings, and vary from lower metal grade lithologically controlled ores at higher crustal levels, to higher metal grade structurally controlled ores at deeper levels, but commonly do not easily demonstrate direct associations with intrusion source rocks. However, the pyritic ores are interpreted to have been derived from a fluid similar to the QS deposits with a distal relationship to the magma source within the characteristic extensional structural settings. Here, and in QS deposits, these fluids deposit Au in association with As bearing pyrite (commonly encapsulated) and with anomalous Ba, Hg and Sb. Recent work (Chakurian, 2001) suggests that the Carlin Trend SHR Au deposits are of the same age (38 m.y.) as porphyry Cu magmatism in that region, and magmatism is also recognised in other districts where these deposits occur (Mesel).

High Sulphidation Au ± Ag

In brief, high sulphidation deposits develop in settings where volatile rich magmatic fluids rise to higher crustal levels without significant interaction with the host rocks or ground waters. Volatiles (SO_2) evolved from the depressurising fluids oxidise to form a two stage hot acid fluid, the initial stage of which reacts with the host rocks to produce the characteristic zoned acidic alteration at epithermal crustal levels (Corbett and Leach, 1998). A later liquid dominated fluid phase deposits sulphides which are characterised by pyrite with enargite, or the latter's low temperature polymorph luzonite. These deposits are generally Cu-rich at depth, and Au-rich, locally with anomalous Hg, Sb, and Te, at higher crustal levels. HS deposits in the SW Pacific are Ag-poor while those in the Americas are Ag-rich. Many sulphide ores are refractory and low grade and so mined only where oxidised.

Magmatic rocks are interpreted to represent the ultimate source of ore fluids as demonstrated by the commonly association of HS deposits with felsic domes (Yanacocha, Mt Kasi) and phreatomagmatic breccias within flow-dome complexes (Pascua, Veladero, Wafi, Lepanto). Many HS deposits display associations with porphyry Cu-Au systems of similar ages (Nena), or are collapsed upon and form part of the porphyry ores (Monywa, Burma). Fluids responsible for the formation of HS deposits rarely evolve to Au- rich lower sulphidation style ores (Wafi; El Indio, Chile).

Conclusion

In magmatic arcs metals concentrate within intrusive rocks and form porphyry Cu-Au-Mo deposits at the apophyses to larger magmatic sources, and at higher crustal levels evolve to epithermal levels. Whereas HS ores develop from saline fluids with little interaction with circulating waters, the LS deposits develop where metals are entrained within circulating dilute meteoric-dominated waters, and are classed as ALS for the group with closest association with intrusion rocks, or the RLS where the magmatic association, although interpreted herein, is less obvious. Variations in metal contents are apparent from the crustal and tectonic setting as well as crustal level and distance from magmatic source. Epithermal deposits of all classes tend to be significantly more Ag-rich in eastern Pacific magmatic arcs which are underlain by continental rather than oceanic crust.

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Granite production in the Delamerian Orogen

John Foden
University of Adelaide

The Delamerian- Ross Orogen is important for several reasons: i) it records the critical transition of SE Gondwana from a passive to subduction margin. ii) it provides a model for the evolution of a tectonic style subsequently perpetuated in the Palaeozoic Lachlan fold belt to the east. iii) it provides a glimpse of the association of thermo-magmatic processes with an extension-dominated style of orogenesis that is very different from classical Alpine-Himalayan and Andean models iv) the geochemistry of its magmas confronts some firmly held views on the use of geochemical discrimination diagrams in their tectonic assignation.

Our results indicate that in spite of general continuity between the Ross and Delamerian belts, the Ross Orogen had a history of active convergent or transpressional tectonism that starting started much earlier at ~540Ma. Felsic magmatism, deformation and metamorphism continued for 25Ma in the Ross before it started in the Adelaide Fold Belt, where the oldest Cambrian granite is 514Ma (Foden et al. 2002). The delayed on-set of subduction in the Delamerian Orogen during which time opening of the Kanmantoo trough continued implies continued westward motion of the Australian portion of eastern Gondwana. This may have been accommodated by either subduction or deformation in either the Mozambique Suture or more probably in the northern end of the South Prince Charles Mountains – Prydz Bay suture until the Mid Cambrian.

In the South Australian sector of the Cambro-Ordovician Ross-Delamerian Orogen (RDO), granites range in age from Middle Cambrian to Early Ordovician. Their occurrence is largely confined to deep, Early Cambrian, sediment-filled basins where they are associated with mafic rocks. The syn-tectonic suites have compositions forming a continuum between I- and S-type granites. After the cessation of convergent deformation at ~490 Ma an abrupt transition to a bimodal magmatic association of mafic intrusions and felsic granites and volcanic rocks of S- and A-type affinities occurred.

As exposed on the south coast of Kangaroo Island, S-type granite originated as *in situ* partial melts of the Early Cambrian sediments locally intruded by either mafic magmas or I-S granite magmas. These migmatite complexes were mingled with intrusions from the magmas that provided the underlying heat sources. Also on Kangaroo Island, composite S-type rhyodacite - dolerite dykes indicate that crustal melting involved mantle-derived melts. Field observations, major and trace element and Nd-Sr isotopic data indicate that granite magmas in this fold belt result from mixing of crustal and mantle source components, and from fractional crystallisation (AFC-type processes). Whilst the Nd-Sr composition of granite suites from the Delamerian Orogen form a continuous geochemical trend between the crust and the mantle melts, the A- and I-types cluster towards the mantle endmember and the S-types towards the crustal endmember. This dichotomy reflects three granite magma production situations: 1. Lower crustal mafic magma chambers which are contaminated by, and mingled with, melts of the local meta-sediments producing I-type magmas, 2. Crustal melts formed in the heated zones above upwelling mantle or close to mafic or I-type granite intrusions producing S-type magmas, and 3. Upper crustal mafic intrusions where closed-system fractionation dominates to produce A-type granite. The extent of fractionation and crustal assimilation varied progressively through the ~ 30Ma deformation history (514 Ma - 485 Ma) of this orogen.

Importantly in this sector of the RDO, the crustal endmember is only represented by the Cambrian basin sedimentary fill (Kanmantoo Group) and expressly excludes the older Precambrian crust.

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Controls on Skarn Mineralisation and Alteration at the Cadia Deposits, New South Wales, Australia.

DAVID B. FORSTER AND PHILIP K. SECCOMBE
Tectonic and Earth Resources Research Group, University of Newcastle, Callaghan, NSW, 2308, Australia.

The Cadia skarns in eastern New South Wales, Australia, are associated with the Late Ordovician, shoshonitic Cadia Intrusive Complex (CIC). The Cadia porphyry gold-copper district is the largest mineralized, intrusive-related system in eastern Australia. Both the Big and Little Cadia skarns are Fe-rich and host Cu-Au mineralisation within a ~40m thick volcaniclastic sandstone and adjacent, predominantly calcareous units. These lithologies represent the most important control on skarn formation. The ore horizon has undergone post-ore displacement along steeply-dipping, predominantly reverse faults, without significant re-mobilisation of ore. Cu-Au mineralisation occurs as chalcopyrite and minor native gold formed in intimate association with epidote>chlorite-quartz-calcite and within interstices of bladed hematite and magnetite. Gold-copper ratios within the skarns are generally lower than for porphyry gold-copper deposits at Cadia, particularly the high tonnage, low-grade Cadia Hill deposit. Ore and calc-silicate gangue mineralogy, including garnet and pyroxene compositions and ratios, are consistent with oxidized, Au-Fe-bearing Cu skarns, commonly associated with porphyry deposits (Fig. 1).

At Big Cadia, mineralisation occurs several hundred meters north of the mineralizing CIC. Magmatic-dominated fluids from the CIC drove progressive consumption of carbonate, and produced classic skarn zonation over a 800m interval from Cadia Quarry to Big Cadia consisting of: i) proximal garnet>>pyroxene; ii) intermediate garnet>pyroxene+scapolite; and iii) distal Fe-oxide skarn with Cu-Au mineralisation (Figs. 2a to d). Alteration of non-calcareous units adjacent to the CIC includes, and magnetite-quartz-biotite hornfels and lesser hydrothermal biotite-K-feldspar-quartz. Sulphide and native gold mineralisation occur adjacent to garnet-bearing veins, peripheral to the main garnet-rich zone, and suggest that garnet-forming fluids carried ore metals in solution.

At Little Cadia and Cadia East, skarn zonation consisting of proximal calc-silicate skarn and distal mineralisation, is approximately similar to Big Cadia and occurs within the same volcaniclastic unit. The zonation is however developed symmetrically north and south about a mineralized quartz-monzonite porphyry (QMP) CIC-related intrusion at depth (Cadia Far East) (Figs. 3). Potassic (K-feldspar-biotite-magnetite) alteration is also developed within a narrow vertical zone above the intrusion. Where this zone intersects calcareous units, there is close association between potassic-alteration and veins and prograde garnet-bearing skarn. Hydrous retrogression (chlorite-calcite-epidote) has altered much of the prograde garnet-dominant mineralogy at Cadia, with overprinting strongest at Little Cadia.

The styles and distribution of alteration and mineralisation suggest that fluids migrating laterally within calcareous units, from strongly altered QMP phases of the CIC at Cadia Quarry, formed the Big Cadia skarn (Fig. 4a). Skarn formation at Little Cadia was probably related to CIC-derived fluids migrating vertically and laterally within permeable calcareous units (Fig. 4b). Structural controls may also have been significant in focusing fluids and the emplacement of late, mineralizing (QMP) phases of the CIC. Potential for additional skarn mineralisation exists in the region, including either reduced Au-skarn types, and/or Cu-Au skarns associated with porphyry deposits.

TABLE 1. Summary geological and resource data for the Cadia deposits

Deposit	Host rock	Deposit style	Alteration	Copper (%)	Gold (g/t)	Contained gold (t)	Size (Mt)
Cadia Hill[a]	Quartz monzonite porphyry	Sheeted veins	Propylitic, phyllic	0.16	0.63	221.3	352
Ridgeway[a]	Monzonite, quartz monzonite, volcanics	Quartz-sulfide stockwork		0.77	2.5	132.6	54
Cadia Quarry[a]	Quartz monzonite porphyry, volcanics	Quartz-sulfide stockwork	Potassic, phyllic	0.21	0.40	16.0	40
Cadia East[a]	Quartz monzonite porphyry	Wallrock-hosted vein system	Potassic, phyllic propylitic	0.37	0.43	94.6	220
Cadia Far East[a, b]	Quartz monzonite porphry	Wallrock-hosted vein system	Potassic, phyllic propylitic	0.48	1.7	107.1	63
Big Cadia skarn[a]	Volcaniclastic sandstone	Stratabound replacement	Propylitic	0.50	0.40	12.0	30
Little Cadia skarn[a]	Volcaniclastic sandstone	Stratabound replacement	Propylitic	0.40	0.30	2.4	8

Resource data: [a]Holliday et al. (2002); [b]Tedder et al. (2001)

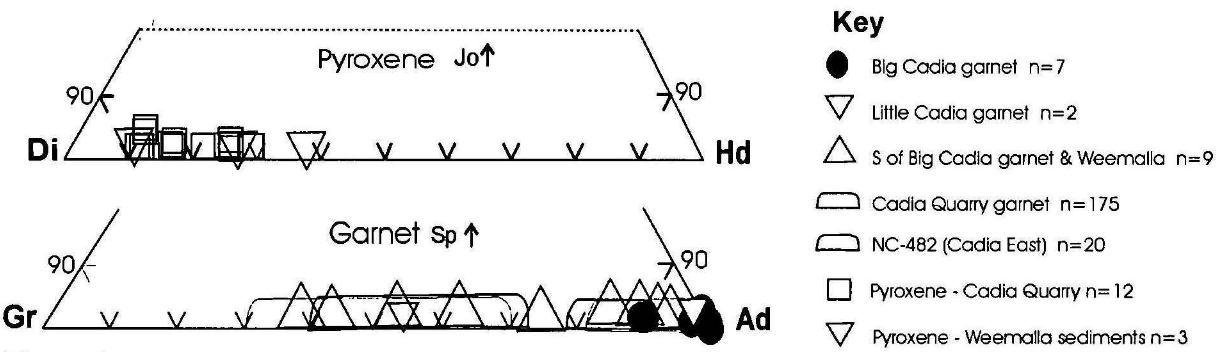


Figure 1.

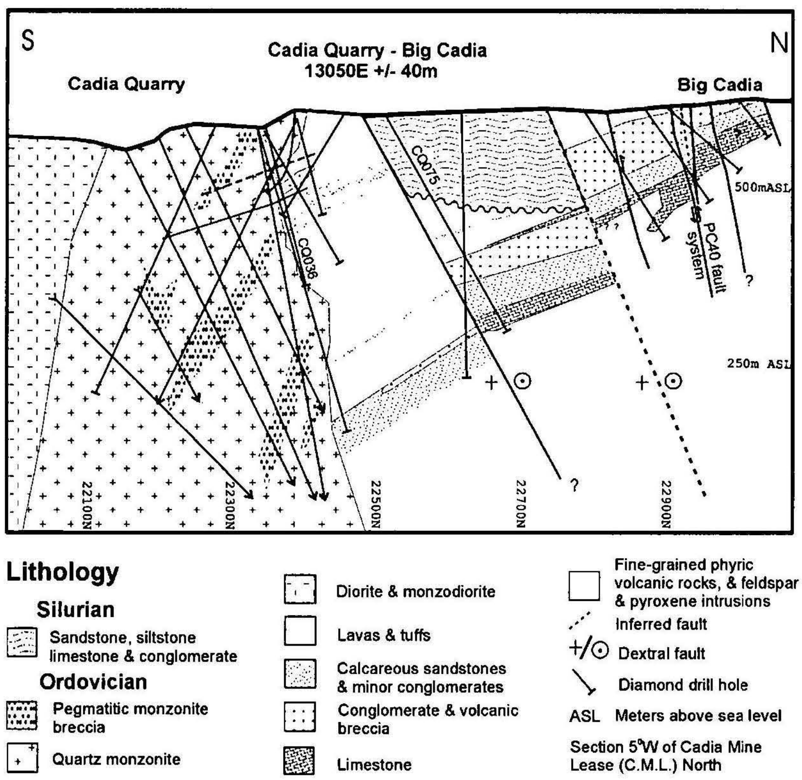


Figure 2a

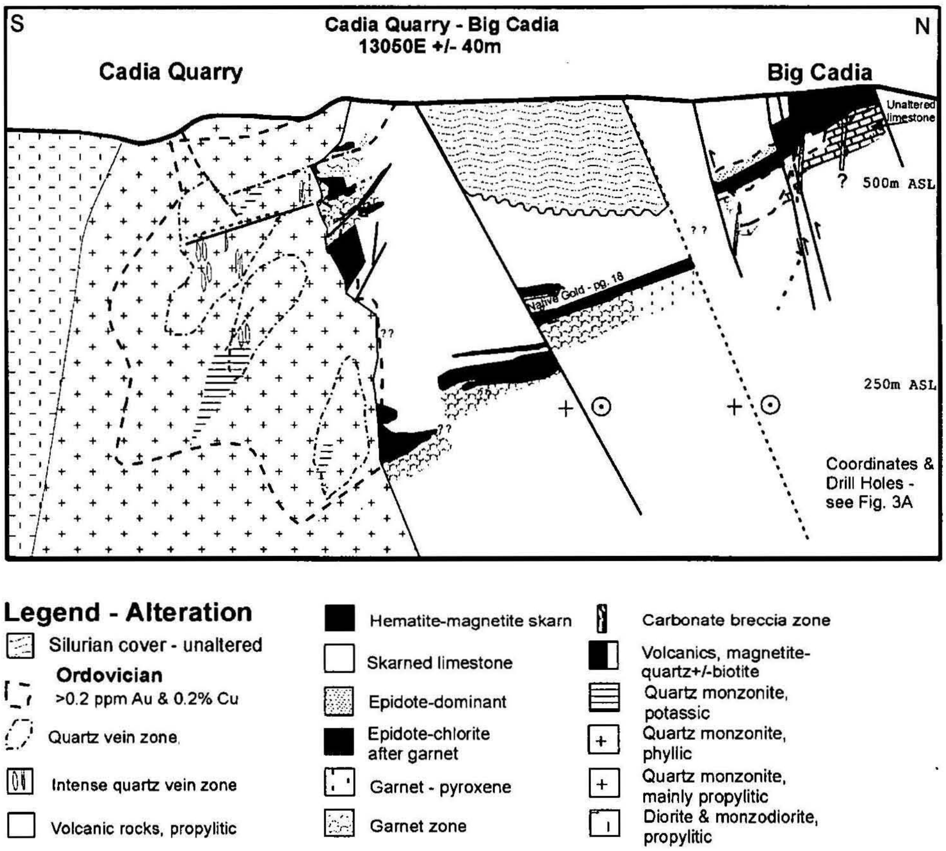
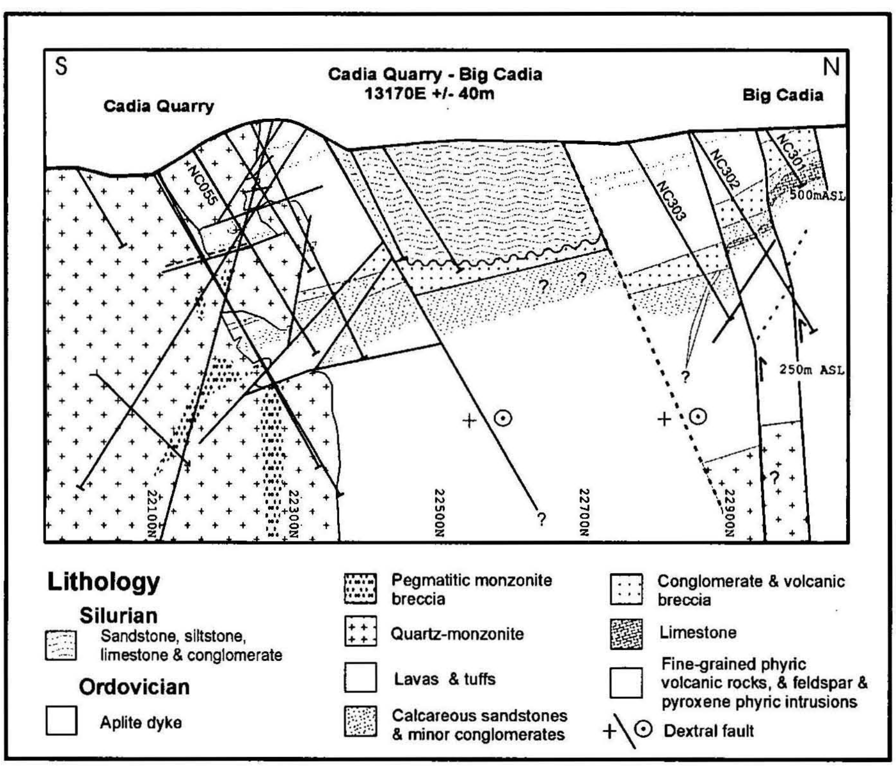


Figure 2b



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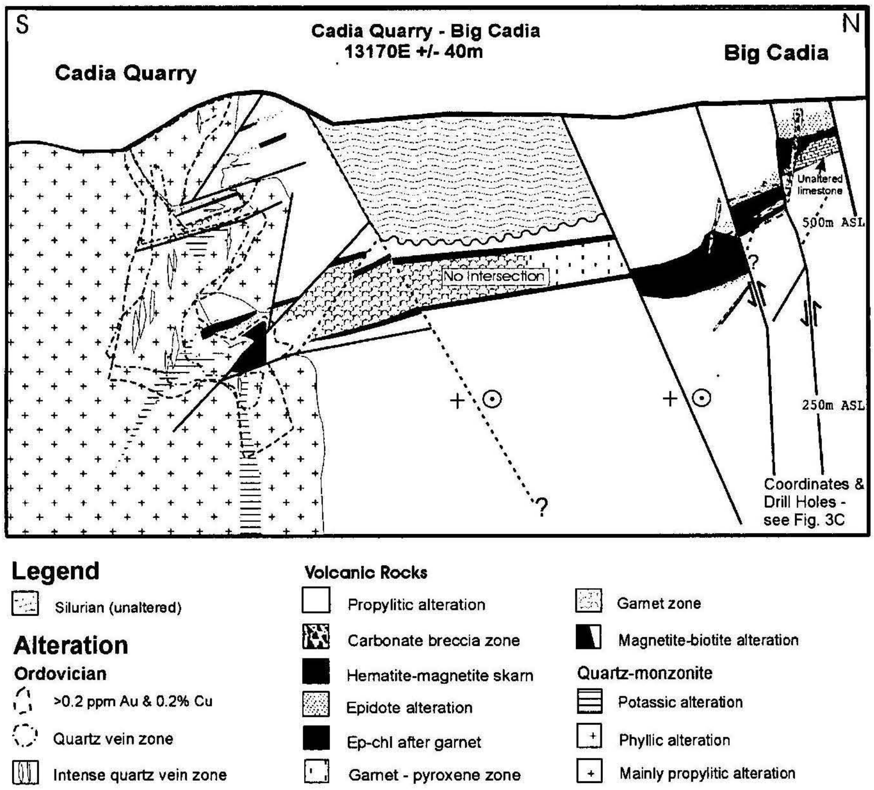

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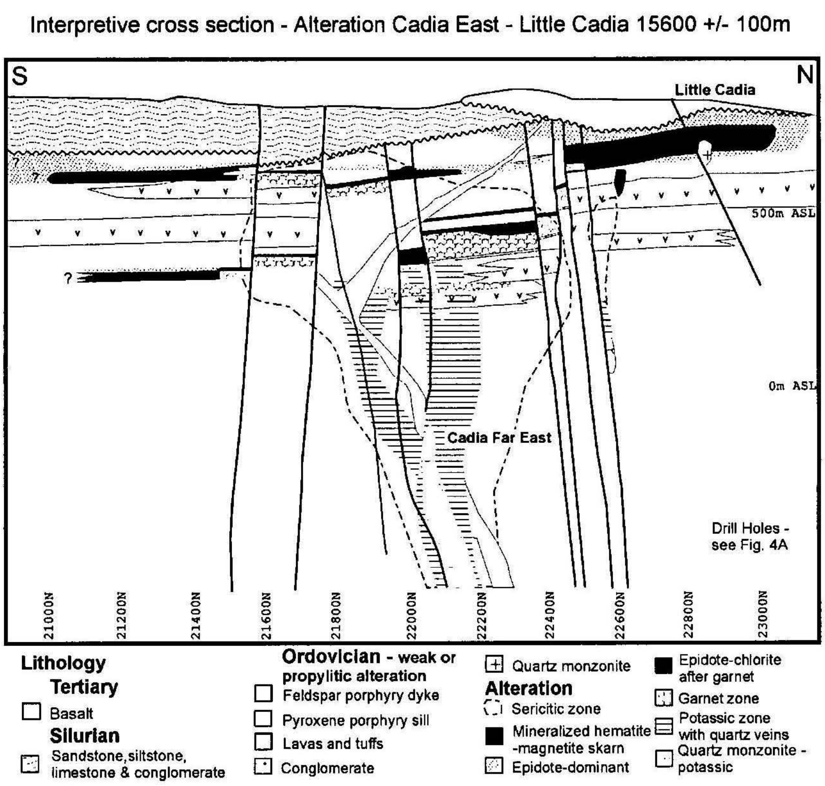
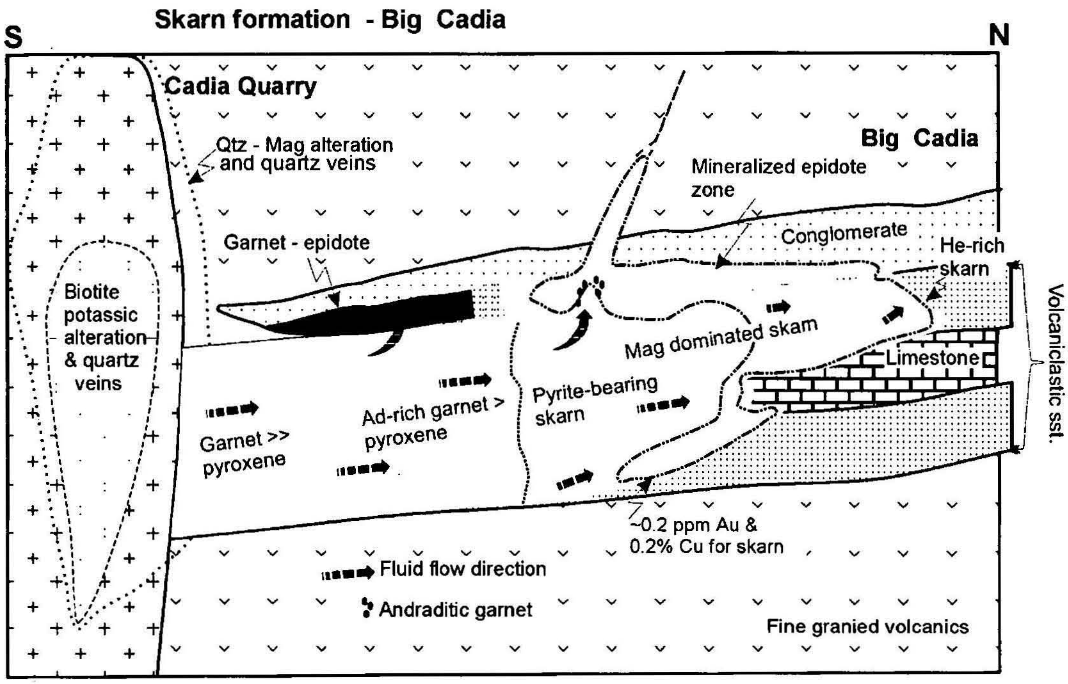


Figure 3



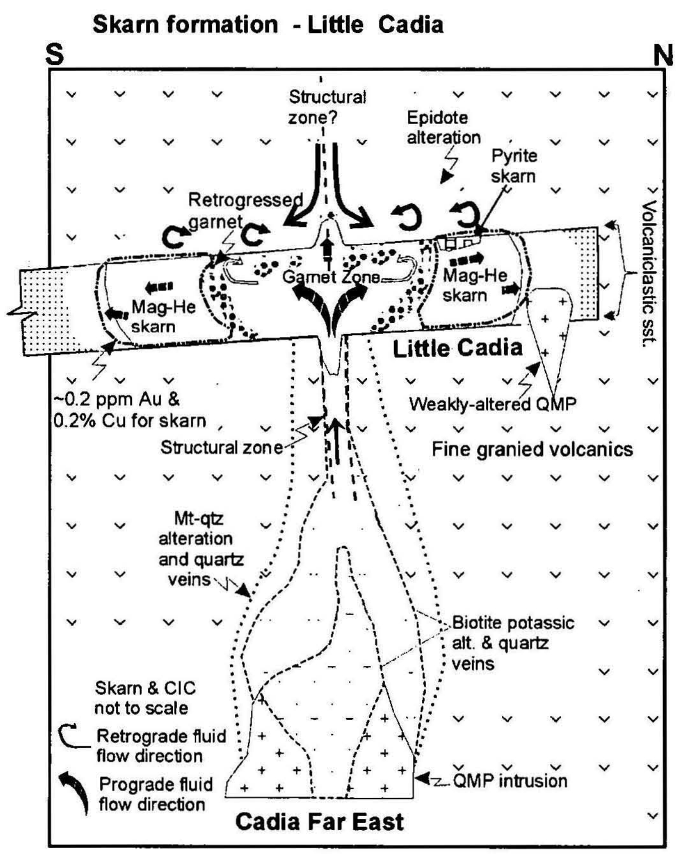


Figure 4 a and b.

Tectonic setting of porphyry copper-gold mineralisation in the Macquarie Arc

R. A. GLEN[1], A. J. CRAWFORD[2], D. R. COOKE [2]
[1]*Geological Survey of New South Wales, PO Box 536, St Leonards, NSW 1590, Australia*
[2]*Centre for Ore Deposit Research (CODES), University of Tasmania, GPO Box 252-79, Hobart, Tasmania 7001, Australia.*

Models of porphyry copper-gold ore formation involve magmatic volatile release from a crystallising intrusion. Incompatible elements are partitioned strongly into the aqueous phase, and fluid release probably commences at depths of several kilometres. Accumulation of volatiles beneath the already crystalline igneous carapace leads to hydrostatic pressures exceeding the combined lithostatic load and tensile strength of the surrounding rock mass, resulting in brittle failure and stockwork vein and/or breccia formation.

In this paper we explore the tectonic setting of porphyry copper-gold deposits in the context of evolution of the Ordovician Macquarie Arc in the Lachlan Orogen.

ARC EVOLUTION

There are four structural belts of subduction-related intermediate and mafic volcanics volcaniclastics and intrusives in the Eastern Lachlan Orogen of southeastern Australia. These are the Kiandra Volcanic Belt near the NSW-Victorian border and three belts in the central west of NSW: the western Junee-Narromine Volcanic Belt, the central Molong Volcanic Belt and the eastern Rockley-Gulgong Volcanic Belt.

Our structural and geochemical reconstructions show that these belts formed by the extension (and subsequent contraction) of a single arc. This arc, the Macquarie Arc, was an intraoceanic island arc developed along part of the boundary between the Australian and proto-Pacific plates from the earliest Ordovician to earliest Silurian. Data, especially from the western and central belts, show that over this time interval of ~50 myr, the arc evolved episodically. The western (Junee-Narromine) volcanic belt and the western and central parts of the Molong Volcanic Belt show evidence of 3 pulses of volcanism, separated by two major hiatuses in volcanism. Here, arc evolution consisted of pulse 1 Early Ordovician activity (~490-475 Ma), a hiatus of ~9 my centered on 470 Ma, pulse 2 Middle Ordovician activity (464-~455 Ma), another hiatus, especially in the west of up to 6.5 my around 452 Ma, and then pulse 3 Late Ordovician-earliest Silurian activity from ~450—439 Ma. The eastern part of the Molong Volcanic Belt and the Rockley-Gulgong Volcanic Belt only show volcanic pulses 2 and 3, although these are not separated by an obvious hiatus in volcanism like further west. As a consequence, pulse 3 commenced around 454 Ma, developed above volcaniclastics of pulse 2 that become finer grained and more 'distal' upwards and eastwards. There is no evidence of pulse 1 volcanism in the eastern (Rockley-Gulgong) volcanic belt, but the presence of ~475 Ma cherts is similar to that in other belts.

The Early Ordovician volcanics are chemically unlike primitive intraoceanic arc lavas: their high ε_{Nd} values preclude their having traversed any significant thickness of continental crust. The nature of their substrate remains unclear, but our view is that it may be the thinned and extended forearc section of the Cambrian arc-backarc system exposed in the greenstone belts in Victoria and Tasmania.

The 470 Ma hiatus may reflect back arc spreading. However, the similarity of the geochemical and isotopic signatures of the Middle Ordovician and Early Ordovician Macquarie Arc rocks suggests that no significant tectono-magmatic break separated generation of these magmas between 480 and 466-455 Ma. Compositions include high-K monzogabbros, monzodiorites and more evolved rocks in the Narromine Igneous Complex, and mainly medium-K rocks in the Cowal Igneous Complex.

The Late Ordovician hiatus centred on 450 Ma in the west of the arc may reflect backarc spreading and/or flat subduction associated with temporary blocking effects of buoyant seamounts or some other presently unidentified collider on the oceanic plate. Subsequent Late Ordovician phase volcanic rocks are shoshonitic everywhere, as are coeval volcanic rocks in the eastern belt, and represent melting of a enriched mantle source that was apparently absent during Middle Ordovician arc evolution.

PORPHYRY GROUPS

Based on age data we recognise 4 groups of porphyry in the Macquarie Arc. Group1 porphyries occurred during the ending of phase 1 volcanism, group 2 porphyries were emplaced during phase 2 volcanism, with some evidence pointing to emplacement early as well as late in this phase of arc evolution. Group 3 porphyries were emplaced at the start up of phase 3 volcanism and Group 4 at the end of phase 3.

Group 1 ~484Ma porphyries were emplaced at the end of the first cycle of volcanism in Junee-Narromine Volcanic Belt. They are represented by the Condobolin Road Intrusive Complex and have high-K calc-alkaline geochemistry; they are almost certainly comagmatic with the early Ordovician Nelungaloo Volcanics that they intrude. Other monzonites, preserved only as occasional clasts in Early Ordovician conglomerates, have high-K and shoshonitic affinities. No mineralisation has been found in Group 1 porphyries to date.

Group 2A ~465 Ma porphyries were emplaced around the initiation of the 2nd phase of volcanism in the Junee-Narromine Volcanic Belt. In the Narromine Igneous Complex, these intrusives range from monzogabbros to monzonites, and form a high-K magmatic suite little different compositionally from the Group 1 porphyries.

Group 2B ~455 Ma porphyries were emplaced near the end of the 2nd phase of arc volcanism in the Junee-Narromine Volcanic Belt

GROUP 3 ~450-445 Ma porphyries constitute the Copper Hill Suite, emplaced at the beginning of the 3rd phase of arc volcanism. Intrusives of this age form common but relatively small-volume mainly felsic intrusives in each of the volcanic belts. Mainly of dacitic composition, although sometimes extending to dioritic to gabbroic compositions, this suite is expressed mineralogically by the common quartz and hornblende phenocrysts in rocks with >60% SiO_2. These rocks have medium K calc-alkaline affinities. These porphyries contain significant amounts of mineralisation in the Molong Volcanic Belt (Copper Hill, Cargo) and in the Narromine Igneous Complex in the Junee-Narromine Volcanic Belt.

GROUP 4~439 Ma porphyries were emplaced at the end of the 3rd phase of arc volcanism in all belts except the Kiandra Volcanic Belt. Intrusives are shoshonitic monzodiorite-monzonite, comagmatic with the most of Late Ordovician volcanics in the arc. Mineralised Group 4 porphyries comprise the world-class gold-copper resources at Northparkes and at Cadia-Ridgeway, as well as scattered mineralisation in the Forest Reefs area.

CHEMICAL CONTROLS ON FORMATION OF PORPHYRY COPPER-GOLD DEPOSITS, MACQUARIE ARC

Previous workers have shown that the oxidation state of the magma appears to impart a strong control on whether a given porphyry system is gold-enriched. Transport of gold and copper together with sulphur from the igneous source regime is most readily accommodated in oxidized melts where sulphur can be transported in high concentrations as SO_2, together with copper and gold. In more reduced igneous melts, sulphur occurs as H_2S, and this has the capacity to form immiscible sulphide liquids that will scavenge copper and gold from the melts and retain them in the igneous source regime. Shoshonites are a particularly favourable oxidized magma composition for gold-rich porphyry copper-gold formation. Shoshonitic magmas are especially common in the third phase of activity in the Macquarie Arc (Group 4 porphyries). However, the presence of shoshonitic group 1 porphyries also means that these rocks form an exploration target as well. The Cowal example shows that intrusives that formed from a less oxidised and lower K rich magma can host major structurally controlled gold deposits.

Key trace element characteristics of the Group 3 Copper Hill suite porphyries, especially the strikingly high Sr/ Y values (80-95) compared with trachytic rocks in the Cowal (5-11) and Parkes region (mainly 30-70), invite comparison with adakitic lavas. However HREE patterns are flat to slightly MREE depleted, ruling out adakitic affinities. Although Group 3 porphyries seem to be less well-endowed in copper and gold than the shoshonitic porphyries, many of the Chilean porphyry copper-gold deposits have this signature, the significance of which is keenly debated.

The strong compositional overlap between the Cowal intrusives and the Copper Hill suite rocks suggests that either the dominant medium-K rocks in the Cowal Igneous Complex are of similar age to the Copper Hill suite (450-445 Ma), or, if the Cowal rocks are indeed older, that similar sources and magma generation conditions existed in the Mid and Early Late Ordovician time in the Macquarie Arc.

KEY CONTROLS ON FORMATION OF PORPHYRY COPPER-GOLD DEPOSITS, MACQUARIE ARC

Porphyries in the Macquarie Arc did not form during steady state subduction, but during critical events in the evolution of the arc. That is, either when subduction became shallower, or turned off, (Group 1, ?Group 2b, Group 4) due to back arc spreading, jamming of subduction zone, or during subduction reversal. Porphyries of Group 2a appear to have been emplaced when subduction recommenced in the Middle Ordovician after a hiatus of ~9 myr.

We can interpret these relationships in terms of stress states required to promote the formation of porphyries. Porphyries in the Macquarie Arc were not intruded in areas or times of maximum tension. Rather, they formed from magmas that fractionated in a crust that was thick and strong enough to hold magmas chambers. A compressive stress regime may assist in preventing lavas venting directly to the surface, and allow magmas to pond in high-level chambers (enabling extended fractionation). The actual formation of porphyry copper-gold deposits required these chambers to be breached, either by magma/fluid pressure build up, and/or by a reduction in differential stress. Release of magma and fluids were focused either along old structures or new structures, with pipe-like intrusions (probably dykes coming off magma chambers) controlled by the prevailing crustal stress field (sigma 1 vertical and sigma 3 horizontal).

These conditions seem to have best been served by transient switches in the stress state of the Macquarie Arc, caused by changes in the direction, rate of subduction or by coupling across the plate boundary. Such switches are facilitated if convergence across the plate boundary was oblique, the most common situation, which sets up a transpressional or transtensional component in arc deformation.

Significantly, the highly mineralised Group 4 Llandovery porphyries were emplaced after arc volcanism had shut down, and during arc deformation and formation of coeval transient basins. The absence in the stratigraphic record of any extrusive equivalents of these intrusives implies either very efficient erosion, or that the intrusives (= plugged dykes) that did not vent to the surface. The regional compression that prevented venting to the surface was associated with deformation within the arc and the weight of overlying structurally thickened volcanics and/or Llandovery basin sediments during the collision between the arc and its backarc.

DISTRIBUTION OF PORPHYRY COPPER-GOLD DEPOSITS, MACQUARIE ARC

Porphyry copper-gold deposits in the Molong Volcanic Belt are concentrated within the Lachlan Transverse Zone, a key arc-normal WNW-trending structure that lies parallel to the transform boundary along the southern margin of the restored Macquarie Arc. Included in this setting are the Cadia Intrusive Complex, intrusives in the Forest Reefs and older volcanics, as well as the Swatchfield intrusive in the Rockley-Gulgong Volcanic Belt. This zone thus underwent (apparently repeated) dilation in the Ordovician, especially near the termination of, or intersection, with arc-parallel structures. The Lachlan Transverse Zone appears to have set up a regional differential stress regime with WNW sigma 1 and NNE sigma 3, which permitted emplacement of WNW elongate porphyries in the Cadia region and Cargo. At Cadia, this stress field also provided a strong control on fracture development, resulting in the formation of sheeted vein arrays.

Whereas intrusives east of Orange also lie within the Lachlan Transverse Zone, the Copper Hill intrusives and those further north at Comobella do not. However, in the reconstructed arc they appear to lie on a WNW trending zone that includes intrusives near Sofala and Gulgong in the Rockley-Gulgong Volcanic Belt.

Further west, porphyry copper-gold deposits and porphyries are spread along the length of In the Junee-Narromine Volcanic Belt, with clusters west and northwest of Parkes lying in dilational zones that were repeatedly reactivated during arc evolution. In contrast to the Cadia porphyries, those at Northparkes show less evidence of emplacement in a differential stress regime. Their location may have been controlled by local jogs within an arc-parallel structure, the Endeavour 'linear', especially at the intersection with WNW structures.

This research was funded by an ARC-SPIRT grant. We thank our sponsor companies for their financial and logistical support: Alkane Ltd., Goldfields Ltd., Homestake Ltd., Newcrest Mining Ltd., and North Ltd. Glen publishes with permission of the Director-General, NSW Department of Mineral Resources. Crawford and Cooke acknowledge the support of the Centre for Ore Deposit Research, an ARC Special Research Centre.

The magmatic-hydrothermal transition: Volatile separation in silicic rocks at Bajo de la Alumbrera porphyry Cu-Au deposit, NW Argentina

Anthony C. Harris, Vadim S. Kamenetsky, and Noel C. White
Centre for Ore Deposit Research, University of Tasmania, GPO Box 252-79, Hobart, Tasmania, 7001, Australia

INTRODUCTION

Ore-bearing hydrothermal alteration in porphyry-related deposits largely form from exsolved magmatic fluids derived from crystallising, upper crustal silicic magmas (e.g., Hedenquist & Lowenstern 1994). If the original water content is sufficiently high, crystallisation causes an aqueous phase to separate from the melt, a process referred to as 'second' or 'resurgent boiling' (Burnham 1979, 1981; Burnham & Ohmoto, 1980). Despite this process being well constrained by numerical models (e.g., Shinohara & Hedenquist 1997), physical evidence for the physical separation and accumulation of an aqueous volatile phase has been limited. We present petrographic observations combined with silicate-melt and fluid inclusion studies of quartz from porphyritic intrusions at Bajo de la Alumbrera Cu-Au deposit, NW Argentina, that complete the continuum of petrological features preserving evidence of volatile exsolution linking magmatic and hydrothermal systems.

DEPOSIT GEOLOGY

Bajo de la Alumbrera is a Au-rich porphyry Cu deposit where Cu-Fe sulfide-bearing pervasive and fracture-controlled potassic (biotite-K-feldspar-quartz±magnetite) alteration assemblages overprint several phases of intrusive rocks. At least five high-K calc-alkaline to shoshonitic plagioclase-biotite(hornblende)-phyric dacite porphyries occur. Medium- to coarse-grained (up to 5 mm) plagioclase phenocrysts (<30%) are common, with lesser hornblende (2-3 mm, <2%), biotite (<5 mm, <5%) and quartz (<5 mm, <15%) crystals; the groundmass is quartzo-feldspathic. A minor amount of K-feldspar also occurs in the late intrusions. Accessory minerals include apatite, zircon, magnetite and titanite. Most disseminated Cu-Fe sulfide and Au mineralization occurs in the potassic alteration zone (J.M. Proffett *writ. comm.* 2001; Ulrich & Heinrich 2001). Fluid inclusion studies and stable isotope geochemistry reveal that a high temperature (between 350°C and 550°C, up to 750°C) and saline (>30 wt.% NaCl equivalent) fluid of magmatic origin (inferred from the calculated $\delta^{18}O$ and δD isotopic compositions) produced this alteration (Ulrich *et al.* 2001).

QUARTZ IN DACITE PORPHYRIES

Quartz in the porphyritic dacite intrusions at Bajo de la Alumbrera occurs, not only as a hydrothermal mineral, but also as a major phase in primary igneous textures (e.g., quartz eyes and comb-quartz layered textures). There are two petrographically distinct types of quartz eyes (Harris *et al.* 2003). Type 1 consists of typical quartz phenocrysts (Fig. 1A); they are large (up to 8 mm in diameter), rounded and irregular anhedral crystals. Individual crystals are dispersed throughout the groundmass, and may have distinct crystal edges, and contain small inclusions of feldspar and magnetite. Some quartz phenocrysts are embayed and apparently resorbed, giving them an ameboid appearance (Fig. 1B). Type 2 quartz eyes are elliptical, small (<2 mm), and consist of sugary aggregates of anhedral quartz crystals (Fig. 1C). They are distinctly different from quartz phenocrysts. Crystals of feldspar and magnetite are intergrown with the quartz. Some type 2 quartz eyes have empty voids in the core.

Although mostly randomly distributed throughout the groundmass, type 2 quartz eyes may exhibit an apparent linear arrangement. These quartz eyes appear to represent quartz (and other mineral phases) formed from an exsolved magmatic aqueous fluid at the earliest stages of its separation from a silicic magma (Harris *et al.* 2003). In essence, type 2 quartz eyes are a type of miarolitic cavity (e.g., Candela & Blevin, 1996).

Comb-quartz layered, or unidirectional solidification textures, have been found along the margins of several porphyries at Bajo de la Alumbrera. More commonly reported in granite-related Sn ± W and Mo systems (e.g., Lowenstern & Sinclair 1996), these textures consist of alternating bands (0.5 to 2.0 cm thick) of coarse-grained prismatic quartz, and radial intergrowths of biotite and sugary quartz-feldspar. Apical terminations of the quartz crystals are directed towards the related intrusions. Distinct primary fluid inclusion trails define growth band in individual quartz crystals (Fig. 1D). Some quartz layers have a wavy texture, with very fine-grained quartz intergrowths imparting a diffuse contact with the aphanitic groundmass of the related porphyritic intrusion.

Magmatic inclusion populations

The silicate-melt and fluid inclusion populations present in both types of quartz eyes and the comb-quartz layered textures are similar. Two populations of silicate-melt inclusions are recognised (Table 1). Volatile-rich silicate inclusions are most common, and have an irregular negative crystal form (Fig. 2A). Room temperature observations reveal small angular, crystalline silicate aggregates throughout: they vary mostly between 5 and 35 µm in diameter. A brine phase also occurs – this brine portion of the silicate-melt inclusion becomes visible following prolonged heating (Fig 2C; see micro-thermometry experiments below). A vapour bubble (20-40 vol.% vapour) is normally present. These composite inclusions contain several opaque phases (possibly chalcopyrite and magnetite). The second and less abundant silicate-melt inclusion population lacks the salt phase (Table 1; Fig. 2D) so prominent in the volatile-rich group IA inclusions (Table 1); these inclusions have a negative crystal or spherical shape and contain a shrinkage bubble (between 20 and 60 vol.%). Their size varies mostly between 15 and 45 µm, rarely up to 60 µm. Opaque daughter crystals (chalcopyrite?) are rare.

In the type 1 quartz eyes, silicate-melt inclusions coexist with vapour and polyphase brine inclusions (Fig. 2B) containing numerous daughter minerals such as halite, anhydrite, chalcopyrite and magnetite (hematite; Table 1). Little to no liquid is visible. Vapour inclusions (Table 1) are larger but less abundant when associated with the polyphase brine inclusions. Some quartz phenocrysts, especially in the earliest porphyry phases, are characterized by vapour inclusions only. Silicate-melt inclusions in the type 2 quartz eyes coexist with brine inclusions that have a higher proportion of liquid. Moreover, they are crowded with halite-anhydrite±magnetite(hematite)-sylvite-chalcopyrite and numerous unidentified phases. Similar inclusion assemblages exist in comb-quartz layered textures (Fig 2E, F). Coexisting vapour inclusions are rare in either case. The polyphase brine inclusions in the quartz eyes and comb-quartz layers are petrographically similar to those found in the earliest potassic alteration at Bajo de la Alumbrera (Ulrich *et al.* 2001; Harris 2002).

Silicate-melt and fluid inclusion micro-thermometry

Homogenization experiments on silicate-melt and fluid inclusions were performed at 1-atm external pressure using a LINKAM TS1500 heating stage. When individual quartz crystals are heated to 800°C for several hours and then quenched, the crystalline silicate aggregates in the melt inclusions fuse and do not reform on cooling; however, well-formed salt crystals and a vapour bubble appear when the inclusions are cooled below 250°C.

Typically, these salts appear in small (<1 to 8 μm) spherical globules crowded with salt crystals and a vapour bubble (< 2 μm) – this makes them morphologically similar to adjacent polyphase brine inclusions.

Micro-thermometric experiments reveal that for the silicate-melt inclusions in quartz eyes (type 1 and 2), the first dissolution of the salt phases occurs by 165°C, and is typically completed by 450°C, whereas vapour bubble disappearance in the brine component is as high as 550°C (Harris *et al.* 2003). The minimum trapping temperature of the silicate-melt inclusions ranges from 750°C to 780°C, based on extended heating experiments on the volatile-poor melt inclusions (Harris *et al.* 2003). Adjacent polyphase brine inclusions also homogenise at high temperatures (615°C to 695°C; by vapour disappearance). Assuming a simple NaCl-H_2O system, the calculated salinities of the inclusions average 45 wt.% NaCl equivalent.

Polyphase brine inclusions trapped in the comb-quartz layered textures exhibit homogenisation by halite dissolution; i.e., vapour disappearance occurs between 315°C and 365°C, whereas the large halite crystal typically disappears by 405°C. On the basis of these phase changes, combined with experimental data, the salinity is between 45 and 47 wt.% NaCl equivalent (as determined by Cline & Bodnar 1994). Reconstruction of the pressure-temperature trapping conditions (following the procedure outlined by Cline & Bodnar 1994) confirms that these inclusion fluids were probably trapped at pressures >0.8 kbar. By contrast, the majority of fluid inclusions in most vein and alteration stages at Bajo de la Alumbrera record fluid pressures of 0.3 kbar (Ulrich *et al.* 2001) – this fluid pressure is commonly reported for fluid inclusions in many porphyry ore deposits.

DISCUSSION AND CONCLUSIONS

The clearest evidence that some silicic magmas exsolve large volumes of magmatic aqueous fluids comes from geologic features, such as the occurrence of voluminous greisens, and the preservation of miarolitic cavities and comb-quartz layered textures in the carapace of some granites (e.g., Candela & Blevin 1995; Lowenstern & Sinclair 1996). In porphyry-related ore deposits, features such as interconnected miarolitic cavities may have been previously overlooked because of intense texturally destructive hydrothermal alteration. Their recognition at Bajo de la Alumbrera, combined with aqueous fluid phase equilibria from inclusion micro-thermometry, provide important constraints for the magmatic-hydrothermal transition.

Physical models (Shinohara & Kazahaya 1995; Shinohara & Hedenquist 1997) for the exsolution of volatiles from a convecting magma body show that at low degrees of crystallisation, individual vapour bubbles formed in the magma will buoyantly rise and coalesce at the top of the magma body. The accumulation of volatiles causes the internal pressure of the system to rise, leading to sudden and rapid failure of the carapace and adjacent wallrock – this occurs once the vapour pressure is greater than the confining pressure and tensile strength of the host rocks. Magmatic fluids escape via the extensive fracture network, and through water-rock interaction, cause hydrothermal alteration. Precipitation of alteration minerals seals the system, and the process is repeated. As the volume of crystals increases in the magma and the viscosity of the residual melt rises, aqueous fluid that has not previously escaped becomes trapped (e.g., Harris *et al.* 2003). At Bajo de la Alumbrera, textures representative of each critical stage are preserved.

Silicate-melt and polyphase brine inclusions from the quartz phenocrysts in the mineralised porphyries preserve the earliest stages of volatile exsolution (e.g., Lowenstern *et al.* 1990). Previous studies have taken such inclusion populations to indicate that silicic melt coexisted with hypersaline fluids (Roedder and Coombs, 1967); however, salt immiscibility is better preserved by composite silicate-melt inclusions (e.g., Kamenetsky & Naumov 2002). In these inclusions, a non-silicate volatile-rich hypersaline phase is immiscible with the magma from which it exsolved (e.g., Reyf & Bazheyev 1977; Frezzotti 1992; Kamenetsky & Naumov 2002). Reconstruction of the volcanic architecture above Bajo de la Alumbrera suggests that this source magma body probably occurred below 3 km (≥ 0.7 kbar lithostatic pressure; Harris 2002). Boiling of an originally supercritical fluid (<10 wt.% NaCl equivalent) exsolved at 1 kbar pressure and 680°C will result in a liquid with a salinity of 45 wt.% NaCl equivalent (Cline & Bodnar 1994 and references therein). Alternatively, as found elsewhere (Cline & Bodnar, 1994), the observed inclusion populations may indicate that aqueous fluids with salinities up to 45 wt. % exsolved directly from the crystallizing melt. If this latter scenario is correct, abundant vapour-rich fluid inclusions should coexist with the saline inclusions (see discussion by Cline and Bodnar, 1994), which is not the case here.

Comb-quartz layered textures are thought to preserve pockets of overpressured magmatic fluid separated from magma during secondary or resurgent boiling processes (Lowenstern & Sinclair 1996). Evidence of this overpressure is preserved in the fluid inclusions from the comb-quartz layered textures at Bajo de la Alumbrera; the inclusions exhibit liquid-vapour homogenisation between 315°C and 365°C, and halite dissolution by 405°C. Where observed (e.g., Cline and Bodnar, 1994), such homogenisation behaviour has been related to the entrapment of a halite-saturated fluid at high temperature and pressure. Over-pressuring causes fracturing of the carapace. Quartz-rich biotite-K-feldspar alteration assemblages probably formed as the pocket was drained of its fluid (Lowenstern & Sinclair 1996). Moreover, melt may also enter the fractures, forming thin dyke-like bodies, referred to as vein-dykes – these features are common in many porphyry ore deposits (e.g., Heithersay & Walshe 1995). In either case, sealing the fracture network above the magma causes the system to re-pressurise. Repeated volatile exsolution and/or degassing, volatile accumulation, over-pressuring and fracturing explains the complex alteration and mineralization patterns that exist in all porphyry ore deposits.

Features similar to those reported here are being increasingly recognised in other deposits (e.g., E26N porphyry Cu-Au, Australia; Lickfold *et al.* 2003). Quartz in the porphyries at Bajo de la Alumbrera records the earliest stages of exsolution, bubble formation (vesiculation), and volatile accumulation, culminating in hydrothermal alteration caused by magmatic aqueous fluids. Aqueous fluid phase equilibria observed during micro-thermometric studies reveal an apparent increase in pressure of the exsolved fluid prior to rupturing of the magma's carapace and the adjacent wallrock. When the volatile pressure exceeds the confining pressure (i.e., > 0.7 kbar), the carapace cracks and hydrothermal alteration and associated ores develop. Data obtained from silicate-melt and fluid inclusions, like that presented here, are providing important insights into the processes that form intrusion-related ore deposits.

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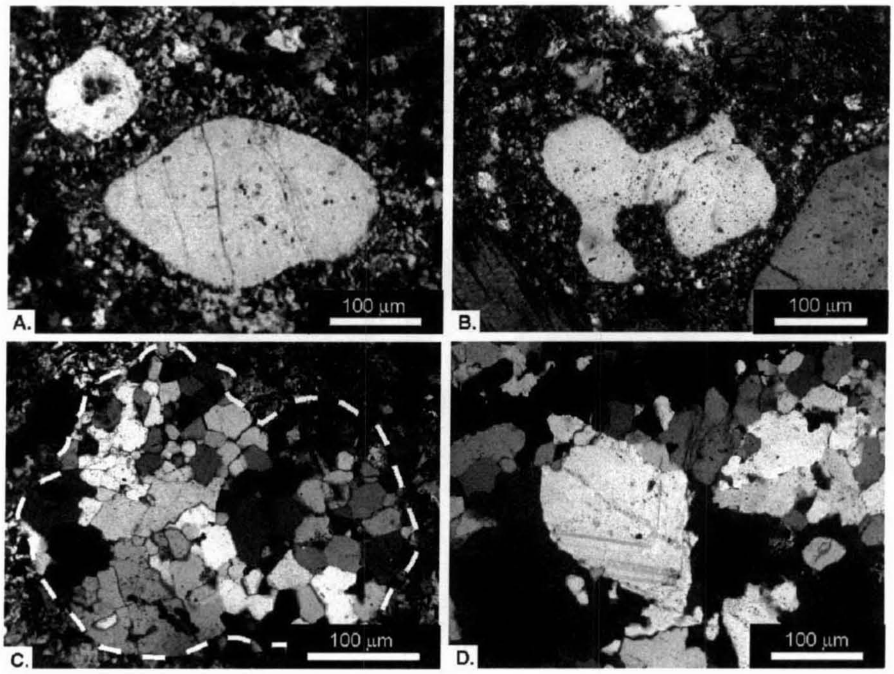

Figure 1. Quartz in dacite porphyries from Bajo de la Alumbrera. A. Type 1 quartz eyes or phenocrysts. B. Some quartz phenocrysts have an ameboid appearance because of embayments. C. Type 2 quartz eyes appearing as polycrystalline quartz aggregates. D. Prismatic quartz crystal, with distinct primary fluid inclusion trails, in comb-quartz layered texture.

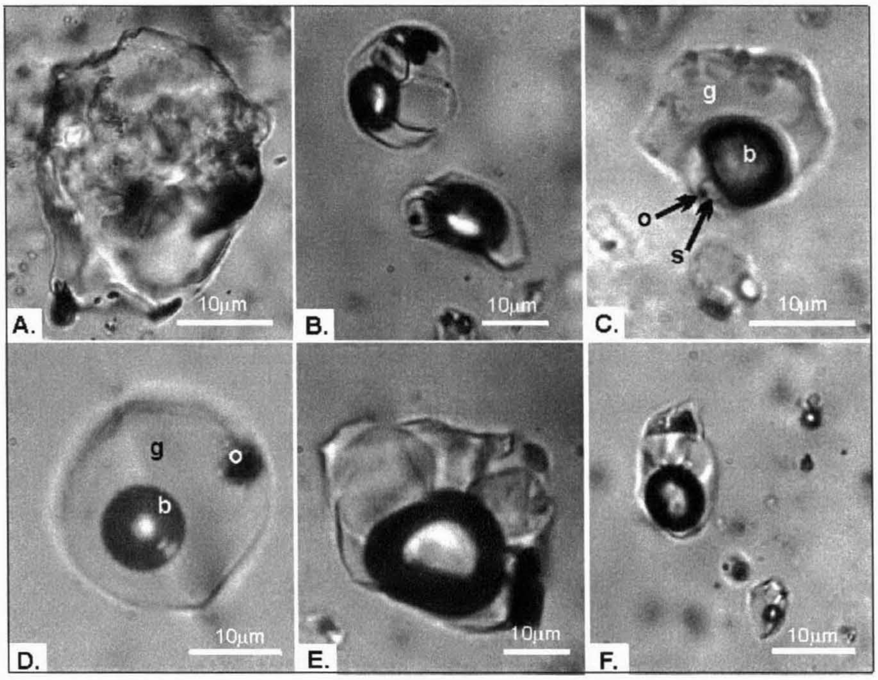

Figure 2. Magmatic inclusion populations in igneous quartz at Bajo de la Alumbrera. A. Silicate-melt inclusion in type 1 quartz eyes. B. Polyphase brine and vapour-rich fluid inclusions that coexist with silicate-melt inclusions in type 1 quartz eyes. C. Heated and quenched volatile-rich silicate-melt inclusion (Group IA; Table 1) with distinct volatile-rich globule containing a large vapour bubble (b), cubic salt (s), and an opaque (o) daughter crystal, surrounded by homogenised silicate glass (g). D. An example of a heated and quenched volatile-poor, silicate-melt inclusion from a late stage dacite porphyry (Group IB). Note the prominent vapour bubble (b) and opaque (o) phase encapsulated by homogenised silicate glass. E. Polyphase brine fluid inclusion (Group II) in comb-quartz layered texture. Note that the inclusion is crowded with salts. F. A primary inclusion trail in comb-quartz layered texture. In these inclusions, a distinct triangular chalcopyrite crystal is clearly visible.

Table 1. Summary of magmatic inclusions in quartz from dacite porphyries at Bajo de la Alumbrera

Inclusion Group		Description	Distribution
IA	*Volatile-rich silicate-melt inclusion*	Silicate crystals-vapour-salt(s) ± cpy.-mt.	Found as primary inclusions in quartz eyes. Coexists with group II and III inclusions. They also appear as primary inclusions in comb-quartz layered quartz textures. In this case, they coexist with group II inclusions.
IB	*Silicate-melt inclusion*	Silicate crystals (rare glass)-vapour ± opaque (?cpy.)	Rare in primary inclusion trails in quartz eyes. Isolated inclusions.
II	*Polyphase brine fluid inclusion*	Salt(halite-sylvite)-anhydrite-vapour-liquid ± cpy.-mt. (hem.)	Occurring in quartz eyes and comb-quartz layered textures. More commonly seen in primary and secondary inclusion trails in potassic alteration assemblages. Coexists with group III inclusions.
III	*Vapour-rich fluid inclusion*	Vapour-opaque (?cpy.) ± liquid	Abundant in primary inclusion trails in some quartz eyes; however, these inclusions are less abundant than group II inclusions.

Abbreviations: cpy. = chalcopyrite; mt. = magnetite; hem. = hematite.

Are Magmas Sources of Most or All Metals in Iron Oxide-Copper-Gold and Related Ore Types?

Douglas W Haynes
Douglas Haynes Discovery Pty Ltd*.
e-mail: dhdiscovery@bigpond.com

Abstract – Magmas are unlikely to be an "ortho-magmatic" source of copper and gold in iron oxide-copper-gold deposits, although data are not sufficient to confirm this inference as yet. Current hypotheses positing ortho-magmatic sources deserve critical examination, because iron oxide-copper-gold deposits display: (1) no consistent local spatial relationships with coeval magmatic rocks; (2) no relationships between the size and grades of their metal inventories and the composition and configuration of regionally or locally associated bodies of coeval magmatic rocks; (3) no stable or radiogenic isotope signature unequivocally indicating an ortho-magmatic source of copper and gold; (4) suites of anomalous elements that do not uniquely characterise any specific magma type; (5) a unique association with geological provinces that contain sodic-calcic alteration; (6) a unique association with a host lithological assemblage which does not contain reduced carbon minerals; or which contains such minerals in minor amounts only, at the regional scale; and (7) complex fluid inclusion chemistries that indicate that two or more fluids have been involved in ore genesis. Where coeval magmatic rocks are closely associated, for example, Olympic Dam, they do not display textures indicative of magmatic volatile phase separation and loss.

Copper and gold in porphyry copper deposits likewise may not have an ortho-magmatic source. Porphyry copper deposits of the SW USA, the SW Pacific arcs, and Chile, display characteristics (2), (3), (4), and (6). Characteristic (6) is marked: the deposits only occur in host lithological assemblages that either do not contain, or which contain very minor, carbonaceous or graphitic rocks, for example, shale or schist, or carbonate, or greywacke, or quartzitic greywacke, at the regional scale.

A modified para-magmatic metal source hypothesis is proposed to account for the characteristics noted. The elements of the hypothesis are: (1) a magma stock is emplaced across a fault or fault sets that comprises part of, or is linked to, a major, seismically active system; (2) the fault is subject to repetitive high slip rates during the seismic activity; (3) strain damage within the crystallised shell of the stock is greatest near the fault; (4) fluid pressures in the fault periodically range from sub-hydrostatic to lithostatic during the seismic cycles; (5) at a lithostatic p_{fluid} at a depth of 8km or so, rocks in the stock adjacent to the fault are brittle at temperatures up to those of an intermediate magma on its liquidus during episodes of high strain rates or where stress regimes are favourable (e.g. Fournier, 1999, Fig 3; Sibson, 2000, Fig 4) (6) fluid is episodically pumped into the solidified part of the stock from a fluid reservoir within the fault, with fluid flow greatest in the zone of strain damage adjacent to the fault; (7) steep thermal gradients, and the thermal reservoir represented by the cooling stock contribute to the fluid pumping; (8) the injected packets of fluid ascend either under ductile conditions within the hot rocks near the interior of the magmatic body; or episodically under brittle conditions in the interior and in the sub-solidus shell of the magmatic body when strain rates are high; (9) the ascending packets of fluid reach their two phase region within or above the upper parts of the magmatic body (e.g. Hedenquist et al. (1998), Fournier (1999); Meinert et al (2003); (10) precipitation of ore minerals occurs in this region and at lower temperatures, (11) metals are sourced from rocks in the fluid flow paths, and from trapped tiny bubbles of "ortho-magmatic" fluid in flow paths of the fluids injected

into the stock; and (12) metals initially transported are controlled by initial fluid salinities and oxidation states.

The speculative hypothesis, clearly requiring further research, may help to account for (a) the association of porphyry copper deposits and iron oxide-copper-gold deposits with lithological assemblages predominantly free of reduced carbon at the regional scale; (b) an absence of evidence for magmatic volatile phase saturation and loss from the ore-associated magmatic rocks in the porphyry copper and iron oxide-copper-gold systems considered here; (c) vein orientations in porphyry copper deposits inconsistent with volatile-saturated magma depressurisation events (e.g. Burnham (1979); (d) faults and fault sets comprising parts of regional scale faults associated with ore-bearing or ore-proximal magmatic rocks; (e) porphyry copper deposits situated on the margins of the concealed parent stocks of the ore-associated intrusive bodies, rather than on their apices; (f) no correlation between metal grades and contents of the deposits and the size and configuration of an associated coeval body of magmatic rock; (g) "magmatic" oxygen and hydrogen isotope signatures of the "magmatic" volatile phase; (h) Sm/Nd systematics, and Pb and other isotope signatures which indicate a component within mineralisation and within the inferred source intrusion with crustal affinities; and (e) lack of robust *primary* geochemical, mineralogical, and textural indicators that differentiate mineralisation-associated magmatic rocks from barren magmatic rocks, even within mineralised districts.

This speculative hypothesis is presented in an attempt to resolve the great question facing exploration geoscientists in their hunt for intrusion centred ore deposits: what are the relations between regional scale fault systems, magmas, host lithological assemblage oxidation state, and the intrusion centred ore deposits? The current ortho-magmatic hypothesis of ore genesis is currently too limited to resolve these questions, and it fails to satisfactorily account for the structural and lithological associations of iron oxide copper gold deposits and many porphyry copper deposits.

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Metallogenic mineralization vs the granite series in the Mesozoic-Cenozoic Circum-Pacific plutonic belts

Shunso ISHIHARA
Geological Survey of Japan

Major metallic mineralizations occur in the form of sulfides, such as molybdenite, chalcopyrite, bornite, sphalerite, galena, argentite, etc. These S-combined metals are brought by oxidized, magnetite-series granitoids, because of predominance of oxidized species sulfur, which takes out metals from the host granitic magmas the vapor phase, then to the granite cusps and the surrounding wall rocks. Gold can be transported and concentrated as bisulfide or chloride complex. The bisulfide Au is concentrated around the oxidized pluton, but the chloride Au may occur with plutons with variety of oxidation status. Identification of oxidized type of granitoids is most fundamental in mineral exploration of important metals in granitic terranes.

The oxidized type of granitoids are most dominant in the East Pacific rim, while the reduced type prevails in the West Pacific rim (Ishihara, 1977). These two types are most easily determined by measurement of magnetic susceptibility. In the largest batholith of the Coast Plutonic complex in Canada, the measurement of L. Carmel on the Jim Roddick collection indicates an average of 14.5 ±11.7 x 10^{-3} SI (n=937) on granitoids of the main Coast Belt and 16.9 ±16.0 x 10^{-3} SI (n=56) on those of the Vancouver Island. Both the values are higher than 3.0 x 10^{-3} SI; thus belonging to the magnetite series. The granitoids are reduced in the katazonal granitoids associated with high-grade gneisses. Calc-alkaline porphyry-type Mo-Cu and alkaline porphyry-type Au-Cu deposits occur mostly related to epizonal oxidized plutons of the Intermontane Belt (Fig. 1).

The Sierra Nevada batholith is also composed of largely oxidized type. Three E-W transects study of magnetic susceptibility passing through north of Bishop by Bateman et al. (1991) indicates that the oxidized type possesses 90 %, 66 %, 55% on the northernmost A-A', central B-B', and southernmost C-C' transects, respectively (Fig. 2). As a whole (n=382), the oxidized type is 68 %. Along each transect, the magnetic susceptibility decreases westward, although the batholith becomes generally mafic toward west, suggesting the western foothill granitoids are reduced to ilmenite-series (below NNO buffer) or intermediate series. The Mother Load Au veins and dissemination, and many of small Au veins occur in the western foothill area. Skarn, vein and porphyry types scheelite and copper deposits tend to occur in the eastern part related to the oxidized-type granitoids.

In the Peninsular Range batholith, variation of the magnetic susceptibility is geographically reversed, i.e., it increases to the west, where the plutonic rocks are associated with coeval volcanic rocks (Fig. 3). The western magnetite-series belt corresponds to low $\delta^{18}O$ (less than +8 ‰) region, and the eastern ilmenite-series belt is
seen in the high $\delta^{18}O$ (more than +8 ‰) region (Gastil, 1991). The magnetite/ilmenite-series boundary is very close to the alignment of La Posta-type zoned plutons. A little mineralization has been known in and around the Peninsular Ranges Batholith.

Along he Peruvian Coast, similar I-type granitoids occur in narrow belt (Cobbing et al., 1981). They were divided into several segments from north to south. Transect study across the central Lima Segment indicates that their magnetic susceptibility is generally higher than 3.0 x 10^{-3} SI (Ishihara et al., 2000), being oxidized type except for local granitic phase (Fig. 4). Large porphyry copper deposits occur in the southeastern, Toquepala Segment, but most other deposits are associated with oxidized smaller intrusions located toward the east of the Coastal Plutonic Complex, e. g., Cordillera Blanca batholith (Fig. 4). The related mineralizations are late Cretaceous Cu veins, Cu-Mo-W skarns, Au-(Cu) veins and Porphyry Cu, and Paleogene Cu-Pb-Zn skarns and porphyry Cu-Mo deposits.

The situation is similar in the north-central Chile. Here, I-type magnetite-series plutonism initiated in Jurassic time onward (Ishihara et al., 1984). In addition to similar styles of the mineralization to Peru, manto-type Cu and magnetite deposits and huge size of the porphyry copper deposits are distinct in the Chilean side.

In porphyry copper deposits, S can easily exceed 10 times of Cu content; thus the ore deposits can be huge sulfur deposits. Sulfur could be carried by mafic magmas because solubility of sulfur correlates with that of iron. There are two possibilities proposed: (1) basaltic magmas but mingled with felsic magma, and (2) andesitic magmas. Ultimate source of sulfur could be juvenile upper mantle or recycled sea-water sulfate. If given magmas are barren in copper, huge pyrite deposits may only be formed. Thus we need magmas initially high in copper to form chalcopyrite deposits. Copper sulfide can occur in magmatic temperature as *iss*, so that copper content of unaltered granitoids can be useful for mineral exploration.

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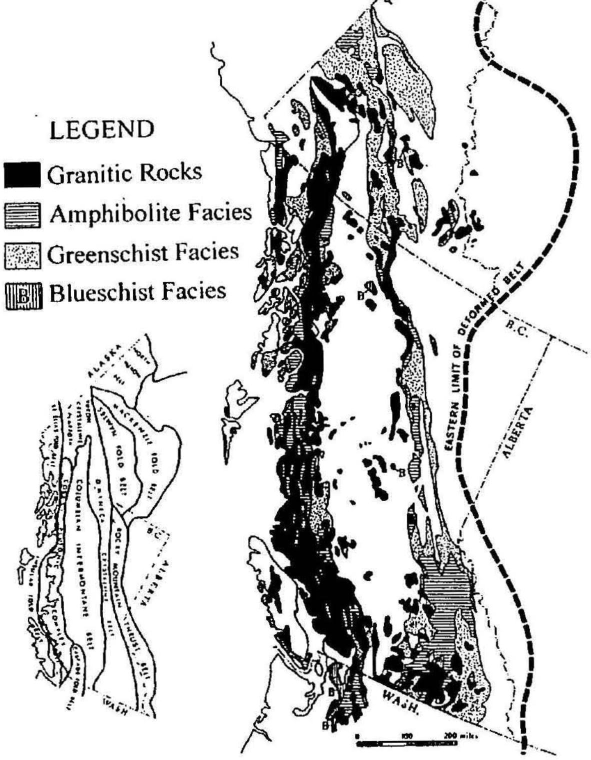
Fig. 1

Coast Plutonic complex
(Roddick & Hutchison, 1972)



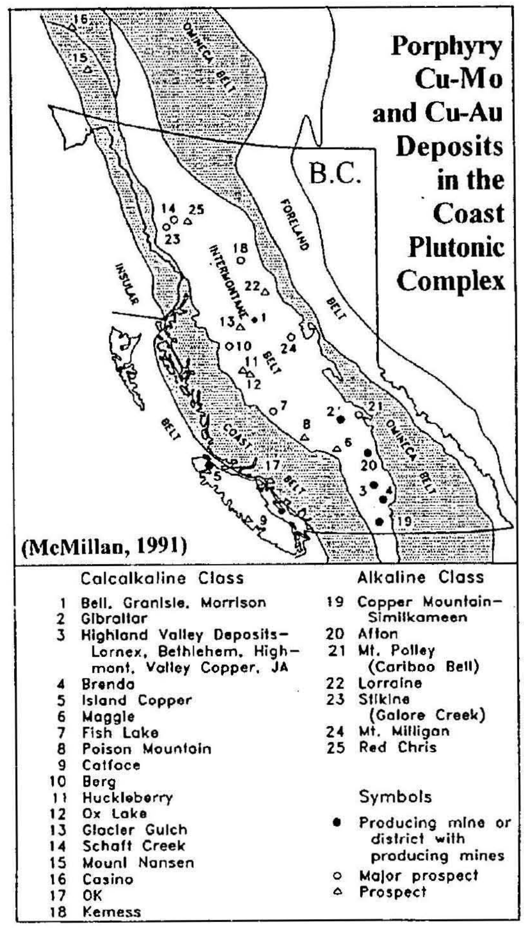


Fig. 2 Magnetic susceptibility across the Sierra Navada Batholith (Bateman et al., 1991)

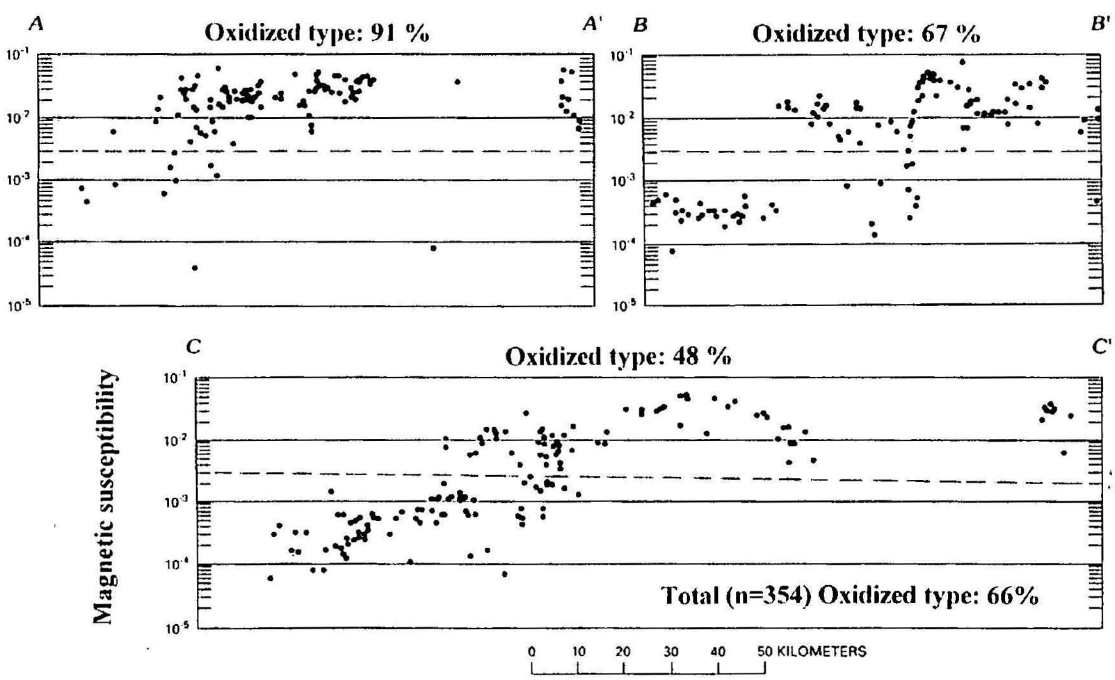


Fig. 3 Magnetic susceptibility and whole rock $\delta^{18}O$ ratio, Peninsular Range Batholith (Gastil, 1990)

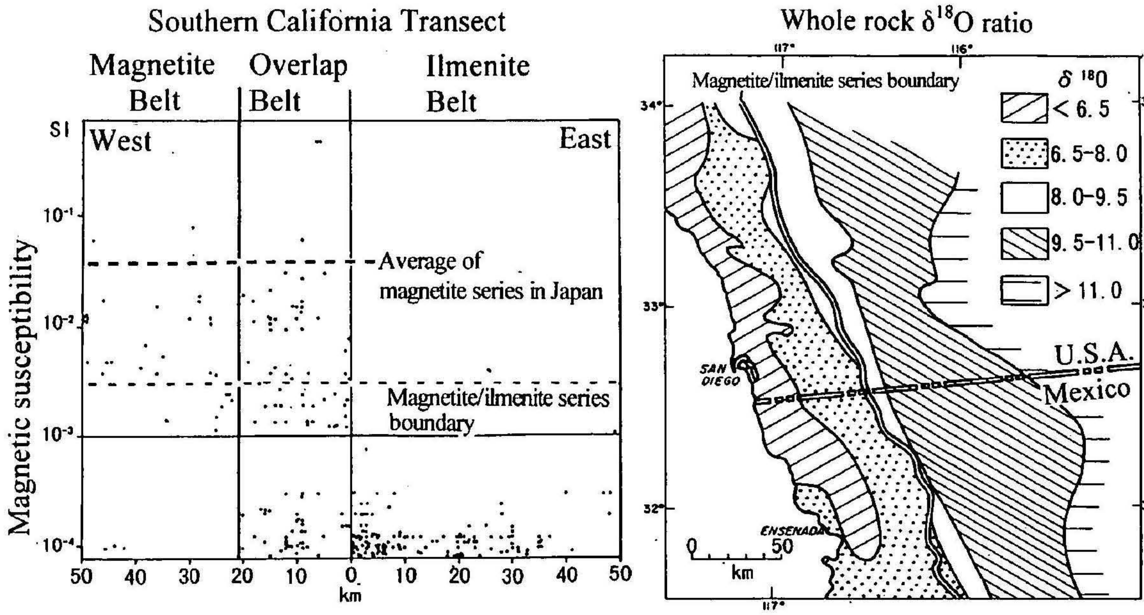
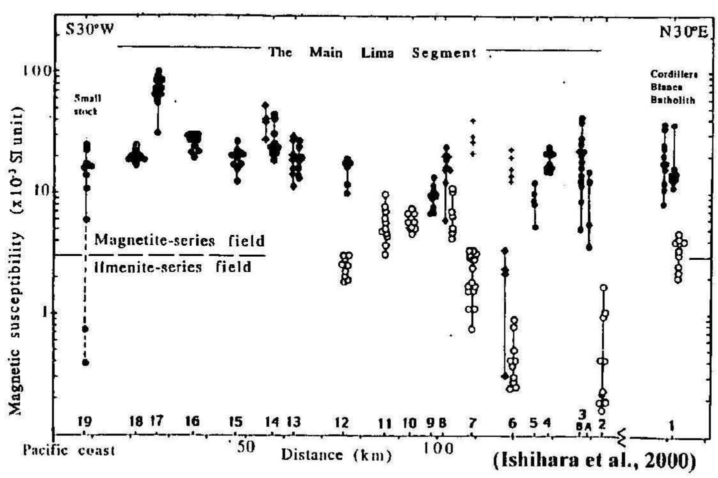
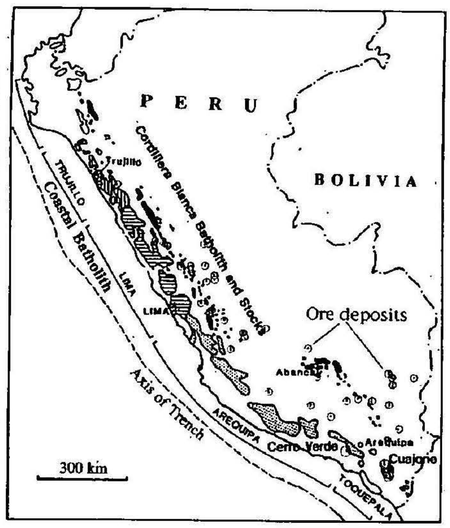


Fig. 4 Magnetic susceptibility across the Lima Segment, Peru



(Ishihara et al., 2000)



Mesozoic Granites and Associated Mineralization in South Korea

Yong-Joo Jwa

Department of Earth and Environmental Sciences, Gyeongsang National University, Jinju 660-701, Korea; GEMOC Key Centre, Department of Earth and Planetary Sciences, Macquarie University, Sydney, NSW 2109, Australia

1. Tectonic Setting and Distribution of Mesozoic Granites

Tectonically, South Korea can be divided into four provinces based on the distribution of sedimentary basins upon Precambrian basements. The pre-Cretaceous basement comprises two Precambrian massifs, the Yeongnam Massif in the South and the Gyeonggi Massif in the north, which belong to the Sino-Korean microcontinent. They exhibit Sinian tectonic trends (SW-NE direction) and are made up of Precambrian gneiss complexes with some Proterozoic to Jurassic metasedimentary cover (Lee, 1987). The Okcheon Belt between the two massifs consists of a northeastern non- to weakly-metamorphosed Paleozoic-Mesozoic sequence which grades into the Okcheon metamorphic belt to the southwest. The Cretaceous sedimentary basins in South Korea were formed by transtension driving the movement of the sinistral strike-slip faults (Lee, 1999). The sedimentary strata, the so-called Gyeongsang Supergroup, comprises non-marine sedimentary and andesitic to rhyolitic volcaniclastic rocks. The basins overlie the pre-Cretaceous sequences with a marked unconformity. The products of Cretaceous granitic magmatism are quite evident in two large Cretaceous basins; the Gyeongsang Basin and the Yeongdong-Gwangju Basin.

Mesozoic granites of South Korea have been divided into two groups based on intrusion age: the younger granites of late Cretaceous to early Tertiary age, and the older granites of Jurassic age (Lee, 1974; Kim, 1975; Hong, 1987). This two-fold discrimination seems to be in accord with the conventional idea that the older granites are genetically associated with the Jurassic Daebo orogeny and the younger granites with the Cretaceous Bulguksa disturbance in South Korea (Lee, 1987). The Jurassic granites occur in the Gyeonggi Massif, the Yeongnam Massif, the Okcheon Belt, and the Gyeongsang Basin, whereas the Cretaceous granites occur in the Okcheon Belt and the Cretaceous Gyeongsang and Yeongdong-Gwangju basins. New radiometric ages reportedly argue that there exist some Triassic granites in the older granite group (Kim and Turek, 1996; Cheong and Chang, 1997; Cheong et al., 2002; Sagong et al., 2002). The Triassic granites have quite distinct petrologic and geochemical characteristics from the Jurassic granites, and they crop out in a restricted area of the Yeongnam Massif and the Gyeongsang Basin.

From a comprehensive study on the radiometric ages of the Mesozoic granites in South Korea, Sagong et al. (2002) argue that the crystallization ages of the granites show three episodes of Mesozoic magmatism in South Korea: Triassic (248-210 Ma), Jurassic (197-158 Ma) and late Cretaceous-early Tertiary (110-50 Ma), with a late Jurassic-early Cretaceous (~50 Ma) hiatus. They suggest that the age structure of the granites is closely related to temporal changes in relative plate motion of the oceanic Izanagi plate to the eastern Eurasian continent during the Mesozoic. The geochemical contrasts among the Mesozoic granites in South Korea possibly reflect different tectonic environments where the granites intruded (Jwa, 1994, 1998, 1999).

2. Geochemical Characteristics of Mesozoic Granites

The Precambrian cratonic crust in South Korea is divided into two massifs – the Gyeonggi Massif to the north and the Yeongnam Massif to the south. Mesozoic granites intrude both massifs, and these are mostly calc-alkaline, I-type and magnetite-series but some S-type and/or ilmenite-series granites are also present. The Jurassic granites form extensive deep-seated batholiths, the Triassic granites are deep-seated stocks, and Cretaceous granites occur as volcanic-plutonic complexes.

Inferred parental compositions of most Mesozoic granites (metaluminous to weakly peraluminous compositions and high $^{87}Sr/^{86}Sr$ initial ratios (> 0.709)) suggest that the magmas formed by melting of an evolved igneous protolith. However, the Cretaceous and Triassic granites, from the Gyeongsang Basin along the southeastern margin of South Korea, are metaluminous and have low Sr isotopic initial ratios (ca. 0.705), implying a more juvenile igneous source material. Because the exposed basement rocks are strongly peraluminous, they are not a feasible source for the metaluminous Mesozoic granites. Also, isotopic compositions of the exposed Precambrian basement rocks differ greatly from those of the Mesozoic granites. The Precambrian basement has highly evolved Nd isotopic signatures ($\varepsilon Nd \approx -20$ to -35), and old depleted-mantle model ages (TDM > 2.0 Ga). In contrast, the Mesozoic granites, except for the granites in the Gyeongsang Basin, have less evolved εNd values (-15 to -20) and younger TDM ages (1.5 to 2.0 Ga). These data imply that the Mesozoic granites were not directly derived from the exposed Precambrian basement rocks. The narrow range of εNd values and TDM ages of the granites would indicate that the granitic magmas were produced from an isotopically homogeneous lower crust that underplated the current exposed basement during the Middle Proterozoic. Intense Middle Proterozoic orogenic events recorded in the Precambrian basement rocks may indicate the underplating of young crust at this time. On the other hand, the isotopic signatures and model ages of the granites could be due to the interaction of the granitic magmas from the juvenile sources with the highly evolved basement rocks. Slightly depleted εNd values (-5 to 4) and younger TDM ages (< 1.5 Ga) of the granites in the Gyeongsang Basin suggest Late Proterozoic addition of more juvenile crust to the continental margin. If the juvenile crust was the source of the Mesozoic granitic magmas then the isotopic data imply that these magmas interacted with the more highly evolved basement rocks.

3. Mesozoic Metallogenesis in South Korea

Metallogenic provinces in South Korea can be divided into four main provinces by means of the metallogenic epoch; Precambrian, Paleozoic, Jurassic, and Cretaceous to early Tertiary (Yun, 1982). The Mesozoic metallogenic provinces are well constrained by the distribution of the Mesozoic granites, showing SW-NE Sinian trends. Hydrothermal vein-type and skarn-type ore deposits which are closely related to the Mesozoic granites are the most important base metal-bearing resources.

W-Mo and Pb-Zn mineralization is the most common among the base metal (W-Mo-Pb-Zn-Cu-Au-Ag-Fe) deposits. Source and host rocks strongly control the metallogenesis of the ore deposits. Hydrothermal fluids from the granitic magma produced most vein-type deposits, and the Paleozoic limestone was an excellent host for the skarn-type metal deposits. The Mesozoic metallogenic provinces can be divided into several sub-provinces (metallogenic zones) according to the distribution of base metals. For example, at least five zones are identified in the Cretaceous Gyeongsang Basin; those are from SE to NW Cu zone, Fe zone, Cu-Zn-Pb zone, W-Mo zone, and Pb-Zn zone.

Certain types of mineralization are closely related to the age and mode of emplacement of the Mesozoic granites. Gold-silver mineralization would be the best example for the spatial and temporal relationship between the mineralization and the felsic magmatism in South Korea. The Au-Ag deposits can be typically divided into auriferous massive quartz veins (Jurassic type), and multistage gold-silver quartz veins (Cretaceous type). The Jurassic auriferous deposits are spatially associated with uplifted Precambrian metamorphic terranes and temporally with the Jurassic granites. On the other hand, the Cretaceous lode deposits are genetically related to the contemporaneous granites intruded in extensional environments such as the Cretaceous sedimentary basins. Choi (2002) divided the Au-Ag deposits into eight subgroups on the basis of Au fineness, associated metals, vein character and mineral assemblages, and argued that each subgroup reflects a variety of thermal episodes and ore-forming fluids from granitic magmas with contrasting age and mode of emplacement.

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GRANITES, VOLATILE SOLUBILITY & TRACKING THE FORMATION OF MAGMATIC FLUIDS

P.L. King[1] & A.J.R. White[2]

1. Dept. Earth Sciences, Uni. Western Ontario, London ON N6A 5B7 Canada
2. VIEPS, The University of Melbourne, Victoria 3010, Australia

Magmatic fluids have an important role in carrying metals from a source region to ultimate deposition and preservation in an ore deposit. Magmatic fluids are typically dominated by H_2O, and generally they are supercritical; that is, they exist at conditions greater than the critical point (374 °C and ~220 bars for pure H_2O). Magmatic fluids may also contain other low-density molecules or "volatiles" such as Cl, other halides, H_2S, SO_2, CO_2, CH_4, N-compounds, and B. In this workshop we summarize aspects of volatile solubility, the initial volatile content of a melt, and the onset of fluid formation.

Water and granite magmas

Water is the most abundant volatile component in silicate rocks and it is highly soluble in granitic melts. For example, at 700 MPa (7 kbar) a granitic melt may dissolve up to 14 wt. % H_2O (Tuttle & Bowen, 1958). Water solubility is primarily dependent on pressure (Tuttle & Bowen, 1958) and therefore the granitic melt can dissolve increasingly less H_2O as it moves to lower pressures.

When water-saturated minimum-temperature haplogranite (albite-orthoclase-quartz) melts move to lower pressure, they crystallize because of the negative slope of the water-saturated solidus in P-T space. Upon crystallization, the H_2O that was dissolved in these melts exsolves as a fluid phase:

Magma with dissolved H_2O → Crystals + H_2O (fluid phase)

In the case of a haplogranite melt, the crystals are quartz, albite and orthoclase, but in nature other minerals are present, including hydrous minerals that take up H_2O.

A conundrum in the literature has been that since water-saturated magmas crystallize upon decompression then they should be trapped deep in the crust! However, we observe shallow level granites and volcanoes that are saturated in magmatic volatiles. This problem is solved if the granitic melt is initially water-*under*saturated because such melts may move to higher levels in the crust without crystallizing due to the positive slope of the water-undersaturated solidus. When water-undersaturated granite magmas are intruded to high levels in the crust (typically ~50 MPa; 0.5 kbar) they become water-saturated and exsolve a supercritical fluid phase:

Water-undersaturated melt with some dissolved H_2O (high pressure & low volume) →
Drier melt, but water-saturated + H_2O fluid (low pressure & high volume)

Miarolitic cavities, essentially holes where well-terminated crystals have grown in contact with the fluid phase, allow us to track the process of volatile exsolution and fluid formation. Large miarolitic cavities occur in granites intruded to pressures <100 MPa (<1 kbar) based on stratigraphy. At 100 MPa granite can dissolve 3.5 – 4 wt% H_2O (Johannes & Holtz, 1996, p. 63) and hence it is suggested that typical granite melt contains ~3 wt. % H_2O.

In some cases, miarolitic cavities are connected in a three-dimensional network, indicating that the partly solidified magma was permeable to (potentially ore-bearing) fluids when the cavities formed (Candela & Blevin, 1996).

Other volatile species in granite magmas

Although H_2O is generally the most abundant volatile phase in magmatic fluids, other volatiles have a significant role in transporting and depositing metals. Since other volatiles have lower solubility than H_2O in granitic melts they may be major contributors to the initial fluid phase. Furthermore, one volatile may affect the solubility of another and therefore onset of fluid phase exsolution is a function of the partial pressures of all of the volatiles in the system.

Halides

Chlorine is an important ligand in ore systems and likely complexes with metals such as Mo and Cu. Chlorine is most soluble in peralkaline melts, followed by peraluminous melts (Carroll & Webster, 1994). Solubility is also dependent on pressure and H_2O content (Webster, 1997). For instance, a haplogranite with 0% H_2O dissolves ~0.28 wt. % Cl at 200 MPa (2 kbar) and dissolves ~0.23 wt. %Cl at 50 MPa (0.5 kbar). In contrast, a haplogranite with ~3 wt.% H_2O dissolves ~0.26 wt. % Cl at 200 MPa and dissolves ~0 wt. % Cl at 50 MPa. Because Cl is not very soluble in granitic melts, it partitions into the vapor phase and only a small amount of Cl is required to produce a volatile phase. It is notable that is relatively easy to produce a fluid in the H_2O-Cl system without a dramatic depressurization or crystallization, relative to the H_2O-only system. For example, at 200 MPa, 800 °C a fluid phase may exsolve with only 1-3 wt.% H_2O and 0.24-0.26 wt. % Cl in the melt, but if Cl is absent then an excess of ~5 wt. % H_2O is required to produce a fluid phase.

Fluorine may also be abundant in granitic systems although it prefers to be in the melt than the fluid phase. Nonetheless, F has two important roles in ore deposits. First, F-rich melts dissolve more H_2O and Cl than F-poor melts, hence, the F-rich melts will exsolve a fluid phase at shallower pressures, all other factors kept equal (Webster, 1997). Second, F has a role in hydrothermal alteration.

Br and I, although low in abundance, may have a role in metal transport because they partition strongly into the fluid phase (Bureau et al., 2000) and Br-bearing salts are found in fluid inclusions from some ore deposits (e.g., Kamenetsky et al., 2002).

Sulfur species

Sulfur is another important ligand in ore systems, but its behaviour is complicated in melts and fluids because it changes speciation, primarily as a function of oxygen fugacity (fO_2). In the fluid, the dominant sulfur species are H_2S at fO_2s lower than ~2.2 log units below the nickel-nickel oxide buffer (<~NNO-2.2) and SO_2 at higher oxygen fugacities (Carroll & Webster, 1994). In granitic melts, at fO_2 <~NNO+0.3, S^{2-} dominates, whereas at higher fO_2, SO_4^{2-} (S^{6+}) is assumed to be present in the melt phase (Carroll & Webster, 1994).

The disconnect between the change in speciation in the fluid phase (~NNO-2.2) and the melt phase (~NNO+0.3) is poorly understood, but it would be helpful to understand to better predict S speciation in ore-forming processes. Proposed reasons include involvement of species in the fluid phase such as H_2S, S_2, O_2, SO_3, and species in the melt such as O^{2-}, H_2O, OH-, FeO, and CaO and can be summarized by reactions of the form (modified after Carroll & Webster, 1994):

H_2S in the fluid ± ? → S^{2-} in the melt + H-O species in the melt ± ?

S_2 in the fluid + O_2 in the fluid ± ? → SO_4^{2-} in the melt

One problem with these existing reactions is that SO_4^{2-} (S^{6+}) is assumed to be the oxidized sulfur species in the melt phase, but in most cases specific analyses have not been made for other species (Carroll & Rutherford, 1988; Nagashima et al., 1972; Paris et al., 2001). Recent work indicates that S^{4+} (as SO_3^{2-} or SO_2) occurs in significant concentrations in silicate glasses (Métrich et al., 2002; M.E. Fleet pers. comm.). In our opinion, the sulfur solubility models need to be modified to account for the presence of S^{2-}, S^{6+} *and* S^{4+} species in the melt, perhaps by consideration of the reaction:

SO_2 in the fluid → SO_2 in the melt

As well as affecting the sulfur speciation, oxygen fugacity also affects the quantity of sulfur-bearing fluid that may form and consequently the sulfur fugacity of that fluid. In dacitic melts at moderate oxygen fugacity (NNO to NNO+1), the formation of an H_2S-bearing magmatic fluid phase is not favored because sulfur diffusivity is low and sulfur goes into sulfide "sinks" (fluid-melt partition coefficient ~1, at ~225 MPa, ~780 °C; Scaillet et al., 1998). In dacitic melts at higher oxygen fugacity (NNO+1.4 to NNO+2.6), sulfur partitions preferentially into a SO_2-rich fluid phase (fluid-melt partition coefficient ~1000, at ~225 MPa, ~780 °C; Scaillet et al., 1998).

In terms of metal transport, these data indicate that very oxidized (>NNO+1.4) conditions are more favorable for production of a S-rich fluid phase. This finding is in agreement with the observations that Cu, Au and Mo are likely transported as S-complexes in the fluid and/or vapor phase (e.g. Audétat et al., 1998) and porphyry Cu-Au-Mo deposits are associated with oxidized granites (e.g., Blevin & Chappell, 1992; Burnham & Ohmoto, 1980).

CO_2

CO_2 is not very soluble in granitic melts where it dissolves as molecular CO_2 species. The solubility increases with decreasing (Si + Al) content and increasing Ca content and accordingly CO_2 is more soluble in intermediate melts where both molecular CO_2 and CO_3^{2-} species are present (King & Holloway, 2002). As a result, granitic suites that are high in Ca (more mafic I-type suites) are the best source rocks for ore deposits with CO_2-rich fluids such as intrusion-related gold deposits (Baker, 2002; Lowenstern, 2001).

Like H_2O, CO_2 solubility increases with pressure. Since CO_2 is more volatile than H_2O, it behaves like Cl and degasses at greater depth and may make up the initial magmatic volatile phase (assuming that other more volatile species are absent). During closed-system decompression, CO_2 contents in a granitic melt will initially decrease when a CO_2-rich, H_2O-poor fluid evolves and as a result the H_2O content of the melt will remain relatively constant (Holloway, 1976). At shallower depths (1-4 km) much of the CO_2 will have degassed and CO_2-poor, H_2O-rich fluids will evolve, resulting in decreasing concentrations of both CO_2 and H_2O in the melt. Some intrusion-related gold systems and porphyry Mo deposits, show the predicted evolution of magmatic fluids from CO_2- to H_2O-rich with decreasing pressure (Baker, 2002; Lowenstern, 1994).

In intermediate systems, the situation is slightly different than felsic systems because CO_3^{2-} is present and H_2O enhances CO_2 solubility; for example, CO_2 solubility in the melt increases by 0.06 wt.% per wt.% of H_2O (1 GPa (10 kbar) and 1350 °C, King & Holloway, 2002). Hence, relative to more felsic systems the total quantity of CO_2 in the fluid would be greater for a given pressure, temperature and H_2O content.

While it is not known whether C-O-species are effective ligands for ore metals in hydrothermal fluids (summary in Lowenstern, 2001), CO_2 readily forms a vapor and for this reason it may cause a hydrothermal fluid to unmix to a vapor and a hydrosaline brine (Joyce & Holloway, 1993). The presence of a CO_2-bearing vapor phase may also incorporate other species that might act as ligands for metals in the vapor phase (Lowenstern, 2001).

Summary and fate of high temperature fluids

Ore deposits in granites are often related to exsolved magmatic fluids that may form during decompression or crystallization. While these fluids are commonly dominated by H_2O, other species such as the halides, sulfur species and CO_2 may partition into the fluid early and aid metal transport. It is possible to infer the presence of a fluid phase by features such as miarolitic cavities that may represent an interconnected fluid network. The evolution of the fluid phase may be tracked using solubility data and analyses of melt inclusions and fluid inclusions.

When the supercritical fluid rapidly cools below the critical P and T to a hydrothermal solution, the concentrations of the fluid species will change dependent on temperature. The fluid composition will be a function of the initial bulk composition, buffering reactions, extent of interaction with the wall rock and organic molecules, input of new hydrothermal or meteoric fluids, unmixing and boiling, changes in the local conduit conditions and other factors (e.g., Thompson, 1995).

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GRAVITY AND GRANITES

Mark A. Lackie[1], Brad T. Bailey[1, 2], and Mark A. Edmiston[1, 3]
[1]GEMOC Key Centre Macquarie University, NSW
[2]Gnomic Exploration Services, Townsville, QLD
[3]Coffey Geosciences, North Ryde, NSW

Geological data is almost never reliable enough to quantify the shape of granitic plutons at depth. For this reason, geophysical surveys are conducted to obtain further information of the sub-surface. Gravity investigation is an effective method of measuring the extent of granitic plutons due to the fact that acid intrusive rocks typically have a lower density than their surrounding country rocks. Utilising the gravity method we can measure negative gravity anomalies over granitic plutons and from these anomalies, the subsurface three-dimensional shape of the plutons can be modelled.

The availability of the Global Positioning System (GPS) for the determination of accurate (cm) real time elevations allows ground gravity data to be acquired at rates sufficient to attain datasets that let gravity images of plutons be produced rather than simply obtaining gravity profiles across the plutons. If the acquired gravity data is a profile, then 2D modelling of the sub-surface shape of plutons and contact relationships can be attempted. If the gravity data is sufficient, then those results can be used to form the basis of comprehensive 3D models of plutons. Before modelling can be attempted, average densities are required to be assigned to the rock units that are to be modelled. It is preferred that the densities selected for the pluton and country rocks are the average of the samples taken in the field, although this may be difficult due to weathering and outcrop availability. The attitude of the contacts of outcropping granites can usually be determined from gravity surveying. Even though the precise dip angle cannot be determined due to regional gravity effects, variations in densities, and variations in the displaced mass, the inward and outward dip property of contacts can usually be determined.

To illustrate the value in acquiring and modelling gravity data to investigate the sub-surface shape of granites we will look at the gravity response of two bodies, one with a negative gravity anomaly and the other with a positive gravity anomaly.

Moonbi and Bendemeer Adamellites

The Moonbi and Bendemeer Adamellites are located at the southern end of the New England Batholith, northeast of Tamworth, New South Wales. The Permian aged I-type plutons intrude the Tamworth Belt, the Woolomin Beds, and part of the S-type plutons of the Bundarra Batholith. Gravity surveying was conducted over the Moonbi and Bendemeer Adamellites, as well as their surrounding plutons and country rock, to improve the gravity field resolution of the area, and to also construct a three-dimensional model of the subsurface.

The Moonbi Adamellite shows a fairly clear low anomaly, while the Bendemeer Adamellite does not produce a very distinct anomaly. Extensive computational modelling revealed information about the subsurface shape of the plutons, and the density variation with depth of the surrounding country rock. From modelling integrated gravity and magnetic data, it was found that the contacts of the Bendemeer and Moonbi Adamellites predominantly dip outwards. The 3D model of the subsurface constructed using the gravity data revealed that the Moonbi Adamellite is on average 2-6km thick, and that the Bendemeer Adamellite is a thinner pluton, typically extending to a depth of 2-4km (Fig. 1). The Moonbi Adamellite contains a NEE trending granitoid root system, which extends to a depth of approximately 11km, when modelled within a layered country rock that increases in density with depth. The Bendemeer Adamellite contains no root system.

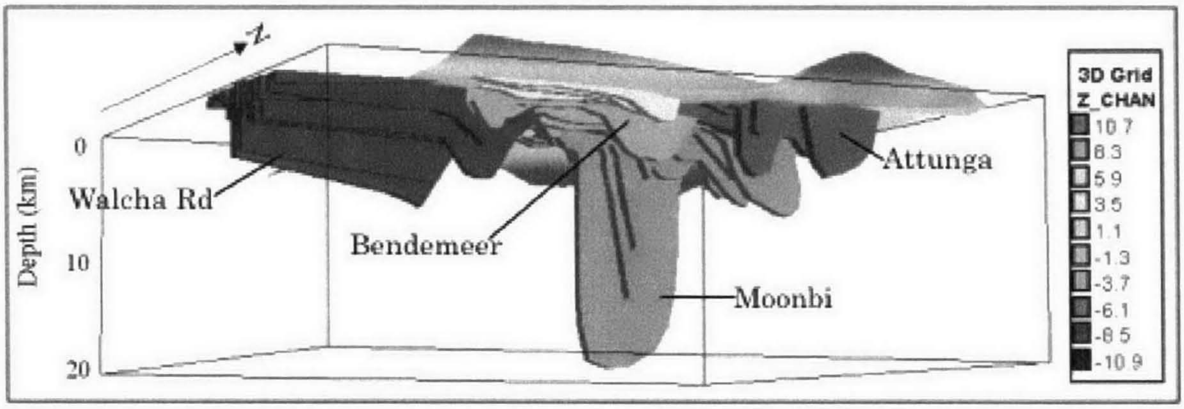

Figure 1. A 3D model for the Moonbi and Bendemeer Adamellites, viewing southwest at an inclination of –5°, the density of the country rock is homogeneous. If the density of the country rock increases with depth, then the root for the Moonbi Adamellite will extend to 11km rather than the unrealistic 20km.

Yeoval Batholith

The Yeoval Batholith is a large Devonian intrusive complex located in central NSW, approximately 400 km to the west of Sydney. Within the Yeoval Batholith there are two different complexes and five individual plutons, with the Nallawa Complex occupying the western side of the batholith and the Yeoval Complex, which makes up almost half the area of the batholith the eastern side. The gravity data for the batholith shows a gravity high, which suggest larger volumes of dense, mafic material than is not seen on the surface. A detailed gravity survey was conducted over the Yeoval Complex of the batholith to examine the density structure and sub-surface shape of the complex. The survey consisted of two detailed profiles, which were used for modelling of the rocks at depth, as well as infilling of the regional gravity data. Samples of intrusive and host rocks were taken to provide information about surface density contrasts that were needed for modelling.

Modelling revealed several important facts about the sub-surface of the Yeoval Batholith. The models reveal that densities found on the surface of the felsic phase of the Yeoval Complex cannot extend to depth (Fig. 2). A rock with a higher density is required beneath this unit to produce the gravity anomaly measured (Fig. 3). The near-surface shape and the density distribution within the felsic phase have been determined, indicating the felsic phase does have a density increase with depth. It is denser around its contact with the host rocks at depth and typically has steep sided contacts near the surface. However, there are ambiguities regarding the thickness of this unit caused by the decreasing resolution of gravity data with depth. A similar density distribution and shape has been modelled for the main unit of the Nallawa Complex. Modelling of the thinner, mafic phase of the Yeoval Complex (Naringla Granodiorite) has revealed a flat basal contact and a depth estimate of 850 m has been made.

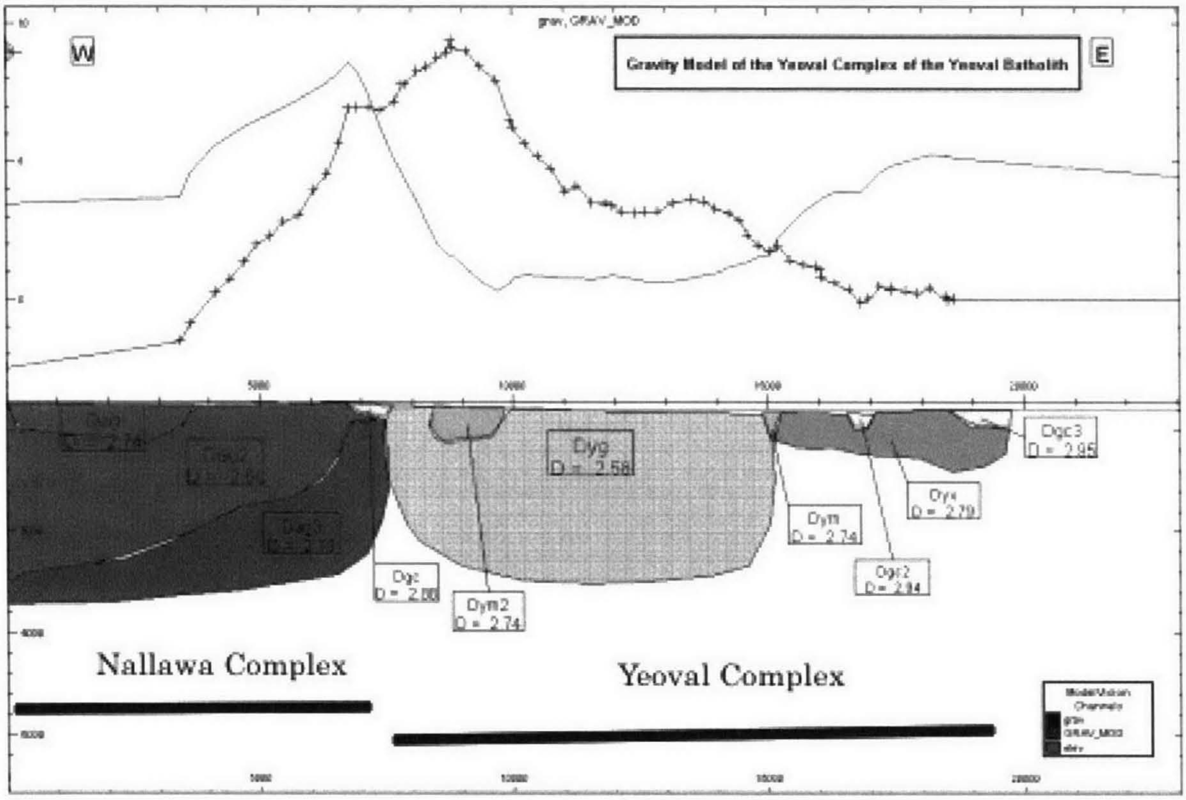

Figure 2. Gravity model for the main profile using the preferred model shape and surface densities at depth for unit Dyg of the Yeoval Complex. The modelled data does not match the measured response, although manipulating the density of Dag (Nallawa Complex) and the thickness of the Dyg unit gives a better but not a good fit.

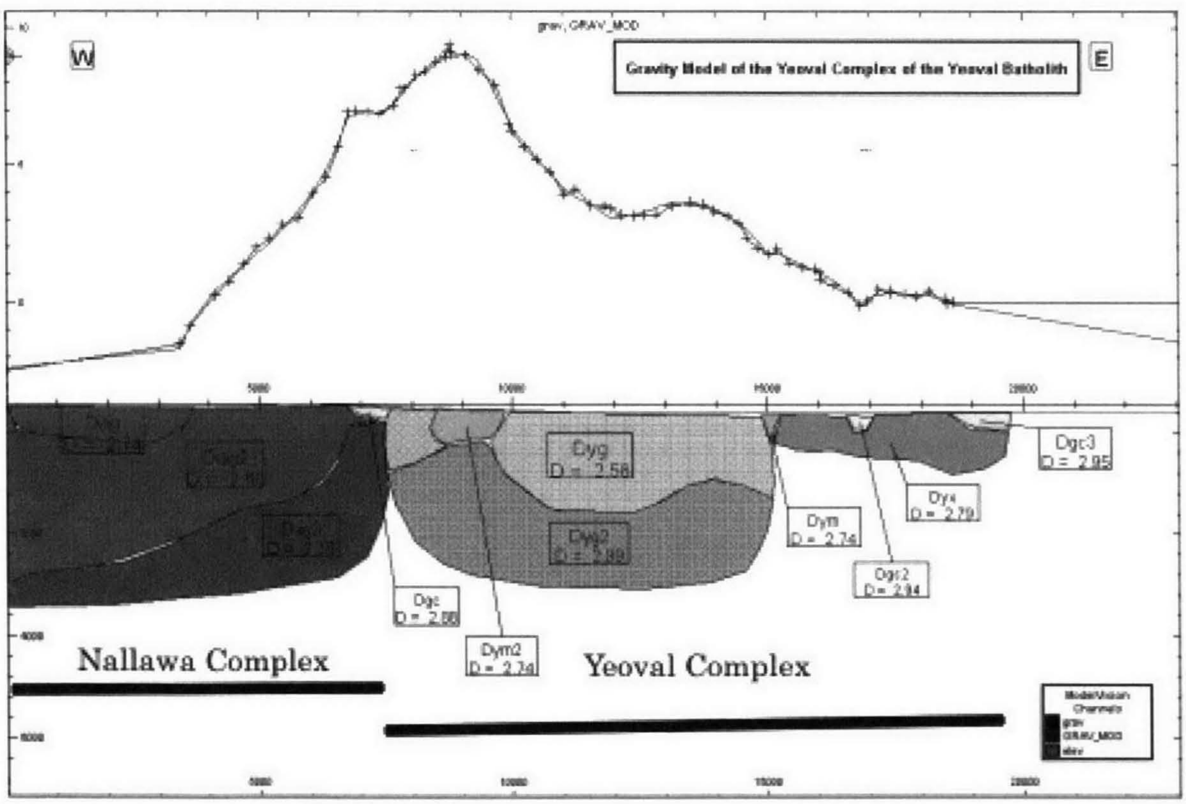

Figure 3. Preferred gravity model for the main profile across the Yeoval Batholith.

The nature of Tombstone Plutonic Suite rocks at Scheelite Dome, Tintina Gold Province: Evidence for an enriched mantle contribution.

John L. Mair[1], Craig J.R. Hart[1,2], David I. Groves[1] & Richard J. Goldfarb[3]

[1]*Centre for Global Metallogeny, School of Earth and Geographical Sciences, University of Western Australia, Crawley, WA, 6009.*
[2]*Yukon Geology Program, Box 2703 (K-10), Whitehorse, Yukon, Canada Y1A 2C6,*
[3]*United States Geological Survey, Denver, Colorado*

Magmatic-hydrothermal systems have long been recognized for their critical role in the generation of many ore deposit types. Examples of such deposits include tin and tungsten deposits related to felsic intrusions (Taylor, 1979), the spectrum of Cu±Mo±Au porphyry deposits (Titley and Bean, 1981; Sillitoe, 2000), and gold deposits related to alkaline magmatism (Muller and Groves, 1995; Jensen and Barton, 2000). Additionally, strong links have been demonstrated between porphyry systems and high-sulphidation epithermal systems (Hedenquist et al., 1998; Cooke and Simmons, 2000), and some workers have invoked an association of iron-oxide-copper-gold deposits with anorogenic alkaline magmatism (Hauck, 1990; Mutschler and Mooney, 1993; Groves and Vielreicher, 2001).

Although a wide range of gold deposit types have an intrusion-related affinity as outlined above, the term 'intrusion-related' has recently been adopted to recognize a specific class of gold deposits (Sillitoe, 1991; Sillitoe and Thompson, 1998; Thompson et al., 1999; Lang et al., 2000; Lang and Baker, 2001). In the literature this deposit class is typically described as: 1) being associated with metaluminous, sub-alkalic intrusions of intermediate to felsic composition that are weakly to moderately reduced; 2) forming inboard of recognized continental magmatic arcs in areas otherwise known for Sn and W mineralisation; 3) associated with variable enrichments of As, Bi, Mo, Sb, Te, and W; and 4) characterized by aqueous-carbonic hydrothermal fluids (Thompson et al., 1999; Lang et al., 2000). A large proportion of data on which this model is based has come from examples in the Tintina Gold Province (TGP), located in the Cordilleran Orogen of both Alaska and the Yukon Territory.

The TGP is a broad geographical expanse across the central Yukon and Alaska, that comprises numerous gold camps and districts that formed at different stages in the evolution of the Jura-Cretaceous orogen (Hart et al., 2002). Significant deposits include Donlin Creek (12.3 Moz), Pogo (5.8 Moz), Fort Knox (5.4 Moz), Dublin Gulch (4.1 Moz), Brewery Creek (0.85 Moz), and True North (0.79 Moz). The province encompasses a wide variety of gold deposits, including orogenic lode-style deposits, epithermal gold deposits, extensive placer-gold deposits, and the recently recognized class of intrusion-related gold deposits (Goldfarb et al., 2000; Hart et al., 2002). Gold mineralisation took place following deformation and metamorphism associated with the collision of exotic terranes and North America, and continued subduction of the Farallon plate under the Cordilleran margin, and in many areas, was co-eval with the emplacement of calc-alkaline plutons (Goldfarb et al., 2000).

Within the TGP, gold deposits that bear the strongest spatial and temporal relationships to intrusive rocks are those associated with the 92 Ma Tombstone Plutonic Suite (*TPS*). The TPS forms a narrow WNW-trending belt that extends for 550 km across the central Yukon, with a continuation in the Fairbanks district of east-central Alaska that was offset by latest Cretaceous to Tertiary displacement along the Tintina Fault. It is the youngest and most northerly (cratonward) of a series of mid-Cretaceous plutonic suites in the Northern Cordillera. Intrusions were emplaced into weakly metamorphosed latest-Proterozoic to Palaeozoic metasedimentary rocks of the Selwyn Basin. Magmatism occurred in a post-collisional setting that followed the waning of mid-Cretaceous subduction. The TPS is characterized by numerous isolated magmatic centres that feature either a number of intrusions of varying composition, a multiphase composite pluton, or a single pluton. Individual intrusions are rarely larger than 5 km in length. Intrusions are calc-alkaline to alkalic, predominantly I-type, and mostly intermediate to felsic, with calc-alkaline lamprophyres also common in many locations. Although both magnetite- and ilmenite-bearing intrusions occur, titanite-bearing intrusions are dominant, suggesting an oxidation state intermediate between magnetite- and ilmenite-series intrusions.

Scheelite Dome is located in the central Yukon, and features a variety of tungsten and gold mineralization styles hosted in, and adjacent to, a TPS magmatic center. In contrast to other renowned systems associated with TPS magmatism, the majority of mineralization at Scheelite Dome is hosted in hornfelsed metasedimentary strata, rather than TPS intrusive rocks. Soil and stream sediment sampling during initial exploration for primary gold occurrences in the 1990's identified an extensive (approximately 10 x 3 km) gold-in-soil anomaly (>20 ppb Au). Within the anomaly, primary gold occurrences are hosted in a variety of reduced skarns, potassic (biotite) alteration, and quartz veins. A TPS pluton that is approximately 5 x 2 km crops out to the immediate north of the anomaly. The pluton is dominated by an early quartz-monzonite phase. Felsic, intermediate, and mafic dikes are emplaced into both the quartz-monzonite and metasedimentary strata to the immediate south, coincident with the location of the gold-in-soil anomaly. The quartz-monzonite is weakly porphyritic with potassium feldspar megacrysts, and mafic phenocrysts of clinopyroxene, biotite, and minor hornblende. Intermediate dykes are alkalic, with a greater abundance of clinopyroxene and biotite. Mafic dykes include both spessartite and minette lamprophyres. Spessartites are amphibole rich (actinolitic hornblende) with resorbed Cr-diopside phenocrysts. Minnettes contain phlogopite and Al-Ti-Cr-rich augite phenocrysts (Mg# >85). Granite dikes are porphyritic with clinopyroxene, hornblende, biotite and potassium feldspar phenocrysts, in a fine-grained matrix of quartz, plagioclase and potassium feldspar. Subordinate aplite and pegmatite dikes occur within the main quartz-monzonite. Collectively, the intrusive rocks form a spectrum of compositions from granite to lamprophyre (excluding aplitic phases). Determining the relative timing of emplacement is restricted by the limited exposure; however, the quartz-monzonite is clearly the earliest phase, crosscut by all others. Intermediate dikes were emplaced next, followed by granitic dikes. Lamprophyres mostly crosscut all other plutonic phases.

Uranium/Pb zircon and titanite dates for the quartz-monzonite yield an approximate age of 92 Ma, and $^{40}Ar/^{39}Ar$ dates for magmatic biotite from the quartz-monzonite yield an age of 92 Ma, whereas phlogopite from a minette that crosscuts both other intrusive phases and gold mineralization yields an age of 90 Ma (minimum age). This time interval is the window for both magmatism and gold and tungsten mineralization. Hydrothermal alteration overprints the quartz-monzonite, but has mutually crosscutting relationships with granite porphyry and lamprophyre dikes. $^{40}Ar/^{39}Ar$ dates of hydrothermal biotite from gold-bearing potassic alteration yield an age of 91.4 Ma., and hydrothermal biotite from a tungsten-rich quartz vein in the quartz-monzonite yields an age of 91.5 Ma, to confirm the co-eval timing of magmatism and hydrothermal activity.

Despite the compositional variation, all intrusive rock types have similar trace-element concentrations, and are strongly enriched in LILEs and LREE. Primitive mantle-normalized trace-element spider diagrams feature distinct negative Ti, Ta, and Nb anomalies. Intermediate to mafic phases contain elevated Cr concentrations (>100ppm), with spessartites containing >500 ppm Cr. Major-element variation diagrams show linear trends for FeO, MgO and CaO, with high variability for Al_2O_3, K_2O and Na_2O. Most intrusive rock types are weakly metaluminous, except for quartz-monzonites, which are weakly peraluminous. Titanite is common to all phases, ilmenite is rare, and magnetite is present in granite porphyry dykes. Most rocks have heavy $\delta^{18}O$ whole-rock values of 10-12.5‰, except some minette dykes, which have lower values of approximately 6-10‰. Additionally, all rocks have similar initial $^{87}Sr/^{86}Sr$ ratios of 0.711 – 0.713 and epsilon Nd values range from -8 to -11.5. An investigation of zircons in intermediate and felsic rocks using a high resolution ion microprobe, indicates that the irregular zircon cores, which have an inherited appearance, are mostly either isotopically reset to the age of magmatism, or they are earlier, partially-resorbed magmatic phases from the same event. This suggests that magma temperatures exceeded those estimated for zircon saturation at Scheelite Dome (780-800°C), as determined following the method outlined by Watson and Harrison (1983).

Mafic enclaves of predominantly augite-diopside, biotite (high Mg #) and apatite are common in intermediate dikes, and to a lesser extent in quartz-monzonites. Such material has compositional similarities to minettes, and could represent pockets of frozen, more primitive magma, or possible restite material from the source region. Clinopyroxene is present in all intrusive phases at Scheelite Dome, excluding aplite dykes. Granite porphyry dikes contain diopside (Mg # ~ 60) with rare resorbed Cr-diopside grains (Mg # > 90) that are rimmed by amhibole. Intermediate dykes commonly contain a variety of clinopyroxenes, with resorbed Al-Ti-Cr-rich augite that has Mg numbers in excess of 85 (similar composition to augite in minettes), Cr-Ti-poor augite that has Mg numbers from 65 - 75, and fine diopside amongst quartz and potassium feldspar that has Mg numbers of 60-65. Coronae of fine diopside grains around quartz are also common. Some intermediate dykes also contain unusual miarolitic cavities with concentric bands of quartz-potassium feldspar-carbonate, and diopside. The cavities contain primary low-salinity aqueous-carbonic fluid inclusions, which are very similar in bulk constituents to fluid inclusions identified in the gangue assemblages of ore specimens.

Tombstone plutonic suite rocks at Scheelite Dome cover a broad spectrum of compositions from mafic to felsic. Lamprophyres represent the mafic end member and are interpreted to be of a mantle origin, with their ultra-potassic nature, extreme enrichment of LREE and LILE's, and strongly radiogenic isotopic signature indicative of an enriched lithospheric mantle source. In contrast to minettes, all spessartites have heavier $\delta^{18}O$ whole-rock values (>10‰) that support greater crustal interaction. Felsic to intermediate phases all feature heavy $\delta^{18}O$ whole-rock values, radiogenic initial $^{87}Sr/^{86}Sr$ ratios, and apparent zircon inheritance, which all support a significant crustal component. However, similar radiogenic isotope signatures and similar trace element compositions across all intrusive phases, and the presence of primitive pyroxenes and mafic enclaves in more-evolved intrusive phases suggest strong genetic ties between the different plutonic phases. Collectively, the data support a model of localized crustal underplating by lamprophyric melts, with the influx of volatiles and heat promoting subsequent melting of the crust. The resultant felsic to intermediate melts have geochemical features indicative of a crustal component, but also have features common to the lamprophyres. Mafic magmatism continued with, and succeeded, felsic magmatism, resulting in intermediate dikes with strong petrographic and geochemical evidence for magma mingling.

Both field relationships and geochronology support a genetic relationship between gold (and tungsten) deposits at Scheelite Dome, and intrusive rocks of the TPS. The more evolved TPS magmas are similar to those more commonly associated with tungsten deposits (Candela, 1995), whereas the more primitive lamprophyric rocks are similar to alkaline rocks more commonly associated with some gold deposits (Muller and Groves, 1994; Jensen and Barton, 2000). In concert with the unusual setting for both gold mineralization and magmatism, TPS rocks can be considered anomalous: the product of a complex hybridized magma system that has both an enriched mantle and crustal component. Moreover, this study suggests that the this style of intrusion-related gold deposits may be derived from highly specific magma types that are not present in the normal fore-arc settings of the more common orogenic gold deposits (Groves et al., 2003).

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EVIDENCE OF A GRANITE-RELATED SOURCE FOR THE BRAIDWOOD-ARALUEN-MAJORS CREEK GOLDFIELDS, NSW, AUSTRALIA

Kenneth G. McQueen
CRC LEME, Department of Geology, Australian National University, Canberra, ACT

Introduction

More than 40 tonnes of gold have been produced from alluvial placer deposits in the Braidwood-Araluen area of southeastern New South Wales (Middleton, 1970). Most of this gold appears to have been derived from the roof zone of the Braidwood Granodiorite. Granite-hosted vein and disseminated lode deposits are also preserved within the pluton, particularly in the Majors Creek area. Evidence from Dargues Reef and other deposits at Majors Creek indicates that igneous-hydrothermal processes accompanying emplacement and crystallisation of the Braidwood Granodiorite were fundamental in the formation of these deposits.

The Braidwood Granodiorite is a major pluton comprising the northern part of the essentially I-type Bega Batholith (Chappell et al., 1988). The pluton is a multiple intrusion formed by at least two separate injections of magma of very similar composition. Both are magnetite-bearing, metaluminous and unfractionated with high K, Rb, REE, Ba and Sr and Fe_2O_3/FeO ratios of 0.45 to 0.70 (Wyborn and Owen, 1986). They now form two meridionally trending phases separated in places by narrow screens of Ordovician metasedimentary rocks. The main Majors Creek lode gold deposits occur within the western phase of the intrusion, but small deposits are also recorded from the more central part of the pluton and within the eastern phase (Gilligan, 1974). Recorded gold production from the Majors Creek lodes is 0.85 tonnes (NSW Depart. Min. Resources, 1997).

Primary gold mineralisation

The gold deposits at Majors Creek consist of mineralised alteration zones in granodiorite and associated aplites, as well as discrete quartz and quartz-calcite veins in granodiorite and the immediately adjacent country rocks (Gilligan, 1975, Wake and Taylor, 1988). These are essentially gold-dominant deposits but with minor base metals, particularly Cu but also including As, Bi, Mo. Pb and Te. The Dargues Reef deposit at Majors Creek has been studied in greatest detail (McQueen and Perkins, 1995) and provides evidence on the general ore-forming processes for these deposits. Lodes at this deposit consist of narrow zones (0.6-10 m wide) of intense sericitic alteration and pyritisation (15-30% pyrite) enclosed in areas of propylitic alteration. Deposition of barren euhedral-subhedral pyrite accompanied early-stage alteration and was followed by deposition of irregular pyrite containing numerous small inclusions of silicates, calcite, chalcopyrite, Bi sulfosalts, galena, gold, trace tellurides, native bismuth and pyrrhotite. The gold varies in fineness from 810-940. Separate aggregates of chalcopyrite, Bi sulfosalts and tetrahedrite are intergrown with the silicate alteration minerals. The unaltered host rock at this deposit is a light coloured, equigranular granodiorite containing normally zoned plagioclase (An_{30-60}), K feldspar, quartz, brown-green hornblende, minor chlorite-altered biotite and accessory magnetite, apatite, sphene, zircon and trace pyrite. This rock shows obvious hydrothermal alteration around the deposit extending up to 80 m from the lodes. Major mineralisation and accompanying alteration are localised on the northern side of a diorite dyke with some minor mineralisation sporadically developed along the southern margin. Small aplite dykes and pegmatite veins are also a feature of the mineralised zones. These are unaffected by the intense sericitic alteration and appear to have accompanied introduction of the hydrothermal alteration fluids. The geochemistry of variably altered rocks at Dargues Reef indicates that the main chemical changes during wall rock alteration involved progressive loss of Na_2O and some CaO, resulting in relative enrichment in K_2O and Al_2O_3, and addition of CO_2, S and possibly some SiO_2. This is consistent with conversion of a dominantly quartz-plagioclase-K feldspar-hornblende-magnetite assemblage to a quartz-sericite-calcite-lesser K feldspar and pyrite assemblage in the most intensely altered sericitic zones. Other areas of sericitic alteration with disseminated barren euhedral-subhedral pyrite occur along the western margin of the Braidwood Granodiorite. Some of the gold-bearing quartz-calcite veins in the Majors Creek area also grade laterally or at depth into low grade or barren, coarse-grained pyrite mineralisation.

Origin of primary mineralisation

Dating of sericite (K-Ar method) from the intense alteration zones surrounding two of the lodes at Dargues Reef has provided dates of 411±5 Ma and 400±4 Ma (McQueen and Perkins, 1995). These dates overlap within error, and are also statistically indistinguishable from established ages for the Braidwood Granodiorite of 401-415±4 Ma (by K-Ar), 399±6 Ma (by Rb-Sr; Wyborn and Owen, 1986) and 402±6 Ma (preliminary SHRIMP dating of zircons, I. Williams pers. com., 2003). This is consistent with the mineralisation occurring close to the time of crystallisation of the Braidwood Granodiorite and would rule out a previous suggestion that the Dargues Reef deposit could be related to Late Devonian epithermal mineralisation in the Eden-Yalwal rift (Wake and Taylor, 1988).

Fluid inclusion data for alteration quartz intergrown with sericite, calcite and sulfides in the lodes at Dargues Reef indicate CO_2-bearing fluids of low to moderate salinity (<16 equiv. wt% NaCl) and medium to low temperature (<350° C, Wake and Taylor, 1988; McQueen and Perkins, 1995). Some CO_2-rich fluid inclusions that homogenise in the vapour phase, would have formed from very dense vapour, suggesting fairly high pressures (>500 bars). There is evidence for multi-stage fluid evolution from inclusions in different generations of quartz. These types of fluids closely match those commonly responsible for mesothermal gold mineralisation, including in intrusion-related gold systems (Lang et al., 2000; Groves et al., 2003).

Stable isotope data for Dargues Reef indicate, or are consistent with, a granite-related origin for the mineralisation at this deposit. Sulfur isotope ratios in pyrite from the mineralisation ($\delta^{34}S$, -0.4 to –3.4‰) and disseminated pyrite in the host granodiorite ($\delta^{34}S$, 1.4 to 2.5‰) are consistent with a magmatic source of the sulfur. Carbon isotope determinations for calcites from the mineralisation indicate $\delta^{13}C$ values for the fluid close to 0 ‰, consistent with a magmatic C source. Oxygen isotope data for calcites from the ores (6.5-10.9‰) and late-stage veinlets (6.5‰) indicate fluid $\delta^{18}O$ values of between 0.5-7.1‰ (for the temperature range 250-350° C) and implicate fluids similar to those in intrusion-related systems, with some possible limited intermixing of isotopically lighter, probably meteoric fluid (McQueen and Perkins, 1995).

A detailed Pb isotope study has been previously carried out on the Braidwood Granodiorite and gold mineralisation at Dargues Reef (Ho et al., 1995). This involved Pb isotope determinations on whole rock, K-feldspar and dispersed pyrite samples from throughout the intrusion and on pyrite samples from the mineralisation. The data show that the dominant Pb in pyrite at Dargues Reef, including in minor lead-mineral inclusions, is indistinguishable from that in the host granodiorite at the time of emplacement, consistent with derivation of Pb from this source. Intruded rocks include predominantly Ordovician metaturbidites and some Silurian felsic volcanic and minor metasedimentary rocks. This package would have different Pb isotopic characteristics.

The intimate spatial association of primary gold mineralisation with the Braidwood Granodiorite and late aplitic and pegmatitic phases, the style of alteration, the mineralisation geometry, fluid characteristics and stable and Pb isotope features all support a genetic association. The mineralisation was clearly introduced after crystallisation and cooling of the main granodiorite in the western phase of the Braidwood pluton and after emplacement of minor diorite dykes. The presence of crosscutting aplite dykes and pegmatite veins suggests a connection with very late-stage magmatic hydrothermal activity in the already crystallised roof zone or with under cooled upper parts of the granodiorite intrusion. This is also consistent with the fluid temperature and compositional evolution.

Implications for exploration and the source of alluvial gold

Geophysical modelling of the magnetic fabric in the Braidwood Granodiorite (Lackie and Flood, 1991) indicates that the eastern contact of the pluton dips steeply to the east whereas the western contact dips at a low angle to the west. The modelling combined with aspects of the regional geology, also shows that the western phase of the pluton could extend for up to 10 km to the west at shallow depth beneath its coeval volcanics. This geometry is consistent with the intrusion having been tilted about 15-20° to the west after emplacement. It also implies that the Majors Creek lode deposits lie close to the roof zone of the intrusion and that most of this zone has been eroded away in the areas to the east. This would in turn suggest that areas to the west of Majors Creek are prospective for additional granite-related gold mineralisation in the shallow subsurface roof zone of the intrusion and in vein and possibly skarn systems in the overlying rocks.

Erosion of large areas of granite containing small but widespread gold deposits, similar to those at Majors Creek, most likely provided the large amount of alluvial gold found in the regional drainage developed in and around the Braidwood Granodiorite. Much of this gold occurred in high level gravels in Tertiary basins and older terraces along the Shoalhaven catchment. For example, alluvial terraces up to 46 m deep covered an area of about 3,400 hectares on the western side of the Shoalhaven River. These are estimated to have contained 75 million m^3 with an average gold content of 0.125 g/m^3 (NSW Dept. Min. Resources, 1996). Extensive erosion of the Braidwood Granodiorite dates to at least the Mesozoic and the major alluvial deposits in the Shoalhaven plain are Eocene in age (Ruxton and Taylor, 1982). Progressive reworking of these deposits produced some of the younger placers exploited during early mining. Block faulting and westward tilting during the Tertiary as well as significant capture-initiated drainage changes likely resulted in varying deposition, preservation and reworking of alluvial materials. Much of the gold in the Braidwood-Araluen alluvials is reported to have been very fine-grained and widely distributed. This is consistent with the character of the gold in the known lode deposits, which typically occurs as small inclusions (generally <100 μm and commonly 5-30 μm) in pyrite.

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GRANITES OF THE NORTHERN NEW ENGLAND OROGEN

Cec Murray
Geological Survey of Queensland
80 Meiers Road, Indooroopilly Qld 4068

Introduction

The northern New England Orogen (NNEO) extends from the sedimentary cover of the Clarence-Moreton Basin in the south to the Bowen area, and west to the Bowen Basin. It contains granites of 4 main age groups: Middle to Late Devonian; mid- Carboniferous to Early Permian; Late Permian to Late Triassic; and Early Cretaceous. Common features shared by all of the granites include:

- They are overwhelmingly high temperature I-type granites with no relict zircon;
- They have low I_{Sr} ratios indicating that old continental crust was not involved in their formation; and
- They are associated with Cu-Mo-Au mineralisation.

Middle to Late Devonian

The Mount Morgan Trondhjemite (MMT) is a relatively small intrusion 20 km long and 4 km wide that is important for three reasons: it is a key to tectonic interpretations of the nNEO; it is spatially associated with the Mount Morgan orebody that produced >250 t Au and 360 000 t Cu; and it provides a reference point of 380 Ma for the age of the Middle-Late Devonian boundary.

The MMT intrudes a Lower to Middle Devonian marine sequence that includes co-magmatic volcanics, and is overlain by Upper Devonian basalts to andesites. It has no distinctive geophysical expression. Trondhjemite is the dominant rock type, consisting of equal proportions of quartz and sodic plagioclase with up to 10% hornblende. The quartz and plagioclase occur in micrographic intergrowth, indicating that it is a high level intrusion. Both pervasive and chloritic vein style alteration are widespread, and breccias with chloritic matrix occur locally. Variations are found in the northern part of the intrusion near the town of Mount Morgan, and include tonalite (typically less altered, and with minor biotite as well as hornblende), quartz diorite, and gabbro.

Geochemically the MMT is high in silica (Figure 1) and low in Al_2O_3 and K_2O, and is similar to island arc dacites and oceanic plagiogranites. Compared to trondhjemite-tonalite suites of the Late Permian-Triassic NEO granites generally interpreted as continental margin arc intrusives, the MMT has higher TiO_2, total Fe, MgO, Sc, V and Y, and lower Al_2O_3, K_2O, Ba, Rb and Sr (Figure 2). Widespread albitisation within the MMT, particularly in trondhjemites, has undoubtedly increased the Na/Ca ratio. However, the low K_2O content is not the result of post-magmatic alteration. In fact, clear evidence of addition of K_2O, rather than removal, is provided by the local replacement of plagioclase by K-feldspar.

An oceanic setting for the MMT is supported by its high Yb/Al_2O_3 and Y/Al_2O_3 ratios, and it falls entirely within the field of island arc dacites on a plot of Rb versus Sr. Messenger (1996) compared the Mount Morgan volcanic-plutonic suite with modern low-K intraoceanic island arcs such as Tonga-Kermadec. He modelled the major and trace element geochemistry of the high-silica rocks by a two-stage process involving low pressure melting of low-K basaltic andesite to produce tonalite, followed by fractional crystallisation resulting in trondhjemitic liquids. He proposed a moderately thick crust, and concluded that the setting was the incipient extensional phase of a continental island arc. However, low pressure melting of basaltic andesite has recently been suggested for the origin of widespread low-K rhyolitic volcanism in the Izu-Bonin arc (Tamura & Tatsumi, 2002), and can match the major element compositions of trondhjemites of the MMT extremely well. The nature of rhyolitic volcanism in the Izu-Bonin arc, with submarine silicic calderas producing thick pumice deposits accompanied in some cases by Au-rich Kuroko-style VHMS mineralisation, is a close analogue of the environment of formation of the Mount Morgan orebody envisaged by Messenger *et al.* (1997).

The orebody occurred in a roof pendant of Middle Devonian volcanic and sedimentary rocks in the northern part of the MMT. Although a replacement origin related to the MMT has been proposed a number of times, the most widely supported interpretation is that the orebody is a large and unusually Au-rich VHMS deposit, and that the ore fluids were a mixture of seawater and magmatic fluids. Recent Pb isotope determinations suggest that the host volcanics were not the source of the ore, and favour a composite model with elements of VHMS, porphyry and intrusive-related replacement mineralisation (Ulrich *et al*, 2002).

Mid-Carboniferous to Early Permian

Apart from some small S-type granodiorites NNW of Brisbane, that are similar in age, petrology and tectonic setting to the Hillgrove suite of New England, mid-Carboniferous to Early Permian granites and associated volcanics are restricted to the Connors and Auburn Arches along the western edge of the nNEO. An unusual and still unexplained feature of these granites is that they coincide with strong positive gravity anomalies, particularly the Auburn Arch, despite the fact that mafic intrusions make up only a small proportion of the granitoids.

The intrusions range from gabbro to granite and are dominantly granodiorite in composition (Figure 1). All are I-type. Ages of the granites appear to increase systematically from north to south. In the northern part of the Connors Arch, the oldest granitoids, the Urannah suite, have given zircon ages of 305±5 Ma, and the crosscutting Thunderbolt Granite is significantly younger at 278±6 Ma (Allen *et al.*, 1998). In the Auburn Arch and the southern part of the Connors Arch, the oldest group of granites have zircon dates of 320 to 330±5 Ma (Hutton *et al.*, 1999 and unpublished data). Similarly, Webb & McDougall (1968) noted that K-Ar ages in the Connors Arch are older from north to south, and explained this by differential uplift. An increase from north to south in the proportion of volcanics relative to intrusives supports a greater degree of uplift northwards. Possible compositional variations with age have not yet been investigated.

The intrusions of the Connors and Auburn Arches, and at least some of the associated volcanics, were regarded as the final products of Devonian-Carboniferous subduction in the nNEO, but recently have been attributed to crustal extension. Evidence from geochemistry, the sedimentary record in adjacent sedimentary basins, and dyke swarms supports an interpretation that both granites and volcanics span the transition from arc to extensional magmatism.

The granites are medium to high-K and have similar geochemistry to well known continental margin arc batholiths (Allen, 2000). They also plot within fields defined by Late Permian to

Late Triassic granites of the nNEO on major and trace element Harker diagrams, although lacking the most alkali-rich compositions of the latter group. Among the volcanic rocks, abundant mafic compositions ranging from basalt to andesite partly overlap with and are transitional between modern continental arc volcanics and rocks of the extensional phase of the Basin and Range province.

Support for formation of the granites of the Auburn Arch and the southern Connors Arch comes from the sedimentary record in the Devonian-Carboniferous forearc basin to the east. These granites can possibly be directly linked to a major change in provenance of forearc basin strata close to the Visean-Namurian boundary (327 Ma), with the appearance of granite clasts and a dramatic increase in radiometric signature. The rapid unroofing required for this provenance linkage has been documented from other continental arc-forearc basin pairs (Kimbrough *et al.*, 2001). The onset of extension at about 305 Ma formed a totally new pattern of depositional basins in which sediments and minor volcanics were laid down disconformably to unconformably on a basement of forearc basin rocks. Commencement of extension at about the Carboniferous-Permian boundary is also supported by Early Permian and younger dates on a regional NNW-trending dyke swarm that cuts the Late Carboniferous granites of the northern Connors Arch, and an age of 294±3 Ma from ignimbrite close to the base of the extensional sequence near Mackay (Allen *et al.*, 1998).

The mid-Carboniferous to Early Permian granites of the Connors Arch have I_{Sr} ratios above 0.7045, and are more radiogenic than Triassic and Early Cretaceous intrusions within or east of the arch. Allen (2000) attributed this change to Early Permian extension and crustal thinning accompanied by mafic underplating. There is no record of this event in the Auburn Arch, where I_{Sr} of 0.7040 for Carboniferous granites is actually lower than that of Late Permian intrusions to the southeast (Webb & McDougall, 1968).

Although mid-Carboniferous to Early Permian volcanics of the Connors and Auburn Arches contain significant epithermal Au mineralisation (Cracow, Mount Mackenzie, Crush Creek), granites of this age are very sparsely mineralised.

Late Permian to Late Triassic

Granites of this age form a NNW-trending belt extending north to Rockhampton, with a few scattered outcrops along the eastern side of the Connors Arch and on offshore islands. They range from multiphase batholiths to small plutons, and have very different topographic expression depending on their composition and texture. Biotite-rich granodiorites disintegrate on weathering due to expansion of biotite to hydrobiotite and vermiculite, and erode rapidly to form topographic basins. In contrast, hornblende-bearing monzogranites with micrographic groundmass are resistant to weathering and form prominent peaks. Ages range from mid-Permian (270 Ma) to the end of the Triassic (205 Ma), and a few may even extend into the Jurassic.

The range and distribution of compositions is remarkably similar to the mid-Carboniferous to Early Permian granites (Figure 1). There is also strong coincidence on Harker diagrams, both groups being medium to high-K, but the Permo-Triassic group includes a greater proportion of more alkali-rich compositions at all SiO_2 contents. Most granites are I-type, but some of the later intrusions are alkaline with sodic amphibole and A-type chemistry. It should be emphasised, however, that the Permo-Triassic group as a whole shows no systematic trend towards more evolved compositions with time. A feature is the presence of several layered gabbros generally marked by strong magnetic and positive gravity anomalies. The geophysical expression of the felsic intrusives is variable. Some are centred on deep gravity lows and must extend to considerable depths.

Many of the plutons are zoned, typically with a mafic rim intruded by a felsic core, giving them a bimodal composition. Some are associated with concentric dyke swarms and can be described as ring complexes. The scarcity of foliation, prevalence of micrographic textures, and narrow hornfels zones indicate emplacement at a high level in the crust. This is supported by the occurrence of remnants of Triassic volcanics throughout the main belt of intrusives as far north as Rockhampton. The Late Triassic volcanics have strongly bimodal compositions.

A subduction-related origin is favoured, with a transition to extensional magmatism in the Late Triassic due to slab rollback (Gust *et al.*, 1993). The chemistry of mafic volcanics is consistent with development at a convergent continental margin. The close association of mafic and felsic magmas suggests an origin involving crustal melting by mantle-derived basalts, although details of this process await further study (Gust *et al.*, 1996). A limited data set suggests that the Late Triassic granites, including those with A-type chemistry, have lower I_{Sr} ratios than older Permo-Triassic intrusives (Webb & McDougall, 1968; Stephens, 1991), requiring either a different source or a progressive change in source composition due to addition of mantle-derived mafic material.

The position of the Norfolk Rise and Lord Howe Ridge in reconstructions pre-dating the opening of the Tasman Sea (Figure 3) is a possible problem in assigning a subduction-related origin to the Permo-Triassic granites. These continental masses could not have been in the position indicated in Figure 3 in the Devonian and Carboniferous, when a classic accretionary wedge assemblage developed along the eastern edge of the present Australian continent. Either they came in contact with Australia after the Middle Triassic, or the trench associated with the postulated subduction zone must have been located several hundred kilometres east of the magmatic belt.

One interesting feature of the Permo-Triassic granites is that their age range completely overlaps that of the Hunter-Bowen Orogeny, which commenced at 267 Ma and concluded with termination of sedimentation in the Bowen Basin at 230 Ma (Fielding *et al.*, 1997). Although the Hunter-Bowen Orogeny was an episodic event with periods of WNW-directed thrusting alternating with stability and perhaps even extension, the almost continuous record of granite ages from 270 to 220 Ma indicates that in many cases emplacement must have coincided with contractional deformation.
This raises the question of how unstressed high level granites were emplaced in a contractional environment characterised by zones of thin-skinned thrusting, particularly as some intrusions extend to considerable depths. Some intrusions of the nNEO have narrow foliated contact aureoles with very steep lineations, suggesting that the mechanism of emplacement may have been similar to that proposed by Paterson & Miller (1998). They argued that downward flow of host rocks in a narrow zone surrounding plutons is the main mechanism to create space in arcs being shortened and thickened.

The proposal that some of the Torlesse terrane in New Zealand (Figure 3) was sourced from the NEO is based on the similarity of the age range of the Permo-Triassic granites to dates of detrital micas and zircons (Adams & Kelley, 1998; Pickard *et al.*, 2000). Apart from the difficulty of transporting these detrital grains to New Zealand, wherever it was located at the time, a major problem is that this correlation was initially based largely on dates from more than 100 muscovite flakes. The fact that muscovite is an extremely minor component of the Permo-Triassic granites and their metamorphosed contact rocks provides a strong argument against the NEO-Torlesse connection.

The Permo-Triassic granitoids are associated with and genetically related to a wide range of mineralisation styles. These include subeconomic porphyry Cu-Mo, base metal and magnetite skarns (Glassford, Many Peaks, Ban Ban, Biggenden), mesothermal Au-quartz veins (Eidsvold, Bouldercombe), breccia-hosted subvolcanic Au-Ag (Mount Rawdon, Mount Shamrock), shear-hosted Cu (Mount Perry), minor Mo and W, and an unusual rutile deposit near Mount Perry. Highly fractionated granites tending to A-type contain Sn mineralisation at two localities. Some layered gabbros include magnetite-ilmenite bands, and have been evaluated for PGEs (Eulogie Park, Hawkwood, Bucknalla, Wateranga). Horton (1978) showed that the porphyry Cu-Mo deposits form a narrow linear belt, consistent with a subduction-related origin. They are associated with small intrusions either within or near the margins of larger plutons. Most of the mineralising stocks are non-magnetic, although some are surrounded by a magnetic hornfels rim. The largest porphyry deposits are Moonmera, Coalstoun and Anduramba.

Early Cretaceous

Early Cretaceous granites occur between Mackay and Townsville within and on both sides of the Connors Arch. The larger plutons west of Bowen are centred on deep gravity lows and must have considerable vertical extent. A younger suite of volcanics with small subvolcanic intrusions forms the Whitsunday Islands and the adjacent mainland. These rocks have ages from 145 to 100 Ma (Allen *et al.*, 1998). Another group of Cretaceous granites, dated at about 140 Ma, occurs along the western edge of the Maryborough Basin west of Maryborough, also associated with volcanics.

Compositions range from gabbro to granite, are medium to high-K, and are bimodal (Figure 1). Allen *et al.* (1997) noted compositional differences with age of intrusions in the Bowen region. Granodiorite dominates for ages from 145 to 125 Ma, with few mafic rocks, whereas there is a broad range of mafic to felsic compositions in the younger group of granitoids, which also includes granites approaching A-type compositions. Limited analyses from the Cretaceous granites of the Maryborough Basin are intermediate between these two groups.

It is universally agreed that the younger Cretaceous intrusions and volcanics formed in an extensional environment, but whether the older granites shared this origin or were related more directly to subduction is debatable. Allen *et al.* (1997) argued on geochemical grounds that the younger intrusive and volcanic assemblage in the Bowen region represented an increase in the geothermal gradient and resultant magmatism compared to the older rocks. If subduction was involved, the associated trench must have been well to the east given the position of the Norfolk Ridge and Lord Howe Rise in the Early Cretaceous (Figure 3).

As for the Permo-Triassic, genesis of the Cretaceous intrusives involved melting and underplating of the crust by basaltic magma, with the possibility that some granites were produced directly from the mantle. Because of their more radiogenic composition, Late Carboniferous to Early Permian granites of the Connors Arch cannot have had the same source as the Cretaceous crustal melts, and could not have been a source themselves.

Mineralisation associated with the Early Cretaceous granites includes subeconomic Cu-Mo porphyry deposits (Horton, 1978), and small but rich mesothermal Au-quartz veins (Dittmer, Normandy goldfield). A unique intrusion is the mid-Cretaceous Goondicum layered gabbro east of Monto, being evaluated as a source of ilmenite and other commodities.

Conclusions

An unusual feature of the 4 age groups of granites in the nNEO is that both average compositions and the most common composition within each group become more SiO_2-rich with decreasing age (Figure 1). The Carboniferous to Permian, Permian to Triassic, and Cretaceous granites of the nNEO, considered as broad groups, include the same range of rock types (although the Cretaceous is bimodal), and have remarkably similar major and trace element geochemistry. This indicates that they shared common elements of source and process in their generation, despite variation in I_{Sr}. For all three groups, a temporal transition from subduction-related to backarc extensional magmatism has been suggested. For the Permo-Triassic and Early Cretaceous, this transition is marked by intrusion of late stage alkaline granites approaching or displaying A-type geochemistry. This does not appear to be the case for Carboniferous to Permian intrusives, suggesting a greater degree of inheritance of a subduction component in upper mantle and crust. The Middle to Late Devonian Mount Morgan Trondhjemite differs from all other granites of the nNEO, and is interpreted as an oceanic island arc trondhjemite.

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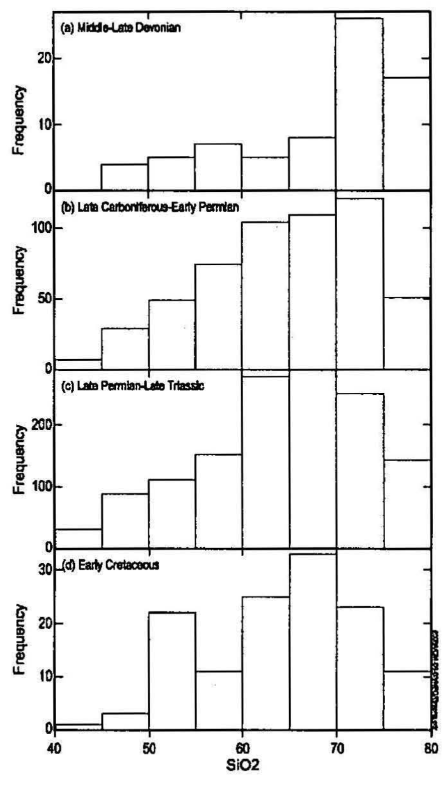


Figure 1. Histogram of SiO_2 contents of age groupings of nNEO granites.

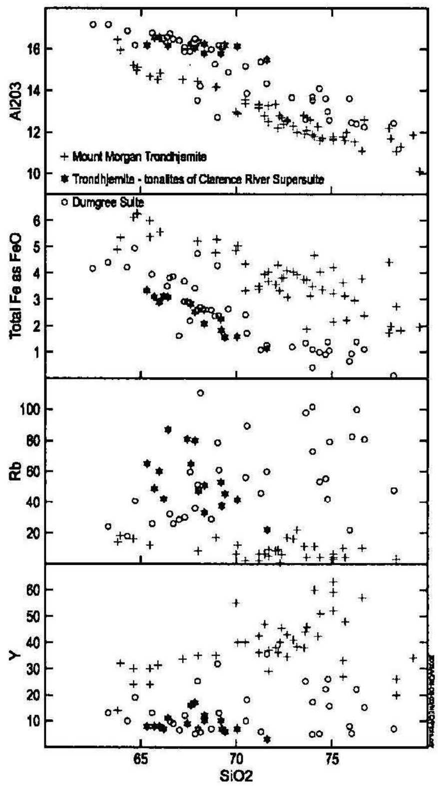


Figure 2. Harker plots showing discrimination of the Devonian Mount Morgan Trondhjemite from Permo-Triassic trondhjemitic and tonalitic rocks of the Clarence River Supersuite (Bryant *et al*, 1997) and the Dumgree suite of the nNEO.

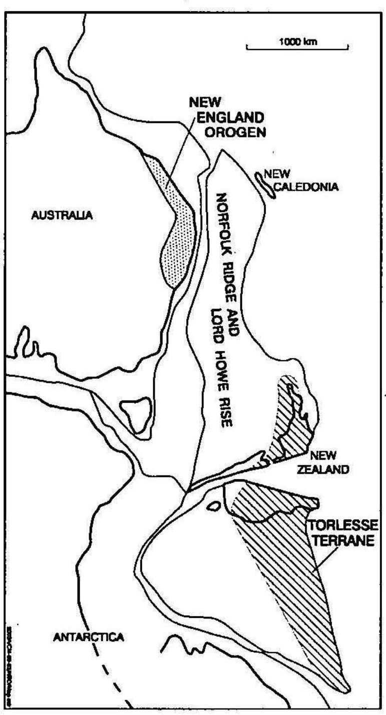


Figure 3. Reconstruction of Australia, Antarctica, Norfolk Ridge, Lord Howe Rise and New Zealand prior to commencement of opening of the Tasman Sea at 80 Ma (after Adams & Kelley, 1998).

Mid-Mesozoic Granites and Mineralisation in Hong Kong

Bryan P. Ruxton
Division or Health, Design and Science
University of Canberra ACT 2601 Australia

Hong Kong lies at the southeast margin of the Mesozoic magmatic belt of the Cathaysia block of southeast China. It is in the centre of the Arcuate coastline which is backed by mainly Jurassic-Cretaceous granite and acid volcanic rocks. In plate tectonic terms, it grew southeast in a northwest dipping subduction zone in Jurassic time, perhaps aided by deep torsion. Hong Kong is only a small part of this, 900 square kilometres, yet some 18 granite plutons and 15 volcanic formations have been recognised. For our purpose, three main areas are defined based on associated mineral type as in this table.

	Northwest	Centre	Southeast
Granite type[1]	I, A	Mixed	A
Granite age (Ma)	165	142-147	140
Mineral type	Sn, W	<u>W</u> Mo F[2]	Be Li F
Acid porphyry	<u>Pb Ag</u>	<u>Pb Ag</u>	-
Acid volcanic	-	Cu Pb Zn	-
Tectonic	Subduction	Dyke swarm	Extension
Strike slip	Dextral	Torsion	Sinistral

[1] An early granite is of mid- Triassic age (S-type)
[2] Underlined, commercial

Mineralisation within and adjacent to the granite is in fissure veins, pegmatites, stockworks and greisens. Hypabyssal acid porphyries are host to lead-silver ores. A large magnetite body in the central area is a skarn deposit with steatization between granite and limestone. Local concentrations of copper, zinc and lead occur in sediments interbedded in the volcanic rocks. Fossil plants in the sediments are dated as between mid-Jurassic to Wealden. Fluorine in the southeast is associated with lithium and beryllium in unusual greisens. The white mica has 4.6% fluorine, 1.2% lithium oxide and 1% magnesia. Major and trace elements will be discussed in the poster.

Contact metamorphism around the granite is locally high grade hornfels; up to sillimanite grade. In all but eastern Hong Kong most of the acid volcanic rocks show recrystallisation (annealing) in the ground mass sometimes to a polygonal mosaic. Local hydrothermal zoning is common.

There are close similarities in chemistry between Hong Kong granitoids and those in the Altai Mountains in Russia. Monzonitic, shoshonitic and peraluminous granites are cut by granite porphyry. They have W-Mo too, but tantalum not tin. Protolithionite and topaz are common to both suites.

Melting the crust – where is the heat?

Mike Sandiford, School of Earth Sciences, University of Melbourne.

Granites don't appear to form randomly! Rather, they show a strong spatial and temporal association with tectonic phenomena that are, more often than not, related to plate boundary processes. Does this follow from any fundamental principle that precludes stable continental crust from developing the thermal regimes appropriate to granite production? For example, the sorts of thermal regimes required to melt the crust and/or underlying lithospheric mantle may well engender sufficient mechanical weakening that such crust is incapable of forming part of a "plate" (in the sense of a plate as a mechanical entity capable of acting as a stress guide over geological timescales). Thus any crust capable of generating significant quantities of granite might spontaneously localise a plate boundary. This notion is consistent with a temperature dependent lithospheric rheology. Thus, we might postulate that in-so-far-as plate tectonics requires the transmission of stress through continental interiors (witness contemporary Australia), plate tectonics precludes steady state thermal regimes appropriate to the generation of granites. Embedded in this is the possibility of a profound "tectonic feedback" that leads to the thermal (and, as we will see, geochemical) self-organization of the continental lithosphere [6], largely facilitated by granite genesis. To explore this hypothesis we need to understand more of the link between thermal regimes and granite genesis.

So, what supplies the heat in the modern crust? Basically we have two sources related to, on the one hand, deep convective processes and, on the other, internal heat production. In as much as the lithosphere forms a thermal boundary layer to mantle convection, thermal regimes in the continental interiors are a function of the vigour and form of convection in the deeper mantle as well as the thermal property (conductivity and heat production) structure of the lithosphere. Analysis of surface heat flow and heat production data indicates that typically about 2/3 of the heat that flows through the surface of the continents ($q_s \sim 65$ mWm^{-2}) is derived from the radiogenic sources within the lithosphere [6]. The thermal regimes in the continental crust reflect not only to the amount of the internal heat production, which we term q_c, but also the way it is distributed with depth which can be represented by the characteristic depth of the heat production, h. The remarkably simple relationship :

$$T_{q_c} = \frac{q_c h}{k}$$

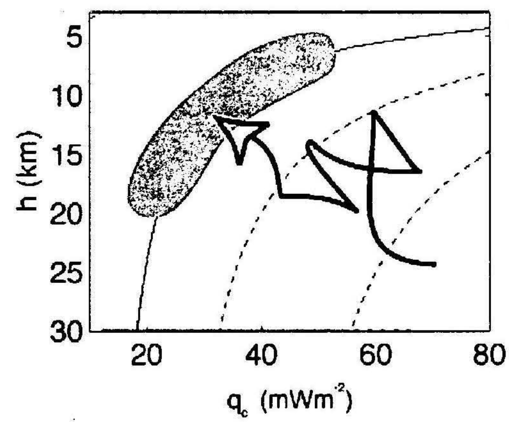
describes the potential Moho temperature contribution (T_{qc}) provided by crustal heat production for a characteristic crustal thermal conductivity, k. Typical continental crust ($q_c \sim$ 45 mWm^{-2}, $h \sim 10$ km, $k \sim 2.5$ Wm^{-1}K^{-1}) gives $T_{qc} \sim 180$°C. The Moho is of course hotter than this due to mantle heat flow:

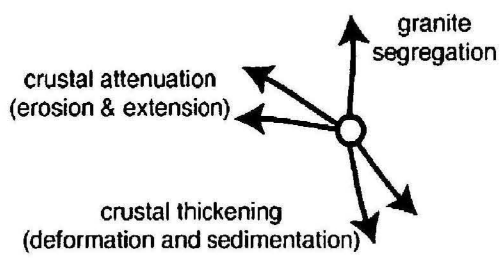
$$T_{q_m} = \frac{q_m z_c}{k}$$

For characteristic values ($q_m \sim 20$ mWm^{-2}, $z_c = 40$ kms) $T_{qm} \sim 320$°C, with T_{Moho} (= $T_{qm} + T_{qc}$) ~ 500°C.

Intriguingly, because granites often host a significant fraction of the crustal complement of heat producing elements (HPEs), their generation and segregation must necessarily lead to changes in the thermal structure of the crust [6]. Consider a crust in which half the complement of HPEs is carried by granites now lodged in the upper 10kms of the crust. Imagine these granites were derived from a source at depths between 30-40 kms depth from which the transported HPEs where extracted. The long-term change in Moho temperatures resulting from the segregation of such granites, is simply given by product of the transported heat production (~20 mWm^{-2}) and the change in depth (-30 kms) divided by the characteristic thermal conductivity. All other things being equal, the stable Moho temperature for this scenario was 240°C hotter prior to granite generation [7]! Importantly there would be no difference in the surface heat flow before or after the granite generation, because the crust contains the same total heat production (q_c), it is now just at much shallower levels!

The simple relationships can be illustrated in the plots of h versus q_c, which although rather naïve have the virtue of being able to illustrate the thermal response to a variety of tectonic processes and the potential coupling between granite generation and thermal and mechanical regimes in the continental lithosphere [6]. An important insight provided by the above analysis, is that for characteristic values of q_m, q_c and z_c, the only way of getting crustal melting (T_{Moho}> ~850°C) is the unlikely scenario of having all the internal heat production at near Moho depths.





There is simply not enough heat in the normal crust to generate granites! So much we probably already know (but at least now we have a simple formalism for understanding it)! However, as we go back in time the effects of secular changes in the heat production assume considerable importance, such that we could imagine for the Archaean (when heat production rates of the crust were 2-3 times modern day rates, and hence q_c was much greater), the above arguments no longer hold. For example, burying highly radiogenic crust beneath thick piles of greenstone could easily generate deep crustal thermal regimes appropriate to crustal melting simply as a consequence of the change in depth of the heat production [5]! For the Pilbara we calculate an effective q_c of 80 mWm^{-2} during the mid-Archaean [1], providing this heat production averaged a depth of 20 kms then potential Moho temperatures of >900°C would prevail (z_c ~ 40 kms) even for the low values of q_m (~ 20 mWm^{-2}) appropriate to the modern crust. An interesting corollary of this is that in order for such terranes to act as cratons (ie mechanically robust), there is very real imperative to achieve a 'sensible' HPE distribution. We see from the geological record that this was achieved by both solid-state and magmatic ascent of the structurally deeper felsic crust through the greenstone carapace producing the classic Archaean granite–greenstone 'dome and keel' architecture. As such, this structural style might be best viewed as a type of *geochemically-motivated* tectonics consistent with the crustal scale self-organization alluded to above.

Some large blocks of crust seem to have unusual concentrations of HPEs - a classic example being the Proterozoic of Australia where the available heat flow measurement suggest relative enrichment of HPEs by as much as a factor of two [3, 4]. For such crust it is conceivable that conditions close to granite melting can be achieved with relatively minor redistribution of the HPEs (see comments below).

So how do we get granites in the modern Earth! Given that the there is simply not enough heat in the typical modern crust to generate granites, we must appeal to thermal transients. We may consider the source of these transients as potentially due to factors internal or external to the lithosphere. Two end-member scenarios are usually considered here, although it is likely that in real world scenarios there is considerable blurring between these. The first is one of crustal thickening in which we take a spatially "spread out" distribution of HPEs and concentrate them in a thickening pile simultaneously increasing the depth to the Moho. A crustal thickening by a factor of 1.5 leading to a factor of 1.5 increase in both q_c and h increases in T_{qc} by 2.25 and in T_{qm} by 1.5 (neglecting any corresponding change in q_m). Our model crust therefore has the potential of achieving Moho temperatures of ~900°C.

Much of the thinking about this kind of process, is motivated by very simple kinematic models in which we take a column of crust, instantaneously deform it to a new state and consider its ensuing thermal evolution. In this scenario, the potential Moho temperature can only be achieved many 10's of millions of years after the crustal thickening. In reality the flow of material (deformation) through orogenic systems is a lengthy and complicated process with strong thermo-mechanical coupling and, potentially, significant viscous dissipation of heat. It is quite possible that channels of high-temperature, low-viscosity material flow great distances and advect considerable heat in comparatively short periods of time, with the effect of greatly compromising many of the timescale arguments implicit in the simplistic kinematic model described above. Still, there is probably not quite the heat we need for widespread crustal melting in moderately thickened, 'normal' continental crust. On the other hand, thick piles of juvenile immature sediment, derived from the erosion of relatively HPE enriched upper crustal sources (such as Lachlan Foldbelt turbidites) do have the potential for generating significant melting if they undergo moderate tectonic thickening on the timescale of a few 10's of millions of years.

The alternative is to provide for more efficient transport of mantle heat into the realm of crustal melting. This may be achieved by thinning the mantle lithosphere [10,11] - tantamount to increasing the mantle heat flow, or by advecting mafic magmas into the crust [8,9]. These process are likely to be coupled, in which case they provide a very efficient way of elevating crustal thermal regimes for sustained periods of time, as evident in the Halls Creek zone [2]. The timescales and relationships between deformation and the expression of granitic magmatism might well be linked by the way in which the heat is advected into the crust [8,9].

Many of the arguments presented here are based on notions of 'normal crust' – for average crustal values of q_c we do not have enough heat production to generate granites without appealing to unrealistic amounts of crustal thickening. For many purposes the natural variation in crustal properties may be of more significance. Radiogenic bits of crust buried within orogenic zones may fundamental impact on the thermal and mechanical evolution of those zones in ways that we still need to understand. If this is the case, then there is a necessity to get this heat production out of the deep orogenic system, in order to stabilise that crust, and clearly granites have provided a very effective way of doing this. *From a thermo-mechanical point of view*, the end product of the geochemical processing has left us with continental crust today which is largely well organised in the sense of facilitating plate tectonics. The way in which this has been achieved has probably changed through geological time, although granites have always played a key role.

Further elaboration of the ideas expressed herein can be found amongst the following papers.

[1] Bodorkos, S., Sandiford, M., Minty, B.R.S., Blewett, R.S., A high-resolution, calibrated airborne radiometric dataset applied to the estimation of crustal heat production in the Archaean northern Pilbara Craton, Western Australia, submitted to *Precambrian Research.*

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[7] Sandiford, M., McLaren, S., Neumann, N, 2002, Long-term thermal consequences of the redistribution of heat-producing elements associated with large-scale granitic complexes, *Journal of Metamorphic Geology,* 20, 87-98

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Subducted Ridges, Magmas, Differential Uplift, and Gold Deposits: Examples from South and Central America

David Shatwell

INTRODUCTION

Magmatic-related Au-Ag deposits of similar age and type in magmatic arcs along convergent margins are not uniformly distributed, but are longitudinally grouped in "gold-rich" regions separated by segments containing few deposits. The nature of the oceanic lithosphere which is being subducted at a convergent margin may influence the rate of uplift and hence the topography of the overlying magmatic arc, through changes to the angle of the subduction zone. Subducted young/warm/light oceanic lithosphere will tend to flatten at about 100 km depth, cause rapid uplift of the overlying crust, modify magma chemistry, and eventually close down magmatic activity. It may result in destruction (by erosion) of existing Au-Ag deposits, and exposure of underlying porphyry systems; conversely, erosion during the cooling cycle of magmatic bodies may promote the formation of large magmatic-related gold deposits at higher levels. This paper examines such processes in Costa Rica and in the Central Andes

COSTA RICA

Metallic mineralisation in Costa Rica and other Central American countries is associated with a Miocene magmatic arc emplaced above Cocos Plate oceanic lithosphere which is being subducted eastward below the Caribbean Plate. Mineralisation in Costa Rica is hosted by ca. 6 Ma calcalkaline volcanics and related domes and plutons, overlain in western Costa Rica, by <2 Ma post-mineral volcanic rocks and active volcanoes (Bagby et al., 1987).

The mineralised belt is divided longitudinally into three zones with contrasting metallogenic characteristics.

1. An 80 km low sulfidation gold belt in western Costa Rica. Deposits have been in intermittent production since 1824, mostly from single-vein underground mines. In recent years, large low grade resources have been delineated at the Bellavista and Las Crucitas deposits – in the latter case, 93 Mt, 1.03 g/t Au. Bagby et al. describe the gold veins as "Sado" type, but the association with vein Mn-Mg carbonates and the lack of adularia places them in the (subsequently-defined) carbonate-base metal class, formed by mixing of magmatic fluids with near-surface CO_2-rich water (Corbett and Leach, 1998).
2. Adjoining the gold belt to the south east there is a 120 km belt of subeconomic polymetallic vein deposits, in which vein minerals include galena, sphalerite, pyrite, chalcopyrite, pyrrhotite, magnetite, and barite, but no significant gold.
3. South east of the polymetallic zone there is a region of porphyry-style mineralisation at high elevations on the Talamanca Cordillera, extending into Panama. Bagby et al. list 24 porphyry-style occurrences, some of which contain chalcopyrite, molybdenite, secondary biotite, quartz-sericite-pyrite alteration, and sphalerite-galena-barite veins. The large Cerro Colorado deposit in Panama (1300 Mt, 0.8% Cu) may be part of this zone.

In the Osa Peninsula on the Pacific coast of Costa Rica, there are a number of small gold placers whose position is consistent with derivation from a primary gold source in the Talamanca Cordillera.

The metallogenic subdivisions 1-3 above correlate closely with tectonic subdivisions which can be identified both offshore in the subducting Cocos Plate, and onshore in the over-riding Caribbean Plate. These include contrasts in bathymetry, topography, seismicity, and dip of the subduction zone (eg Fisher et al. 1998; Protti, 2002):

The gold belt (1) coincides with a region of relatively subdued landscape (except where modified by recent volcanism) at low elevation in the magmatic arc. The volcanic arc is still active, shallow earthquakes are relatively infrequent, and the Wadati-Benioff zone dips steeply. The large Lake Nicaragua, in neighbouring Nicaragua, is in a back-arc position and in outline resembles a pull-apart basin resulting from back-arc extension. Offshore, the subducting Cocos Plate exhibits "smooth" ocean-floor topography.
The polymetallic belt (2) is a region of more elevated terrain, in which the Plio-Pleistocene volcanic arc terminates. There is increased shallow seismicity, and the subduction zone flattens. There are at least six inbound seamounts offshore. Back-arc extensional features are absent, and instead, arc-parallel thrusts are present between the Miocene arc and a Cretaceous-Eocene oceanic sequence which lies between the trench and the arc.
The "porphyry" belt (3) contains the highest part of the Talamanca Cordillera, with elevations above 2000m. There are no Plio-Pleistocene volcanoes, and a Late Miocene batholith is exposed. Offshore, there are no seamounts, but there is an area of shallower water, where the Cocos Ridge and the Panama Fracture Zone are both being subducted. The Wadati-Benioff zone is absent in this segment (Johnson and Thorkelson, 1998).

The boundaries between these three divisions are defined by pronounced arc-normal features, including elongated sea-floor ridges in the Cocos Plate, which extend onshore as topographic discontinuities and normal faults in the Caribbean Plate. The boundaries coincide with concentrations of shallow seismicity in both plates.

In segment 1, "smooth" ocean floor was generated at the north-trending East Pacific Rise. In contrast, the inbound seamounts (segment 2) and the Cocos Ridge (segment 3) originate at the site of an active mantle plume crest centred on the Galapagos Islands, situated just south of the east-west trending Nazca-Cocos ridge-transform system.

The seamounts and the relatively warm and buoyant Cocos Ridge first arrived at the Middle America Trench at <2 Ma, flattening the subduction zone and extinguishing volcanic activity. Segment 2 was uplifted and eroded to expose the polymetallic roots of the carbonate-base metal gold systems, while uplift in segment 3 was sufficient to unroof a large batholith and associated porphyry systems. Gold from the eroded Talamanca vein systems was re-deposited to the SW as placers in low-lying coastal regions of the Osa Peninsula.

I infer that ridge and seamount subduction played no obvious part in the origin of the gold deposits, but caused their subsequent destruction by erosion.

CENTRAL ANDES

Eastward subduction of the Nazca Plate below the South American Plate has resulted in gold deposits whose ages range from Jurassic to Pliocene. Resources are dominated by Miocene high sulfidation and porphyry deposits, grouped in two regions:

I North-Central Peru, between 6° and 13° S.
II Northern Chile and Argentina, between 27° and 30° S.

Miocene high sulfidation and porphyry deposits in each of these regions contain approximately 90-100 Moz gold, in terms of current resources and past production. In contrast, Miocene deposits elsewhere in the Central Andes contain only about 17 Moz, largely but not exclusively in low sulfidation epithermal deposits. All of the large Miocene gold deposits in Regions I and II are either high sulfidation or porphyry style, and there are no known world-class high sulfidation Au-Ag deposits outside these two regions. Regions I and II lack Quaternary or modern volcanic activity, but are flanked by the Northern, Central, and Southern Volcanic Zones of Neogene and Quaternary volcanism.

Region I – North-Central Peru, 6-13° S (Figure 1)

The region contains at least fifteen large magmatic-related copper and/or gold deposits (Shatwell, 2002). Among these are the world-class Yanacocha, Pierina, and Alto Chicama high sulfidation deposits, and the Minas Conga and Michiquillay porphyry copper-gold systems. Some porphyry and high sulfidation systems are associated with enargite-cored lead-zinc-silver limestone-replacement deposits. The large high sulfidation deposits were formed between 14.5 and 11 Ma, whereas porphyry systems span the range 20 Ma to 7.4 Ma. High sulfidation deposits are typically hosted by the Oligocene-Miocene Calipuy Volcanics, and exhibit zoned alteration systems with a core of massive or vuggy silica ± alunite, an intermediate zone of kaolinite and other clays ± alunite, and an outer zone of clay, sericite, and chlorite.

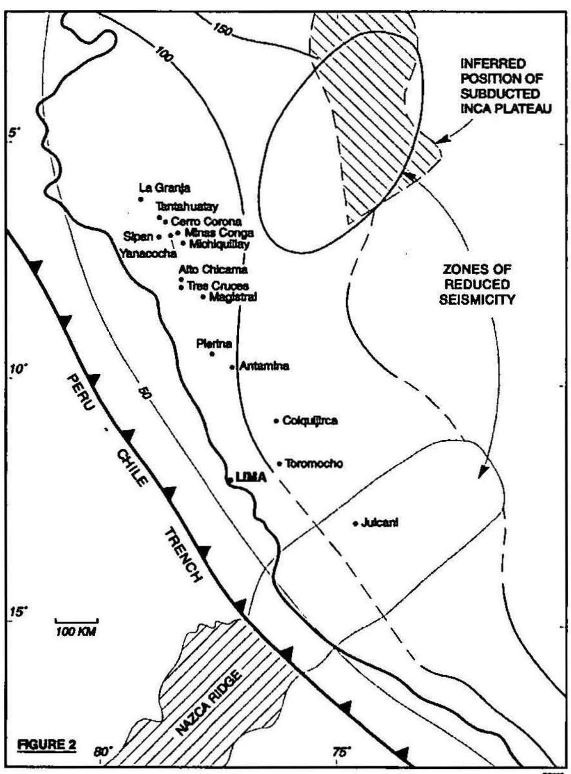

Figure 1. "Flat-slab" region of northern and central Peru, showing the Nazca Ridge, areas of reduced seismicity, and inferred position of the subducted Inca Plateau, based on Gutscher et al., 1999, Figure 2A, p.338, with permission from Elsevier Science. Contours are depths in km to the Wadati- Benioff zone. The named deposits are Miocene Cu ± Au porphyries (La Granja, Cerro Corona, Michiquillay, Minas Conga, Toromocho), Au-Ag high sulfidation systems (Tantahuatay, Sipán, Yanacocha, Alto Chicama, Tres Cruces, Pierina, Colquijirca, Julcani) and Cu ± Zn skarns (Antamina, Magistral). Deposits enclosed by the dotted line contain 88 Moz Au.

In Region I, Noble and McKee (1997) recognise three Miocene compressive events: Quechua 1 (19 Ma), Quechua 2 (9.5 Ma), and Quechua 3 (6 Ma). The large high sulfidation deposits were emplaced between Quechua 1 and Quechua 2 deformations, during which time the Andes of central and northern Peru underwent several stages of uplift (Noble and McKee, 1977). Peneplanation resulted in the mature Puna erosion surface by 10 Ma.

The subducted Nazca Plate in Region I is sub-horizontal below about 100 km depth, but is not a planar surface: Gutscher et al. (1999) point out that there are two "spurs" or salients in the flat section, each corresponding to an area of low seismicity. The southern spur coincides with the onshore (subducted) part of the incoming Nazca aseismic ridge (Figure 1), but there is no offshore ridge corresponding to the northern spur.

Gutscher et al. consider that the northern spur is the "missing" mirror image of the volcanically-active Marquesas Ridge in the western Pacific, and refer to it as the Inca Plateau. According to their kinematic reconstruction, the Inca Plateau would have arrived below northern Peru at 10-12 Ma; all major Miocene Au-Ag high sulfidation deposits and Cu-Au porphyries in Peru lie immediately outboard of its inferred present position (Figure 1), and have production and/or resources totalling 88 Moz Au. I propose that the arrival of the Inca Plateau below northern Peru at 10-12 Ma, and uplift and erosion resulting in the Puna surface, were linked events. These events played a key role in the emplacement of high sulfidation deposits between 14.5 and 11 Ma,, and perhaps unroofed older Cu ± Au porphyries such as Michiquillay and Minas Conga.

Region II – Chile-Argentina 27-30° S

The magmatic-related Miocene gold deposits in Region II occur in three sub-regions (Figure 2):

(a) The Maricunga district in Chile at 27°-28° S, dominated by porphyry gold ± copper deposits, but also containing the important Ag-Au La Coipa high sulfidation district. Deposits are estimated to contain 45 Moz Au, and their ages range from 24 to 13 Ma (Sillitoe et al., 1991).

(b) The Pascua-El Indio district at 29°-30° S on the Chile-Argentina border, containing the now-closed El Indio-Tambo Cu-Au intermediate-to-high sulfidation district (Chile), and the undeveloped high sulfidation Pascua-Lama-Veladero Au-Ag district straddling the Chile-Argentina border. All mineralisation was emplaced between 9.4 and 6.2 Ma (Bissig et al., 2002), and total gold content is estimated at 40 Moz.

(c) The Sierras Pampeanas region in the eastern Andes of Argentina, containing isolated 7-5 Ma Cu-Au porphyries and associated high sulfidation mineralisation at Nevados del Famatina, Bajo la Alumbrera, and Agua Rica, with 20 Moz Au in total.

In sub-regions (a) and (b), mineralisation is hosted by late Oligocene to early Miocene volcanics (plus underlying Triassic sediments at La Coipa). In sub-region (c), the host rocks are late Miocene volcanic-subvolcanic complexes intruded into Precambrian-lower Paleozoic metamorphic basement.

The subduction zone south of 27° S flattens to form a southward-broadening plateau between 100 and 125 km depth, terminated abruptly by the onshore projection of the Juan Fernandez Ridge at 32°-32.5° S (eg Ramos, 1994). All of the deposits in sub-regions (a), (b), and (c) are located between 27° and 30° S, on the "flat-slab" plateau. Flattening is thought to have commenced at 18 Ma and accelerated between 11 and 7 Ma. (Vila and Sillitoe, 1991).

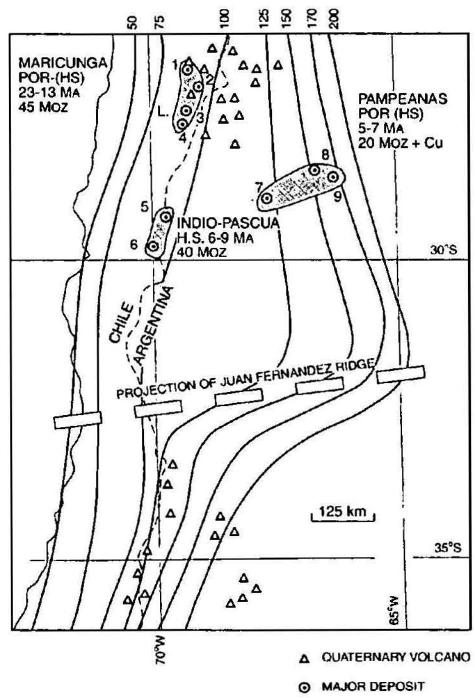

Figure 2. Flat-slab Region of Chile-Argentina, showing Quaternary volcanoes (triangles), projected position of the subducted Juan Fernandez Ridge, and depth contours in km to Wadati-Benioff zone, after Ramos (1994). Numbered deposits/districts are: 1, La Coipa; 2, Marte-Lobo; 3, Refugio; 4, Cerro Casale; 5, Pascua-Lama-Veladero; 6, El Indio-Tambo; 7, Nevados del Famatina; 8, Bajo la Alumbrera; 9, Agua Rica. Deposits 1, 5, 6, and 7 are high sulfidation Au-Ag; 2, 3, 4, 8, and 9 are porphyries; and 7 includes both types. Por = porphyry. HS = high sulfidation.

Bissig et al. identified three pediment surfaces in sub-region (b): Frontera-Deidad (17-15 Ma), Azufrera-Torta (14-12.5 Ma), and Los Ríos (10-6 Ma). These developed within the inferred period of slab flattening. The youngest (Los Ríos) surface coincides approximately with the 11-7 Ma period of accelerated flattening, and with the 9.4-6.2 Ma age range of the predominantly high sulfidation Au-Ag-(Cu) deposits in the Pascua-El Indio region.

CONCLUSIONS

In general terms, any process that removes overlying rock from an active, gold-rich hydrothermal system may extract gold from the intrusive and deposit it at higher levels. Such processes may include the sector collapse of an overlying stratovolcano, and there can be no better example of this than the Ladolam gold deposit on Lihir Island, Papua New Guinea.

Slab-flattening accompanied by erosion and peneplanation or pediment formation may destroy existing gold deposits (Costa Rica), but may also be an ore-forming process (Andes). For this to happen, several hundred metres of cover would have to be stripped off a porphyry intrusion while the associated hydrothermal system is still active, typically around 500,000 years or less. Evidence in support of high rates of erosion in the Peruvian Andes is provided by the Cordillera Blanca Batholith, for which radiometric ages as young as 2.7 Ma have been obtained (Petford and Atherton, 1994). It has been estimated that the batholith was unroofed when the Cordillera Blanca was uplifted on a major fault along its western margin by over 4 km in the last three million years, following Quechua 3 compression.

An active hydrothermal system will initially be subject to lithostatic pressures below the brittle-ductile transition at approximately 400° C and several km depth (Einaudi 1994). A vapour phase may separate, cross the brittle-ductile transition, rise to the near-surface, and condense to form a barren silica-alunite alteration zone. The liquid phase would remain at depth until the system cools sufficiently for hydrostatic conditions to be established, during which time gold may be deposited in the cooling porphyry environment. Under hydrostatic conditions, the gold-depleted liquid would rise convectively and may deposit silver in shallow low sulfidation veins.

On the other hand, if the ground surface is rapidly lowered during the cooling cycle of the intrusive, the transition from ductile to brittle conditions will be accelerated. Instead of circulating for an extended period in the porphyry environment, the liquid phase may cross the brittle-ductile boundary before it has deposited much of its gold content. Gold-silver deposition may then occur in the epithermal environment, typically in porous, leached rocks of the silica-alunite alteration zone formed earlier by the vapour phase.

These two scenarios may explain the contrast between high sulfidation Au-Ag deposits in north-central Peru and in Chile-Argentina, and low sulfidation Ag-rich veins in southern Peru and Bolivia.

Acknowledgements
I thank Mel Jones and Phil Blevin for reviewing this paper; Oliver Gaul (GEMOC) and Denese Oates kindly drafted the figures.

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High Sr/Y (HiSY) granitoid magmatism in convergent margins; nomenclature and setting

Andy Tulloch

Institute of Geological and Nuclear Sciences, Private Bag 1930, Dunedin, New Zealand

David Kimbrough

Department of Geological Sciences, San Diego State University, San Diego, CA 92182, USA

Cretaceous plutons of the eastern Peninsular Ranges Batholith (PRB) and the Separation Point Suite of New Zealand represent major fluxes of relatively high Na, Sr and low Y, HREE magmas. They have similarities to Archean Tonalite-Trondhjemite-Granodiorite (TTG) granitoids and Cenozoic adakites, but their genesis in Phanerozoic subduction zone settings is controversial.

We consider that the term *adakite* is inappropriate to describe the Phanerozoic plutonic rocks discussed here because it refers to volcanic rocks, to rocks which have a strong association with a particular origin (slab melting), and because adakites are mafic-intermediate rocks with relatively high Mg-numbers. We also have reservations about using the term *TTG* to describe rocks suites and associations in Phanerozoic batholiths because the acronym was defined from, and carries an association with, Archean rocks for which many models argue for a slab-melting origin. Furthermore, the term TTG does not include dioritic rocks that are a major part of the compositional spectrum in the especially deeply exhumed crustal section in New Zealand. The term *sodic* does not convey many other significant features, such as rock type, trace element chemistry and plutonic nature, nor does it indicate distinction from sodic undersaturated alkaline rocks. The term *BADR* (Basalt-Andesite-Dacite-Rhyolite) to describe the associated relatively low Na, Al, Sr etc rocks is not favoured for use in this context because it emphasises *volcanic* rocks and is not especially definitive. Thus we suggest a non-genetic terminology based on the single most distinctive parameter, Sr/Y:

HiSY for High-Sr/Y, Na, Al, Sr, low Y rocks (Sr/Y > 40 boundary adopted from Drummond and Defant, 1990).

LoSY for the complementary Low Sr/Y etc, rocks.

It is not appropriate to distinguish the LoSY rocks as calc alkaline etc., because HiSY and LoSY suites in any given convergent margin have similar or identical alkali-lime indices. Similarly, because both suites may be major components of Cordilleran batholiths, it is not appropriate to distinguish the LoSY component as "Cordilleran". Adakites and TTG suites could be regarded as particular varieties of HiSY rocks.

The well-documented margin-normal asymmetry of the PRB is similar to that observed in the Median Batholith of New Zealand (Tulloch and Kimbrough, 2003). In both areas similar-sized belts (800-900 km-long) of high Na, Al, Sr and low Y (HiSY) diorite-tonalite-granodiorite plutons developed continental-ward of, and 10-15 m.y. after, parallel belts of (LoSY) gabbro-diorite-granite plutons, the latter representing at least 30-40 my of convergent margin magmatism. In the PRB the HiSY La Posta Suite (~ 99-92 Ma) lies inboard of a western belt of LoSY plutons (~130-104 Ma) over the ~ 800 km length of the batholith. In New Zealand plutons of the HiSY Separation Point Suite (126-105 Ma) mostly lie inboard of the LoSY Median Suite (mostly 170-128 Ma). Chemical and isotopic links between HiSY and LoSY belts indicate genetic relationships between the paired belts within each area.

Comparative features from both margins support a model that involves underthrusting of the outboard LoSY arc base during shallowing subduction to a deeper, more continental-ward position. The mafic arc base is then partially melted under high pressure conditions resulting in plagioclase-poor or absent, garnet-bearing residual mineral assemblages that produce high Sr/Y partial melts. The La Posta plutons appear to represent mixtures of HiSY magmas and Paleozoic metasedimentary crust.

The widespread occurrence of similar paired rock suites in the Ross Orogen of the Transantarctic Mountains, the Antarctic Peninsular, the Peruvian batholiths and elsewhere, indicate that mafic crust-derived HiSY, and mantle wedge-derived LoSY plutons, represent two major subgroups of magmas in convergent margin batholiths.

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Paleozoic plutonism in the New Zealand sector of Gondwana

A.J. Tulloch
Institute of Geological and Nuclear Sciences, Private Bag 1930, Dunedin, NZ
D.L. Kimbrough
Dept of Geological Sciences, San Diego State University, CA 92182, USA
K. Faure
Institute of Geological and Nuclear Sciences, PO Box 30368, Lower Hutt, NZ
A.H. Allibone
School of Earth Sciences, James Cook University, QSLD 4811, Australia

Mid-Paleozoic granitic rocks intrude two distinct metasedimentary terranes (western Buller, eastern Takaka) in western New Zealand. Early and late Paleozoic granitoid rocks are volumetrically insignificant. Five mid-Paleozoic granitoid suites are defined on the basis of 27 new U-Pb ages, mineralogical and chemical characteristics:

Karamea Suite	382-369 Ma	S-type	Buller Terrane
Ridge Suite	353-342 Ma	S-type	Takaka (& Buller?)
Paringa	364 ± 4 Ma	I-type	Takaka & Buller
Tobin	345 ± 4 Ma	I-type	Takaka & Buller
Foulwind	290-320 Ma	A-type	Takaka & Buller

Tobin I-type suite overlaps in age with Ridge S-types, but no coeval I-types are recognised to be associated with the voluminous Karamea Suite S-type Suite. Isotopic and chemical compositions of the S-type suites (Karamea and Ridge) appear to reflect the nature of their host sedimentary terranes (Buller and Takaka, respectively), suggesting that these terranes extend vertically to the lower crust source regions. Amalgamation of Buller and Takaka terranes occurred between emplacement of the Karamea Suite (absent in Takaka Terrane) at ~ 380-370 Ma, and emplacement of Paringa I-type Suite across both terranes at 368-360 Ma. We suggest that the Karamea Suite formed during continental thickening associated with subduction-related terrane amalgamation. Paringa Suite (Sr/Y ~ 25-100) may have been subsequently derived from partial melting of associated subduction-generated mafic underplate. A poorly-defined I/S boundary at ~ 345 Ma may be analogous to the "0.706" line of western North America, and reflects outwards growth of the Gondwana continental margin. No associated volcanics or subduction-related sedimentary sequences have been yet been unambiguously observed for any suite.

Paringa and Tobin 368-341 Ma I-type magmatism in New Zealand forms part of the one event that can be recognised along the entire Gondwana margin from West Antarctica to eastern Australia. S-types are less regularly developed along the margin. Voluminous 430-400 Ma magmatism of the Lachlan Fold Belt is not observed in New Zealand. Conversely, no Late Devonian S-type magmas comparable in volume to the Karamea Suite are observed in Australia. However, accretionary complexes of comparable age to the Karamea Suite are recognised in the New England Fold Belt, and slate belt metamorphism in New Zealand, North Victoria Land and Marie Byrd Land is of similar age to the Lachlan Fold Belt granites. The ages and chemical/isotopic compositions of the New Zealand granites suggest more direct correlation with Marie Byrd Land of West Antarctica, and an original along-strike position *between* the older Lachlan Fold Belt of SE Australia and the younger (outboard and increasingly juvenile) New England Fold Belt of eastern Australia. The results from the New Zealand section of the margin assist recognition of a more or less continuous episode of ocean-wards building magmatism from 430–280 Ma which extended 3000-4000 km along the Gondwana margin from NE Australia across NZ and the Campbell Plateau to West Antarctica.

Granite Transport and Emplacement: a Review

Roberto Weinberg
School of Geosciences, Monash University, Victoria 3800, Australia
weinberg@earth.monash.edu.au

There has been considerable discussion about the transport mechanism of felsic magmas through the crust. Diapirism has been discredited as an efficient transport mechanism partly because diapirs rise slowly and are thought to freeze early and close to the magma source, and partly because it has recently been shown that *sufficiently wide* dykes (2 to 20 m wide) are able to rapidly transport felsic magmas through the crust without freezing. Several authors now consider that felsic plutons are fed by dykes and that the observed ductile structures around plutons result form the pushing aside of the heated wall rocks by expanding magma chambers (ballooning plutons, Clemens and Mawer, 1992, Petford et al., 2000). However, there are remarkably few recognised feeder dykes to granitic plutons, and it remains thus far unclear how felsic dykes grow to the metric to decametric widths required for their survival. It may ultimately be the ability of dykes to grow within the magma source area that controls whether or not dykes will be the preferred transport mechanism.

Within a partially molten source, magma may reside in a range of structures with a wide range of shapes, sizes and degrees of connectivity. Whereas the growth of an individual dyke within a partially molten zone, and the self-propagation of wide dykes into subsolidus crust, have both been studied in some detail, little attention has been given to the crucial intermediate step of the growth of a network of dykes in the source, capable of feeding wide, crustal-scale transporting dykes. The rarity of granite dyke swarms suggests that, if dyking is the preferred magma transport mechanism, felsic magmas sources produce only a few major transporting dykes during their lifetime. Alternatively dyking is not an important mechanism.

Weinberg and Podladchikov (1994) demonstrated that, contrary to previous work, diapirism may be an efficient way of transporting viscous magma through the crust. These authors used the power-law rheology (stress-dependent viscosity) of crustal rocks and the buoyancy stress of diapirs to calculate the effective viscosity of crustal rocks. This approach contrasts with previous works which had used an estimate of crustal viscosity to calculate diapir velocity and cooling (the hot Stokes models of the 1980s). The high buoyancy stress of diapirs causes the power-law crust to respond with much lower viscosities than those previously estimated, allowing rapid diapir ascent and late magma freezing.

In contrast to dykes, diapiric ascent of magmas imposes a convective flow pattern in the crust with two important consequences: a) upward flow of the wall rocks may cause decompression melting of the hot aureole around the diapir, adding magma and buoyancy to the diapir; b) downward crustal flow to replace the rising diapiric mass provides the source area with fresh, potentially fertile rocks that may undergo melting and give rise to another diapir, resulting in a sequence of diapirs using the same crustal path. Whereas source renewal is a direct result of diapirism, dyking leads to the accumulation of refractory restite in the source preventing further melting. Through decompression melting and source renewal diapirs are capable of recycling and fractionating large crustal volumes.

Rubin (1993a,b) suggested that the response of the crust to applied magmatic stresses may be a combination of elastic (dyking) and viscous (diapirism) behaviour, in which the rapidly applied stresses at the propagating tip of a dyke cause an elastic response in the form of propagating cracks, whereas the continued stresses on the wall rocks along the main dyke body causes viscous deformation and outward bulging of the dyke's walls. Weinberg (1996) applied Rubin's results to study the conditions in which dykes can successfully propagate from the top of a diapir. He found that in the lower crust dykes will freeze as they leave the diapir, whereas in the upper crust, conditions are more favourable for dykes to propagate successfully away from and drain the diapir. Thus, diapirs may be the preferred mechanism of magma transport in the lower crust, while dykes may take over in the upper crust.

An alternative mode of transport characteristic of hot crustal regions, close to the magma source, is pervasive flow. Pervasive magma flow leads to magma sheets emplaced preferentially parallel to the foliation or shear zones. Four mechanisms act locally to promote magma migration and these are: a) local dyking; b) overpressure related to volatile exsolution; c) tectonic pumping; d) magmatic wedging. The latter two are driven by local, tectonically-driven mean pressure gradients. Pervasive magma migration requires hot crust, and makes use of the fact that the solidus temperature of partial melts is generally lower than that of the source rock. This implies that above the magma source there are solid rocks which themselves are not undergoing melting but that are above the solidus of partial melts produced below. Within these solid rocks, the melts are freed from the constraints of freezing and may intrude them pervasively. Magmas rising pervasively may gradually migrate to form a large magma body which may then rise diapirically, produce dykes or simply freeze as a pluton overlying an injection migmatite such as those in Shuswap, Canada (Vanderhaeghe and Teyssier, 1997) and Pangong, India (Weinberg and Searle, 1998).

Field evidence and inheritance patterns of zircons in the 600-km long, Andean-type calc-alkaline, pre-continental collision, Ladakh Batholith, in the Indian Himalayas, suggest that older mantle-derived batholithic rocks were remelted within a few million years of their crystallization to give rise to younger batholithic magmas. This suggests that magma fractionation and ascent took place over a series of cycles of intrusion, solidification, remelting, and ascent. In each cycle older, more primitive magmatic rocks remelted to give rise to younger, more fractionated rocks. A dynamic environment is envisaged in which mantle-derived magmas underplate and intraplate the crust, maintaining high crustal temperatures for several tens of millions of years. Local temperatures and pressures constantly fluctuate in this environment and early igneous intrusion may remain close to its solidus for a long time, melting and remelting. Partial melts segregate and rise through dyking, diapirism, and pervasive flow, all of which may act in parallel or sequentially leading to a vertical fractionation of the batholith. If this cycling documented through zircons in Ladakh is a general feature of Andean-type batholiths, it explains the origin of voluminous granodioritic magmas from mantle-derived melts, with little or no involvement of felsic crustal material.

Considerable evidence world-wide suggests that shear zones play a significant role in the transport and emplacement of plutons. However, the relationship between magma transport/emplacement and regional scale transcurrent shear zones has been a topic of recent controversy. In the Brasiliano-age (Panafrican) Borborema Province, NE Brazil, pre-tectonic plutons are elliptical or irregular in shape, and generally crop out away from late-developed regional shear zones. By contrast, syn-tectonic plutons generally have *en cornue* or blister shapes, characteristic of transcurrent terranes. These plutons were emplaced preferentially at the margins of 1-km to 10-km wide, regional scale transcurrent shear zones and the largest plutons were emplaced where shear zones cut across major terrane or lithological boundaries, defining a regional triple point. The sympathetic relationship between syn-tectonic plutons and shear zones, particularly regional triple points, suggests shear zone control of pluton emplacement.

As has often been argued in the literature, shear zones provide favourable pathways to granitic melts. If this is so, why are the syn-tectonic plutons commonly emplaced at shear zone shoulders rather than within shear zones? The intriguing relationship between plutons and regional triple points in the Borborema Province suggests that the combination of shearing and regional rheological changes could play a role in pluton emplacement, through the development of regions of strain incompatibility. In order to investigate this hypothesis, numerical models were designed to explore the nature of deformation and stress distribution in such triple points during shearing. Models reveal that triple points are important regions of crustal weakness, where the combination of low mean stress and high differential stress, leads to intense brittle or ductile dilational strain. For magma emplacement, these low-mean-stresses, fragile triple points act as magma sinks, because magmas migrate towards areas of low mean stress. Once magma intrudes into and pond at the triple points, the stress gradient may be partly equilibrated but heating and weakening of the country rocks, associated with continued straining may lead to pluton ballooning. It is concluded that emplacement of granite magmas in transcurrent terranes is controlled by the development of low mean pressure magma traps at the shoulders of shear zones as a result strain incompatibility caused by changes in rheological properties.

In summary, a single transport mechanism is incapable of explaining the variety of features related to felsic intrusions. Magma transport and emplacement are most likely controlled by a number of alternative mechanisms acting in parallel or in sequence. The preferred mechanism at any time results from the interaction of a number of controlling variables, from the interconnectivity of small magma batches in the source, to crustal rheology and temperature profile.

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The geophysical characteristics of granites and shear zones in the Yilgarn Craton, and their implications for gold mineralisation

Alan Whitaker
Geoscience Australia, GPO Box 378, Canberra, ACT, 2601.

The Archaean Yilgarn Craton provides two thirds of the Australian gold output of ~ 300 tonnes per year yet occupies only 10% of the continent. Granite[2] and gneiss of granitic composition, comprise more than 80% of the craton. Extensive, generally thin (less than 100 m) regolith, however, conceals much of the basement geology. Aeromagnetic and gravity data effectively "see" through the regolith and their interpretation provide detail of the basement not readily obtained from outcrop mapping. Note, however, that geophysical and geological mapping are not equivalent. For example, variations in granite mineralogy and texture, observed in outcrop, are often unresolved in regional geophysical surveys.

The following sections describe the granite-dominated aeromagnetic map units of the Yilgarn Craton, discuss the correlations between geophysical data and geochemical suites, and speculate on the relationships between shear zones seated in felsic crust and greenstone hosted gold. Gravity data (broad station spacing, low resolution), and gamma-ray spectrometric data (limited ground penetration, <0.5 m), are drawn on where they complement the discussion.

Aeromagnetic map units

The Yilgarn Craton has been subdivided into five main, regionally distributed, aeromagnetic map units (Whitaker, 2001, Whitaker and Bastrakova, 2002): undivided gneiss–migmatite–granite, banded (granitic) gneiss, granite plutons, sinuous gneiss, and greenstone. Rocks of granitic composition, which may contain diffuse compositional layering or zonation, make up the components of the first three map units. Inter-layered rock types including basalt, ultramafic rocks, sedimentary rocks, and intermediate to felsic volcanic rocks, give the well developed compositional layering in sinuous gneiss and greenstone. Only the first three map units are described here.

Undivided gneiss–migmatite–granite (Agmg; Fig.1) comprises 60% of the Yilgarn Craton. Moderate magnetisation characterises much of the unit. Compositional banding and internal boundaries are rare. Regional variations in magnetisation are gradual and not readily ascribed to changes in mapped geology. Poorly magnetised faults and moderately- to highly-magnetised dykes are commonly the most visible features. Agmg includes several ovoid-shaped, composite bodies of granite and granitic gneiss, ranging in size from 10 km to 40 km diameter. Diffuse internal banding, where present in these 'domes', parallels adjacent margins. Large areas of Agmg coincide with Bouguer gravity anomalies in the range of -750 to -450 $\mu msec^{-2}$. In outcrop, changes in rock type, from granitic gneiss to migmatite to granite, may occur across nebulous boundaries over short distances (tens of metres), and remain unresolved in regional geophysical data. Agmg envelopes examples of all other geophysical map units.

Banded (granitic) gneiss occurs in elongate, moderately- to highly-magnetised belts, 50 km to 100 km long and 5 km to 25 km wide. Diffuse internal bands of higher and lower magnetisation parallel the elongation of the belts. Locally, large-scale, tight to isoclinal folds overprint the banding. Banded gneiss is spatially associated with regional shear zones and is inferred to result from earlier shear zone-related deformation events. It often forms the interface between Agmg and greenstone. Enclaves of greenstone, and amphibolite of uncertain origin, are locally abundant in several of the belts. Banded gneiss is, on average, more highly magnetised than adjacent Agmg and is also associated with relatively higher Bouguer gravity anomalies (approximately 70 $\mu msec^{-2}$ higher than adjacent Agmg).

[2] Granite is used here as a general term to indicate felsic intrusive rocks

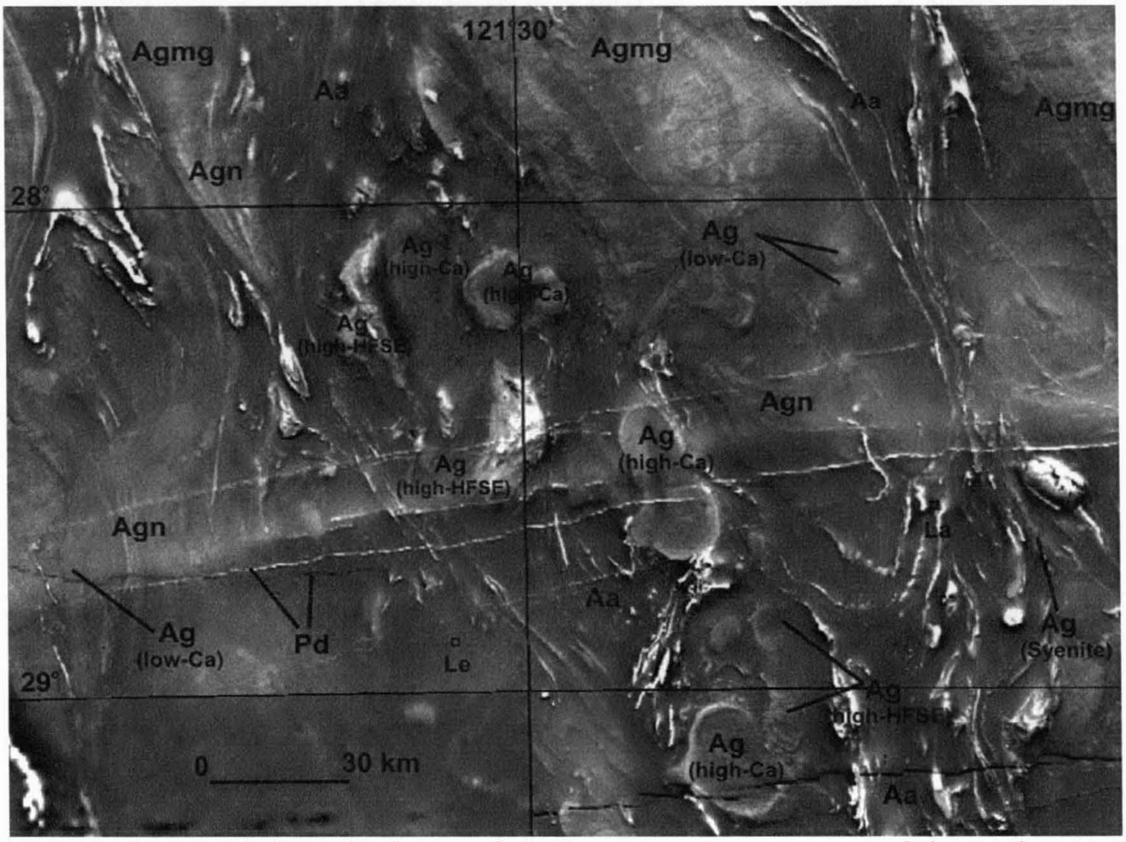

Figure 1 Total magnetic intensity image of the Leonora – Laverton area of the northeastern Yilgarn Craton. Black to white represents low to high magnetisation. Aeromagnetic map units are labelled; Agmg = undivided gneiss-migmatite-granite, Agn = banded (granitic) gneiss, and Ag (high-Ca) = granite (geochemical group). Other features labelled include greenstone = Aa, and Proterozoic dykes =Pd. Leonora (Le) and Laverton (La) are also located.

Circular to elongate granite plutons comprise less than 10% of the basement surface of the Yilgarn Craton. They range in diameter from 1 km, and less, to greater than 30 km, and from poorly- to highly-magnetised intrusions. Many plutons are simply zoned with more magnetised rims than cores. Granite plutons are particularly abundant within greenstones of the Norseman-Wiluna Belt (Gee et al. 1981), often forming regionally aligned groups. Poorly magnetised plutons correlate strongly with the greenstone belts and are rare in extensive regions of Agmg. Moderately- to highly-magnetised plutons define an unusual, 200 km-wide, northwest-trending corridor that traverses Agmg in the southern parts of the Southern Cross and Murchison domains. They, too, are much less common in regions of Agmg throughout the rest of the Yilgarn Craton. Bouguer gravity anomalies associated with several of the larger granite plutons are very low (-750 to -850 $\mu msec^{-2}$) and are commonly 100–150 $\mu msec^{-2}$ lower than adjacent regions of Agmg.

Geochemical granite groups, magnetic susceptibility, and gamma-ray data

Champion and Sheraton (1993; 1997) subdivided the granites of the eastern Yilgarn Craton into two main (high-Ca, 60% of granites; low-Ca, 20% of granites) and three minor (high-HFSE, mafic, and syenitic) geochemical groups. These groups are not uniquely discriminated by aeromagnetic data (e.g., in extensive regions of Agmg, high-Ca and low-Ca granite types are not resolved). This lack of discrimination is readily explained by magnetic susceptibility data which show that greater than 90% of susceptibilities for high-Ca and low-Ca granites fall within the same range ($0–900 \times 10^{-5}$ SI). The only real differences between the two are the greater relative abundance of low susceptibility granite ($<100 \times 10^{-5}$ SI) for the high-Ca group and the associated more pronounced bimodal character to their data (Fig. 2). Fewer susceptibility data are available for the minor granite groups, however, values extensively overlap with the major granite groups. Both the syenitic and mafic groups show peaks at low susceptibility (0–100 × 10^{-5} SI), coincident with the lower modal peak of the high-Ca group. The spatial relationships of these low susceptibility values is yet to be determined, but many correlate with the abundant, poorly magnetised intrusions in, and around, greenstone belts. It is surprising that more intrusions are not resolved in the aeromagnetic data, given the range of measured susceptibilities and the apparent capacity of high-Ca granites, particularly, to form magnetically zoned plutons. It may be that modes of intrusion differ between regions; harder-to-detect granite sheets may be more prevalent in areas where individual intrusions are not resolved.

Gamma-ray spectrometric data provide some discrimination of the main geochemical suites. In outcrop areas, high-Ca granites correlate with K-only anomalies in ternary (K, Th, U) images of the data, low-Ca granites with regions of anomalously high K, Th, and U. High-HSFE granites also correlate with K-only anomalies and are not discriminated from the high-Ca group. Syenite correlates with anomalously high K, Th and variable to high U. The radiometric characteristics of the mafic group are unknown but are expected to be similar to the high-Ca group on geochemical grounds. Gamma-ray spectrometric data are, however, of limited regional use for classifying granite in the Yilgarn Craton due to the very small ground penetration of gamma rays and the laterally extensive regolith cover.

Shear zones in felsic crust and gold mineralisation

Gold mineralisation in the Yilgarn Craton is highly correlated with greenstone belts but it is rarely coincident with high amplitude, or even moderate amplitude, geophysical anomalies. Several authors have inferred that gold mineralisation is commonly located in second and third order structures adjacent to regional shear zones (e.g., Groves et al., 1990). However, the importance of the shear zones has been disputed (Vearncombe, 1998). There is also disagreement as to the nature of some large scale structures that disrupt the greenstone belts and felsic crust. Although gold mineralisation is generally located along faults, the vast majority of faults are barren and regional spatial associations with mineralisation have been difficult to establish. However, an empirical association between gold mineralisation and regional shear zones is apparent.

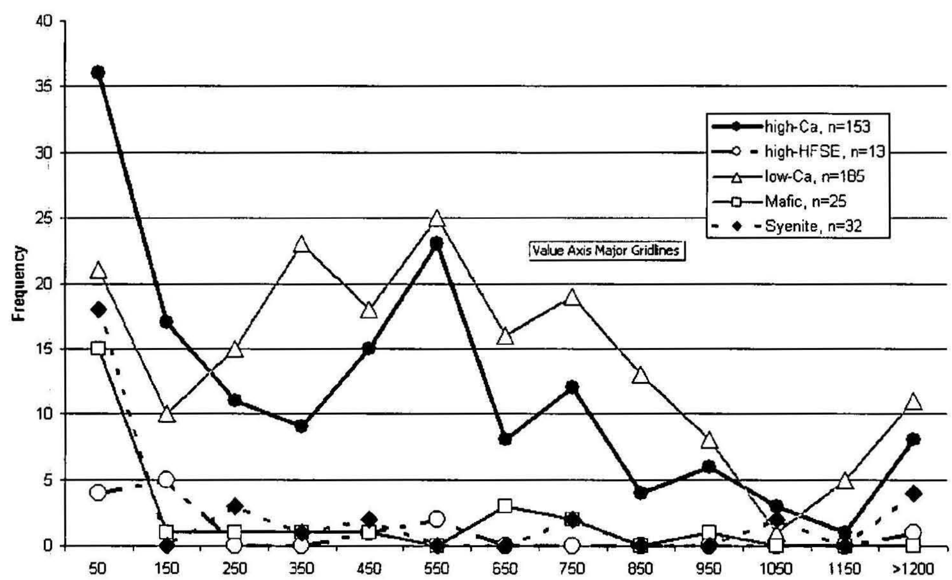

Figure 2 Plot of the susceptibility distribution for the five granite geochemical groups of Champion and Sheraton (1997). Note the extensive overlap of values between groups. The cause of the high number of samples at low susceptibility for all groups may relate to sampling of abundant, poorly magnetised intrusions, spatially associated with the greenstone belts.

Abundant shear zones delineate a 200 km wide, north-trending corridor that transects both greenstone and adjacent felsic crust in the central east of the Yilgarn Craton. This corridor is largely coincident with the Norseman-Wiluna Belt (Gee et al., 1981), the region of highest gold production and resources for the Yilgarn Craton. Within this corridor, intersecting north-northwest and north-trending shear zones define a distinctive rhomboid to sigmoidal internal geometry. Greenstones are strongly aligned with these shear zones and are extensively disrupted. Highly mineralised sites include greenstones adjacent to bends and intersections of the shear zones. Interpretation of seismic reflection data indicates that many of these structures pass through the greenstones and extend deep into underlying felsic crust (Goleby et al., 2003). Ridley (1990) and Mikucki & Ridley (1993) argued that the silicic and potassic alteration associated with many of the Norseman-Wiluna gold deposits provides circumstantial evidence that mineralising fluids were in chemical equilibrium with (underlying) granitic rocks.

In contrast, the architecture of other areas of the Yilgarn Craton is different. For instance, in the vicinity of the Yalgoo Dome in the north west of the Yilgarn Craton, large, circular to ovoid, granite intrusions dominate the regional structure and greenstone is not greatly disrupted by, or preferentially aligned with, the sparse shear zones. The gold endowment of this area is low. Proximity of shear zones and dismemberment of greenstone is successively higher for the Southern Cross and north-east Murchison domains which correlate with an apparent increase in gold endowment. The shear zones are, therefore, considered the main mineralising fluid pathways in the crust, as has been suggested by numerous authors. Greenstones adjacent to the shear zones provide effective structural and chemical traps (see Hagemann & Cassidy, 2000).

Is this empirical relationship between shear zone patterns, greenstone alignment and disruption, and gold endowment applicable in other Archaean terranes? Certainly structural patterns in the Superior Province of Canada lend support to the model. Greenstone alignment and intersecting regional structural zones in the Abitibi sub-province define a remarkably similar rhomboid geometry to that of the Norseman-Wiluna Belt in the Yilgarn Craton. Further more, like the Norseman-Wiluna Belt, the Abitibi sub-province hosts several world class lode-gold deposits spatially associated with the regional fault or shear zones (see Fig. 2 in Robert & Poulsen, 1997). Elsewhere in the Superior Province, these structures are less abundant, greenstone belts are less regionally aligned, and gold endowment is considerably lower. The Pilbara Craton of northwest Australia provides another example. Large ovoid-shaped regions of granite dominate the structure of the Plibara, greenstones are not regionally aligned, and shear zones are not abundant. The structural style of the Pilbara Craton is most similarly linked with that of Yalgoo Dome area in the Yilgarn Craton and its greenstones are equally poorly mineralised with gold.

In summary, gold mineralisation is strongly correlated with shear zones and associated disruption of greenstones. The relationship between felsic crust and mineralisation is more tenuous but is implied through continuity of shear zones in greenstone into surrounding and underlying felsic crust and the nature of alteration associated with gold mineralisation. Thus felsic crust plays an important role in the mineralisation process in the Yilgarn Craton. This role is related to subsequent deformation of the felsic crust rather than directly with magmatic events.

Acknowledgments
Fugro Airborne Surveys Pty. Ltd. is gratefully acknowledged for access to Multi-Client aeromagnetic data covering the Menzes to Norseman area of the Yilgarn Craton. This abstract has benefited from reviews by David Champion, Lynton Jaques and Patrick Lyons and is published with the permission of the Chief Executive Officer, Geoscience Australia.

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SUITES WITH PARTICULAR REFERENCE TO GRANITES OF EASTERN AUSTRALIA

Allan J. R. White
VIEPS, The University of Melbourne, Victoria 3010, Australia

This presentation closely follows that in the published paper:

White A.J.R., Allen, C.M., Beams, S.D., Carr, P.F., Champion, D.C, Chappell B.W., .Wyborn, D. & Wyborn, L.A.I. 2001, Granite suites and supersuites of eastern Australia. ***Australian Journal Earth Science*** **48,** 515 – 530.

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"Separate granite plutons in southeastern Australia can commonly be grouped into suites on the basis of shared similarities of field, petrographic and compositional data. Granites in different plutons of the same suite share common properties or exhibit a sequence of such features. Rocks of the same suite are cogenetic, but the details of their genesis need not be known or agreed on, to group granite units in such a way. These rocks are cogenetic in the sense that they shared a similar petrogenesis and were derived from source materials of essentially the same composition, whereas differences between suites reflect analogous differences in their source rocks. The term suite is lithologic or lithodemic in a stratigraphic sense and is closely analogous to the lithostratigraphic term group. As such, the plutons within a suite need not be of the same age, and age is not a factor in recognising a suite. However, the fact that the petrogenesis of the components of a suite resulted in such similar products means that their ages are likely to be similar. Granite plutons that share many similar features, but which also show distinct differences and which may be assigned to more than one suite, may be grouped into supersuites. The allocation of granites to suites is fundamental to understanding their petrogenesis. Suites vary in the complexity of their compositional variation. Simple suites show variations in element abundances that are highly correlated and the dispersion of composition within such suites is considered to result from varying degrees of fractionation of entrained restite from a melt. Intricate suites vary in composition in more complex ways and their variation is considered to be a consequence of processes such as fractional crystallisation. Any mineralisation is generally associated with intricate suites, and the occurrence of mineralisation and its precise character is generally specific to particular suites."

GRANITE MELT FORMING REACTIONS

Allan J.R.White
VIEPS, The University of Melbourne, Victoria 3010, Australia

Partial melting within the crust is widely accepted for the production of at least some, if not most granite magmas. It is considered that partial melting is not a response to increasing temperatures in rocks containing haplogranite components but is a result of melt-forming reactions as temperature and possibly pressure increases (White et al. 2003, and refs therein). Melt-forming reactions are mainly dehydration reactions. The process has been called "vapour-absent melting".

At low temperatures, melt reactions involving dehydration of muscovite in the presence of quartz and plagioclase produces a granite melt that is strongly peraluminous because Al_2SiO_5, a bi-product of the reaction, dissolves in the melt. On cooling this melt crystallises to muscovite granite. Crystallization involves a back reaction to new muscovite.

At temperatures near 800 to 850°C and pressures near 500 to 600 MPa (5 – 6 Kb), there are reactions in a protolith containing quartz + feldspars + biotite which produces melt and orthopyroxene as a bi-product. In this case only a small amount of the orthopyroxene is soluble in the melt. The remainder appears as residual crystals or restite. Orthopyroxene is the first mafic phase to crystallise from this melt whether it is separated from the restite or not. Consistent with this model, S-type volcanic rocks of the Lachlan Fold belt contain large crystals ("phenocrysts") of orthopyroxene most of which are considered to be restite. On the other hand, granites having the same composition as these S-type volcanics, contain no orthopyroxene because there has been a back reaction of orthopyroxene to form biotite. The magma is quenched.

Experiments (e.g. Johannes & Koepke 2001) have shown that dehydration melting of the assemblage hornblende + plagioclase produces a tonalite melt (I-type) with residual clinopyroxene and lesser orthopyroxene both of which are only partly soluble in the melt. I-type dacites contain crystals of both pyroxenes. Crystallisation of a magma of this sort to tonalite, results in back reactions (peritectics) to generate hornblende and biotite respectively. Experiments also show that many or most of the solid products of melt-forming reactions appear as perfectly-shaped crystals e.g. orthopyroxene (Johannes & Koepke 2001 fig. 8). Crystals produced by melt-forming reactions if carried along with the magma as restite crystals are indistinguishable from phenocrysts.

Plagioclase may completely dissolve in the melt phase if the protolith is low in Ca and Na. In protoliths containing more Ca and Na (e.g. metamorphic plagioclase), plagioclase reacts. Johannes (1989) showed that partial melting of plagioclase (An_{60}) in the system Qz-Ab-An-H_2O at 200 MPa (2 Kb) and 850°C produces new plagioclase crystals An_{82-85} as well as a more sodic plagioclase component in the melt. It is suggested that new plagioclases resulting from melt reactions in the Earth's crust will be in local equilibrium because reaction occurs with rising temperatures. The relicts of calcic plagioclase (near An_{80}) in the Jindabyne tonalite are interpreted as new plagioclases produced during the melt-forming reaction that produced the tonalite magma. Near uniformity of core compositions indicate local equilibrium during formation of the calcic plagioclase but the corrosion of cores and complex zoning of the outer parts seen in the rocks, indicates disequilibrium. The plagioclase was not completely "made over", to use Bowen's (1922) term, as crystallisation proceeded with falling temperatures. The corroded calcic plagioclase cores are all that remain of restite plagioclase.

Johannes and Holtz (1991 showed that, at least at low pressures, the plagioclase loop is very flat in the haplogranite system when the activity of H_2O is well below 1. A similar explanation is therefore likely for the corroded calcic cores common in many low temperature granites. In volcanic rocks with the same chemical composition as those low temperature granites, plagioclase "phenocrysts" with the same calcic compositions as in the granites but without the complex, outer more sodic zones, are mostly restite plagioclase. These have not re-equilibrated because the rock has cooled rapidly.

The phenocrysts, we contend, may not have crystallized from the melt but may be restite phases carried along by the magma from the source of partial melting – the new uniform plagioclases like those produced in the experiments of Johannes (1989). The partial "making over" as Bowen (1922) put it, of the equilibrium plagioclase of the partial melt during cooling and crystallization, is a type of back reaction.

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PORPHYRY COPPER MINERALISATION OF WESTERN USA

Allan J.R.White

VIEPS, The University of Melbourne, Victoria 3010, Australia

Porphyry copper deposits of western USA are very large low grade deposits dominated by disseminated Cu mineralisation but commonly with appreciable Mo and Au. Many deposits began as gold camps. Mineralisation is centred on, and mostly within, near surface quartz monzonite intrusions in which there is inner and deeper concentric Mo-rich shells. Mo shells are followed by Cu-rich shells, then pyrite and there may be an outermost Pb-Zn-Ag zone as in the country rock skarns of the Bingham deposit (John 1978). Cu-Mo mineralisation occurs within a "potassic" alteration zone characterised by secondary biotite (e.g. Moore 1978). Extensive outer sericitic (phyllic), argillic and propylitic alteration zones do not necessarily conform to the concentric pattern. Large scale bulk mining of a porphyry deposit was first carried out at Bingham.

There is a belt of economic deposits extending from Butte Montana, through Bingham Utah, to Arizona where deposits are most abundant, and New Mexico. This review is based on visits to many deposits along the whole length of the belt and various petrological observations at Butte, Bingham, Bagdad, Miami-Globe and Sierrita.

Most deposits are Laramide (approx. 70 Ma), a notable exception being Bingham (40 Ma). The Laramide belt is inboard up to 1200 km from the Pacific coast of the US where there are Recent to Mesozoic subduction related rocks. It is suggested that the Laramide igneous rocks were not formed as a result of subduction but as a result of rifting within the Precambrian basement.

At Butte Montana (references in Miller 1978) where the rich "main" veins (e.g. Anaconda Vein) cut typical shells of the porphyry system, the host rock is quartz monzonite. Two suites of associated rocks have been recognised within the Boulder Batholith. Rocks of the high-K, mineralised suite range from mafic monzonites or high-K diorites through quartz monzonites to low quartz granites. Associated volcanic rocks include voluminous latites. Latites are high-K, acid to intermediate SiO_2 rocks in which there are virtually no quartz phenocrysts. The original quartz monzonite was described from Walkerville (a northern suburb of Butte) more than 100 years ago, but the significance of this rock has been lost, mainly because many later petrologists referred to the rock type as granite or adamellite (now "monzogranite") probably because the Butte sample is on the borderline between quartz monzonite and granite. A sample, collected near the type locality, is described. It consists of plagioclase, K-feldspar, quartz, biotite, hornblende (commonly with pyroxene cores), relatively abundant magnetite and very small amounts of titanite and apatite. Quartz is lower than in typical granite and magnetite is more abundant. Magnetite is commonly seen as aggregates along with apatite, suggestive of crystallisation from an immiscible Fe-P melt phase!

Monzonites very low in quartz are very common at Bingham. At Miami-Globe (Peterson 1962) there are typical quartz monzonites and very low quartz granites, and at Sierrita (Anthony & Titley 1988) rocks range from high-K diorites (and high-K andesites) through quartz monzonites (and latites) to low quartz granites (and rhyolites). Bagdad (Anderson

1950) is a high-K diorite lower in K_2O than most other igneous rocks of the Laramide belt.

The quartz monzonite host rocks for the US deposits reviewed here have high $K_2O + Na_2O$. As in host rocks of other economic porphyry Cu deposits, K_2O is high but normally less than Na_2O. Gerel (1995) says Cu-Au porphyry systems have $K_2O/Na_2O = 0.7$ to 1.3 whereas the porphyry Cu-Mo deposits are associated with rocks with $K_2O/Na_2O = 0.3 - 0.7$. Bingham and Butte both have $K_2O/Na_2O = 1.2$ to 1.3 but have produced about 1000 and 100 tonnes of Au respectively. Bingham has produced appreciable Mo. Higher alkalis in the quartz monzonite magma produced higher feldspar in the rock and consequently lower quartz. Another characteristic geochemical feature is high Ba commonly amounting to 1000 ppm or more. Oscillatory zoning within K-feldspar seen in the field and in thin section is indicative of high Ba. Oxygen fugacity is extremely high. Values of $\Delta NNO > +2$ can be calculated from more reliable rock analyses in which FeO and Fe_2O_3 have been recorded, and from biotite compositions (e.g. Anthony & Titley 1988).

The following features indicate that host rocks were intruded close to the surface at pressures near 50 MPa (500 bars):

1. There are associated volcanic rocks.
2. Some intrusions are porphyries that are pressure-quenched rocks.
3. There are acid rocks with miarolitic cavities (crystals of copper and molybdenum sulfide have been reported in some cavities).
4. Granophyric intergrowths of quartz and alkali feldspar are seen in thin section.
5. Occurrence of hydrothermal breccias.
6. Quartz monzonites have closely spaced vertical joints.

It is concluded that economic porphyry copper systems of the western USA are associated with, and probably derived from, high temperature monzonitic suites in which the variety of rock types are the result of fractional crystallisation. Mineralised rocks are near-surface quartz monzonites similar to I-type granites but with lower quartz contents. Many are on the borderline between quartz monzonite and granite. Some deposits are only economic if there has been secondary enrichment.

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Measuring the ages of granites: the challenge to get it right

Ian S. Williams

Research School of Earth Sciences, The Australian National University, Canberra, ACT, 0200

To measure the ages of igneous rocks by isotope geochronology is, in principle, a relatively simple procedure. There is a variety of dating techniques to choose from (e.g. K–Ar, Ar–Ar, Rb–Sr, U–Pb, Sm–Nd) and, with a few exceptions, the technicalities of each method are well understood. This point has been reached only by considerable trial and error, however, particularly when it comes to dating granites.

In the very simplest case, accurate dating of an igneous rock requires two basic conditions to be satisfied. When the rock crystallised, it must have incorporated the radioactive isotope of choice, but none of its stable daughter product. After crystallisation, the rock must have remained a closed system—no daughter or parent isotopes can have been added to, or lost from, the rock other than by in situ radioactive decay. Rarely are these criteria met, although the K–Ar system in erupted basalt magmas is one such example. Most igneous rocks, including granites, incorporate significant amounts of all the decay products of interest, even Ar, at the time of crystallisation. One solution is to analyse, not the granite as a whole, but selected minerals that concentrate the radioactive element of choice yet exclude its decay product. Micas and hornblende, for example, are enriched in K but contain trivial Ar, micas are strongly enriched in Rb relative to Sr, and some trace minerals such as zircon and monazite are enriched in U but exclude Pb.

Much of the early dating work on granites was done using mineral K–Ar and Rb–Sr. The requisite micas and hornblende were relatively abundant and easy to separate, the enrichments in K and Rb were large, and the procedures for extracting and analysing the elements of interest were not particularly difficult. There was the minor complication that some micas contain significant amounts of initial Sr, but its isotopic composition could be measured on Sr-rich, Rb-poor minerals and a correction made. A refinement of the Rb–Sr technique was to measure the composition of a variety of minerals with different initial Rb/Sr ratios, and commonly also the whole rock. If the isotopic composition of the initial Sr was the same for all, which it should be in an isotopically homogeneous magma, then a plot of mineral Sr isotopic composition versus Rb/Sr defined an isochron, the slope of which gave the age of the rock. Ages were measured with analytical precisions of about 0.25%.

The widespread use of K–Ar and Rb–Sr mineral dating provided the first direct measurements of granite ages on a regional scale, and thereby the first direct measurements of the extent and duration of those magmatic events. As the data base increased, however, inconsistencies emerged. Occasionally ages were higher than expected, indicating the presence of excess argon. More commonly ages were lower than expected, reflecting a radiogenic Ar and Sr deficiency. Biotite only retains radiogenic Sr and Ar quantitatively below about 350 °C. Muscovite and hornblende have closure temperatures of about 500 °C. Only if granites cooled quickly and remained unmetamorphosed were K–Ar and Rb–Sr ages an accurate estimate of the emplacement ages. Where magmatic provinces had cooled slowly or been metamorphosed, these ages simply recorded the last time that the various minerals had cooled below their closure temperatures.

Rb–Sr analysts attempted to solve this problem by measuring ages using only whole rocks. Although some radiogenic Sr might be lost from individual minerals, it was expected to remain within the rock, so the isotopic age of the granite would be preserved. Whole-rock dating relies on granitic magmas being isotopically, but not chemically, homogeneous. Rb–Sr analyses of several rocks from a single intrusion are therefore expected to define an isochron, the slope indicating the granite age and the intercept its initial Sr isotopic composition. In practice the whole-rock dating method has major weaknesses. First, most granites are chemically relatively homogeneous, with much lower Rb/Sr than minerals such as micas. To obtain rocks with enough range in Rb/Sr to define an isochron precisely can be very difficult, and it is not necessarily valid to extend the range by sampling enclaves and aplites. Secondly, the Sr isotopic composition of a granitic magma is rarely homogeneous. If the heterogeneity is random, then the whole-rock analyses scatter about the isochron, making the age determination imprecise, even if many rocks are analysed. More importantly, if the initial Sr isotopic variation is not random, but correlated with Rb/Sr, then the age of the granite can be grossly overestimated. Constructing isochrons from analyses of rocks that are not cogenetic can cause similar errors.

K–Ar analysts tackled the problems of excess Ar and Ar loss by developing the ^{40}Ar–^{39}Ar technique, whereby neutron irradiation is used to convert some of the ^{39}K in a mineral into ^{39}Ar. The method assumes that in cases of partial radiogenic Ar loss, some domains in some mineral grains remain unaffected, and that excess Ar has a different distribution in mineral grains from the Ar produced by *in situ* ^{40}K decay. When the irradiated mineral separate is step heated to release its Ar in small increments, the most loosely held Ar is released first and the most tightly held Ar released last. ^{39}Ar being a proxy for ^{40}K, the $^{40}Ar/^{39}Ar$ of each gas fraction gives its K–Ar age. Excess Ar is identified by its high $^{40}Ar/^{39}Ar$, Ar from domains of Ar loss by its low $^{40}Ar/^{39}Ar$. Domains unaffected by either process yield the same $^{40}Ar/^{39}Ar$ (hence same age) over several temperature steps. The ^{40}Ar–^{39}Ar technique has been applied very successfully to granites, although crystallographic effects on Ar release sometimes reduce the precision of ages measured on biotite. The technique is still limited, however, by the relatively low closure temperatures of the minerals analysed.

Slow cooling and metamorphism are lesser issues for U–Pb dating. Zircon, the mineral most commonly used for U–Pb dating of granites, has a closure temperature of over 900 °C, comparable to the temperatures of high-temperature granitic magmas. Even so, zircon was slow to be widely used for geochronology because of the technical difficulties involved. To obtain enough trace zircon for analysis required tens to hundreds of kilograms of rock, the chemical procedures for extracting and purifying U and Pb were complex, and the isotopic analysis of Pb was very difficult. Following development of improved chemical and mass spectrometric techniques, however (high-pressure bombs, ultra-pure reagents, ion-exchange chemistry, silica gel), zircon U–Pb quickly became the method of choice for dating granite, particularly in terranes with complex thermal histories. The technique continues to be developed, wet chemical isotopic analyses of single 10 μg zircon grains now being commonplace, producing age determinations with analytical precisions of better than 0.1%. The accuracy that can be achieved is now limited principally by the uncertainties in the U decay constants.

Zircon geochronology also has its limitations, however. Many granitic magmas, particularly magmas produced by low-temperature partial melting of predominantly crustal rocks, are zircon saturated. Zircon is an extremely robust mineral, both physically and chemically, so zircon from the source rocks of granites, and also potentially from wall rocks, becomes entrained in granitic magmas and preserved in the consequent granitic rocks. This inherited older zircon acts as nuclei for the new zircon precipitated during magma genesis. The radiogenic Pb in the inherited nucleus is preserved, so U–Pb dating of even single zircon crystals can yield, not the age of the granite, but the meaningless averaged 'age' of a mixture. Inherited zircon is particularly common in the Palaeozoic granites of eastern Australia, making accurate zircon age measurements by wet chemistry extremely difficult.

Melt-precipitated zircon in inheritance-rich granites is best dated by *in situ* microsampling. This can presently be done by ion microprobe (SIMS) or laser ICP-MS. In both cases the zircon samples are prepared as grain mounts which are polished to section the grains and expose their growth zones. For SIMS analysis, a 10–30 μm diameter beam of oxygen ions is focused onto the zircon, sputtering secondary ions that are analysed in a double-focusing mass spectrometer. Each analysis takes about 15 minutes, the ion beam penetrating about 2 μm into the grain. For laser ICP-MS analysis, a 10–100 μm diameter laser beam is used to ablate particles that are dissociated and ionised in a plasma then analysed in a rapid-switching magnetic sector or quadrupole mass spectrometer. Each analysis takes about 2 minutes, the laser beam penetrating 10–100 μm into the grain. The precision of individual Pb/U analyses by the two techniques is similar, normally 0.5–4%, depending upon U content. Much higher precision on the final age determination is achieved when multiple analyses are pooled. Precision must not be confused with accuracy, however. The accuracy of both techniques is limited by the need to calibrate the Pb/U measurements against either zircon (SIMS, ICP-MS) or solutions (ICP-MS) of known composition. Calibrations against zircon in both cases are limited by the micron-scale heterogeneity of available natural standards. The best accuracy achieved by both techniques is currently about 1%, although some issues of inaccuracy up to 5% still remain to be resolved.

Microsampling makes it possible to date melt-precipitated zircon free from the effects of older inherited zircon. It also makes it possible to date the inheritance, and thereby to obtain direct information on the age and relative abundance of the zircon components incorporated in the granite magma. These inherited ages appear to be preserved unaffected by the magmatism, and provide valuable 'fingerprints' that help to identify the likely sources of the granites and even the possible provenance of those sources. Microsampling is equally applicable to dating other U-rich trace minerals, for example titanite and monazite, but as with zircon, in the absence of inheritance or severe isotopic disturbance, the best precision and accuracy is still obtained by wet chemical techniques.

Petrogenesis of Proterozoic Anorogenic Granitoids from the Mazury Complex (NE Poland)

Janina Wiszniewska, Polish Geological Institute, 00-975 Warszawa, ul. Rakowiecka 4, Poland

jwis@pgi.waw.pl

Boguslaw Bagiński Warsaw University, 02-089 Warsaw Al. Żwirki i Wigury 93, Poland

The crystalline Proterozoic Mazury Complex is situated in northeastern Poland and forms the westernmost part of the large East European Craton (EEC). The basement is covered by Phanerozoic platform sediments whose thickness varies from 420 m in the east to 6,500 m along the Trans European Suture Zone (TESZ), as the crystalline basement is dipping towards the southwest. The Polish part of the EEC consists of several tectono-structural and lithological units, revealing complex Precambrian evolution. The tectonic setting of the Mazury Mesoproterozoic magmatism has been considered as an E-W trending belt of post-collisional provenance, or rejuvenation of older lineaments or a terrane boundary. Several intrusions of anorogenic character and bimodal composition, mostly rapakivi type granites and anorthosite-norite massifs (Suwałki, Sejny, Kętrzyn) have been described within the area. The rapakivi-like granites are rather differentiated with variable density, but mostly with higher density than the anorthosite-norite massifs. In the vector image of the fractional vertical derivative the gravity lineaments, marking density contrasts, are enhanced (Wiszniewska, Wybraniec, 2000). Rapakivi granite plutons, whose compositions range from monzodiorite to leucogranite, are probably multiple intrusions that were emplaced at a relatively shallow level.

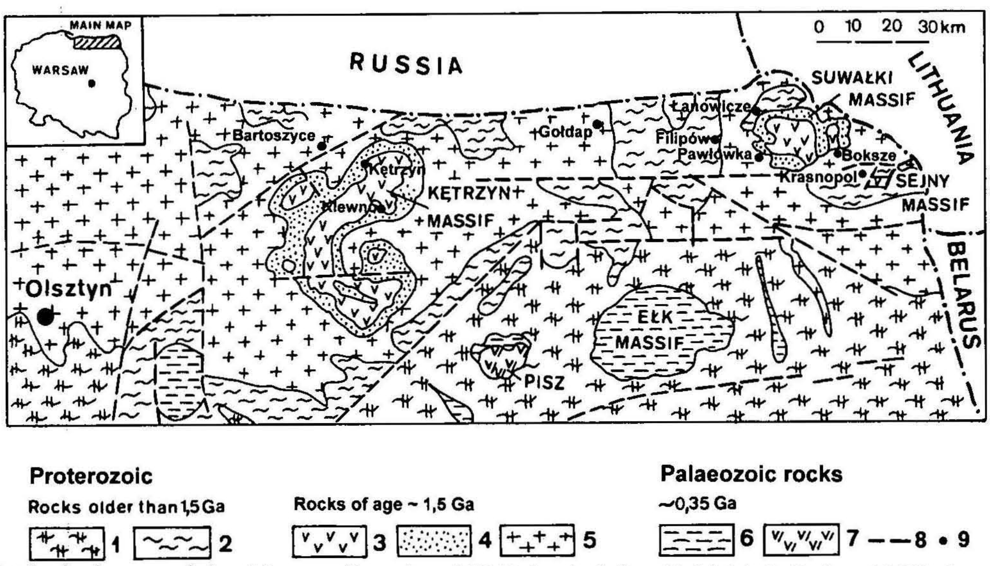

Fig. 1. Geological map of the Mazury Complex, NE Poland, (after Kubicki & Ryka, 1982) 1- granites and migmatites, 2- granulite domains, 3- anorthosites and norites, 4- diorites, 5- rapakivi-like granites, 6- syenites, 7- gabbros, 8- lineaments, 9- borehole location.

The rocks were studied for major and trace elements (Bagiński *et al.*, 2001a,b) and for Sr and Nd isotopes (Bagiński *et al.*, 2001c). They show a widespread differentiation trend with SiO_2 contents ranging from 46% to 76% and no indication of the classical Daly gap between mafic and felsic rocks. All massifs have very similar patterns in both REE and spider diagrams, which are interpreted as evidence of their consanguinity. However, each massif has its own characteristics when major and trace element variation diagrams are considered, which possibly reflects variable modes of differentiation from one massif to the other. In addition, all samples plot along a major trend similar to the jotunitic liquid line of descent defined in the anorthosite - mangerite – charnockite - (rapakivi) granite (AMCG) suite from Rogaland (Norway). The Mazury complex belongs chemically to the ferro-potassic alkali-calcic type of rocks and is comparable with rock complexes such as in Veisiejai in Lithuania or Rogaland in southern Norway (Skridlaite *et al.*, 2003). The most felsic varieties of the granites approach the classic rapakivi granites in their petrogenetic characteristics, elevated contents of incompatible elements and REE, and hence have A-type affinities. The granites are assigned to the 'Post-collisional granite' field. The overall evolution from mafic to felsic rocks is characterised by well-defined trends, which most probably represent a liquid line of descent. Fractional crystallisation with or without assimilation and hybridisation can account for the continuous evolution from mafic to felsic compositions.

A recent geochronological study of granites from the Mazury Complex by the U-Pb method on single zircons and titanite fractions allows the recognition of three distinct episodes of igneous activity lasting 35 m.y. (Dörr *et al.*, 2001). The first magmatic episode (I) is represented by monzodiorite (jotunite) rocks of the Sejny intrusion, dated with a concordant zircon at 1548 ± 7 Ma, which is in accordance with earlier dated Re-Os ages of the ore deposits in the Suwalki anorthosite massif (Morgan *et al.*, 2000). The second episode (II) is dated with a subconcordant zircon at 1525 ± 4 Ma ($^{207}Pb/^{206}Pb$ age) and with subconcordant titanite at 1525 ± 25 Ma ($^{207}Pb/^{206}Pb$ age) from a monzodiorite-tonalite of Krasnopol 6, which proves a rapid cooling below 550°C. The Bartoszyce quartz monzonite is dated with three concordant zircons at 1522 ± 2 Ma. The youngest (III) episode is represented by the Boksze diorite (east cover of the Suwalki Massif), which is dated with a concordant zircon age at 1513 ± 4 Ma.

The Mazury felsic rocks have depleted mantle Nd model ages $T(Nd)_{DM}$ of 2.1 to 2.2 Ga (Claesson *et al.*, 1995), while the Suwałki anorthosite-gabbronorite complex has yielded Nd model ages of 1.7 to 2.3 Ga (Wiszniewska *et al.*, 1999). Titanomagnetite and sulfide ores from the Suwałki massif dated by the Re-Os method have given isochron ages of 1559 ± 37 Ma and 1556 ± 94 Ma (Stein *et al.*, 1998, Morgan *et al.*, 2000, Wiszniewska & Stein, 2000). The ε_{NdT} recalculated at 1.5 Ga (age of emplacement given by U-Pb zircon data) ranges from –0.62 to –6.82, while ε_{SrT} ranges from –10 to +287. These values indicate that crustal contamination has played an important role in the genesis of these magmas. Moreover, as the data plot along a single hyperbola in a ε_{NdT} *vs* ε_{SrT} diagram, it can be proposed that contamination resulted from a single and quite homogeneous crustal contaminant. This later could be the Svecofennian basement that is widespread in this part of Poland.
In conclusion, we adopt the hypothesis that the various components of the Mazury Complex were derived through variable degrees of partial melting of a single and quite homogeneous source. These magmas batches were contaminated to different degrees by the basement in which they were emplaced, and each massif evolved independently by low degrees of differentiation

The 1548 to 1513 Ma protoliths of the Mazury Complex are coeval with those of the other AMCG complexes of western Russia, southern Finland, Estonia, Latvia and central Sweden. The formation of the suite is concentrated in the period covering almost 50 m.y., from 1.55 to 1.50 Ga. A thick crust and a Moho offset on the recent EUROBRIDGE geophysical profiles could indicate that a slab of lower crustal rock has been melted under the Suwalki massif to produce the AMCG rocks. Recent structural and kinematic observations indicate dominant transpressional/compressional regimes.

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Assessing the Metallogenic Potential of Proterozoic Granite Suites from First Principles

Lesley Wyborn: Geoscience Australia, GPO Box 378, Canberra, ACT, 2601

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

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

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

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

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

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

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

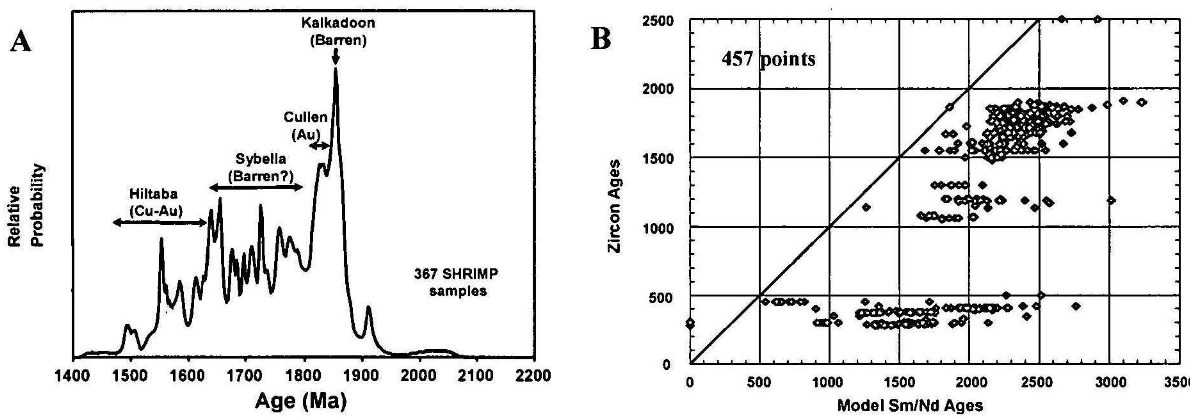

Figure 1: A. Relative probability plot of 367 Shrimp U-Pb zircon age determinations of Australian Proterozoic Granitic Rocks. The approximate ages of 4 of the major Proterozoic I-type granite associations and their Metallogeny (Table 1). B: Plot of Zircon ages Proterozoic and Palaeozoic granitic rocks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

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

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

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

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

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

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

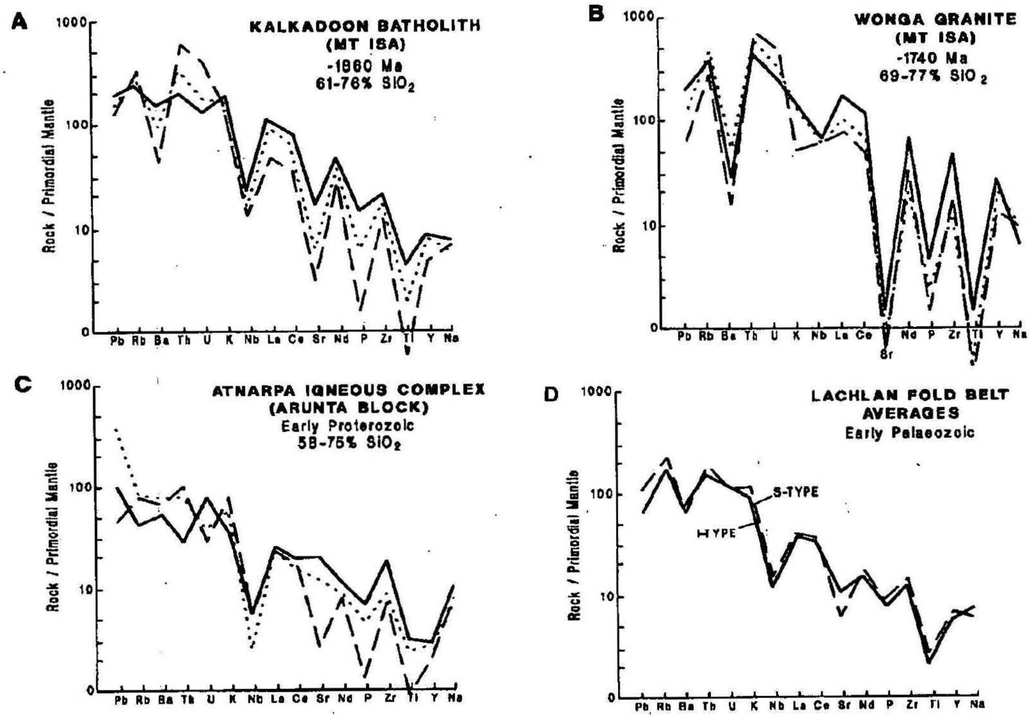

Figure 2: Multi-element primordial-mantle-normalised abundance diagrams for representative Australian granites. Normalising values are from Sun and McDonough (1989). In A,B, and C, the solid line is the lowest SiO_2 content, the dotted line is an intermediate SiO_2 content and the dashed line the most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

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

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

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

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

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

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

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

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

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

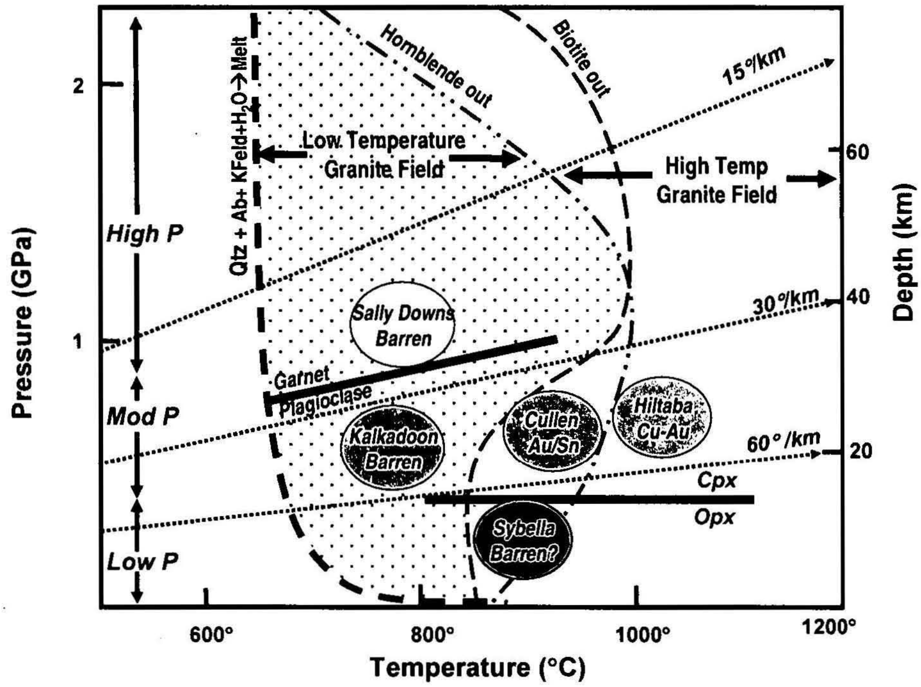

Figure 3. A petrogenetic Grid for Australian Proterozoic Granite Associations. Source for the data are 1) qtz (quartz) Ab (albite) KFeld (K-Feldspar) + H_2O → melt: Johannes & Holtz (1996); 2) cpx (clinopyroxene) →opx (orthopyroxene) boundary: Patiño Douce (1997); 3) garnet →plagioclase boundary: Wyllie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

2. Second Order Influence of host rock compositions on Metallogeny

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

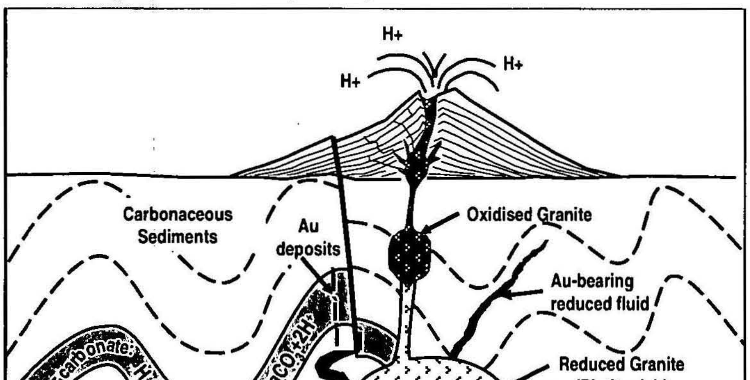

Figure 4: Cartoon expressing observed control of carbon-rich country rock on the redox state of the magma. It is proposed that H+ diffused into the magma caused the magma to reduce as it crystallises

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

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

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

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

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