Redox and Compositional Parameters for Interpreting the Granitoid Metallogeny of Eastern Australia: Implications for Gold-rich Ore Systems

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Abstract: Granitoids and related rocks of eastern Australia can be classified according to their 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.

The granitoids 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. The most unevolved intrusive igneous rocks comprise those of the Ordovician of the Lachlan Orogen, and the Devonian of the New England Orogen. Strongly fractionated and evolved I-type granites occur in western Tasmania, the southern New England Orogen, and far north Queensland. Other fractionated suites tend to occur relatively rarely in the Lachlan Orogen and elsewhere. Oxidation states vary markedly. The most consistently oxidised rocks occur in the Ordovician of the central Lachlan Orogen, and the northernmost New England Orogen. The Carboniferous I-types of the northeastern Lachlan Orogen are consistently more oxidised than other Lachlan Orogen I-types.

Gold-rich, Cu-poor systems associated with felsic I-types in eastern Australia are associated with W-Mo mineralised suites with gold occurring within a predictable metallogenic zonation. Gold mineralised I-types comprise weakly to moderately oxidised, high-K granitoid suites that, at least in the east Australian context, have low K/Rb ratios and show strong fractionation trends. Gold is readily removed from granitic magmas through the early precipitation of sulfides, or to a lesser extent by magnetite. Crystallisation of Fe-poor, silica-rich granitic magmas in a relatively narrow oxidation window between the FMQ and NNO buffers may provide conditions where retention of Au in magmas in felsic granitic magmas is optimised.

Keywords: granites, Australia, redox, metallogeny, gold

1. Introduction

The choice of a universal classification scheme for granitoids is a subject of an enduring, and ultimately fruitless debate. This is because a single classification scheme cannot serve all the purposes for which a granitoid classification would be required to fulfil. Purely descriptive schemes based on observable features and parameters such as actual or normative mineralogy (e.g. Streckeisen, 1976) serve their purpose as a petrographic classification tool, while other schemes are interpretative as to granitoid source or tectonic setting (e.g. Chappell and White, 1974; Maniar and Piccoli, 1989; and Pearce et al., 1984).

The magnetite-, ilmenite-series classification of Ishihara (1977) remains a highly effective, purpose-designed metallogenic classification scheme for granitoids. In this scheme granitoids are classified into magnetite-series if they are magnetite-bearing, and ilmenite-series if they are magnetite-free. As a result of consequences for metal and sulfur behaviour driven by differences in f_{O_2}, magnetite-series granitoids are associated with Cu, Pb-Zn and Mo sulfide-related mineralisation, while ilmenite-series granitoids are associated with Sn-W (wolframite) mineralisation. Scheelite mineralisation also appears to be associated with magnetite-series granitoids. The magnetite-, ilmenite-series classification is easily applied in the field and allows immediate metallogenic interpretations to be made.

Blevin and Chappell (1992, 1995) studied relationships between granitoid chemical compositions, source and intensive variables (most importantly oxidation state) and the ore element assemblages of associated mineralisation. A trend was apparent, from Cu (-Au) associated with the more mafic end of the granitoid spectrum, W with the intermediate compositional range, and Mo (±W) and Sn (±W) related to the felsic, fractionated granitoids. A strong oxidation control was also present, with the Cu-Au-Mo series associated with oxidised rocks and Sn with reduced rocks, in complete

agreement with the results of Ishihara and his co-workers. Tungsten is associated with both series but was best developed in granitoid suites with intermediate to relatively reduced oxidation states.

Further studies of the relationships between various geochemical properties of granitoids and their associations with mineralisation in eastern Australia have allowed refinement of these relationships. In this paper, parameters considered important in the metallogenic classification of granitoids are discussed and refined. The main igneous-related metallogenic associations (Mo, Sn, Cu, W) present in eastern Australia are discussed in terms of these parameters. In addition, deposits that may be considered members of "Intrusion-Related Gold Deposits" (Thompson et al., 1999) are also compared with a view to understanding where they fit in with the overall metallogenic scheme of granitoid rocks.

2. Metallogenic Classification Parameters for Granitoid and Related Rocks of Eastern Australia

Eastern Australia provides an excellent natural laboratory for granite studies. There is wide range of intrusive-igneous rock types present, extensive chemical data is available, and there is a diverse range of mineral deposits (Fig. 1). The basic relationships between granite compositional parameters and mineralisation have been explored by Blevin and Chappell (1992), with a more detailed focus on the Lachlan Orogen (LO) having
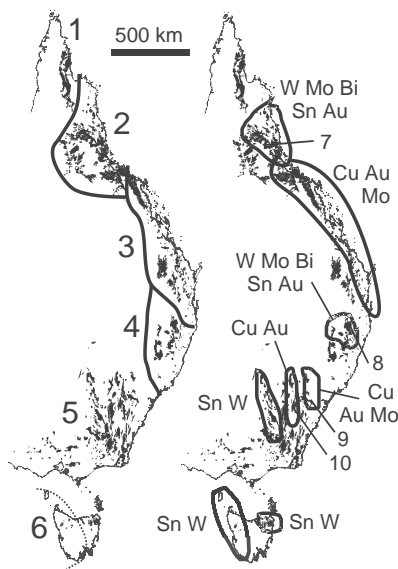

Fig. 1 Distribution of provinces and regions of eastern Australia and important igneous-related metallogenic associations. Numbers: 1 – Cape York Province, 2 – North Queensland, 3 – Northern New England Orogen, 4 – Southern New England Orogen, 5 – Lachlan Orogen, 6 – Western Tasmania. Some deposits mentioned in the text: 7 – Kidston, 8 – Timbarra, 9 – Burraga, 10 – Cadia.

also been undertaken (Blevin and Chappell, 1995). Based on these relationships, an empirical classification scheme can be constructed with a view to classifying and comparing granitoids, igneous suites and even igneous provinces according to their known metal association. For the purposes of this study a wide variety of intrusive igneous rocks have been used, ranging from typical granites (*sensu lato*, or granitoids) but also including monzonitic series intrusive igneous rocks and arc type tonalites.

In this paper the following parameters have been used to assess metallogenic relationships:
- Oxidation State
- Composition (Type, silica and K_2O content, and alkalinity)
- Degree of Compositional Evolution
- Presence of Fractional Crystallisation (including high and low temperature classification status)

These parameters are regarded as being the most useful in determining the overall metallogenic "flavour" of magmatic-hydrothermal mineralisation that might be associated with an igneous suite should it be mineralised.

2.1. Oxidation state

The relative oxidation state of a magma is of paramount importance in controlling the compatible/incompatible nature of many ore and related elements in magmas (Candela, 1992; Blevin and Chappell, 1992; Lehmann, 1990), recognised earlier by Ishihara and co-workers (e.g. Ishihara et al., 1979). The division of granitoids into magnetite- and ilmenite-series is a very useful metallogenic classification because Cu, Mo and Au deposits are typically related to magnetite-bearing (magnetite-series) granitoids and Sn (±W) deposits with magnetite-free (ilmenite-series) granitoids (Ishihara, 1977; 1981). The division between the two was initially on petrographic grounds, but subsequently extended to include chemical (whole rock Fe_2O_3/FeO; Ishihara et al., 1979) and geophysical (magnetic susceptibility; Ishihara, 1981) criteria. Such relationships have subsequently been validated by theoretical and experimental investigations, which have served to emphasise the importance of magma redox in determining ore element ratios in magmatic-hydrothermal mineral deposits (e.g. Candela, 1992; Blevin and Chappell, 1992).

Oxidation state of a magma is largely inherited from its source region (Carmichael, 1991) although the effects of wall rocks can be locally important. There is a general trend to lower relative oxidation state in granitoids from arc settings through continental margin settings to those of continental interiors. S-types are almost invariably reduced. The progressive reduction of granitoid magmas is most probably due to the interaction of I-type materials with graphite-bearing crustal materials (Ishihara, 1981), either through direct assimilation or

fluid interaction and exchange.

The oxidation state of iron is the dominant expression of redox state in magmas. The FMQ buffer comprises the reaction of fayalite to quartz and magnetite in f_{O_2}-T space:

$$3Fe_2SiO_4 + O_2 = 2Fe_3O_4 + 3SiO_2$$

Magnetite is stable at f_{O_2} above this reaction. So it is important to locate this line relative to measured whole rock Fe_2O_3 and FeO contents and the ratio between them. For typical granitic rocks at any given SiO_2, the range of possible Fe-bearing minerals and their relative proportions is very limited, so reasonable comparisons can be made. In plotting Fe_2O_3/FeO, whole rock Fe expressed as FeO* rather than SiO_2 has been used (Fig. 2).

The fundamental division in the classification scheme is thus the division between oxidised (O) and reduced (R) igneous rocks at or close to the FMQ buffer. In eastern Australia the line in Fe_2O_3/FeO and FeO* space has been defined using magnetic susceptibility measures and petrographic observations.

A positive correlation relationship exists between Fe_2O_3/FeO and SiO_2 (and thus inverse between Fe_2O_3/FeO and FeO*). At high SiO_2 (>72 wt%), corresponding and low FeO* (below 2 wt%) the Fe_2O_3/FeO ratios of most granitoids increases markedly to values that are unrealistic in terms of inferred magmatic f_{O_2} values, and for these rocks other methods of determining relative oxidation state need to be used (Fig. 2).

Additional redox boundaries can be added to this diagram to delineate rocks that are strongly oxidised and strongly reduced (Fig. 2). The boundary between moderately oxidised (MO) and strongly oxidised (SO) rocks correlates with the occurrence of the titanite-magnetite-quartz-hedenbergite-ilmenite buffer or TMQHIL (formally SMQHIL where "S" stood for sphene; Wones, 1989). In Lachlan and New England Orogen Granitoids the mg# (atomic Mg/(Mg+Fe)) of amphiboles coexisting with titanite is typically in the range 0.5–0.6. For intermediate Fe and Mg activities the TMQHIL buffer should correspond to a logf_{O_2} value of ~ –15.5 at 700°C which is just below NNO.

The boundary between moderately reduced (MR) and strongly reduced (SR) was chosen to correspond with the division between typical reduced S- and I-type granitoids and the strongly reduced Strathbogie Batholith of central Victoria which is characterised by very low Fe_2O_3/FeO ratios (average Fe_2O_3/FeO = 0.07). Phillips et al. (1981) in their study of the Strathbogie Batholith recognised spinel-cordierite-sillimanite assemblages that yield log f_{O_2} = –18.3 at 700°C, which is 1.3 log units below FMQ at those temperatures.

Most suites and supersuites of granites lie along relatively linear trends parallel to the boundaries on this
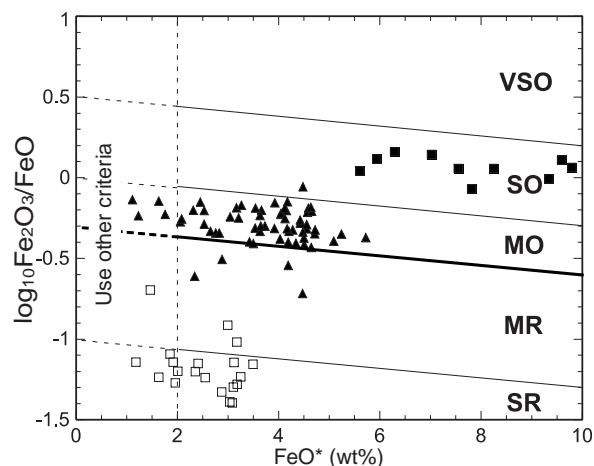

Fig. 2 Redox classification scheme for igneous rocks. FeO* refers to all Fe in the sample reported as FeO. Labels: VSO – very strongly oxidised, SO – strongly oxidised, MO – moderately oxidised, MR – moderately reduced, SR – strongly reduced. In the "Use other criteria" region, petrographic and magnetic criteria should be used, or less felsic members of the same suite in addition to whole rock Fe_2O_3 and FeO data. Three representative suites are shown from the Lachlan Orogen: closed squares – Cadia Igneous Complex, triangles – Glenbog Supersuite, open squares – Strathbogie Suite.

plot over the range of SiO_2 values less than 72 wt% or show a slight increase with increasing SiO_2. This relatively parallel, linear relationship allows the calculation of an oxidation parameter (ΔOx) for granitoid suites using the following relationship:

ΔOx = $\log_{10}$ (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.

The boundaries between VSO and SO, SO and MO and MR and SR occur at ΔOx values of 0.8, 0.3 and –0.7 respectively. The dividing line between oxidised and reduced rocks occurs at a value of ΔOx = 0. The dividing line between moderately and strongly oxidised rocks also separates typical oxidised granitic rocks from those known to be associated with large porphyry style Cu-Au mineralising systems. Intrusions associated with porphyry Cu-Au deposits tend to occur in the upper half of the strongly oxidised (SO) field and have ΔOx values in the range 0.5–0.8. Typical metaluminous to peraluminous granitoid rocks do not fall into the VSO field, and the VSO field may represent a "forbidden zone" for granitoids containing normal Fe-Ti and Fe-Mg minerals that do not include primary haematite.

2.2. Compositional classification

Classification according to broad compositional character (I, S, A; metaluminous, peraluminous, peralkaline)

is important as a guide to the abundance of elements and volatiles in the granitoids, and their potential contrasting behaviour during fractionation processes. Granitophile elements are associated with silica-rich granitoids while Cu tends to be associated with granitoid of more intermediate silica contents. Peralkaline granitoids tend to be strongly compositionally evolved and high in Ta, Nb, Zr and related elements.

2.2.1. Aluminium saturation and alkalinity: Aluminium saturation and alkalinity are important parameters in granitoids as they have important effects not only on the mineralogy and source of granitoids, but directly on the behaviour of ore forming elements during fractionation. Weakly peraluminous granitoids, where A/CNK, or molecular $Al_2O_3/(CaO+Na_2O+K_2O)$, is typically in the range 1.0–1.1 are those in which excess Al is typically incorporated into biotite. Strongly peraluminous granitoids (A/CNK>1.1) require a more aluminous phase (e.g. cordierite, garnet, muscovite) to be present in the granitoid. Strongly peraluminous, cordierite-bearing (the "S-types") have a more restricted SiO_2 range than the transitional to weakly peraluminous granitoids of terranes such as the western USA and Japan which may extend back to gabbroic compositions. I-type magmas may also become slightly peraluminous due to hornblende fractionation and/or assimilation of metasedimentary materials and may be also mildly peraluminous across a broad silica range. These granitoids are typical of the western US (White et al., 1986) and Japan, but are uncommon in eastern Australia.

Peralkaline granitoids (those which have molecular $Al_2O_3/(Na_2O+K_2O)$ ratios less than 1) are rare in eastern Australia, comprising well below 1 % of all granitoids. Compared to peraluminous and metaluminous granitoids, peralkaline granitoids tend to have high SiO_2, total alkali contents and Fe/Mg ratios, and low CaO, Eu and Sr. Contents of Zr, REE (except Eu), Y, Nb and Ta are strongly elevated. Their generally SiO_2-rich compositions, high abundances of HFSE, plagioclase and feldspar fractionated compositions (low CaO, Ba, Eu) and association with other granitoid types, suggest that most peralkaline granitoids are the products of fractional crystallisation processes.

Although an association between high-K or potassic rocks and porphyry Cu mineralisation is widely touted (e.g. Müller and Groves, 2000), this is not always the case, and porphyry Cu mineralisation may also be associated with low- and medium-K rocks. Most Sn- and Mo-mineralisation in compositionally evolved rocks are associated with high-K granitoids and this would seem to indicate that processes which allow granitoids to evolve to high-K compositions are also conducive to mineralisation. Recognition of K content of granitoids would therefore be useful, as would their total alkali con-

tent. This is because high total alkalies also correspond to more monzonitic rock compositions and is thus useful for the general purposes of typifying rock types.

2.2.2. SiO_2 content: The silica (SiO_2) content of granitoids range from around 50 % for gabbroic and cumulate phases to around 75–77 % for granitoids at the "thermal minimum", i.e. where granitic melts precipitate quartz and feldspar crystals in the same relative abundances as they occur in the melt. Champion and Heinemann (1994) chose 68 % as the divide between mafic and felsic igneous rocks. In the TAS classification scheme acid rocks are defined as having SiO_2 contents greater than 63 %; intermediate rocks as $52<SiO_2<63$ %; basic rocks as $45<SiO_2<52$ % and ultrabasic as $SiO_2<45$ %. The classification of Champion and Heinemann (1994) is used here.

An important feature of granitoid batholiths and provinces in eastern Australia is that there is a marked variability in the range of SiO_2 contents (Fig. 3). For example Ordovician intrusive igneous rocks of central LO in NSW have SiO_2 contents almost exclusively less than 68 % (Fig. 3). In contrast, granitoids of the Coastal Ranges in north Queensland, and Taswegian Batholith have SiO_2 contents overwhelmingly greater than 68 %. Other granitoid provinces show contrasting patterns in SiO_2 contents. Large SiO_2 ranges also occur in individual supersuites, particularly those that show evidence for dominant fractional crystallisation processes (e.g. Boggy Plain Supersuite in Fig. 3). Virtually all S-types have SiO_2 contents greater than 68 %.

Granitophile elements (Mo, Sn) are associated with silica-rich granitoids while Cu tends to be associated with granitoids with lower silica contents. Provinces with silica distributions "skewed" to high values are unlikely to be associated with Cu, but are typically associated with Sn, Mo, U and related Au associations, while those skewed to intermediate or lower SiO_2 values are more likely to be associated with Cu.

2.3. Compositional evolution

A granitoid can be thought of as being compositionally evolved if its chemistry is no longer compatible with mantle peridotite. In a conceptual sense "degrees" of evolution have been recognised previously. Granitoids derived from the partial melting and/or fractionation of mantle derived basalts have been termed M-types (Whalen, 1985), or "primary granitoids" (Clarke, 1992). These include oceanic plagiogranites, and most granitoids and tonalites in primitive island arc settings. Second "generation" granitoids are derived substantially from the remelting of these rocks and their related materials (volcanics and immature arc sediments) to produce continental margin arc granitoids (the "I-tonalites" of Chappell and Stephens, 1988; "secondary granitoids" of Clarke, 1992; or "Andean" granitoids of Pitcher, 1982).
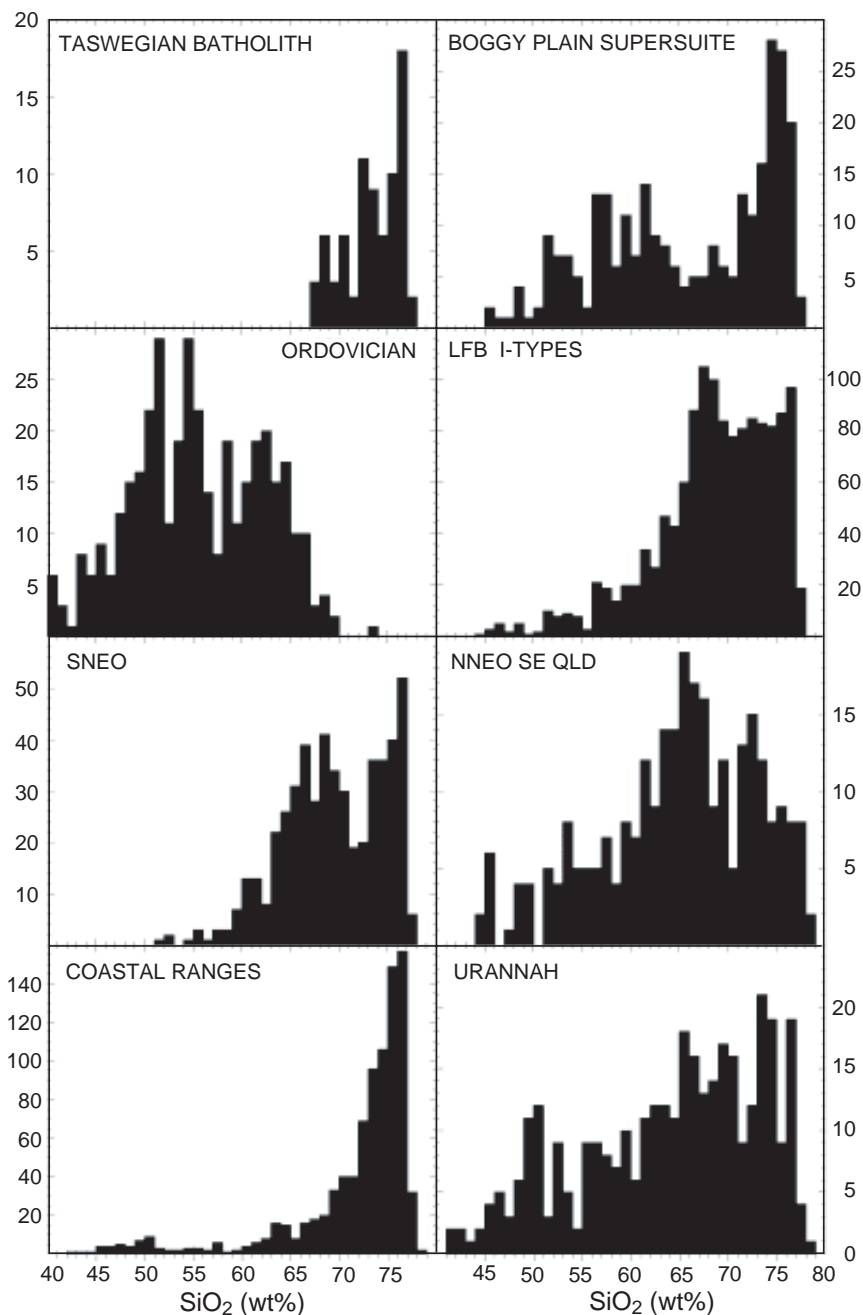
Fig. 3 Histograms (in 5 % intervals) of SiO_2 contents of representative igneous rocks of eastern Australia.

patible elements and ratios between incompatible and compatible elements. Each parameter in turn is dependant however on processes (melting, mixing, crystallisation and fractionation among others) in addition to source. For example, while the Rb/Sr ratios is a useful parameter, in that granitoids with low Rb/Sr ratios are less "evolved" than granitoids with high Rb/Sr ratios. However, "in the middle" values can vary according to process such as plagioclase accumulation and fractional crystallisation mechanisms and Sr contents can vary markedly between otherwise very similar granitoids.

Another more useful ratio is the K/Rb ratio. Both K and Rb are mantle incompatible elements and Rb behaves similarly to K in geochemical processes. Both K and Rb substitute into the same site in a range of minerals, but Rb is less able to do so as easily as K on account of its larger ionic radius, so Rb is progressively retained in residual melts. In more felsic granitic rocks, the K/Rb is controlled dominantly by K-feldspar fractionation. Biotite and muscovite are also important residences for K and Rb, however these are rarely abundant enough in granitoids to affect the dominant role of K-feldspar.

Ishihara and Terashima (1992) found that granitoids of Japan fell into distinct groups based on K/Rb, with sodic granitoids having K/Rb ratios of the order 500–1000, most other magnetite-series rocks having K/Rb ratios of 250–500 and 250–140 for ilmenite-series granitoids. Further the K/Rb ratio was inversely correlated with the initial $^{87}Sr/^{86}Sr$ ratio. There is usually only a small change (usually negative) in the K/Rb ratio as igneous rock suites differentiate from mafic to felsic. Although Gill (1981) suggested that K/Rb decreases with increasing K_2O contents in orogenic andesites such a trend is not evident in Australian arc-related intrusive igneous suites such as those of the Ordovician of the LO (Blevin, 2002), where K/Rb ratios are uniformly high in sample suites ranging from medium-K calc-alkaline to shoshonitic.
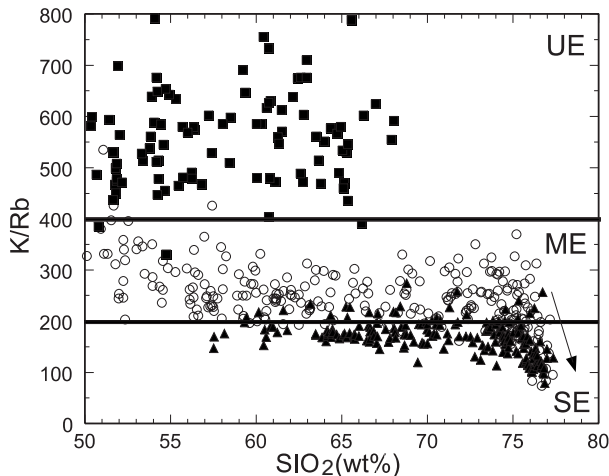
Third cycle granitoids are the products of the fusion of these materials within a continental setting to produce more felsic and compositionally evolved granitoids ("I-granodiorites" of Chappell and Stephens, 1988; or "Caledonian" granitoids of Pitcher, 1982). In addition to these are the S-type granitoids derived from mostly supracrustal material.

There is no single or easy counter that defines the compositional evolution of the granitoid. Possible parameters could include trace element abundances of mantle incom-

Fig. 4 K/Rb versus SiO$_2$ classification plot for granites of eastern Australia. Field labels: UE – Unevolved, ME – moderately evolved, SE – strongly evolved. Arrow indicates direction of K/Rb–SiO$_2$ trend with strong alkali feldspar fractionation. Representative examples: closed squares – Ordovician intrusions of the Lachlan Orogen, open circles – Boggy Plain Supersuite (Lachlan Orogen), closed triangles – Moonbi Supersuite of southern New England Orogen.
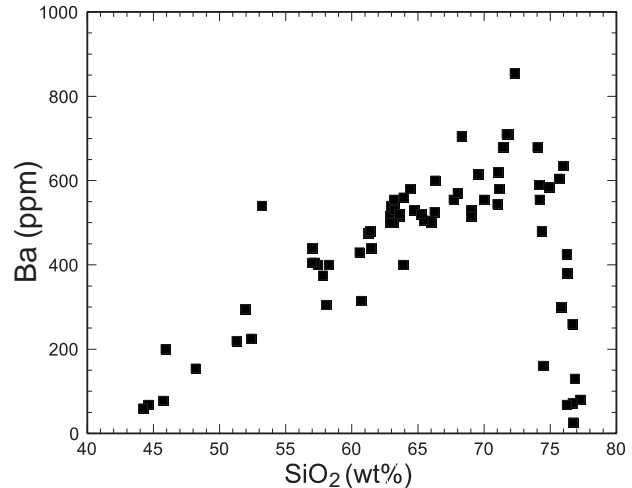

Fig. 5 Example of fractional crystallisation processes in the Permian I-type granites of the Ravenswood Batholith, North Queensland. Note steeply increasing Ba with increasing SiO$_2$ until its removal by early crystallisation of alkali feldspar in more felsic magmas.

The K/Rb ratios of east Australian granitoids divide naturally into three main groups (Fig. 4). Those granitoids with K/Rb ratios greater than 400 can be regarded as being compositionally unevolved. The only intrusive igneous rocks that fit this criterion are the Ordovician of NSW and the Devonian of the New England Orogen (NEO). The second group comprises granitoids with K/Rb ratios between 400 and 200 (Fig. 4). These are termed "moderately evolved", and comprise the bulk of granitoids in eastern Australia. Most granitoids tend to fall in the K/Rb range of 200 to 300.

I-type granitoids with K/Rb values under 200 are termed "highly evolved". These include the Coastal Ranges granitoids in northern Queensland, Moonbi Supersuite in the southern NEO and the granitoids of western Tasmania. These granitoid suites also tend to show a gradual decrease in K/Rb with increasing SiO$_2$, consistent with the progressively earlier and more prominent role of K-feldspar in fractionation processes. Almost all S-type granitoids in eastern Australia have K/Rb under 200, although some S-types from the NEO have slightly higher K/Rb ratios. These have previously been recognised on mineralogical, chemical and isotopic grounds to having been derived from more immature source rocks than the S-types of the LFB.

There is also a pronounced trend of felsic granitoids with K/Rb values extending to very low values. Granitoids with K/Rb ratios under 140 are also highly fractionated. These comprise granitoids with minimum melt compositions undergoing fractional crystallisation. Granitoids associated with granitophile mineralisation (Mo, W-wolframite and Sn) will tend to have K/Rb ratios around to under 200, while those associated with Cu and Cu-Au systems will tend to have K/Rb ratios greater than 200. Low K/Rb suites include those with relatively unevolved isotopic compositions (Sr and Nd). Perhaps the best examples are the granitoids of the southern NEO which include some of the most compositionally evolved granitoids in eastern Australia that are also among the most isotopically primitive (Hensel et al., 1985). The K/Rb ratio is more useful in this regard as a measure of relative compositional evolution rather than as a tectonic or source discriminant. Care must also be used when interpreting the K/Rb ratios of rocks more generally, for example with adakites, which although isotopically and compositionally primitive, have high Al, and low K/Rb and Nb because of the presence of amphibole in their source regions (e.g. Drummond et al., 1996).

2.4. Presence of fractionation crystallisation

The degree and type of fractionation is important in determining both the potential for mineralisation and the type of mineralisation with which a granitoid suite is associated (Blevin and Chappell, 1992). Fractional crystallisation can be measured in many ways: use of compatible/incompatible element ratios (e.g. Rb/Sr ratio) and the behaviour of selected trace elements that indicate the incoming or outgoing of crystallising phases (e.g., inflections in Ti, Mg, Ca, Ba, Zr, Y and others; Fig. 5). K/Rb ratios are also useful in highly fractionated melts near or 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.

In the field fractional crystallisation is manifest by zoned and compositionally diverse intrusions. Chappell et al. (1998) also recognised high and low temperature granitoids. These correlate well with fractional crystallisation: low temperature granitoids do not show evidence for fractional crystallisation, while high temperature granitoid suites do.

3. Application to Eastern Australian Palaeozoic Granitoids

3.1. General relationships and observations

The Palaeozoic granitoids of eastern Australia exhibit a wide range of compositional character in terms of the metallogenically significant parameters discussed above. Specific examples have been mentioned above, but broadly speaking large regional tracts of granites can be broadly grouped according to these parameters. For example compositionally highly evolved and fractionated I-type granites (K/Rb<200) with elevated Rb/Sr and high SiO_2 are broadly confined to western Tasmania (Devonian), the southern NEO (Permo-Triassic) and northern Queensland in the area west of Cairns. Smaller isolated suites and individual plutons are present in the LO but it is only the three aforementioned locations that this compositional feature can be considered as a regional characteristic.

There is distinct contrast within the LO between the Ordovician volcanic intrusions and subsequent Siluro-Devonian magmatism in terms of relative oxidation state and compositional evolution (see Blevin, 2002). I-types of the LFB contrast also with those of both the southern NEO, where I-types have low K/Rb ratios and the northern NEO, where I-types have higher K/Rb ratios. Regions that are characterised by low K/Rb I-types are also those characterised by generally felsic, SiO_2-rich compositions. This contrasts with supersuites such as the Boggy Plain Supersuite, which has a broad SiO_2 range consistent with fractionation of mafic materials to obtain compositionally evolved felsic differentiates. This suggests that felsic provinces characterised by a high proportion of high SiO_2 granitoids may have obtained their general compositional character via the partial melting of already enriched and compositionally evolved source materials, as evidenced by the low K/Rb ratios in even the least felsic granitoids. These evolved sources do not necessarily represent old crust as the highly evolved granitoids of the southern NEO are also isotopically juvenile.

3.1.1. Northern Queensland: Both the granitoids of Cape York and the Coastal Ranges Province are relatively felsic with the majority 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 Lachlan Orogen (and the Siluro-Devonian of the Ravenswood Batholith). 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.

3.1.2. New England Orogen: Devonian igneous rocks of the northern New England Orogen (e.g. the Mount Morgan Tonalite Complex, MMTC) share with the Ordovician of the Lachlan Orogen 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 in the north of this orogen are on average less compositionally evolved than granites further to the south (i.e. have many units with K/Rb values between 300 and 400). 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 (see below).

Horton (1982) described the presence of more than 40 porphyry-type mineralisation systems of Permo-Carboniferous, Permo-Triassic and Early Cretaceous age in the northern NEO of eastern Queensland. Low protore and secondary enrichment grades are characteristic of these systems, in addition to poorly zoned and predominantly fracture-controlled alteration and sulfide assemblages. The overall metallogenic character of this province, and its tectonic setting would suggest that the northern NEO should be prospective for continental margin type porphyry Cu-Mo-Au systems. An objective of any first pass metallogenic assessment of the mineralisation potential of the northern NEO is to assess whether there might be any simplistic reason, apparent from whole rock geochemical data, why mineralisation systems in this belt are not more productive in terms of grade and metal content.

The granitoids of the northern NEO have moderately evolved compositions (200<K/Rb<400; see above). The

Mount Morgan Tonalite and related volcanic rocks of the Devonian of central Queensland are compositionally unevolved and comparable in this regard only with the Ordovician of the LO in NSW. Oxidation states of the northern NEO granitoids are also rather surprising. Although some regions within the northern NEO (i.e. the Cretaceous and pre-Cretaceous units of the northern portion of the NEO) are strongly oxidised, all other units are transitional between moderately and strongly oxidised (Fig. 6). High magmatic oxidation states are favourable for the formation of major porphyry Cu-Au systems. In regard to both compositional and redox parameters, it would appear that most of the granitoids of the northern NEO are not oxidised enough, and are too evolved to be associated with significant porphyry Cu-Au deposits of the island and continental arc type associations. The only significant exception is the Devonian in which occurs the Cu-Au mineralised MMTC and related volcanics.

The granites of the southern New England Orogen fall into two distinct groups in terms of K/Rb. The Clarence River Supersuite has K/Rb ratios around 250 to 350 similar to that of the northern NEO, while all other supersuites in the southern NEO have markedly lower K/Rb ratios. The Moonbi Supersuite granites within the southern NEO are similar in terms of compositional evolution to that of the Carboniferous I-types of the Coastal Ranges Province of far north Queensland. 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 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 low. However, these granites should be prospec-
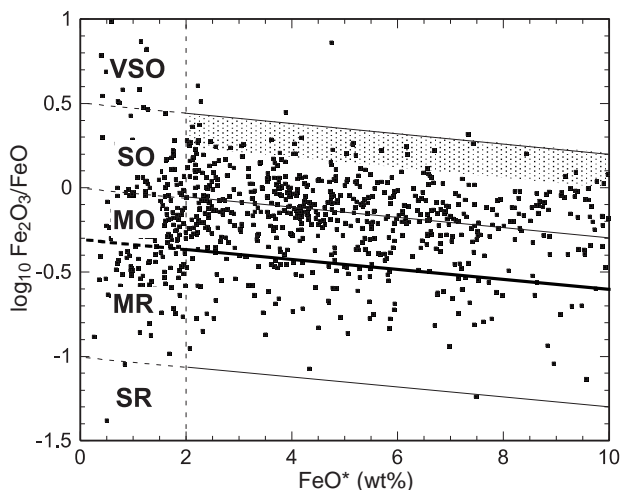
tive for Au-Ag associations in both vein and epithermal styles. There is no equivalent of the Moonbi Supersuite within the northern portion of the NEO.

3.1.3. Lachlan Orogen: The Ordovician igneous systems of the Lachlan Orogen (LO) are hosted in four longitudinal belts. More recent petrochemical and geophysical studies have supported a contemporaneous intra-oceanic island arc setting (Blevin, 2002). 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 falls 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.

Post-Ordovician granitic magmatism comprises a substantial proportion of the present exposed area of the LO of south eastern Australia. 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 Tasmanian 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 King Island) 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*.

The Carboniferous granites of the north eastern 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

Fig. 6 FeO* versus $log_{10}(Fe_2O_3/FeO)$ for granitoids from the Northern New England Orogen. Also shown is the area (shaded) corresponding to Fe_2O_3/FeO ratios of igneous rock suites associated with porphyry Cu-Au mineralisation.

extensive areas of highly fractionated granites as other systems, some strongly fractionated members exist and they are typically more oxidised than most other LO I-type granites.

3.2. Mineralised granitoids (Cu, W, Mo and Sn)

Tin mineralised granitoids in Australia are felsic, K-rich and invariably strongly compositionally evolved and fractionated. While most Sn mineralised I- and S-type granitoid suites are moderately reduced, some I-type suites are weakly oxidised. Strongly reduced granitoid suites are not necessarily more richly Sn mineralised than less oxidised ones. Molybdenum mineralisation, though widespread as small showings and occurrences, does not occur in eastern Australia as major deposits. Even historical deposits, famous for the size of their molybdenite crystals (e.g. Kingsgate in the southern NEO, and Bamford Hill and Wolfram Camp in Queensland) have only collectively produced a few thousand tonnes of Mo. Granitoids associated with the deposits, although K-rich, strongly evolved and fractionated, are not strongly oxidised, and are not as strongly fractionated or oxidised as magmas associated with the porphyry Mo systems of North America (Mutschler et al., 1981). The Grassy Granite on King Island best represents scheelite mineralised intrusions: weakly oxidised, intermediate SiO_2 content, high-K, but not strongly fractionated.

Major Cu systems in eastern Australia are associated with unevolved magmas ranging from low-K to high-K that are strongly oxidised. These include Ordovician systems of the Lachlan Fold Belt of New South Wales (Fig. 7; Blevin, 2002; though actually monzonitic in bulk compositional character), and the low-K Mount Morgan Cu-Au deposit in central Queensland. Whole rock indicators of oxidation state in the Mount Morgan Tonalite Complex are affected by pervasive subsolidus alteration which has seen all biotite replaced by chlorite and destruction of original opaques in the main phases of the complex. The complex is regarded as originally being magnetite-rich because of the preservation of exsolution lamellae textures consistent with the original presence of magnetite.

3.3. Gold mineralised granitoids

Although Au-rich Cu mineralisation is well documented associated with granitoids and related rocks of intermediate SiO_2, Au-rich, Cu-poor mineralisation comprises a relatively new class of mineralisation (Intrusion-Related Gold Deposits or IRGD; Sillitoe, 1991; Thompson et al., 1999). These deposits occur in a variety of styles and are generally associated with metaluminous, sub-alkalic intrusions that span the boundary between the ilmenite-magnetite series and are characterised by metal associations comprising Au, Bi, W, As, Mo, Te and/or Sb (Lang et al., 2000). In Australia, several deposits are potential members of this deposit type. These include the Kidston Au-rich porphyry and Red Dome skarn deposits in Queensland; and the disseminated style Timbarra deposit and Burraga skarn deposit in New South Wales. Of these systems, Kidston, Red Dome and Timbarra are associated with minor early Mo veining and these deposits share with Burraga an association with highly fractionated and evolved K-rich granitoids (Fig. 8). Compositionally these granites are similar to their related intrusions and suites in being K-rich, having high SiO_2 contents, compositionally evolved, and weakly to moderately oxidised.
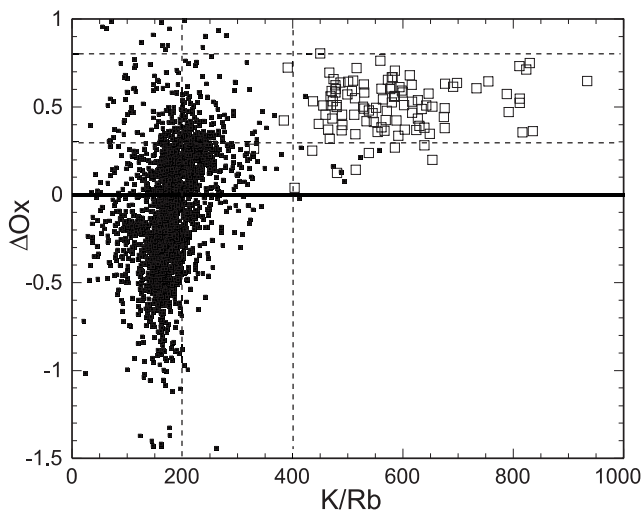

Fig. 7 K/Rb ratio versus relative oxidation state for intrusive igneous rocks, Lachlan Orogen. $\Delta Ox > 0$ are oxidised (see text). Open squares = Ordovician units, closed squares = Siluro-Devonian units. Ordovician units fall into the field associated with porphyry Cu-Au.
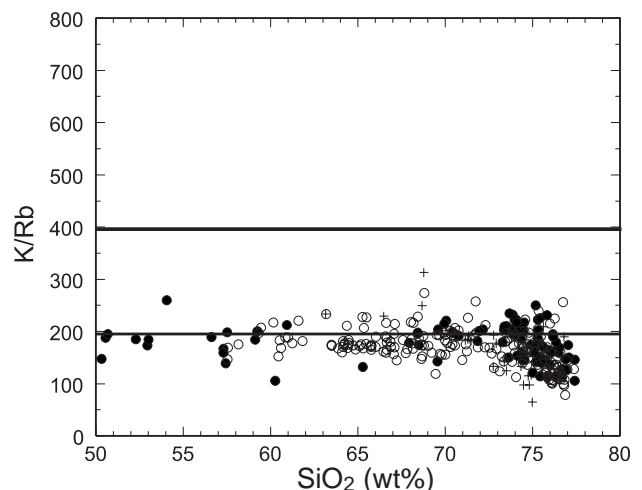

Fig. 8 K/Rb versus SiO_2 for granites suites associated with intrusion related gold deposits in eastern Australia. Closed circles – Kidston and related granite suite, open circles – Timbarra and related granites, crosses – Burraga and related granites.

4. Discussion

The parameters described above confirm previous observations regarding the relationship between ore element associations and granite compositions that do not need re-amplification here. However a conclusion that can be drawn from the present study is that the observed variations in metallogenic parameters seen in eastern Australia are consistent with the presently known compositional data and there remains little apparent scope for the discovery of significant new metal associations outside those currently known and defined from the presently known distribution of granitoid-related mineral deposits. The distribution of significant Sn systems seems always to be associated with suites and supersuites of granitoids that have low K/Rb across their entire compositional range, not just the felsic, fractionated members with which mineralisation is most intimately associated.

4.1. Granitoid-related Au deposits and metal zoning

The relationships between the degree of fractionation and oxidation state of granitoids for the main ore element assemblages (Cu, Cu-Mo, Mo W and Sn) were explored by Blevin and Chappell (1992, 1995) and Blevin et al. (1996). This was done using relationships between granitoids and proximal mineral deposits in eastern Australia, and using overseas examples where reliable chemical data was available. These main metal assemblage groupings represent the proximal, high temperature "cores" to magmatic-hydrothermal systems associated with granitoid rocks and parallel the main classes of porphyry systems. However, magmatic hydrothermal ore systems are fundamentally polymetallic in nature and medium to large systems are typically zoned in time, space and temperature.

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". The five such core metal associations (Cu, Cu-Mo, Mo, W, Sn-W) relate back in a systematic way to compositional features of the related igneous suites.

Metal zoning outwards spatially and down temperature from these proximal core metal associations patterns define mineral camps and districts. Gold is associated with all of these core metal associations. In oxidised porphyry Cu systems Au occurs with the Cu in the high temperature proximal core of the systems. In porphyry Cu-Mo systems, for example the Mount Leyshon deposit in north Queensland, Au is located more distally from the
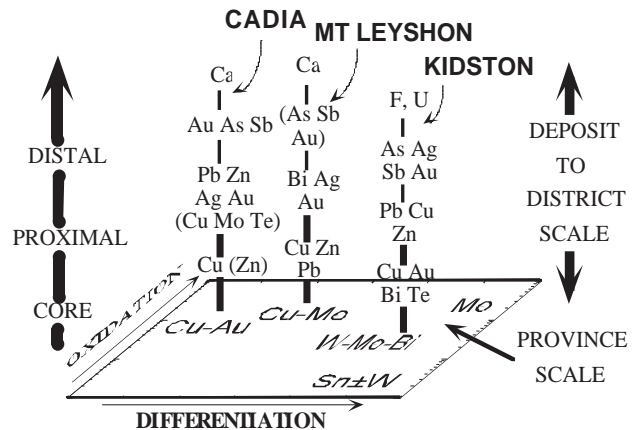

Fig. 9 Relationships between metal zonation at the deposit or district scale and how they relate back to higher temperature, proximal igneous centred systems (Cu-Au, Cu-Mo, W-Mo, Sn-W, Mo). These correspond to the main porphyry deposit types. The example for economic gold systems of diverse metallogeny is shown. Note that economic Au mineralisation tends to be located further from the proximal core of the hydrothermal system in deposits associated with progressively more felsic and differentiated magma suites.

high temperature alteration associated with Bi and Te minerals. In more felsic and evolved systems still (e.g. Kidston, Red Dome) economic Au mineralisation is located distally (spatially and paragenetically) from the higher temperature W-Mo cores of the systems. At Kidston deep drilling indicated that metal zoning in that deposit separated the higher temperature W-Mo portion of the system from the Au-rich zone by 1400 m (Morrison et al., 1996). 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). At Timbarra, minor, early high temperature quartz-molybdenite veining is overprinted at lower temperatures by disseminated Au mineralisation (Mustard et al., 1998).

These zonation relationships, if superimposed on a redox-fractionation plot of core element assemblages suggest that the location of economic Au in granitoid-related mineral deposits occurs paragenetically more distant from the higher temperature core element association in deposits associated with progressively more felsic and evolved (and less oxidised) systems (Fig. 9). This indicates that the Au-rich portion of granitoid related mineral deposits may be locally distant from the higher temperature parts of the hydrothermal system, and that obvious genetic links between the Au-rich portions of these deposits and their related granitoids may be more difficult to establish. The element assemblages associated with the lower temperature, more distal deposits (Au±As, Bi, Te,

Sb) also resemble those of mesothermal deposits.

4.2. Some possible compositional controls on the formation of Au-rich mineralisation associated with felsic magmatism

The compositional properties of granites associated with Au-mineralisation provide important clues to the origin of IRGD systems. Although seen as part of a predictive relationship in the zoning of most polymetallic magmatic hydrothermal ore systems, some systems are enriched in Au with respect to other metals making them "gold deposits", economically at least, while still being fundamentally polymetallic hydrothermal ore systems. The f_{O_2} for the related granitoids, determined from mineralogy, magnetic susceptibilities and Fe_2O_3/FeO indicate that they are weakly oxidised, with oxidation states just above FMQ. They are not strongly reduced or oxidised. They are also metaluminous, or may be weakly peraluminous if very felsic, although this does not imply a strongly peraluminous ancestry of the granitoid rocks or their source rocks. Compositionally, they are too evolved and/or felsic to be associated with Cu, too oxidised to be associated with significant Sn production, and are not oxidised enough to be associated with significant Mo. They occur in the redox-fractionation zone normally associated with minor W-Mo±Sn occurrences and W-scheelite mineralisation.

The behaviour of Au in granitoids is poorly understood. Gold is removed from granitoid melts by crystallisation of magnetite and sulfides (Cygan and Candela, 1995). Partition coefficients indicate that sulfides are much more important than magnetite, and Cu-Fe sulfide phases in particular relative to pyrite-pyrrhotite (Cygan and Candela, op. cit.). In order to maintain Au within the melt phase of granitoid magmas, it is important that early crystallisation of sulfides be suppressed. Sulfur solubility is at a minimum when f_{O_2} is near NNO for basaltic, hawaiitic and rhyodacitic melts (Katsura and Nagashima, 1974). At $f_{O_2}>$ NNO, S dissolves in melts dominantly as sulfate, while at $f_{O_2}<$NNO, S is present as sulfide. Where $f_{O_2}>$ FMQ, S contents correlate with CaO content because of the stability of anhydrite, while at $f_{O_2}<$FMQ, S contents correlate with FeO. The contrasts in behaviour of S across the NNO divide parallels the division of magnetite- and ilmenite-series granitoids essentially at NNO (Fig. 10). Sulfur saturation is more easily reached in reduced magmas and the precipitation of sulfides in these magmas would be expected to occur earlier than in oxidised ones. Elements such as Cu, Co, Ni and Au would be partitioned into these early sulfides and not concentrated into late stage melts and the aqueous phase.

Granitoids forming in the low S solubility f_{O_2} "window" between FMQ and NNO will thus have the lowest initial S contents due to their low S solubility, and the gap
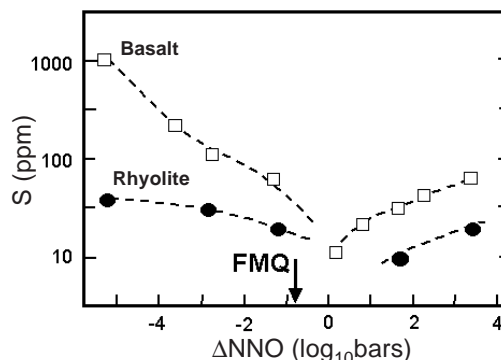

Fig. 10 Sulfur solubility in magmas as a function of composition and oxygen fugacity. ΔNNO refers to log f_{O_2} of the magma relative to that of NNO at any given temperature. Note that the region between FMQ and NNO corresponds to low S solubility in igneous magmas for both rhyolitic (i.e. granitic) and basaltic compositions. Magmas evolving compositionally through this oxygen fugacity window would be expected to have low S contents. Modified after Carroll and Webster (1994).

between mafic and felsic members will also be small relative to more oxidised and reduced equivalents (Fig. 10). Granitoids that form and differentiate in this oxidation range have the best possibility to preserve elements that otherwise would be strongly partitioned either into SO_2-bearing fluid phases at high f_{O_2} or into early crystallising sulfides at low f_{O_2}. Magnetite crystallisation (particularly early crystallisation) will also be relatively minor in such granitoids. Such relationships would therefore be considered optimal for the retention of Au in magmas until volatile saturation occurs. Another feature of many of the suites with which Au-rich mineralisation is associated is that the granitoid suites are skewed to high SiO_2 values, suggesting derivation from intermediate felsic source and evolved source materials suggesting that some of the suites may not have undergone differentiation from initially mafic (i.e. high Fe) source materials.

References

Blevin, P. L. (2002) The petrographic and compositional character of variably K-enriched magmatic suites associated with Ordovician porphyry Cu-Au mineralisation in the Lachlan Fold Belt, Australia. Mineral. Deposita, 37, 87–99.

Blevin, P. L. and Chappell, B. W. (1992) The role of magma sources, oxidation states and fractionation in determining the granitoid metallogeny of eastern Australia. Trans. Roy. Soc. Edinburgh: Earth Sci., 83, 305–316.

Blevin, P. L. and Chappell, B. W. (1995) Chemistry, origin and evolution of mineralised granitoids in the Lachlan Fold Belt, Australia; the metallogeny of I- and S-type granitoids. Econ. Geol., 90, 1604–1619.

Blevin, P. L., Chappell, B. W. and Allen, C. M. (1996) Intrusive metallogenic provinces in eastern Australia based on granite source and composition. Trans. Roy. Soc. Edinburgh: Earth Sci., 87, 281–290.

Candela, P. A. (1992) Controls on ore metal ratios in granitoid-related ore systems: an experimental and computational approach. Trans. Roy. Soc. Edinburgh: Earth Sci., 83, 317–326.

Carmichael, I. S. E. (1991) The redox states of basic and silicic magmas: a reflection of their source regions? Contrib. Mineral. Petrol., 106, 129–141.

Carroll, M. R. and Webster, J. D. (1994) Solubilities of sulfur, noble gases, nitrogen, chlorine, and fluorine in magmas. *in* Carroll, M. R. and Holloway, J. R. (eds.) Volatiles in Magmas. Rev. Mineral., 30, 231–279.

Champion, D. C. and Heinemann, M. A. (1994) Igneous Rocks of Northern Queensland: 1:500,000 Map and Explanatory Notes. Austral. Geol. Surv. Organization Record 1994/11.

Chappell, B. W. and Stephens, W. E. (1988) Origin of infracrustal (I-type) granitoid magmas. Trans. Roy. Soc. Edinburgh: Earth. Sci., 79, 71–86.

Chappell, B. W. and White, A. J. R. (1974) Two contrasting granite types. Pacific Geol., 8, 173–174.

Chappell, B. W., Bryant, C. J., Wyborn, D., White, A. J. R. and Williams, I. S. (1998) High- and low-temperature I-type granites. Resource Geol., 48, 225–236.

Clarke, D. B. (1992) Granitoid Rocks. Chapman and Hall, London, 283p.

Cygan, G. L. and Candela, P. A. (1995) Preliminary study of gold partitioning among pyrrhotite, pyrite, magnetite, and chalcopyrite in gold-saturated chloride solutions at 600 to 700 °C, 140 MPa (1400 bars). *in* Thompson, J. F. H. (ed.) Magmas, Fluids and Ore Deposits. Mineral. Assoc. Canada Short Course, 23, 129–138.

Drummond, M. S., Defant, M. J. and Kepezhinkas, P. K. (1996) Petrogenesis of slab-derived trondhjemite-tonalite-dacite/adakite magmas. Trans. Roy. Soc. Edinburgh: Earth Sci., 87, 205–215.

Gill, J. (1981) Orogenic Andesites and Plate Tectonics. Springer-Verlag, Berlin, 390p.

Hensel, H. D., McCulloch, M. T. and Chappell, B. W. (1985) The New England batholith: constraints on its derivation from Nd and Sr isotopic studies of granitoids and country rocks. Geochim. Cosmochim. Acta, 49, 369–384.

Horton, D. (1982) Porphyry-Type Copper and Molybdenum Mineralisation in Eastern Australia. Geol. Surv. Qld. Publ., No. 378.

Ishihara, S. (1977) The magnetite-series and ilmenite-series granitic rocks. Mining Geol., 27, 293–305.

Ishihara, S. (1981) The granitoid series and mineralization. Econ. Geol. 75th Ann. Vol., 458–484.

Ishihara, S. and Terashima, S. (1992) K/Rb ratio of two contrasting magma series of the Neogene plutonic belts in Japan. *in* Tu, G. Z., Xu, K. Q. and Qiu, Y. Z. (eds.) Petrogenesis and Mineralization of Granitoids, 23–33, Science Press, Beijing.

Ishihara, S., Sawata, H., Arpornsuwan, S., Busaracome, P. and Bungbrakarti, N. (1979) The magnetite-series and ilmenite-series granitoids and their bearing on tin mineralisation, particularly on the Malay Peninsular region. Geol. Soc. Malaysia Bull., 11, 103–110.

Katsura, T. and Nagashima, S. (1974) Solubility of sulfur in some magmas at 1 atmosphere. Geochim. Cosmochim. Acta, 38, 517–532.

Lang, J. R., Baker, T., Hart, C. J. R. and Mortensen, J. K. (2000) An exploration model for intrusion-related gold systems. Soc. Econ. Geol. Newsletter, 40, l, 6–15.

Lehmann, B. (1990) Metallogeny of Tin. Springer-Verlag, Berlin, 211p.

Maniar, P. D. and Piccoli, P. M. (1989) Tectonic discrimination of granitoids. Geol. Soc. Amer. Bull., 101, 635–643.

Morrison, G., Seed, M., Bobis, R. and Tullemans, F. (1996) The Kidston gold deposits, Queensland: A piston-cylinder model of gold mineralisation in a porphyry system. Geol. Soc. Austral. Abstr., 41, 303.

Müller, D. and Groves, D. I. (2000) Potassic Igneous Rocks and Associated Gold-copper Mineralization. Springer-Verlag, Berlin, 252p.

Mustard, R., Nielsen, R. and Ruxton, P. A. (1998) Timbarra gold deposits. *in* Bekrman, D. A. and Mackenzie, D. H. (eds.) Geology of Australian and Papua New Guinean Mineral Deposits. 551–560, The Australasian Institute of Mining and Metallurgy, Melbourne.

Mutschler, F. E., Wright, E. G., Ludington, S. and Abbott, J. T. (1981) Granite molybdenum systems. Econ. Geol., 76, 874–897.

Pearce, J. A., Harris, N. B. W. and Tindle, A. G. (1984) Trace element discrimination diagrams for the tectonic interpretation of granitic rocks. Jour. Petrol., 25, 956–983.

Phillips, G. N., Wall, V. J. and Clemens, J. D. (1981) Petrology of the Strathbogie Batholith: a cordierite-bearing granite. Canad. Mineral., 19, 47–63.

Pitcher, W. S. (1982) Granitoid type and tectonic environment. *in* Hsu, K. J. (ed.) Mountain Building Processes. 19–40, Academic Press, London.

Sillitoe, R. H. (1991) Intrusion-related gold deposits. *in* Foster, R. P. (ed.) Metallogeny and Exploration of Gold. 165–209, Blackie, Glasgow.

Streckeisen, A. (1976) To each plutonic rock its proper name. Earth Planet. Sci., 12, 1–33.

Thompson, J. F. H., Sillitoe, R. H., Baker, T., Lang, J. R. and Mortensen, J. K. (1999) Intrusion-related gold deposits associated with tungsten-tin provinces. Mineral. Deposita, 34, 323–334.

Whalen, J. B. (1985) Geochemistry of an island-arc plutonic suite: the Uasilau-Yau Yau Complex, New Britain, P. N. G. Jour. Petrol., 26, 603–632.

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

Wones, D. R. (1989) Significance of the assemblage titanite+ magnetite+quartz in granitic rocks. Amer. Mineral., 74, 744–749.