Australian Proterozoic Mineral Systems: Essential Ingredients and Mappable Criteria

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ABSTRACT

Most orebodies have cross-sections of less than 1 km^2 and hence do not offer a particularly large target for exploration. Fortunately, although in the geological record ore deposits are small and rare and result from the exceptional coincidence of certain geological processes, these processes are mappable on a much larger, district to regional scale and constitute a mineral system in which the ore deposit is the central feature. A mineral system can therefore be defined as 'all geological factors that control the generation and preservation of mineral deposits, and stress the processes that are involved in mobilising ore components from a source, transporting and accumulating them in more concentrated form and then preserving them throughout the subsequent geological history'. The mineral system concept emphasises that for many ore deposit types, although economically viable mineralisation may only occur on a scale of say, hundreds of metres, the total system of fluid-rock interactions that led to ore formation can extend over a distance of tens to hundreds of kilometres around the deposit. When mapped out, the total mineral system provides a far larger exploration target than the actual ore deposit itself. Important geological factors defining the characteristics of any mineralising system include:

1. sources of the mineralising fluids and transporting ligands;
2. sources of the metals and other ore components;
3. migration pathway;
4. thermal gradient;
5. energy source;
6. a mechanical and structural focusing mechanism at the trap site;
7. chemical and/or physical traps for ore precipitation.

Many of these factors individually are common throughout time and space and are mappable on a regional scale. The delineation and empirical prediction of mineral systems can thus be approached by combining two components of metallogenic research. Firstly, the development of maps of regional geoscientific data and data sets of the distribution of factors significant for mineral systems in general. Secondly, the determination of the essential ingredients of particular styles or types of deposits in terms of mappable elements that any exploration program could focus on.

INTRODUCTION

The earliest mineral discoveries were made on the basis of surface expressions as outcropping ore or gossan. Increasingly exploration for ore deposits is dominated by drilling geophysical or geochemical anomalies that are thought to indicate potential buried deposits. Early explorers were rarely concerned with the regional geological setting of the deposit, let alone where the mineralising fluids came from. Ore genesis studies focussed on the ore itself and its immediate environs, and concentrated on defining factors such as the temperature of ore deposition and the chemical parameters of the mineralising fluid (fO_2, pH, salinity etc). Fewer studies focussed on regional alteration zones in the same district and their relation to the ore generating systems. On a regional scale most geological maps do not portray regional alteration zones, even when they are larger than lithological units shown on the map, whilst rock descriptions on map legends rarely highlight the presence of reactive minerals such as graphite, magnetite or pyrite.

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The emphasis of exploration is now rapidly changing with the greater acceptance that an ore deposit results from an exceptional 'coincidence' of ordinary mechanical and chemical processes, many of which are quite common in the geological record. The relatively rare 'coincidence' in space and time of the several essential component processes is what makes ore deposits uncommon. Because an ore deposit rarely exceeds more than several kilometres in length or breadth, it represents a very localised, specific target for exploration. However the formation of most ore deposits results from the influence of various associated geological factors many of which can cover tens of kilometres (district scale) if not hundreds of kilometres (regional scale). The ore deposit is thus the central point of a regional mineral system. Ore-forming systems of these magnitudes are therefore likely to have left observable geological evidence well away from the deposit (eg Henley and Hoffman, 1987) on a scale comparable with modern regional geoscientific mapping such as carried out by geological surveys.

Ore genesis research should therefore attempt to determine which component processes and observable geological features are essential ingredients to the enrichment process for a particular mineral deposit type or style, whilst regional geoscientific data collection should attempt to determine the spatial and temporal distribution of geological features that record these component processes. All of these pieces of evidence then have the potential to become clues or specific exploration indicators that may help detect similar mineral systems elsewhere, and could be particularly useful in assessing the potential of 'greenfields' areas.

This paper focuses on the definition of a mineral system and shows using recent examples, how the collection of metallogenically relevant regional geoscientific data sets, combined with a better understanding of the essential ingredients to form a specific ore deposit type from ore genesis studies, can help to more effectively focus regional exploration programs.

MINERAL SYSTEMS - A DEFINITION

For many years the petroleum industry has followed the concept of the 'Petroleum System' which was defined by Magoon and Dow (1991) as 'a pod of mature source rocks and all its generated oil and gas accumulations, and includes all the geologic elements and processes necessary for oil and gas to exist'. This principle can also be applied to mineral deposits, although it is recognised that in contrast to petroleum systems, mineral systems are both more diverse and more complex.

Mineral systems can be defined as 'all geological factors that control the generation and preservation of mineral deposits, and stress the processes that are in involved in mobilising ore components from a source, transporting and accumulating them in more concentrated form and then preserving them throughout the subsequent geological history'. Important geological factors defining the characteristics of any hydrothermal system include:

1. sources of the mineralising fluids and transporting ligands;
2. sources of the metals and other ore components;
3. migration pathway, which must include inflow as well as outflow zones for large amounts of fluids (in contrast to petroleum migration paths);

4. thermal gradient (does the fluid move from hotter to cooler zones or visa versa?);
5. energy source to physically mobilise sufficient quantities of fluid to transport economic amounts of metal;
6. a mechanical and structural focusing mechanism at the trap site;
7. a chemical and/or physical cause for enriched mineral precipitation at the trap site.

Many of these important factors define geological features that are mappable on a district to regional scale. For example, tracing the extent of fault systems known to control a specific mineral deposit type or style will help elucidate potential fluid pathway(s). Maps of metamorphic zonations will indicate if the regional metamorphic temperatures were sufficient to mobilise a specific metal during metamorphic-hydrothermal fluid circulation; maps showing distribution of organic-rich rocks may indicate potential chemical traps for metals preferentially transported in oxidised solutions, and maps showing the distribution of hematite-rich alteration zones could indicate the pathway taken by oxidising solutions.

The delineation of mineral systems can be approached as two components of modern regional-metallogenic research. The first component involves expansion of regional geoscientific data collection to develop 'maps' and data sets (preferably digital) which highlight the distribution of geological factors significant to mineral systems in general. The second component involves focussing on specific ore deposit styles or types so as to define the essential ingredients that are part of their associated mineral system. By defining these essential ingredients and mappable criteria, regional exploration programs can be more effectively focussed.

MAPPABLE INGREDIENTS

With the rapid developments in Geographic Information Systems (GIS), regional mapping programs can now collect and store in readily useable format important parameters that can help to define a mineral system. No longer is the final product restricted to the conventional two-dimensional map of the past: many thematic layers (eg metamorphism, alteration, distribution of organic-rich rocks) can now be compiled at the same scale (eg Jagodzinski, Wyborn and Gallagher, 1993a) and integrated interactively to show areas that contain the essential ingredients for a particular deposit type or style. Most of these layers are backed up by point data bases that can record the accurate point location of significant alteration or metamorphic mineral assemblages or more detailed descriptions of mineral deposits and occurrences. Maps can be drawn from these point data bases that can show the regional distribution of geochemical data and mineralogical data (eg Jagodzinski, Wyborn and Gallagher, 1993 a, b).

Important mappable features in metallogenic analysis include the distribution of key minerals and rock types (Al silicates, Fe-bearing minerals, evaporites, carbonates), significant granite types, regional alteration, thermal history and the identification of specialised traps. Each of these mappable features can define several component parts of any mineral system. For example, the presence of magnetite may indicate an oxidised alteration zone that could be part of either an inflow or outflow zone; a magnetite-rich alteration zone could also denote a potential trap rock for metals carried in reduced solutions. Maps of these key features will rarely uniquely define a specific mineral system. However, the maps could indicate the distribution of a potential key parameter that has been targeted by ore genesis research as a critical ingredient to form a specific deposit type or style.

Metal availability in source rocks may commonly be a second-order factor and is still amenable to regional mapping (eg Jagodzinski, Wyborn and Gallagher, 1993b). It is accepted that the metabasalts surrounding the Mount Isa copper deposit have above average concentrations of Cu (Wilson, Derrick and Perkin, 1984) and that graniteo in the region surrounding the Alligator Rivers U deposits have above average concentrations of U (Wyborn, 1990). However, additional factors are essential and possibly more critical than the slight background source enrichment, which is only a small component of the overall enrichment factor of 100 to 10 000 required to form a major ore body. Metal solubility rather than availability is probably the limiting source control in most sediment-hosted ore systems as base metal solubilities can vary by ten orders of magnitude (eg Skinner, 1979).

In regional mapping programs field geologists should contribute to defining the distribution of as many of these key mappable ingredients as possible. Petrological data bases should also note the modal percentages of the key minerals present and ought to identify the individual opaque mineral phases present (eg magnetite, hematite, pyrite, pyrrhotite, chalcopyrite) rather than listing 'opaques' or 'sulphides'.

Distribution of key minerals and rock types

K-Na-Al silicates

K-Na-Al silicates are the main crustal pH buffers with feldspars occurring in neutral to alkaline or hot brine, muscovite in intermediate pH and temperature, and kaolinite in acid or cooler environments (eg Meyer and Hemley, 1967). The presence of these minerals can be important in depositional processes. For example, in unconformity-style U + Au + PGE deposits, high feldspar content at the depositional site enhances the chances of precipitating Au + Pd + Pt without significant U. The Al-silicate mineralogy of fault-related and regional alteration zones can also give a clue to the pH of the parent solutions and can indicate if these zones show inflow or outflow characteristics.

Traditionally mapping of the distribution of K-feldspar, muscovite and kaolinite depends on field visual observations of the coarser grained rocks or laboratory based petrographic or XRD determinations. Portable field spectrometers can now rapidly identify K-feldspar, muscovite and kaolinite. Airborne geophysics is unable to distinguish uniquely between these minerals, neither is LANDSAT TM. However, LANDSAT TM can distinguish clays, and when combined with the K channel from radiometric data, will distinguish kaolinite from other clays. Some experimental airborne scanners have shown the capacity to identify muscovite, kaolinite and even dickite, but these are not routinely used (see Huntington, 1992).

Redox: Fe-O-S-C-H mineralogy

Redox reactions are important in depositional processes and clues can be gained from the Fe-O-S-C-H mineralogy. Oxidised and reduced fluids can carry significant amounts of certain metals, whereas interaction with contrasting reduced or oxidised environments, respectively, can cause significant precipitation. The Fe-O-S-C-H mineralogy of regional scale alteration systems is important as these can become a potential trap region for ore-bearing fluids generated in a later event. Regional scale alteration zones can also be indicators of fluid pathways, eg kilometre-scale Fe-carbonate alteration zones east of the Mount Isa Cu deposit are thought to represent oxidised fluid pathways and indicate that Cu (U) was transported in SO_4-bearing late metamorphic fluids (Bain, Heinrich and Henderson, 1992). In the western Mount Isa Inlier to the southern McArthur Basin, altered felsic and mafic volcanics around and below sequences hosting Pb-Zn deposits are characterised by hematite-K-feldspar alteration assemblages, whilst the one common feature to all Pb-Zn deposits in this region is that they are hosted by organic-rich rock types. Early alteration events can also enhance the ability to extract metals during later alteration events. For example the high oxidation state of basalts surrounding the Mount Isa copper is considered a more essential ingredient than their high Cu content (Heinrich *et al*, in prep). Recognition that Cu is mobile and readily leached under oxidising conditions from basic volcanics was a key element in the exploration model that led to the discovery of the Olympic Dam deposit (Woodall, 1994).

Unfortunately, routine petrological studies commonly report the Fe-O-S-C-H minerals simply as 'oxides' or 'sulphides' and rarely distinguish between magnetite, ilmenite and hematite or pyrite, chalcopyrite and pyrrhotite, respectively. Airborne magnetics can facilitate mapping the distribution of magnetic minerals such as magnetite and pyrrhotite. Fe-oxides can also be distinguished in spectrally processed LANDSAT TM data, and by integrating with aeromagnetic data, hematite can be differentiated from magnetite. Calibration of TM scenes with direct spectrometer readings on reference or field based samples can provide better discrimination of hematite (eg Bierwirth, 1990). Palaeomagnetism provides an ideal tool for timing the development of hematite-rich alteration zones relative to nearby deposits using the Apparent Polar Wander Curves (Idnurm, Giddings and Plumb, in press; Wyborn, Idnurm and Giddings 1993). Bulk rock Fe^{2+}/Fe^{3+} can give an indication of the oxidation state of variably altered rocks (eg Wyborn, 1987).

The importance of evaporites and meta-evaporites

Evaporites are important in many Proterozoic sedimentary sequences, particularly in the period 1750-1500 Ma, when most of the major shale-hosted Pb-Zn deposits in Australia were formed. Brines generated from these extensive evaporites, either during diagenesis or later metamorphism, have the capacity to carry large amounts of metals through Cl-complexing and the low pH of rock-buffered saline fluids.

In regional mapping, evaporites can be recognised by the presences of pseudomorphs of gypsum and halite, and in higher grade rocks by the presence of scapolite. Br/Cl analyses of fluid inclusions are useful to trace and characterise pathways and alteration products of brine systems at different scales (eg Heinrich *et al*, 1993). The distribution of evaporites and meta-evaporites can sometimes be determined remotely by processing of LANDSAT TM scenes and by composite Red-Green-Blue (RGB) radiometric images.

Carbonates

The highlighting of limestones, dolomites and their metamorphic equivalents (marbles and calc-silicates) is essential in regional mapping. The occurrence of carbonate cements in clastic units such as sandstones and shales, as well as the distribution of regional-scale, carbonate-rich alteration zones should also be recorded. Carbonate-rich rocks are excellent acid-neutralisers and many skarn-hosted deposits form by reaction with Fe-rich carbonates.

In regional mapping occurrences of carbonate should be recorded and the specific mineral species (eg calcite, siderite, dolomite, magnesite etc) identified. Where possible occurrences of Fe- and Mn-rich carbonates should be noted. Whole-rock geochemical analyses should routinely include CO_2 (as well as H_2O^+ and H_2O^-). Carbonate-rich alteration zones often have associated magnetite and could be detected in airborne magnetic data. Spectral processing of LANDSAT TM data may also define carbonate-rich units.

The importance of granites and other related igneous rocks

There is increasing recognition that granites may be an important component of many Proterozoic Au ± base metal deposits (for this paper, the term 'granite' is used to apply to all felsic intrusive rocks including diorites, tonalites, granodiorites, adamellites, and granites (*Sensu Stricto*)). An Australia-wide compilation shows that Proterozoic granites which have hydrothermal Au ± base metal mineralisation within 2 to 3 km of the contact have many field, petrographic and chemical characteristics in common (Wyborn and Heinrich, 1993). In the field, granites related to mineralisation are heterogenous and individual plutons are often circular in shape. Some plutons consist entirely of leucogranite and have > 74 wt per cent SiO_2. Pegmatites, aplites and greisens, indicating later magmatic fluid saturation, are common in some of these more felsic end members. Some plutons are strongly zoned, and the more mafic varieties contain magnetite and hornblende. Where comagmatic felsic volcanics occur, they are usually compositionally distinct. The granite intrusions have distinct and mappable contact aureoles up to 3 km wide and upper amphibolite grade contact metamorphism is often recorded adjacent to the intrusions, indicating that the granite was in considerable thermal disequilibrium with the contact rocks at the time of intrusion. Specific geochemical characteristics include a wide range in SiO_2 content from at least as low as 60 up to 78 wt per cent. The more felsic end members have high values of Rb (> 250 ppm) and U (> 15 ppm) which increase exponentially with increasing SiO_2 whilst the K/Rb ratio decreases. In some areas Y (> 40 ppm) and Li may also increase with fractionation. The more mafic end members all have the alumina saturation index (ASI; Zen, 1986) below > 1.1, increasing above 1.1 in some of the more fractionated members. As the ASI increases 1.1 the Fe_2O_3/FeO ratio may decrease and vein Sn, W and U mineralisation are commonly associated with granites with these characteristics.

Many of these important characteristics are mappable by regional geophysics and detectable in regional rock geochemical data bases. The heterogeneity of the granite types is reflected in the extremely variable magnetic signature. The leucogranite bodies are poorly magnetised, whereas the concentrically zoned plutons can have a strong positive magnetic signature in the outer rim. Depending on the rock types present adjacent to the granite, the contact aureole can form distinct ring-shaped bands around individual plutons. These are caused by the conversion of pyrite to pyrrhotite or magnetite by the process of contact-metamorphic desulphidation. The radiometric signature can also be extremely variable although commonly the more fractionated plutons have distinct and uniform high U, K and/or total count signatures while the zoned plutons have distinct concentric zoning. Unmineralised granite systems rarely show these variable geophysical signatures. Maps or digital data sets can be developed to highlight the distribution of metallogenically important granite types (eg Chappell *et al*, 1991; Jagodzinski, Wyborn and Gallagher, 1993a; Champion and Mackenzie, 1994).

Regional alteration

On a district scale, most Proterozoic ore deposits are surrounded by alteration halos. Although these halos can extend for up to 5 km from known areas of mineralisation, they tend to be concentrated along major fault systems, in zones that are rarely more than 1 km wide (eg Coronation Hill (Wyborn *et al*, 1989), Mount Isa copper (Bain, Heinrich and Henderson, 1992)). The large scale of these alteration zones associated with known areas of mineralisation is expected, as to form significant hydrothermal ore deposits, the mineralising fluid must have interacted with a large volume of rock on a scale of tens, if not hundreds, of cubic kilometres. For example, Heinrich (1993) has estimated that the plumbing system that formed the Mount Isa copper deposit has affected at least 50, and more likely 500 km^3 of crust.

Regional mapping programs should include thematic layers that portray the distribution of regional alteration zones (eg the carbonate-Fe oxide alteration zones portrayed by Henderson and Bain (1991) on the 1:35 000 scale geological map of the east Moondarra Area, east of Mount Isa). Because the fluids associated with most Proterozoic ore deposits are brines with distinctive redox characteristics, they leave alteration haloes that form mappable features that are readily detected by regional geophysics. In the Coronation Hill area, alteration zones associated with mineralisation were detected as magnetic lows and as highs in imaged spectrometric channel ratios of uranium^2/thorium (Wyborn *et al*, 1989). Alteration zones can also be mapped by whole rock geochemistry and fluid inclusion studies, particularly in igneous rocks. For example, in the alteration zones around the Coronation Hill deposit the felsic volcanics have lost all Na_2O and CaO (Wyborn *et al*, 1989), whereas many altered igneous rocks immediately below the 1600-1700 Ma evaporite sequences in the McArthur/Mount Isa area have up to 12 wt per cent K_2O and up to 13 wt per cent Fe_2O_3 (AGSO ROCKCHEM database). Information collected on alteration zones should also focus on the mineralogy, particularly the opaques and Al silicates. Their timing relative to structures should be determined as well as their development relative to the protolith.

Temperature distribution and thermal history of an area

Because base metal solubilities increase near-exponentially with increasing temperature in a regional-metamorphic metal system, metamorphic grade can determine the potential of an area for hosting a particular ore deposit type. For example, in the Mount Isa Inlier, Jagodzinski, Wyborn and Gallagher (1993a) showed that all Cu deposits with > 20 tonnes contained Cu were in rocks of greenschist grade or higher. Temperature perturbations can be induced by increasing depth of burial in a sedimentary package, regional deformation, or localised effects such as magmatic intrusions or emplacement of hot basinal brines (eg Crick *et al*, 1988). Many Proterozoic granites are enriched in K, Th and U relative to their Phanerozoic and Early Archaean counterparts. Solomon and Heinrich (1992) argued that these K, Th and U enriched granites which generate heat at a rate of about 6 mW m^{-3} could have driven episodic convection of saline basement and basin fluids and that these high heat producing granites may be an essential ingredient for the formation of major sediment-hosted Pb-Zn deposits.

In metallogenic analysis, preparation of metamorphic facies maps at the same scale as the digital base geological map is critical. These maps must not just include the metamorphic grade as determined by observation of silicate mineralogy as this is not particularly effective in most silicate-bearing rock types below 250°C. Most transportation of U and of base metals, particularly Pb and Zn, occurs at temperatures lower than 250°C and methods such as illite crystallinity or organic maturation (eg Glikson, Taylor and Morris, 1992) need to be considered to define isograds in these low temperature domains. Radiogenic isotopes can define the age of metamorphism, whilst palaeomagnetism can give an age of the metamorphic event relative to the protolith.

The identification of specialised traps

Deposition of ore from hydrothermal fluids requires either a chemical reaction and/or a rapid change in the physical conditions (eg rapid fall in T or P) at the trap. Deposition is greatly enhanced by structurally focussed fluid flow.

Structural traps

Structural analysis of major fault zones can identify dilatant areas in which fluid flow is likely to be focussed. Detailed analysis can also lead to the prediction of ore-body shapes, which in turn can better target exploration. Valenta (1991) has shown that in the South Alligator Mineral Field, ore deposits are localised in two types of structural traps. One type has a wide surface expression, but does not extend at depth, whereas the second type of trap has a small surface expression and extends at depth. Thus, an anomaly which has a small surface expression, may have greater potential than one that has a large surface expression.

Specialised trap rocks

Depositional traps are the chemical driving forces of precipitation and form the main limitation on development of economic ore grade. Even in areas of focussed fluid flow, without a suitable chemical or physical trap non-mineralisation is the order. Many precipitation mechanisms are controlled by chemical reactions involving fluid/wall rock interactions or mixing of contrasting fluids. Specialised trap rocks include acid neutralisers such as carbonate- and feldspar-rich rocks; reductants such as organic- and magnetite-rich rocks; whilst oxidants include hematite BIF's and sulphate-bearing evaporites. Pyrite-rich rocks can also provide a source of S ± Fe to form $CuFeS_2$ (eg Mount Isa) whereas magnetite-rich rocks provide a sink for S and a reductant for Fe (eg Tennant Creek, Selwyn). Hematite-rich rocks are oxidants and can cause precipitation of Sn that is transported in more reduced form (eg red-rock hosted Sn ores in Renison Bell). Carbonates are important traps in skarn mineralisation of various types (eg Pb mineralisation).

All of these specialised trap rocks represent mappable features and their occurrence should be emphasised in any regional geological mapping system. The presence of many of these units can be detected by regional airborne geophysics and indirectly, by processed LANDSAT TM data.

A CATALOGUE OF INGREDIENTS AND EXPRESSIONS OF MAJOR ORE DEPOSIT TYPES

Mineral systems can be extremely complex, and for any particular ore deposit type the relative importance and combination of the various geological factors necessary to form a particular metal accumulation vary. However for any system, the mappable component features are relatively few.

Ore genesis research should aim to determine which of the component processes and observable geological features occurring in a particular deposit type are essential for its formulation, and try to rank 'essential' versus 'desirable' ingredients. Where present desirable characteristics can enhance the grades and tonnages of the ore deposit formed, even though they may not be essential to forming a significant deposit. Often it is not possible from a study of a single orebody to determine if a geological factor or process is critical, and comparative studies with other similar ore deposits may help to rank essential and desirable criteria. For example, with unconformity deposits, the unconformity is not considered an essential ingredient. What is essential is that there be a chemical and competency contrast between two major rock bodies which can be provided by either an unconformity or a major fault (Johnston and Wall, 1984). With Mount Isa-style Cu deposits, the essential ingredients in the formation of a chemical trap are pyrite and graphite in the host rock. Most comparable deposits to Mount Isa style Cu also contain carbonate (eg Nifty, (Norris, 1987); Sheep Creek (Rankin and Zieg, 1990)) but is not clear whether the presence of carbonate is essential to the depositional process. Comparative studies of all mineral occurrences (from small shows to world class deposits) of a particular deposit type or style on a regional (if not continent-wide) scale can also help to elucidate which key factors cause the larger accumulations.

AGSO and its Precambrian Metallogeny Project, have been accumulating empirical and genetic criteria on several major Precambrian mineral deposit types with the aim of better defining predictive criteria for their associated mineral systems. The aim is to build a catalogue of key parameters (geological, geochemical, geophysical) for the formulation of Precambrian ore deposit types. The catalogue will list the essential ingredients to make the deposit type, and the likely expressions of both the mineralisation and the key geoscientific factors of the associated mineral system. Work on three deposit types is nearing completion and results to date are as follows.

The granite related Au ± base metal mineral system

Essential ingredients

The essential ingredients of the granite related Au ± base metal system are a specific type of magnetite-bearing granite, fracture pathways and suitable reductant (± Fe, S-rich) trap rocks. The granites associated with Proterozoic Au + base metal deposits have the field and geochemical characteristics already described. Based on field and chemical criteria, Proterozoic granites associated with Au ± base metal mineralisation can be further subdivided into two types: Type 1 is dominated by hornblende while Type 2 are of higher temperature and can have comagmatic pyroxene-bearing volcanics. These two distinctive granite types are each associated with a specific type of mineral district: Type 1 granites are Au dominant with minor Cu + base metals (eg Cullen Mineral Field, Granites-Tanami area), whilst the mineral district associated with Type 2 is Cu dominated with Au ± U (Olympic Dam, Ernest Henry, Osborne). In both cases, as granite intrusion can occur up to 100 Ma after the deposition of the country rock, migration pathways are along major fracture zones and faults, and deposits can occur up to 5 km from the granite boundary. Trap rocks tend to be dominated by reducing hosts such as rocks rich in magnetite, graphite and/or sulphide although interaction with a reducing fluid could also cause precipitation.

Larger grades and tonnages occur in the deposits hosted by Fe-rich lithologies as opposed to those hosted by or near graphitic units. This is probably because firstly the host ironstones are present in greater volumes than carbonaceous hosts and secondly the Fe-rich hosts are also more likely to fracture and brecciate enhancing wall rock interaction.

Mappable features

Mappable features should emphasise a specific granite type, fracture zones and reductant hosts. The specific granite type can be identified by whole-rock geochemistry and field criteria. Regional geophysics can highlight the presence of major fracture zones and also identify potential hosts. Many of the deposits that are hosted in Fe-rich rocks are magnetic anomalies eg Ernest Henry, Osborne (Keough, 1993). Deposits hosted in carbonaceous shales have smaller tonnages and are more difficult to find as electrical geophysical methods do not easily distinguish between mineralisation and high carbon/graphite content of the host metasediments. Alteration zones may not necessarily define a specific target as for example, in the type 2 granites in the Eastern Fold Belt at Mount Isa regional alteration zones are ubiquitous throughout both the granite system and the country rock both close to and away from mineralisation (Wyborn, 1992).

'Unconformity' style U + Au + PGE

Essential ingredients

Important ingredients in this system are a thick, cover sequence of chemically neutral to oxidised, quartz-rich sandstones adjacent to reactive rocks that contain either a reductant and/or an acid neutraliser such as carbonate or feldspar. The boundary between the two rock types is most commonly an unconformity, although it can also be a fault. In either case, faulting localises individual deposits by providing the 'plumbing' or fluid circulation pathway. Mineralising fluids are highly oxidised, saline, $CaCl_2$-rich brines which originate in, or above the cover sequence (Mernagh, 1992; Mernagh *et al*, in press). Trap environments can be of two sorts: reducing, which leads to U-dominated deposits that can contain Au + PGE (eg Jabiluka, Ranger) or acid-neutralising which results in Au+PGE deposits with minor U (eg Coronation Hill) (Mernagh, 1992; Mernagh *et al*, in press).

Larger tonnages occur in the deposits of the Alligator Rivers region. Their size is possibly enhanced by firstly the thick, neutral cover sequence which acts as a thermal blanket, such that when fluids reach the unconformity, temperatures of ca 150°C develop: temperatures which are ideal for the transport of U, Au and PGE. Secondly, this neutral to oxidised cover sequence provides a strong contrast to the reduced rocks and/or basement-derived fluids which occur in structurally focussed traps in the basement sequence below the unconformity.

Mappable features

Predictive criteria would highlight regions which contain a thick neutral to oxidised cover sequence overlying a basement sequence which contains either a reductant or an acid neutraliser. Dilatant faults are critical for focussing fluid flow to cause more effective interaction with basement rocks and/or basement-derived fluids. Because of the highly oxidised nature of the ore-bearing fluids replacement of magnetite and chlorite by hematite is common along fault zones that are feeders to the mineralisation: these zones can appear as major magnetic lows. Chemically, U is enriched to varying degrees at or adjacent to the deposits, whilst Th is depleted at the sites of mineralisation, but enriched in zones above. On airborne radiometric data these regional alteration zones adjacent to the deposit appear as U highs and Th depleted zones which can be enhanced by the ratioed image U^2/Th. Outflow zones can be recognised as Th highs.

Mount Isa style Cu

Essential ingredients

Empirical observations note that numerous Cu deposits in the Mount Isa Inlier are hosted by greenschist grade (or higher) metamorphic rocks and formed late in the metamorphic history of the Inlier. Predictive criteria emphasise a metamorphic grade of greenschist or higher, trap rocks rich in graphite + pyrite, and fault structures for enhanced permeability. The Mount Isa Cu deposit is regionally associated with carbonate + Fe oxide alteration (hematite and/or Fe-rich epidote-bearing) of metabasalts (source and transport paths of fluids). Alteration haloes in massive carbonate rocks of the deposit environment have $\delta^{18}O$ depletion (Waring, 1990). The mineralising fluids are oxidised brines in equilibrium with sulphate-bearing evaporites.

Although hundreds of small size deposits in the Mount Isa region indicate large-scale Cu mobility, only one deposit hosted by pyritic, graphitic, carbonate rocks is of world-class economic importance, presumably because of extreme trap rocks forming a strong contrast to the oxidised mineralising fluids.

Mappable criteria

Mappable criteria would emphasise a reductant and sulphide-bearing host rock adjacent to a large area of oxidised rocks (eg hematite and/or Fe-rich epidote-bearing). These oxidised rocks are basalts at Mount Isa (favourable) but in other areas may include meta-redbeds or other oxidised meta-igneous rocks. Major fault structures are essential for enhanced permeability and associated alteration zones, and a sharp break between high and low metamorphic grade may be favourable as a thermal contrast and/or driving force for fluid flow. Mappable criteria would also emphasise a metamorphic grade of greenschist or higher.

CONCLUSIONS

The approach of defining mineral systems and their mappable geological criteria is multidisciplinary and requires observations on all facets of geoscience. The approach recognises that all relevant geoscientific criteria must be considered. For example, it is insufficient to have structurally focussed fluid flow and metal-bearing solutions if there is not a suitable chemical trap available as well. By thinking of an ore deposit as part of a mineral system that involves the interaction of many common geological processes over tens to hundreds of kilometres, it is often easier to understand why some deposits are located where they are, and what key processes are essential to forming the major deposits.

The approach also emphasises that regional mapping projects and ore genesis studies must be effectively expanded and well integrated and co-ordinated. Ore genesis research should focus on determining which component processes and observable geological features are essential ingredients to the enrichment process for a particular mineral deposit type, while regional geoscientific data collection should attempt to determine the spatial and temporal distribution of geological features that record these component processes. The advent of modern techniques such as image processing (LANDSAT TM, SPOT, airborne magnetic and radiometric data) and digital relational databases, all of which can be effectively integrated within a GIS, should make these expansions easily attainable.

ACKNOWLEDGEMENTS

Discussions on aspects of the potential of satellite imagery with John Creasey are gratefully acknowledged, as are reviews by Liz Jagodzinski, Terry Mernagh and an anonymous reviewer. This paper is published with the permission of the Executive Director, Australian Geological Survey Organisation.

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