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OVERVIEW OF IRON OXIDE-COPPER-GOLD DEPOSITS IN THE CURNAMONA PROVINCE AND CLONCURRY DISTRICT (EASTERN MOUNT ISA BLOCK), AUSTRALIA

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Abstract – The Curnamona Province (South Australia/New South Wales) and Cloncurry district (NW Queensland) are both extensively metasomatised terrains containing hydrothermal iron oxide copper-gold and related deposits. Structural timing criteria and geochronological data suggest that the deposits formed at 1630 to 1600 Ma (Curnamona) and 1540-1500 Ma (Cloncurry). The Cloncurry deposits have a close temporal association with I-type granitoids and limited data suggest a similar relationship exists in the Curnamona Province. The majority of deposits are hosted by metamorphosed Palaeoproterozoic supracrustal rocks of varying age, composition and metamorphic grade. Mineralisation was localised by a range of brittle-ductile and brittle structures and produced vein, stockwork, breccia and replacement orebodies. Variations of fluid chemistry, host rocks and physical conditions produced mineralogically-diverse alteration zones, varying Cu:Au ratios, many different minor element associations, and inconsistent spatial relationships between magnetite and ore metals. Regional-scale alteration systems are dominated by Na-(Fe-Ca)-rich assemblages in which the most characteristic mineral is albite. Most of the ore deposits are specifically associated with pre- to synmineralisation alteration assemblages composed of medium to high temperature K-Fe-(Ca-Mg)-rich minerals together with late-stage parageneses containing carbonates. The deposits formed in deep-seated (>5 km) environments by a variety of different geochemical mechanisms from complex H_2O-CO_2±CH_4±N_2-salt fluids of magmatic and/or metamorphic derivation .

Introduction

In current mining terms, Australia has the world's most significant concentration of iron oxide-copper-gold deposits. Mimicking many other deposits of this group worldwide (cf. Hitzman *et al.*, 1992), the Australian examples appear to have formed during a restricted period of middle Proterozoic (1.9 to 1.5 Ga) Earth history. There are three main space-time clusters in Australia (Fig.1), namely (1) within Tennant Creek Inlier (~1.85 Ga, Compston, 1995), (2) widely-distributed in the Gawler Craton and Curnamona Province (1.63 to 1.59 Ga, Johnson and Cross, 1995; Skirrow *et al.*, 2000), and (3) in the eastern part of the Mount Isa Block (commonly referred to as the Cloncurry district, 1.55 to 1.50 Ga, Pollard and Perkins, 1997; Perkins and Wyborn, 1998). This paper describes the geology of the deposits in the Curnamona and Cloncurry regions whose general character and affinities have only been relatively-recently recognised. In the latter case these include several mineable resources discovered after 1980 in a district which up till then lacked known deposits amenable to modern mining methods (e.g. Williams, 1998). The Curnamona Province could currently be regarded as under-explored as was the Cloncurry District twenty years ago.

Deposits of the Curnamona Province

Regional geology

The Curnamona Province comprises the Broken Hill Domain (BHD), Olary Domain (OD) (Fig. 2), and the Mt Painter and Mt Babbage Inliers in the northwest. Most of the known significant Cu-Au deposits are located in the Olary Domain, although numerous copper occurrences have been documented in both the BHD and OD. The sequence in the OD is divided into two lithostratigraphic packages, the basal Curnamona Group and overlying Strathearn Group (Conor, 2000). The Curnamona Group includes A-type felsic volcanic rocks and comagmatic intrusions (Basso Suite), that were emplaced between ~1715 and ~1700 Ma (Ashley *et al.*, 1996; Fanning *et al.*, 1998). These Na-rich felsic igneous rocks are associated with albitic psammopelites, massive to laminated albitite, quartzo-feldspathic gneisses, and iron formation. The uppermost Curnamona Group contains calc-silicate ± magnetite ± hematite bearing laminated albitite and minor Mn-rich rocks, passing upwards into the Bimba Formation. This thin regional marker is variably represented by marble, calc-silicate-rich rock (e.g. clinopyroxene, garnet, amphibole, epidote), pelitic schist, and gradations into bedded pyritic

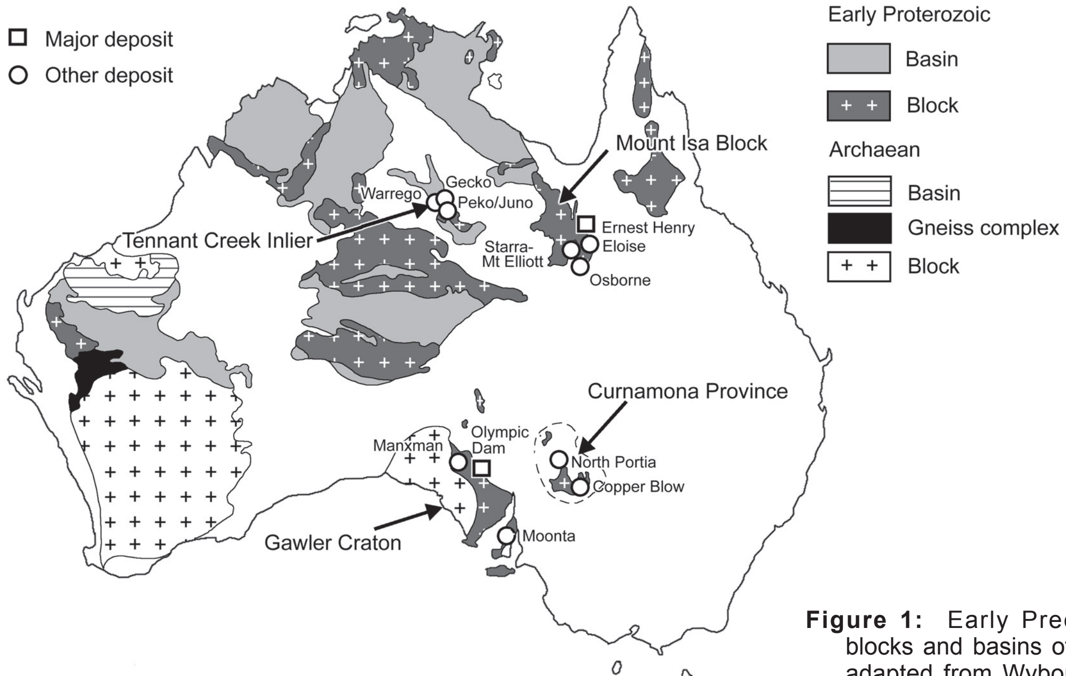


Figure 1: Early Precambrian blocks and basins of Australia adapted from Wyborn (1988), showing the locations of the main Fe oxide-Cu-Au districts and deposits.

and pyrrhotitic zones with anomalous Cu, Pb, Zn, As and Co. The Strathearn Group is dominated by pelitic and psammopelitic lithologies, locally containing carbonaceous and aluminosilicate-bearing strata, banded iron formation and tourmalinite.

The Curnamona Group is temporally broadly equivalent to the Thackaringa Group in the BHD (Page *et al.*, 2000). However, the uppermost Curnamona Group, which hosts some of the most significant Cu-Au deposits in the province, differs from the Thackaringa Group in containing greater proportions of calc-silicate rich strata, laminated Fe-oxide rich albitite, and manganiferous strata. The Broken Hill Group in the BHD, the host to the Broken Hill Pb-Zn-Ag lodes, and the overlying Sundown Group, have thinner equivalents in the OD (uppermost Curnamona Group, lowermost Strathearn Group; Cook and Ashley, 1992).

Four igneous suites occur in the OD, of which temporal equivalents of the first two and the fourth have been recognised in the BHD. The Basso A-type felsic igneous suite (~1715 to 1700 Ma, Fig. 3; see above) was succeeded by the Lady Louise Suite, including a ~1680 Ma mafic intrusion (Conor, 2000). The Poodla Hill Suite has been recognised only in the OD, and occurs as small, relatively mafic, granitoid intrusions with U-Pb zircon ages of 1641 ±11 and 1629 ±29 Ma (Fig. 3; Cook *et al.*, 1994; Ashley *et al.*, 1997). These Na- and K-altered 'tonalite' and 'monzonite' intrusions require further dating and petrogenetic study to confirm whether they are of I-type affinity (Ashley *et al.*, 1997). The Bimbowrie Suite (~1616 to 1580 Ma) includes the 'S-type regional granitoids' of Ashley *et al.* (1997), and probably is represented in the BHD by the Mundi Mundi granites, among others (Page *et al.*, 2000). None of the igneous suites have been demonstrated to be spatially or temporally directly associated with Cu-Au mineralisation, although there is some temporal overlap of Cu-Au with the last two granitoid suites and stable isotope evidence points to a magmatic (and metamorphic) fluid input to the mineralising systems (see below; Skirrow *et al.*, 2000).

Regional metamorphism attained granulite facies in the southern BHD and upper amphibolite facies conditions in the southern OD during the Olarian Orogeny at ~1600 Ma (Phillips, 1980; Clark *et al.*, 1986; Page and Laing, 1992; Page *et al.*, 2000). Metamorphic grade decreases northwards in the OD and BHD, reaching only upper greenschist facies conditions on the Benagerie Ridge (Teale and Fanning, 2000). The Willyama Supergroup underwent three deformation events during the Olarian Orogeny, and several subsequent deformation events including those of the Delamerian Orogeny. The Olarian D_1 and D_2 high grade events occurred close to ~1600 Ma (Page and Laing, 1992), although some recent studies suggest D_1 may have occurred as early as ~1690 Ma (Gibson, 1998, 2000). Upright folds and shear zones related to the retrograde (but locally amphibolite facies) D_3 event were produced at ~1585 to 1600 Ma (Gibson, 2000; Page *et al.*, 2000; Skirrow *et al.*, 2000). The D_3 and possibly D_2 events were most significant for Cu-Au and regional alteration systems (see below).

Regional Alteration

A defining characteristic of both the BHD and OD are the exceptionally widespread Na-rich lithologies in particularly the lower parts of the Willyama Supergroup (Fig. 2; Stevens and Stroud, 1983; Cook and Ashley, 1992; Ashley *et al.*, 1998; Ashley, 2000). Regional alteration occurs in two principal styles: pre- to early-tectonic stratabound Na ± Fe metasomatism, and syntectonic stratabound to discordant Na ± Ca ± Fe metasomatism. Both are distinguished from generally localised K ± Fe alteration (Ashley and Plimer, 1998); this biotite ± K-feldspar ± magnetite ± hematite alteration is associated in places with Cu-Au mineralisation

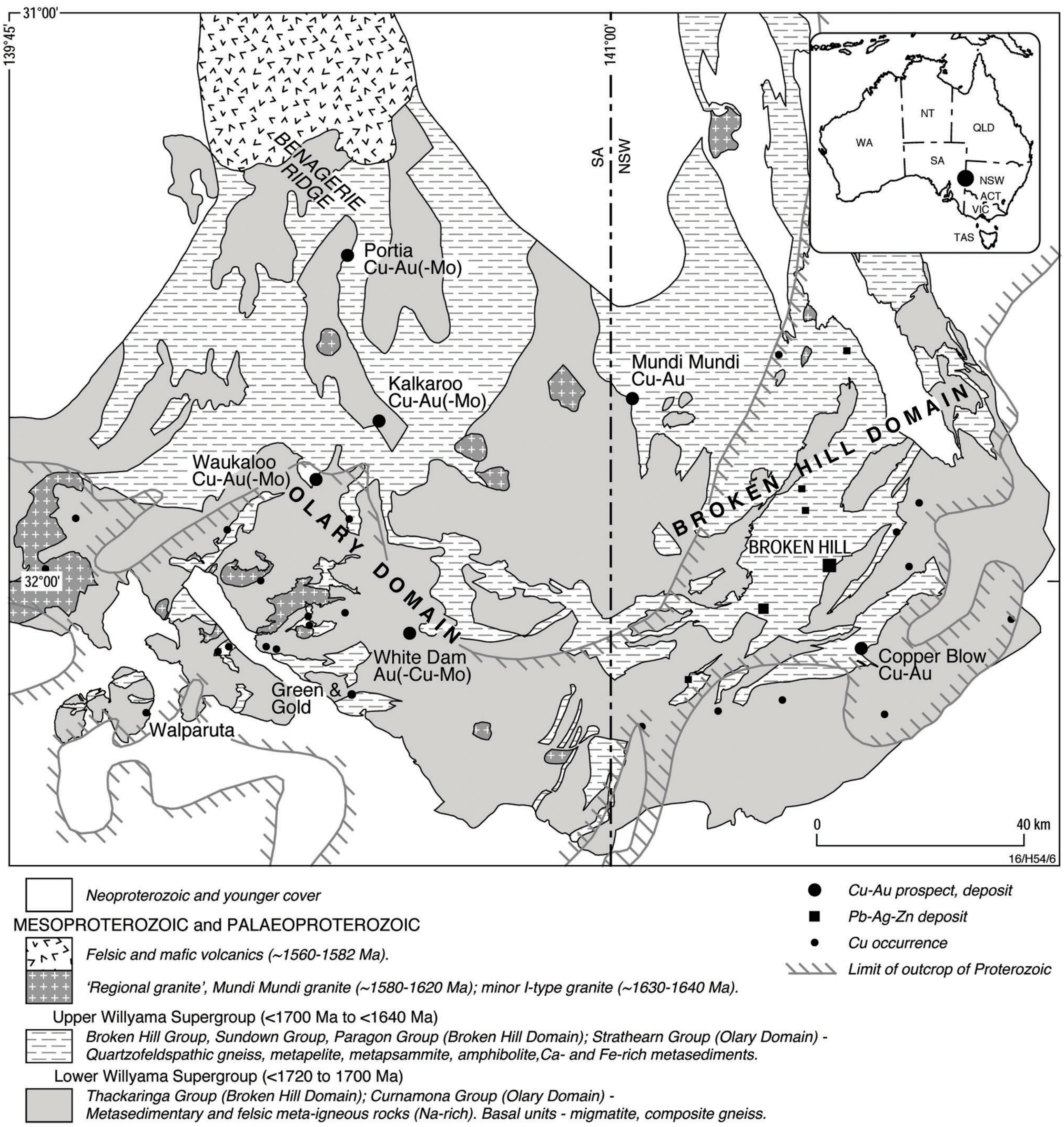


Figure 2: Geology, copper-gold deposits and occurrences, and other selected deposits of the Curnamona Province (adapted from Skirrow *et al.*, submitted, and original sources cited therein).

(see below). Textural evidence in low grade metasedimentary rocks of the Benagerie Ridge bracket the timing of the regional Na ± Fe-oxide alteration to a period after diagenetic formation of carbonate ± evaporite(?) nodules and before or during metamorphic recrystallisation to albite ± magnetite during D_1 and D_2 (Cook and Ashley, 1992; Skirrow and Ashley, 1998; Teale and Fanning, 2000).

Syntectonic Na ± Ca-Fe alteration was localised by shearing and folding mainly during the D_3 regional deformation event, and is mostly restricted to upper parts of the Curnamona Group in the OD. Styles include calc-silicate-matrix breccias and calc-silicate vein networks, brecciated ironstones, and intensely 'albitised' zones affecting diverse lithologies, with assemblages including Na-plagioclase, clinopyroxene, clinoamphibole, quartz, magnetite, hematite, garnet and titanite (Ashley *et al.*, 1997, 1998; Lottermoser and Ashley, 1996; Skirrow and Ashley, 1998). Titanite from such assemblages yielded U-Pb SHRIMP ages in the range ~1588 to 1583 Ma (Skirrow *et al.*, 2000), which are within error of a Sm-Nd age for massive garnet-epidote replacement zones (1575 ±26 Ma, Sm-Nd, Kent *et al.*, 2000). The titanite ages are considered to be minima for regional syntectonic Na ± Ca-Fe metasomatism, but may be close to crystallisation ages. Hypersaline high temperature (450 to 550ºC) fluids were involved (Yang and Ashley, 1994; Kent *et al.*, 2000; Skirrow *et al.*, 2000). With rare exception, Cu-Au mineralisation is notably lacking in the syntectonic Na ± Ca-Fe metasomatic zones, which are progressively less well developed northwards in the OD. Potassic and

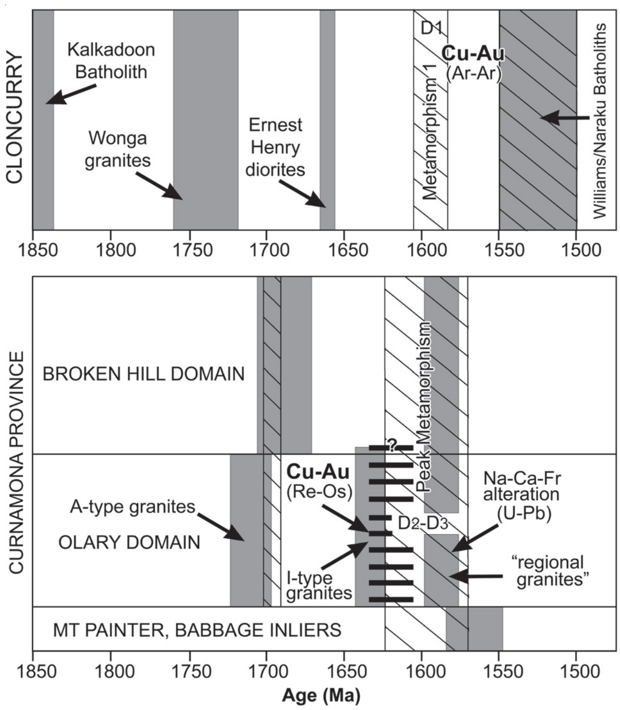


Figure 3: Summary of deformation, magmatic and hydrothermal events in the Curnamona Province and eastern Mount Isa Block.

hematitic alteration, however, are more prominent in the well mineralised Benagerie Ridge region than in the southern OD. Age dating and stable isotope studies suggest that regional syntectonic Na ± Ca-Fe alteration developed at least 10 Ma later than Cu-Au mineralisation (Fig. 3), from fluids of differing (metamorphic) origin to the ore fluids (Skirrow *et al.*, 2000).

Deposit Characteristics

The larger known Cu-Au systems in the Curnamona Province are unified by several characteristics, namely the association of Cu-Au ± Mo with abundant iron oxides in some parts of the hydrothermal systems, potassic alteration (but commonly lacking syn-ore muscovite), syn- to late-tectonic timing around 1630 to ~1580? Ma, moderate temperatures of formation (~300 to 450ºC), and involvement of both hypersaline and carbonic fluids. As shown schematically in Figure 4, styles of mineralisation vary from ironstone-hosted high grade Cu-rich deposits (e.g. Copper Blow), through generally lower grade stratabound Cu-Au(-Mo) systems in which magnetite is confined largely to footwall zones (e.g. Kalkaroo, Portia, Waukaloo), to high grade Au with minor Cu-Mo disseminated in Fe-oxide poor quartzo-feldspathic gneiss (e.g. White Dam).

Stratabound replacement and vein networks styles in the northern OD are hosted predominantly by amphibolite or upper greenschist facies albitic and calc-albitic metasedimentary rocks of the uppermost Curnamona Group. In places, Cu-Au(-Mo) mineralisation and associated potassic ± sodic alteration extend across the regional redox interface near the Bimba Formation into carbonaceous pelites of the lower Strathearn Group. In keeping with its somewhat unusual characteristics, the White Dam prospect occurs in upper amphibolite facies gneisses at a stratigraphic position within the Curnamona Group that is different to Kalkaroo and many other Cu-Au(-Mo) systems of the region. Syn-tectonic K-feldspar - albite – biotite – quartz veins or segregations host chalcopyrite-pyrite-molybdenite-Au, representing possibly high temperature mineralisation that shares mineralogical and textural features with intrusion-related gold systems (Lang *et al.*, 2000).

Syn- to late-diagenetic regional albitisation ± magnetite alteration was overprinted by a characteristic suite of hydrothermal assemblages associated with Fe-oxide Cu-Au mineralisation. Early, high temperature chalcopyrite – pyrite ± molybdenite in some deposits is associated with Fe-Ca rich veins and replacements of magnetite – actinolite ± K-feldspar ± quartz ± albite ± titanite ± allanite. Most chalcopyrite (rare bornite), Au and molybdenite were deposited in association with biotite – quartz – pyrite ± K-feldspar potassic alteration, or biotite – albite, that overprinted the Fe-Ca rich assemblages. White mica typically is absent from these assemblages, but carbonate is locally abundant. Magnetite-biotite and Cu-Au deposition were coeval and spatially coincident in some deposits with strong structural controls (e.g. the shear-related Copper Blow, Walparuta, Green and Gold, and Wilkins prospects), whereas magnetite is restricted to footwall alteration zones in stratabound systems of the northern OD (e.g. Kalkaroo, Portia). Late-stage chloritisation, carbonate replacements and sericitisation are locally significant, along with fluorite, hematite and rutile development.

Timing of Mineralisation

Relative timing of Cu-Au(-Mo) introduction varies from pre- or syn-peak metamorphic at the White Dam Au(-Cu-Mo) prospect, through syn- and post-peak metamorphic at the Kalkaroo, Waukaloo, Mundi Mundi, Lawsons, Wilkins, Dome Rock, Green and Gold, Copper Blow and Walparuta prospects. Rhenium-osmium (Re-Os) isotopic dating of molybdenite from mineralisation in the Kalkaroo, White Dam, Waukaloo, and Portia areas yielded nine Re-Os ages clustering in two groups, ~1632 to 1624 Ma, and ~1616 to 1612 Ma, with errors of 1 to 8 Ma (Fig. 3; Skirrow *et al.*, 2000; Suzuki *et al.*, *in prep.*). Molybdenite is paragenetically associated with chalcopyrite in most of the dated assemblages, although molybdenite also occurs independently of Cu-Au in some prospects.

The Re-Os dating results for mineralisation in the OD are remarkably consistent with U-Pb (SHRIMP) dating of hydrothermal monazite in the Portia area. Teale and Fanning (2000) reported ages of ~1630 Ma for monazite associated with early invasive albitisation and molybdenite, and ~1605 Ma for monazite in Cu-Au assemblages. Ages obtained by $^{40}Ar/^{39}Ar$ analysis of white mica and biotite associated with mineralisation in a wide range of epigenetic sulphide deposits of the OD generally reflect Delamerian thermal events (~450 to 480 Ma, Bierlein *et al.*, 1996a), although Mesoproterozoic ages are preserved in hydrothermal muscovite at the Mundi Mundi Cu-Au prospect in the northern OD/BHD (Skirrow *et al.*, 1999). Both the Re-Os and U-Pb results imply Mo and initial Cu-Au introduction in the dated systems prior to or coeval with the metamorphic peak at 1600 ± 8 Ma, as determined from zircon U-Pb dating in medium and high grade areas (Page and Laing, 1992; Page *et al.*, 2000). However, uncertainties of up to 1.0% in the Re-Os absolute ages, and lack of detailed published information on the timing of metamorphism in low grade areas and of pre-1600 Ma thermal events, allow us to conclude that Cu-Au(-Mo) mineralisation was broadly contemporaneous with the Olarian Orogeny.

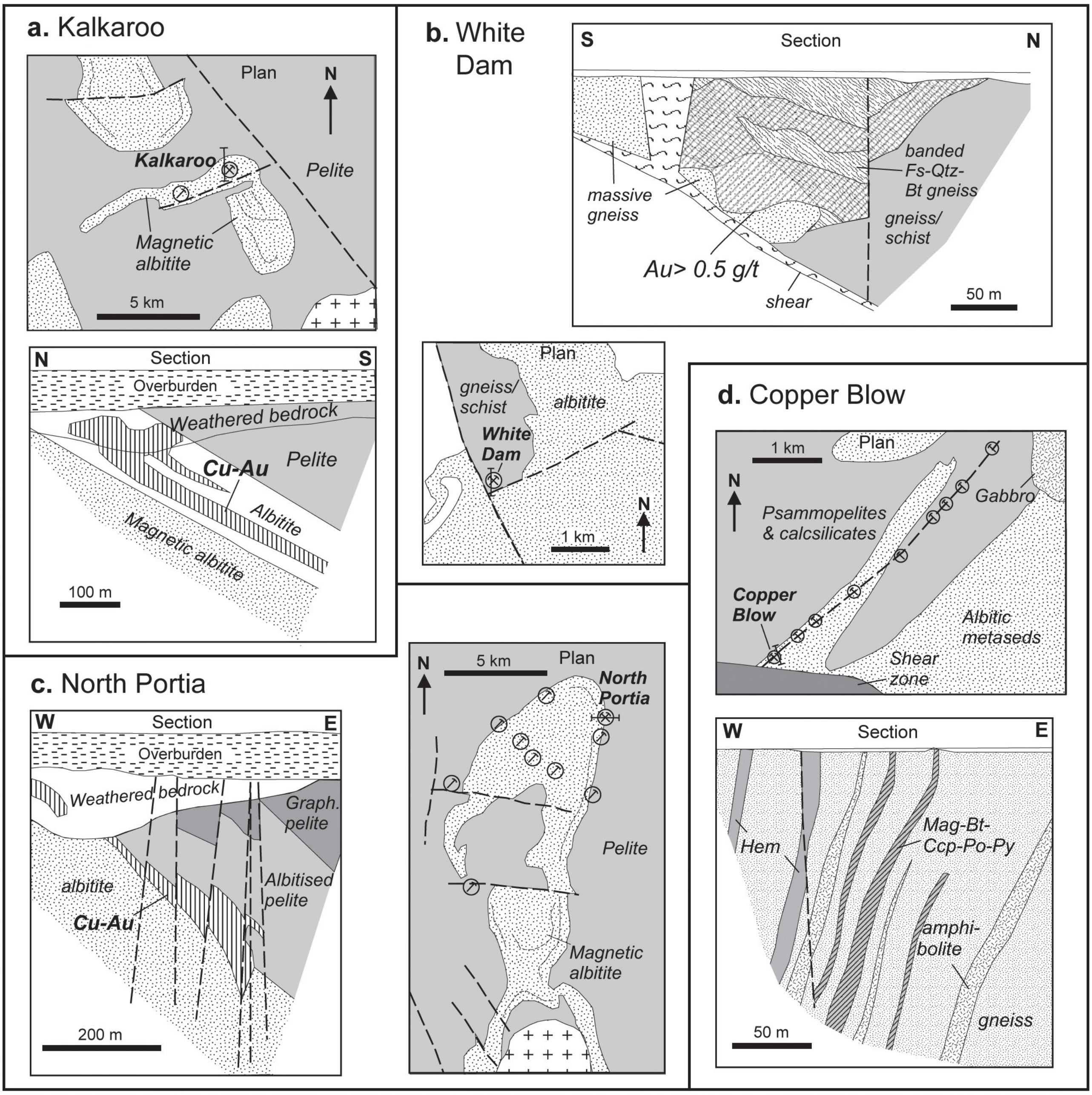


Figure 4: Schematic geological models for the principal copper-gold deposit styles of the Curnamona Province. Adapted from sources listed in Table 1.

- **a Kalkaroo:** Positioned along a northeast-trending linear magnetic anomaly that has both strike-parallel and discordant segments. Stratabound chalcopyrite-pyrite replacements best developed in weakly magnetic biotite-albitites that overlie strongly magnetic and Fe-K-Ca altered albitites, and underlie very weakly magnetic metapelites ±carbonaceous matter ±pyrrhotite.
- **b. White Dam:** Situated near the intersection of several steep and shallow dipping faults/shears (some or all of these may postdate Au), within a magnetically quiet domain. Disseminated Au and minor Cu-Mo occur in banded to massive quartz-feldspar-biotite gneiss.
- **c. North Portia:** Replacement and vein Cu-Au-Mo ±Fe-oxide mineralisation localised in stratabound zones on eastern flank of the Benagerie Ridge Magnetic Complex. Footwall albitised pelites are magnetic, hanging wall pelites are very weakly magnetic.
- **d. Copper Blow:** Localised by a northeast-trending steeply inclined shear zone that transgresses regional strike of host gneisses at a low angle. Chalcopyrite-pyrrhotite are intimately associated with sheets of shear-related magnetite-biotite ironstone, whereas later deformation resulted in quartz-chalcopyrite-pyrite-chlorite infills.

Deposit	Resource Information 2000 Status	Main Host Rocks	Confining Structure Style
Copper Blow	Best intercept 10.8 m @ 4.0% Cu, 0.8 g/t Au Prospect	?1715-1700 Ma Qtz-Ab-Kfs-Bt ± Sil ± Grt gneiss, amphibolite	Steeply dipping shear zone Replacement bodies, veins
Kalkaroo	30 Mt @ 0.28% Cu, 0.14 g/t Au; Prospect	1715-1700 Ma[1] laminated albitite in footwall; younger meta-pelites in hanging wall	Linear fold/fracture/shear? zone Veins and disseminations
North Portia	Best intercept 76m @ 1.1% Cu and 1.2 g/t Au Prospect	1702 ± 6 Ma[4], pelite (albitite), calc-silicate	? Nose of regional antiform and steep cross-faults Veins, disseminations
Walparuta	Best intercept 28m @ 0.31% Cu, 0.3 g/t Au Prospect	1715-1700 Ma Ab-Qtz-Bt ± Mag ± Ms banded gneiss and albitite	? Shear-related Veins and breccia matrix with sulphides
Waukaloo	Best intercept 35m @ 0.3% Cu Prospect	?1715-1700 Ma laminated to massive, brecciated magnetic albitite, pyrrhotitic metapelite	NNE-trending linear fracture/ shear zone? on fold limb. Disseminated, vein net-works and breccia
White Dam	Best intercept 14m @ 1.7% Cu, 7.2 g/t Au Prospect	?1715-1700 Ma Qtz-Ab-Kfs-Bt banded to massive gneiss, Ms-Bt retrograde schist, amphibolite	Shallow-dipping shear zone? Disseminated

Sources of geochronological data: [1] Conor (*pers. comm.*, 1999); [2] Skirrow *et al.* (2000), Suzuki *et al.* (*in prep.*); [3] Skirrow and Ashley (1999); [4] Teale and Fanning (2000); [5] Bierlein *et al.* (1996a)

Table 1: Summary characteristics of iron oxide-copper-gold deposits of the Curnamona Province.

Ore Fluid Characteristics and Origins

Temperatures obtained from oxygen isotope geothermometry at the Kalkaroo and Waukaloo prospects indicate formation of early magnetite – quartz – actinolite – chalcopyrite ± K-feldspar assemblages at ~420 to 450ºC (Skirrow *et al.*, 2000). Halite dissolution temperatures (total homogenisation) in fluid inclusions from the same Cu-bearing assemblages at Kalkaroo are ~350 to 380ºC, whereas in other epigenetic sulphide deposits of the OD fluid inclusions associated with the main stages of mineralisation have homogenisation temperatures (liquid-vapour) ranging from 225 to 325ºC (i.e., representing minimum trapping temperatures; Bierlein *et al.*, 1996b). As in the Cloncurry district, there is a common association in the OD deposits of hypersaline Na-Ca-K-Cl and carbonic fluid inclusions. Brine inclusions contain multiple daughter minerals, including halite, sylvite, nahcolite, mica, carbonate, gypsum, anhydrite, hematite, and possibly sulphide (Bierlein *et al.*, 1996b; Skirrow *et al.*, 2000). Both CO_2- and CH_4-rich carbonic fluid types were recognised by Bierlein *et al.* (1996b), as well as a range of low to moderate salinity inclusion fluids.

Fluids involved in Cu-Au-Mo mineralisation have calculated ($\delta^{18}O$ compositions of 4.2 to 8.5‰ (n=12, calculated at ~300 to 450º C), which are significantly lower than ($\delta^{18}O$ values of syntectonic regional alteration fluids (8 to 11‰, n=25, calculated at ~450 to 500º C; Skirrow *et al.*, 2000). There is no distinction between calculated (δD for fluids in regional alteration and Cu-Au-Mo mineralisation (-44 to -67‰; n=14). The oxygen and hydrogen isotopic compositions of fluids involved in Cu-Au(-Mo) mineralisation are consistent with a significant input of 'magmatic water', i.e., fluids equilibrated at high temperature with felsic magmas or igneous rocks. It should be noted, however, that no 'causative' intrusions have so far been indentified in the Curnamona Cu-Au systems. Input of fluids equilibrated with metamorphic rocks was subordinate in the ore fluids, whereas 'metamorphic waters' were dominant in fluids responsible for syntectonic regional alteration.

Deposits of the Cloncurry District

Regional Geology

The Cloncurry mining district includes the eastern portion of the Paleo- to Mesoproterozoic Mount Isa Block in northwest Queensland along with adjoining areas with thin cover of Cambrian and/or Mesozoic sedimentary rocks (Figs. 1 and 5). Older rocks crop out in the west and include basement units that were affected by the Barramundi orogeny at around 1890 to 1870 Ma along with granites and volcanic rocks that were emplaced shortly after that event (e.g. Blake and Stewart, 1992). Younger supracrustal

Paragenesis	Age	Ore-forming Conditions	Element Association	References
1) Mag-Bt-Po-Ccp ± Py ± Gt; 2) Chl-Qtz-Py-Ccp	?1600-1570 Ma (no dating)	?300-450ºC	Ag, Pb	Burton (1994); Skirrow *et al.* (submitted)
1) Ab ± Mag 2) Mag-Act-Qtz-Ccp-Mol-Kfs-Py ± Ab; 3) Bt-Ccp-Mo-Py ± Cal/Dol;	~1632-1624 Ma (Re-Os)2	300-450ºC	Mo, As, F, LREE	Hayward (1998); Skirrow et al. (submitted)
1) Ab; 2) Kfs/Hyl-Qtz-Mag-Hem-Ccp-Py; 3) Qtz-Cal-Ft-Ccp-Py	~1614-1616 Ma (Re-Os)[2]; ~1605 &1630 Ma (U-Pb)[4]	?250-400ºC	F, P, V, Zn, Se, Mo, Ag, Te, Ba, LREE, Pb, Bi	Bryant (1998) Teale (2000) Teale & Fanning (2000)
1) Ab (I), 2) Ab (II) 3) Mag-Bt-Kfs-Ccp-Py-Bn ± Brt; 4) Ms ± Sd ± Brt ± Fl	>450 Ma[5]	250-400ºC	F, Ba, LREE, U	Graham (1999); Skirrow *et al.* (2000)
1) Mag-Act-Ab-Ccp-Py-Mo-Bt ± Kfs ± Cal/Dol; 2) Qtz; 3) Chl	~1613 Ma (Re-Os)[2]	300-450ºC	Mo, As	MIM, CEC and Esso open file data; Skirrow *et al.* (2000)
1) Kfs/Ab-Qtz-Bt-Ccp-Py-Mol-Au; 2) Ab ± Mag; 3) Chl-Ms-Cal/Dol	~1612-1631 Ma (Re-Os)[2]	?350-550ºC	Mo	McGeough and Anderson (1998), Cordon (1998); Skirrow *et al.* (1998, 2000, submitted)

Mineral Abbreviations (Tables 1 and 2): Act - actinolite; Ab - albite; Alm - almandine; Adr - andradite; Anh - anhydrite; Ap - apatite; Brt - barite; Bt - biotite; Bn - bornite; Cal - calcite; Cc - chalcocite; Ccp - chalcopyrite; Chl - chlorite; Di - diopside; Dol - dolomite; Fl - fluorite; Gn - galena; Hem - hematite; Hbl - hornblende; Hyl - hyalophane; Kfs - k feldspar; Mag - magnetite; Ms - muscovite; Phl - phlogopite; Py - pyrite; Po - pyrrhotite; Qtz - quartz; Rds - rhodochrosite; Scp - scapolite; Sd - siderite; Sps - spessartine; Sp - sphalerite; Tur - tourmaline.

sequences (cover sequences 2 and 3 of Blake, 1987 and Blake and Stewart, 1992) are widely distributed further east and are the main hosts of the Fe oxide-Cu-Au deposits. Cover sequence 2 (1780 to 1760 Ma) comprises a diverse package of metamorphosed clastic, carbonate and evaporite sedimentary, and mafic, intermediate and felsic volcanic rocks. These are extensively intruded by 1760 to 1720 Ma granites (Wonga Granite) and gabbros in a north-south belt in the central western part of the district. More localised intermediate plutons emplaced at around 1660 Ma occur near the Ernest Henry mine (Pollard and McNaughton, 1997). The younger sequence (1670-1600Ma) is largely composed of metamorphosed siliciclastic sedimentary and basic volcanic rocks which host a number of Pb-Zn-Ag deposits including a the world class Cannington mine. Two major phases of compressional deformation and regional metamorphism occurred at around 1600 Ma (Diamantina orogeny) and 1550-1500 Ma (Isan orogeny; e.g. Laing, 1998; MacCready *et al.*, 1998). The current structural pattern is dominated by steeply inclined, broadly north-trending Isan folds and faults. The metamorphic grade varies from upper greenschist to upper amphibolite facies. The eastern part of the district was extensively intruded by mafic to felsic granitoids of the Williams and Naraku batholiths during the Isan orogeny (Pollard and McNaughton, 1997; Page and Sun, 1998). These granitoids are mainly magnetite series, metaluminous and alkaline to sub-alkaline. They are predominately potassic though minor sodic rocks are also present (Pollard *et al.*, 1998; Wyborn, 1998). They were mainly emplaced at 10 to 15 km depth and are spatially and temporally-associated with the iron oxide -copper- gold deposits. In one case (Lightning Creek, Fig. 5) granitoids host a very large (~1000 Mt) hydrothermal magnetite deposit (Perring *et al.*, 2000).

Regional Alteration

The eastern Mount Isa Block contains huge volumes of rock that experienced significant metasomatism during fluid circulation in middle to upper crustal regimes (Williams, 1994; De Jong and Williams, 1995; Oliver; 1995; Rubenach and Barker, 1998). The alteration products now crop out in areas occupying hundreds of square kilometres. Sodic alteration characterised by albitic plagioclase and locally-developed scapolite predominated in the regional systems varying to sodic-calcic (actinolite, diopside) and iron-bearing (magnetite) styles. Such alteration was episodic and occurred over an extensive time period during a number of quite discrete thermal events, including Wonga granite emplacement, regional metamorphism during the Isan orogeny, and Williams-Naraku batholith emplacement. Products of the youngest episode predominate in the eastern part of the region and are concentrated along the flanks, and in the roof zones of the granitoids. There is no simple or consistent relationship between the distribution of this later large-scale sodic alteration and the broadly

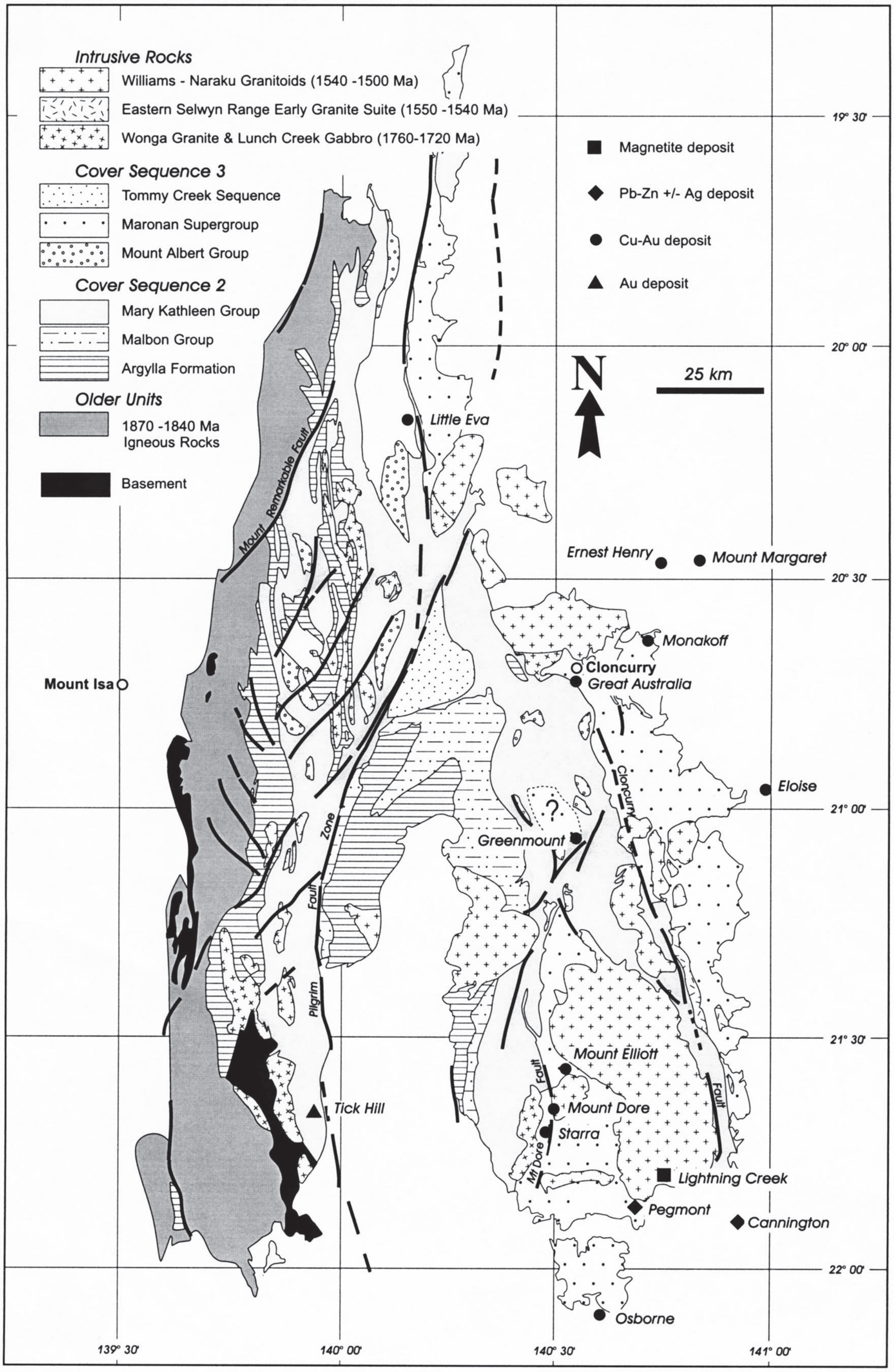


Figure 5: Geology and significant metalliferous deposits of the Cloncurry district (adapted from Williams, 1998, and original sources cited therein).

contemporaneous copper-gold deposits. The largest tracts of altered rocks mostly lack significant deposits though drilling around the concealed Ernest Henry deposit suggests the ore-related alteration and mineralisation there is superimposed on rocks with widespread sodic alteration (Mark and Crookes, 1999). The other significant ore deposits are restricted to relatively narrow structural features though these are commonly characterised by sodic alteration which consistently predates potassic and/or iron-rich alteration styles that had a closer time-space association with mineralisation (Table 2).

Deposit Characteristics

There are hundreds of documented mineral occurrences in the Cloncurry district , most of which are very small Cu deposits (e.g. Raymond, 1992). Only the larger documented iron oxide-copper-gold and related deposits are discussed specifically here (Table 2; Figs. 5 and 6). These display a number of important shared characteristics, including (1) fault or shear zone controls; (2) post-metamorphic timing; (3) presence of high temperature alteration assemblages characterised by minerals such as biotite, garnet, hornblende, clinopyroxene and scapolite; (4) evidence of hypersaline brine and carbonic fluid components present during mineralisation (cf. Pollard, 2000); (5) calculated fluid $\delta^{18}O$ for pre-ore and ore stages in the range 6 to 11‰ (Pollard *et al.*, 1997); and (6) marked cobalt-enrichment. Structural styles, pressure estimates based on the densities of carbonic fluid inclusions, and geobarometry of temporally-associated plutons are all consistent with ore emplacement at depths in excess of 5 km (e.g. Adshead, 1995; Adshead-Bell, 1998; Pollard *et al.*, 1998; Rotherham *et al.*, 1998). A typical characteristic of the ore-related paragenetic sequences is a progression from early sodic alteration to some sort of pre-ore high temperature potassium and/or iron-rich alteration, followed by sulphide deposition with syn- and/or post-ore carbonates. These similarities provide a sound basis for treating the deposits as a related group with shared genetic elements including their age, crustal setting and ore fluid characteristics. However, in detail the deposits are so variable that classification into subgroups with similar geological and exploration characteristics is largely pointless, though as previously noted by Beardsmore (1992), it is possible to define a group of fault-controlled vein and breccia deposits that are stratabound in carbonaceous metasediments (e.g. Greenmount; Fig. 6).

The main variable characteristics, several of which have significant implications for exploration and mining, include: (1) total metal content and grade; (2) Au:Cu ratio, though it is notable that deposits in which the dominant ore assemblage is magnetite+chalcopyrite+pyrite (i.e., lacking pyrrhotite or hematite) typically have Cu (%):Au (ppm) close to 2:1; (3) host rock age, lithology and metamorphic grade; (4) chemistry and mineralogy of high temperature alteration assemblages, e.g. K-Mn-Fe-Ba signature at Ernest Henry (Twyerould, 1997), K-Ca-Mg-Fe at Eloise (Baker, 1998), and Mg-Ca-Fe at Mount Elliott (Wang and Williams, 2001); (5) local structural controls and geometries; (6) relative importance of breccia, vein and replacement mineralisation styles; (7) relationship between magnetite and Cu-Au distribution; and (8) minor element associations.

The lack of any consistent relationship between the abundance of magnetite and Cu-Au enrichment in the deposits at both regional and deposit-scales (cf. Fig. 6) is a particularly important feature for exploration. The Lightning Creek occurrence is an example of a huge magnetite accumulation that apparently only has minor late-stage Cu-Au (Perring *et al.*, 2000). Elsewhere, barren magnetite veins and magnetite-rich breccias are common within the regional sodic alteration systems (Williams, 1994). In some deposits there is a close paragenetic and spatial relationship between magnetite and Cu-Au ore as at Ernest Henry and Osborne though in both these cases the ore environments contain large amounts of earlier-formed magnetite that has no associated sulphides. At Starra, the orebodies are selectively developed in early-formed massive magnetite ironstones but many ironstones lack economic mineralisation, Furthermore, the thin prospective ironstones prove difficult to resolve geophysically from enveloping broad zones of magnetite-altered silicate rocks (Collins, 1987). Yet other systems are zoned such that magnetite displays various degrees of separation from ore metals. At Eloise, the greatest concentration of magnetite lies some 500m away from the economic lodes which themselves have only subordinate magnetite. Zoning at Mt Elliott on the other had has produced both magnetite-rich, and magnetite-absent ore zones in close spatial proximity to each other. The stratabound deposits in carbonaceous rocks are especially notable in that magnetite may be absent (as at Mt Dore) or essentially restricted to alteration assemblages in nearby, less reduced lithologies such as calc-silicates and igneous rocks (as at Greenmount, Krcmarov, 1995).

Age of Mineralisation

All public domain direct geochronological constraints on Cloncurry ore deposits have been obtained from the $^{40}Ar/^{39}Ar$ dating method applied to micas and amphiboles (Twyerould, 1997; Pollard and Perkins, 1997; Perkins and Wyborn, 1998: see Table 2). Structural timing criteria show that the dated minerals crystallised after local metamorphic peak. However, some dates may be less than actual mineralisation ages as some temperatures of ore-formation exceeded the lowest geologically-realistic closure temperatures for the minerals (as low as 250°C for micas , e.g. Richards and Noble, 1998). Amphiboles should have had higher closure temperatures and several have been dated from metamorphic rocks and alteration packages not related to mineralisation that give realistic ages greater than 1550 Ma (Pollard and Perkins, 1997; Twyerould, 1997). This suggests it is probably reasonable to assume that, good younger plateau age spectra from ore deposit amphiboles reflect the actual ages of the systems. On this basis it seems that the ore deposits were created over a significant time interval from at least as old as 1540 Ma (Osborne), through examples formed at around 1530 Ma (Eloise), and others as young as 1510 Ma (Mt Elliott). Younger ages have been obtained from Starra and Ernest Henry biotites that allow for the possibility that some systems might be as young as

Deposit	Resource Information 2000 Status	Main Host Rocks	Confining Structure Style
Eloise	3.2 Mt @ 5.8% Cu; 1.5g/t Au; 19g/t Ag: Underground mine	1.67-1.60 Ga meta-arkose, mica schist, amphibolite	Steeply inclined shear zones Massive sulphide replacements
Ernest Henry	167 Mt @ 1.1% Cu; 0.54 g/t Au Open cut mine	?1.75-1.73 Ga2 metamorphosed intermediate volcanic rocks	Anastomosing dipping shear zones Breccia, minor veins
Great Australia	1.7 Mt @ 1.2 % Cu (oxide) Open cut mine (C&M)	1.67-1.60 Ga metabasalt, metadolerite (upper greenschist facies)	Fault jog Veins
Greenmount	3.6 Mt @ 1.5% Cu; 0.78 g/t Au 0.04% Co Prospect	1.66-1.61 Ga[3] carbonaceous slate, metasiltstone	Fault jog Vein stockwork
Monakoff	1 Mt @ 1.5% Cu; 0.5 g/t Au Open cut mine (closed)	1.67-1.60 Ga schist	Reactivated shear zone Replacement bodies, veins
Mount Dore	26 Mt @ 1.1% Cu, 5.5 g/t Ag Prospect	1.67-1.60 Ga carbonaceous schist	Moderately-dipping faults Veins and breccia
Mount Elliott	3.3 Mt @ 3.6% Cu; 1.8 g/t Au Underground mine	1.67-1.60 Ga carbonaceous schist, amphibolite, trachyandesite	Steep to moderately dipping faults Veins and breccia
Osborne	11.20 Mt @ 3.51% Cu, 1.49 g/t Au Underground mine	1.67-1.60 Ga, pelitic gneiss, plagioclase-biotite schist, magnetite-quartz ironstone	Fault bends Replacement bodies
Starra	6.9 Mt @ 1.65% Cu; 4.8 g/t Au Underground mine (not operating)	ca 1750 Ma schist, calc-silicate	Shear zone Selectively mineralised ironstone replacement bodies

Sources of geochronological data: [1] Baker *et al.*, (1997); [2] Page and Sun (1998); [3] Page and McCready (1997); [4] Pollard and Perkins (1997); [5] Perkins and Wyborn (1998).

Table 2: Summary characteristics of iron oxide-copper-gold deposits of the Cloncurry District.

about 1500 Ma. This range of ages corresponds exactly to those obtained by the SHRIMP U-Pb method from granites of Williams-Naraku batholiths (Pollard and McNaughton, 1997; Page and Sun, 1998).

Ore Fluid Characteristics

Several fluid inclusion studies of Cloncurry ore systems have revealed a consistent association of hypersaline brine and carbonic inclusions (Beardsmore, 1992; Adshead, 1995; Pollard *et al.*, 1997; Baker, 1998; Cannell and Davidson, 1998; Rotherham *et al.*, 1998). Pre-ore brine inclusions typically display extreme salinities (50 to 70% salts) manifested in multisolid-bearing inclusions, and have high homogenisation or decrepitation temperatures (350 to 550°C). Ore-stage brine inclusions typically have lower salinities and were mostly entrapped at 250 to 350°C, and are commonly accompanied by discrete populations of $NaCl$-$CaCl_2$-bearing inclusions. The carbonic fluid inclusions consist predominantly of CO_2 though methane (up to around 15 mole %) occurs in pyrrhotite-associated inclusions from Osborne. Proton microprobe studies of individual brine inclusions have revealed that a considerable diversity of compositions is present with differing Na-K-Ca-Fe-Mn-Ba salt components (Williams *et al.*, 1999). The same studies also suggest that the Cu-contents of these brines were 50 to 2000 ppm and varied from deposit to deposit. Estimated fluid $\delta^{18}O$ is typically in the range 6 to 11‰ (e.g. Pollard *et al.*, 1997; Twyerould, 1997; Rotherham *et al.*, 1998). This suggests the fluids were magmatic and/or metamorphic and that surficial fluids did not play a significant role in ore-genesis.

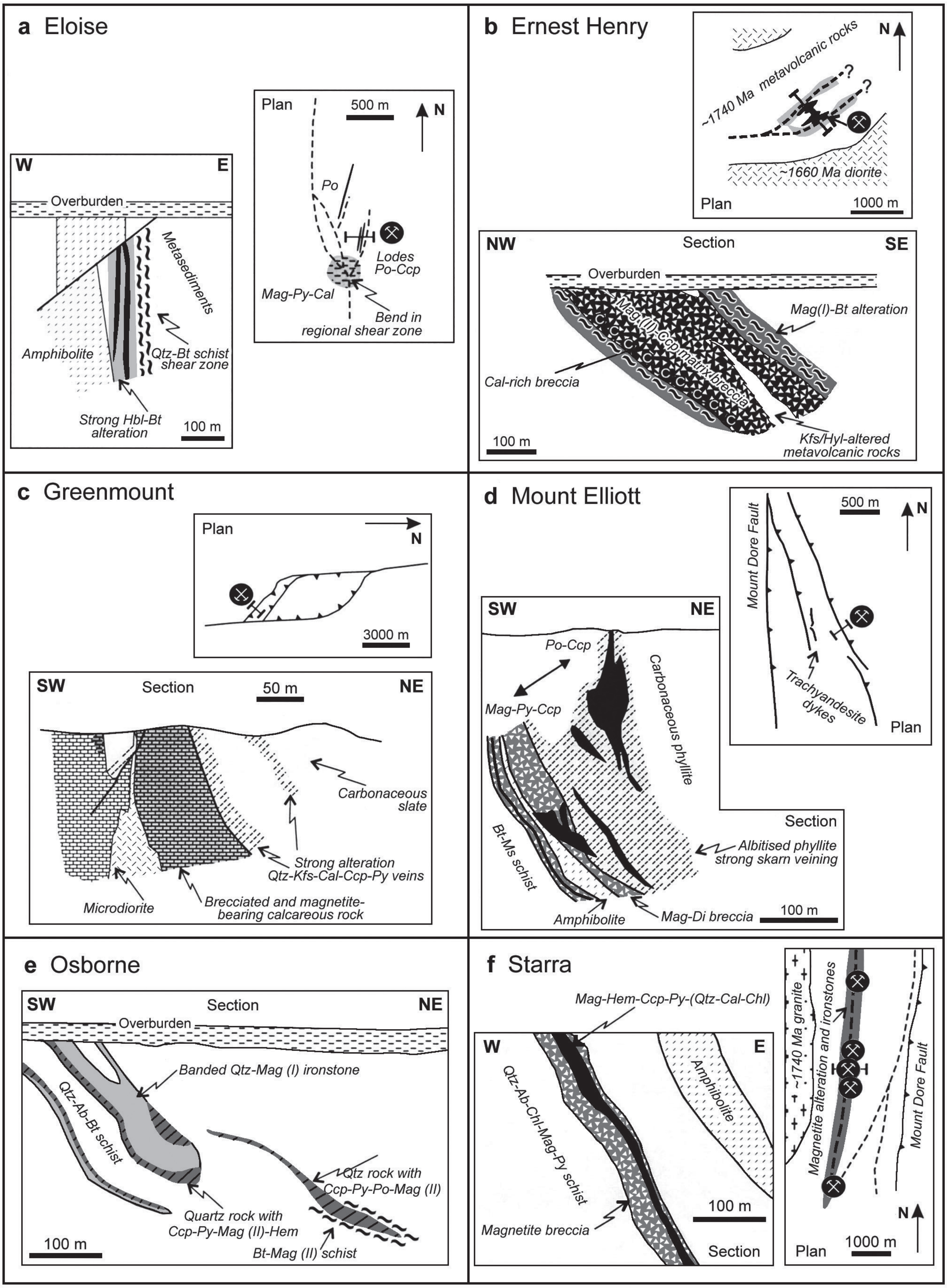
Paragenesis	Age	Ore-forming Conditions	Element Association	References
1) Ab; 2) Hbl-Bt-Qtz; 3) Chl-Ms-Act-Cal-Mag-Ccp-Po-Py	1536-1512 Ma[1] Ar-Ar (Bt, Hbl)	200-450°C	Co, Ni, Zn, As, Pb, Bi	Baker *et al.* (1997); Baker (1998); Baker and Laing (1998)
1) Ab-Di-Act-Mag; 2) Bt-Alm/Sps-Kfs-Mag; 3) Kfs/Hyl; 4) Bt-Qtz-Mag-Ccp-Py-Cal-Brt-Fl; 5) Cal-Dol-Qtz	ca 1510 Ma Ar-Ar (Bt)	400-500°C	F, Mn, Co, As, Mo, Ba,	Twyerould (1997); Ryan (1998); Mark and Crookes (1999)
1) Ab-Act-Mag; 2) Bt-Ms-Hem; 3) Ab-Act-Mag; 4) Chl-Act-Qtz-Cal-Dol-Py-Ccp	<1550 Ma (no dating)	200-500°C	Co, Au	Cannell and Davidson (1998)
1) Ab-Qtz; 2) Kfs-Qtz-Phl-Mag-Cal-Py-Ccp	>1480 Ma[4] Ar-Ar (Ms)	220-500°C	As, Mo	Krcmarov (1995); Krcmarov and Stewart (1998)
1) Sps/Alm-Bt-Mag; 2) Qtz-Mag-Rds/Sd-Brt-Fl-Po-Ccp-Sp-Gn	1508±10 Ma[4] Ar-Ar (Bt)	?	F, P, Mn, Co, Zn, As, Ag, Ba, LREE, W, Pb, U	Davidson and Davis (1997); Davidson (1998)
1) Kfs-Bt-Ms-Qtz-Tur; 2) Dol-Cal-Ap-Py-Ccp	1550-1500 Ma	?300-400°C	B, F, P, Co, Zn, Au, Pb, U	Beardsmore (1992)
1) Ab; 2) Di-Act-Scp; 3) Adr-Mag-Py-Ccp-Po; 4) Cal-Ap	1510±3 Ma[4] Ar-Ar (Act)	ca 350°C	F, P, Co, Ni, LREE	Little (1997); Drabsch (1998); Fortowski and McCracken (1998); Shiqi Wang and Williams (*in press*)
1) Ab; 2) Bt/Phl-Qtz-Mag; 3) Qtz-Mag-Hem-Py-Po-Ccp; 4) Ms-Chl-Cal	1545-1535 Ma[5] Ar-Ar (Bt, Hbl)	300-400°C; > 1.5 kba	Co, Mo, W, Hg	Adshead (1995); Adshead *et al.* (1998)
1) Ab; 2) Bt-Mag; 3) Ms-Chl-Hem-Cal-Anh-Py-Ccp-Bn-Cc	1502± 3 Ma[5] Ar-Ar (Bt)	200-350°C	Co, W	Davidson *et al.* (1989); Rotherham (1997); Adshead-Bell (1998); Rotherham *et al.* (1998)

See Table 1 for explanation of mineral abbreviations.

Synthesis: Curnamona and Cloncurry Deposits Compared

The Curnamona and Cloncurry ore systems formed at quite different times in regions with distinct tectonometamorphic histories (cf. Fig. 3). However, there are striking similarities between the deposits and their geological settings that suggest key aspects of the metallogeny are shared between the two districts. In both cases, mineralisation was a component of regionally-extensive metasomatic systems related to orogeny. The deformation and metamorphism affected latest Palaeoproterozoic (i.e. post-Barramundi) supracrustal sequences with diverse clastic, carbonate-evaporite and volcanic components that had formed in intra-cratonic basins. The ore deposits are largely–restricted to these supracrustal sequences but are controlled by structural features that are not limited by stratigraphy, host rock composition or metamorphic grade. Ore fluids in both regions had brine and carbonic components with stable isotope compositions suggestive of magmatic and/or metamorphic sources, and it seems that the deposits formed at many kilometres depth in environments isolated from surface-derived fluids. Most deposits have a high iron content and high bulk Fe:S resulting in the presence of large amounts of magnetite and/or hematite while chalcopyrite is commonly more abundant than pyrite. In broad terms therefore the deposits of the two regions are products of the same types of distinctive geotectonic setting, geological envrionment and ore-forming fluid.

In many respects though, the deposits throughout the two regions are curiously unified by their differences as much as their similarities. This can be viewed as an inherent feature of the metallogenic context and is a complicating factor in exploration. It is evident that varying host rocks have had a significant influence on both the mineralogical products and styles of alteration and mineralisation. The nature and geometries of the structures that channelled the ore fluids also vary greatly from place to place. Furthermore, detailed metallogenic studies have shown that there was substantial variation in the major component chemistry of the ore-forming fluids and that the precise conditions of mineralisation also varied. It seems that a number of different ore-precipitating mechanisms have dominated in individual cases, including some strongly influenced by specific wall rocks (e.g. ironstones, carbonaceous sedimentary rocks) and others involving quite different processes such as fluid mixing or



phase separation of the carbonic component. Consideration of the Curnamona and Cloncurry deposits together reveals a greater diversity of exploration characteristics than seen in either terrain alone and thus broadens the range of exploration targets in both regions. Experience to date suggests that continued exploration will uncover yet more variations of this ore deposit theme.

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Figure 6: (Facing page) Schematic geological models for iron oxide-copper-gold deposit styles of the Cloncurry district. Adapted from sources listed in Table 2.

a. **Eloise:** Localised in a steeply-inclined north-trending splay related to a bend in a regional shear zone interpreted from geophysical data. High grade pyrrhotite-chalcopyrite replacement lodes are localised by earlier-formed biotite-hornblende alteration zones in meta-arkose and schist. Magnetite is strongly partitioned from copper and concentrated with calcite and pyrite in an altered amphibolite body some 500 m south of the lodes.
b. **Ernest Henry:** Localised by brecciated and K-(Ba) feldspar-altered metavolcanic rocks. These form a southeast-plunging body constrained within an anastomosing shear system with regionally-anomalous northeast-trend and moderate dip. This is developed in a metavolcanic-rock dominated sequence with ca 1660 Ma intermediate plutons to the north and south. Extensive pre-ore fine-grained magnetite-biotite-garnet alteration developed in the largely ductile shear zones whereas the breccia matrix is characterised by a second generation of coarser-grained magnetite that has a close time-space relationship to Cu, Au and pyrite. Syn- to post ore carbonate becomes more abundant towards the footwall.
c. **Greenmount:** Localised along NNW-trending, moderately east-dipping fault within a regionally-extensive north-south fault zone that exploits a major unconformity. Selective magnetite-free, chalcopyrite-pyrite mineralisation was associated with carbonate-K feldspar-quartz veining and alteration of carbonaceous slates in the hanging wall. Magnetite-bearing veining and alteration affected calc-silicate rocks and diorite in the footwall.
d. **Mount Elliott:** Localised on NNW trending splay of regional north-trending fault system. A highly dilational environment was created by northeast-dipping reverse faults and flatter-lying linking faults. Distinctive pre-ore diopside-rich skarn formed largely by infill. Zoned pyrite-pyrrhotite-chalcopyrite-magnetite vein and breccia-hosted mineralisation occurs with abundant late stage calcite infill. Intra-ore trachyandesite dykes are present.
e. **Osborne:** Occurs in an area of anomalous moderate to shallow-dipping, northwest-trending fabrics. Correlation with regional structures is hindered by lack of exposures (blind deposit). High grade quartz-chalcopyrite-pyrite-pyrrhotite-magnetite bodies are developed in feldspathic metasediments and pegmatite and commonly display thin biotite-magnetite alteration selvages overprinted by syn- to post-ore sericite-chlorite-calcite alteration and veining. Crudely banded magnetite-quartz ironstones predate ore emplacement, are widespread in the mine area, and are generally barren or weakly mineralised.
f. **Starra:** Localised by steeply inclined NNE- to north-trending shear zone within a regional shear/fault system. The orebodies are associated with brittle and ductile stuctures. Massive-replacive magnetite ironstone lenses occur over more than 7 km of strike and are enveloped by deformed breccias with magnetite-rich matrix. Some of the magnetite ironstones are selectively mineralised in plunging shoots characterised by a younger chalcopyrite-pyrite-hematite-carbonate association. Hypogene bornite and chalcocite are present locally and associated with high gold grades.

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