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Skirrow, R.G., Bastrakov, E., Davidson, G., Raymond, O.L. and Heithersay, P., 2002 - The Geological Framework, Distribution and Controls of Fe-Oxide Cu-Au Mineralisation in the Gawler Craton, South Australia: Part II: Alteration and Mineralisation; *in Porter, T.M. (Ed.), Hydrothermal Iron Oxide Copper-Gold & Related Deposits: A Global Perspective,* Volume 2; PGC Publishing, Adelaide, pp 33-47.

THE GEOLOGICAL FRAMEWORK, DISTRIBUTION AND CONTROLS OF Fe-OXIDE Cu-Au MINERALISATION IN THE GAWLER CRATON, SOUTH AUSTRALIA.

PART II - ALTERATION AND MINERALISATION

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Abstract - The Olympic Cu-Au province on the eastern margin of the Gawler Craton includes three major regions of hydrothermal alteration and mineralisation: Stuart Shelf basement (including the Olympic Dam Cu-U-Au deposit), Mount Woods Inlier and the Moonta-Wallaroo-Roopena region. Each of these regions contains high-, moderate- and low-temperature Fe-oxide rich alteration, Cu-Au±U mineralisation, and felsic to mafic Mesoproterozoic (~1590 Ma) intrusions of the Hiltaba Suite with or without coeval Gawler Range Volcanics. The three regions are interpreted to represent the ‘footprints’ of separate crustal-scale thermal anomalies. Three key hydrothermal alteration and ore mineral assemblages are recognised in the metallogenic province: (1) CAM: calcsilicate - alkali feldspar ± magnetite ± Fe-Cu sulphides (generally minor); (2) MB: magnetite-biotite ± Fe-Cu sulphides; and (3) HSCC: hematite-sericite-chlorite-carbonate ± Fe-Cu sulphides ± U, REE minerals. Ore grade Cu-U-Au mineralisation is generally associated with the HSCC assemblage, which is paragenetically later than the CAM and MB assemblages in most deposits and prospects. The crustal level of exposure of the hydrothermal systems may vary significantly between and within the three mineralised regions. The CAM, MB and HSCC assemblages and associated Cu-Au mineralisation represent a possible spectrum of settings from deeper, higher temperature, shear-hosted environments to near-surface, low-temperature breccia and fault settings.

Introduction

The Olympic Cu-Au province is a metallogenic belt in the eastern Gawler Craton (Fig. 1) containing a wide range of Fe, Cu, Au, U, REE, and Ag mineralisation. It includes the giant Olympic Dam Cu-Au-U deposit and the recently discovered Prominent Hill Cu-Au prospect. The province is of early Mesoproterozoic age, and extends over 500 km along the eastern margin of the Gawler Craton from the Mount Woods Inlier in the north, through the basement of the Stuart Shelf, to the Moonta-Wallaroo district in the south. Although its boundaries are not yet well defined, this metallogenic province may transgress several tectonic domains including the Mount Woods Inlier and Olympic Domain (Fig. 1; Ferris *et al.*, this volume). Possible extensions of the Olympic Cu-Au province may include hydrothermal systems of the Peake and Denison Domain, Mabel Creek Ridge (southern Nawa Domain; Fig. 1), and the south-central Gawler Craton. The systems may also transgress the Torrens Hinge Zone (THZ), which has been generally regarded as the eastern boundary of the Gawler Craton (Fig. 1). Adelaidean sedimentary rocks rapidly thicken to the east of the THZ, but most probably overlie Gawler Craton basement.

Much of the Olympic Cu-Au province is covered by flat-lying Neoproterozoic to Recent sedimentary rocks and regolith ranging in thickness from a few tens of metres to a kilometre or more. Outcrop is only present in the Mount Woods Inlier and Moonta-Wallaroo district, albeit sparsely. Consequently, almost all of the geological information available for the Olympic Cu-Au province is derived from drilling and geophysical data.

This review paper presents a first synthesis of hydrothermal alteration and mineralisation types and distribution for the Olympic Cu-Au province. This is followed by summary descriptions of the major hydrothermal systems and mineralisation of the Stuart Shelf basement (Fig. 1), Moonta-Wallaroo district, and Mount Woods Inlier. Finally, ore formation models are reviewed, and a new interpretation of crustal settings of the mineralised hydrothermal systems is presented. The geological framework and stratigraphy of the eastern Gawler Craton are described in the companion paper by Ferris *et al.* (this volume).

In addition to the mineralised systems described here, Fe-oxide related Cu-Au mineralisation is known from a number of other areas of the eastern Gawler Craton. For example,

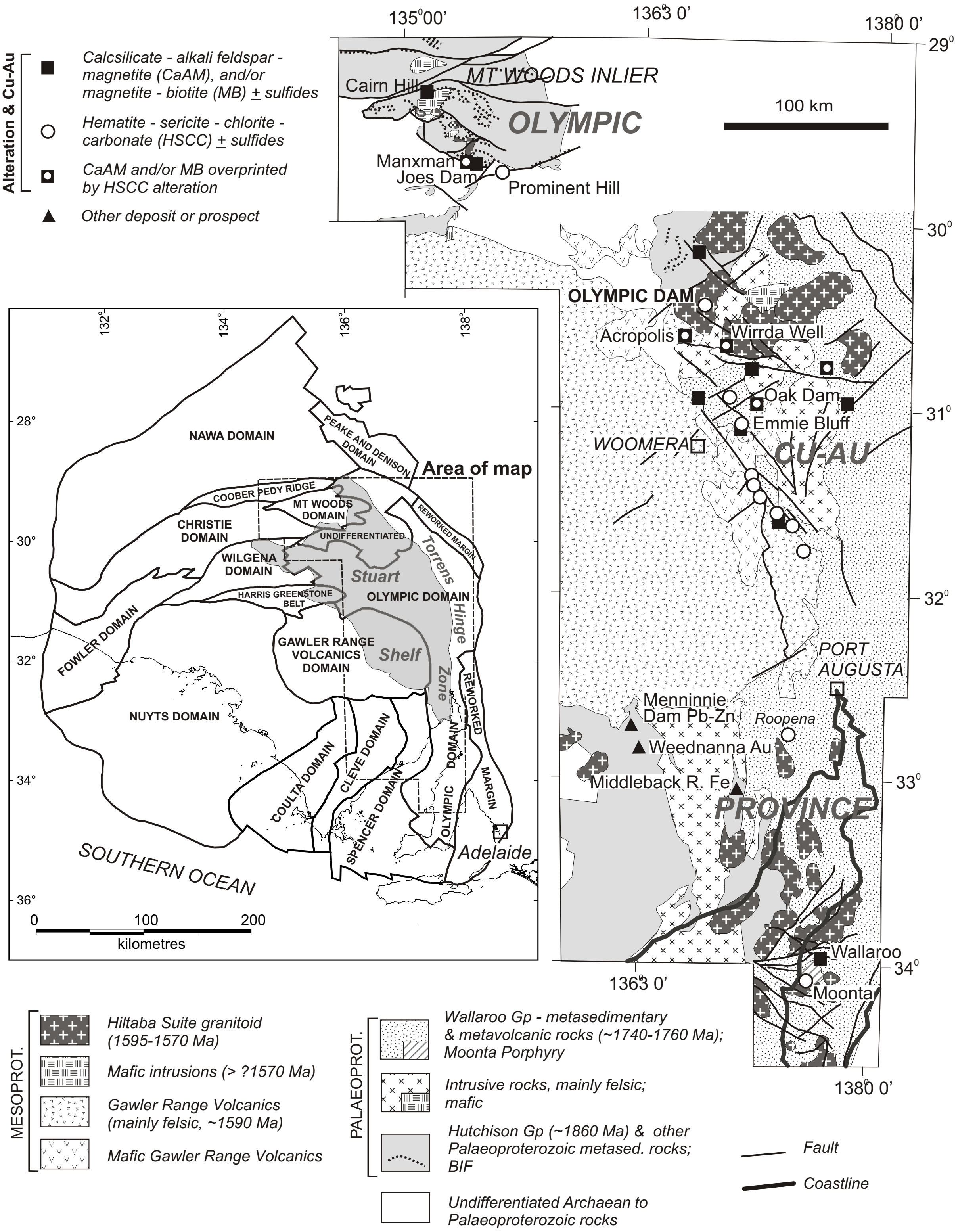

Figure 1: Basement geology interpretation (pre-Pandurra Formation) and alteration in the Olympic Cu-Au province (right), shown in relation to tectonic/magnetic domains of the Gawler Craton (left; from Ferris *et al.*, this volume). Principal Cu-Au±U deposits and prospects are named within the Mount Woods Inlier, basement to the Stuart Shelf, and Moonta-Wallaroo-Roopena regions. The extent of the Mesoproterozoic Pandurra Formation and Neoproterozoic and younger sedimentary rocks of the Stuart Shelf, is shaded in the map at left. Geology map at right compiled from new interpretations of basement to the Stuart Shelf (N. Direen, P. Lyons, L. Jagodzinski, written communication, 2002) and Moonta-Wallaroo district (O. Raymond, written communication, 2002); remaining areas are based on Daly *et al.* (1998).

recent exploration by Helix Resources NL near the Iron Monarch and Iron Prince iron ore deposits in the Palaeoproterozoic Hutchison Group (Fig. 1) has revealed anomalous geochemical values of Cu, Au, Ag, U, Co, Bi (Helix Resources Ltd, 2000). In the Roopena area, to the east of the Middleback Range iron ore deposits, widespread hematitic alteration is accompanied in places by anomalous copper (Drexel *et al*., 1993). As noted by Budd *et al.* (1998) and Ferris *et al.* (this volume), mineralisation in the central and southern Gawler Craton that is believed to be associated with Hiltaba Suite - Gawler Range Volcanics (GRV) magmatism is dominated by gold (eg., Tarcoola, Tunkillia) and base metals (eg., Menninnie Dam; Fig. 1), and apparently lacks Fe-oxide rich or high-temperature alteration.

Overview of Hydrothermal Alteration in the Olympic Cu-Au Province

The Olympic Cu-Au province contains enormous volumes of hydrothermally altered rock, represented by highly diverse oxide-sulphide-silicate-carbonate mineral assemblages formed under a range of conditions of temperature, pressure, oxidation-reduction and pH. Re-logging of diamond drill core, being undertaken in current studies at Geoscience Australia and PIRSA, has resolved three broad groupings of alteration assemblages, which are now recognised in hydrothermal systems occurring from the Mt Woods Inlier through Stuart Shelf basement to the Moonta-Wallaroo district:

- CAM: calcsilicate (clinopyroxene, amphibole, garnet) - alkali feldspar (K-feldspar, albite) ± magnetite ± Fe-Cu sulphides
- MB: magnetite - biotite ± Fe-Cu sulphides
- HSCC: hematite - sericite - chlorite - carbonate ± Fe-Cu sulphides ± U, REE minerals.

Gow (1996) documented high temperature ‘skarn’ and lower temperature hematitic assemblages, roughly corresponding to the first and third groups above, in several prospects hosted by basement to the Stuart Shelf. The CAM and MB assemblages were described in the Moonta-Wallaroo district by Conor (1996), whereas Hampton (1997) recorded aspects of all three broad assemblages in the Manxman and Joes Dam prospects in the Mount Woods Inlier. The Olympic Dam deposit is dominated by the HSCC assemblage, although magnetite ± siderite are also present (Reeve *et al*., 1990) and may be related to the CAM or MB alteration types observed elsewhere in the Olympic Cu-Au province. Not all minerals in each broad assemblage are necessarily present at any particular occurrence, and numerous variations on these themes are present. The assemblages CAM and HSCC may represent end-members of high-temperature and low-temperature hydrothermal conditions, with MB as a transitional style.

Few absolute age constraints exist for hydrothermal activity in the Olympic Cu-Au province. Constraints from U-Pb zircon dating at Olympic Dam indicate that brecciation, ore metal deposition, and Hiltaba Suite-GRV igneous activity occurred at about 1590 Ma (Reeve *et al*., 1990; Johnson & Cross, 1995). For the Acropolis prospect, southwest of Olympic Dam, Mortimer *et al*. (1988) report U-Pb and Pb-Pb ages of 1601±8 Ma and 1602±7 Ma for apatite in veins containing magnetite.

Multi-stage paragenetic sequences have been identified in individual deposits and prospects, yet, in almost all occurrences one or more of the CAM, MB and HSCC assemblages is recognised. In all cases documented in the present study, the CAM and MB assemblages are paragenetically earlier than the HSCC assemblages. Each of the three assemblages developed in a wide variety of host rocks including metasedimentary, mafic and felsic volcanic, and granitoid rocks, indicating that metasomatism commonly involved major mass transfer between fluid and rock. The products of the most intense metasomatism were only locally or partially controlled by host rock composition, eg., in calcareous sedimentary rocks.

Textural styles of the three alteration assemblages vary widely according to the nature of structural controls, crustal depth, host rock permeability, etc. Open-space fill, brecciation, and vein networks are characteristic of alteration styles in upper crustal environments (eg., Olympic Dam, Reeve *et al*., 1990; Prominent Hill, Minotaur Resources, 2002), whereas pervasive replacement zones controlled by ductile or brittle-ductile deformation elements are typical of alteration at deeper crustal levels (eg., Moonta-Wallaroo district).

Other minerals that may be present in the CAM assemblages include pyrite, quartz, titanite, scapolite, epidote, and minor pyrrhotite, chalcopyrite, and allanite. Based on drill hole data, CAM assemblages have been documented in the Mt Woods Inlier (Hampton, 1997), the northern Stuart Shelf basement, with the notable exception of the Olympic Dam deposit, and in the Moonta-Wallaroo district. Although calcsilicate-rich metasedimentary rocks are present in the Mt Gunson area, they contain little or no hydrothermal magnetite. These assemblages may reflect isochemical thermal metamorphism of calcareous precursor sedimentary rocks (Gow, 1996). Thus, as at Olympic Dam, hydrothermal alteration found in the Mt Gunson area appears to be dominated by HSCC assemblages.

Magnetite-biotite assemblages are known mainly from the Mt Woods Inlier and Moonta-Wallaroo districts. In the Manxman and Joes Dam prospects, the MB assemblages are interpreted to have overprinted clinopyroxene-scapolite-albite CAM assemblages (Hampton, 1997). One, or more, of pyrite, pyrrhotite, chalcopyrite, molybdenite (Moonta-Wallaroo only), apatite, amphibole, titanite, albite, tourmaline, stilpnomelane, fluorite, and monazite, may be present in MB assemblages. Most Fe-Cu sulphides in Wallaroo-style mineralisation were deposited with the MB assemblage, whereas Hampton (1997) proposed a separate, post-MB chalcopyrite-pyrite ± hematite event at Manxman and Joes Dam.

The HSCC assemblages are the most significant associates of Cu-Au-U mineralisation at the Olympic Dam deposit and Emmie Bluff prospect (Reeve *et al*., 1990; Gow, 1996).

Based on limited open-file data, this association may also be present at the Wirrda Well and Prominent Hill prospects (Cross, 1993; Minotaur Resources, 2002). The major Fe-Cu sulphides are chalcopyrite, pyrite, and hypogene bornite and chalcocite, although these did not necessarily form synchronously and occur in zoned assemblages at Olympic Dam (chalcopyrite-pyrite and bornite-chalcocite zones; Reeve *et al.*, 1990). Various minerals containing U, LREE, Th, Co, Ni, Pb, and As are found in HSCC assemblages (Reeve *et al.*, 1990; Gow, 1996; Hampton, 1997). Fluorite and barite are locally present in HSCC assemblages, and also form post-sulphide veins (eg., Olympic Dam, Reeve *et al.*, 1990).

Previous studies and recent results from Geoscience Australia and PIRSA studies suggest that occurrences of albite, K-feldspar, sericite, and biotite in hydrothermal alteration assemblages are regionally zoned within the Olympic Cu-Au province. Albitisation is widespread and locally intense in the Moonta-Wallaroo district, and is also present in the Mt Woods Inlier, generally in association with CAM assemblages that may contain scapolite. K-feldspar alteration is known from much of the Olympic Cu-Au province, although it is notably absent from Olympic Dam where sericite is the sole hydrothermal K-silicate. Sericitisation is widely distributed in alteration systems in basement to the Stuart Shelf, but it is uncommon in the Moonta-Wallaroo district where biotite is the dominant layer-silicate alteration mineral. In the Mt Woods Inlier, sericite is not a major constituent at Manxman and Joes Dam, though it is present in the Prominent Hill prospect. The regional distributions of feldspar and K-silicates, along with other minerals in alteration assemblages, provide important constraints on variations in fluid properties and conditions of metasomatism and mineralisation in different parts of the Olympic Cu-Au province. Further documentation and interpretation will be presented elsewhere.

Olympic Dam Cu-Au-U-Ag-REE Deposit

As comprehensive descriptions of the Olympic Dam deposit have been given by Reeve *et al.* (1990), Cross *et al.* (1993), Haynes *et al.* (1995), and Reynolds (2000), only a summary of the broader scale features and paragenesis is given here.

The Olympic Dam deposit (Table 1) was discovered, in 1975, by WMC beneath ~300m of flat lying Stuart Shelf sedimentary rocks, and came into production in 1988. Although the orebody extends more than 3 km in a roughly northwest-southeast direction, it occupies only a small proportion of the Olympic Dam Breccia Complex (ODBC). The ODBC is entirely hosted by the Roxby Downs Granite, a member of the Burgoyne Batholith which, in turn, forms part of the Hiltaba Suite. Brecciated granite forms a zone measuring about 7 km x 5 km in plan, centred on a core of barren hematite-quartz breccias. The core is flanked to the northwest, north and east by diverse and multi-stage hematitic breccias, which are the main host to Cu-U-Au mineralisation. Minor rock types in the ODBC include high-level, ultramafic to felsic intrusives, laminated tuffs, and other volcaniclastics. U-Pb ages of zircons from some of the felsic rocks in the ODBC are indistinguishable from the age of the Roxby Downs Granite and GRV and indicate

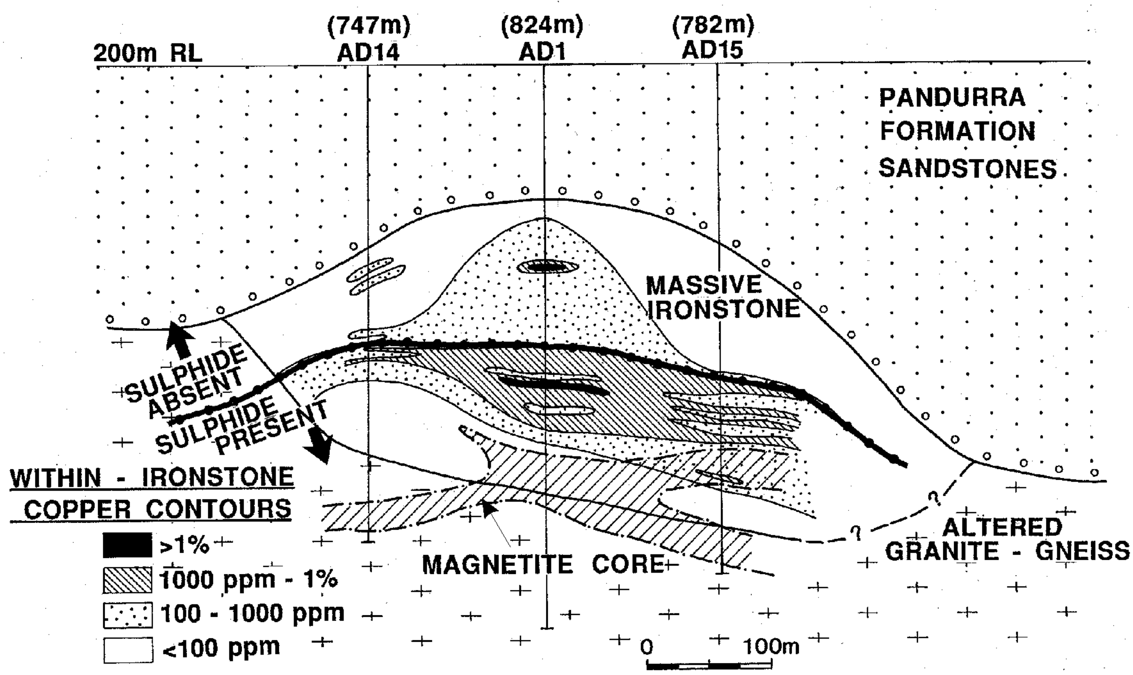

Figure 2: East-west geological cross-section of the Oak Dam East mineralised ironstone, showing the relationship to the Adelaidean unconformity, the location of high susceptibility magnetic zones, and geochemical contours for Cu. Note that the section commences 200 m below surface.

that development of the ODBC was coeval with Hiltaba Suite-GRV igneous activity (Cross *et al.*, 1993; Johnson & Cross, 1995). The volcaniclastic rocks are interpreted to have formed in maar craters by phreatic and phreatomagmatic processes, concurrent with emplacement of ultramafic to felsic dykes (Reeve *et al.*, 1990; Cross *et al.*, 1993; Haynes *et al.*, 1995).

Most of the breccia zones within the ODBC are elongate and have steep dips; north-northwest trends are common along a west-northwest axis. This structure has been interpreted to have developed within a dilational jog related to dextral strike-slip movement on a regional west-northwest trending fault zone (Cross *et al.*, 1993). The hematitic and granitic breccias are the product of a complex interplay between faulting, phreatomagmatic activity, and hydrothermal processes within an eruptive environment.

Three mineral associations are documented (Haynes *et al.*, 1995). The paragenetically earliest (*association 1*) in each of multiple mineralisation episodes comprises magnetite ± hematite, chlorite, sericite, siderite, pyrite, chalcopyrite, and pitchblende. Magnetite is only locally abundant, as this assemblage is in general overprinted by *association 2* containing hematite, sericite, chalcocite, bornite, pitchblende, barite, fluorite, and chlorite. The later stages of mineralisation are characterised by hematite, quartz, and vein barite (*association 3*).

Although overlapping in time and space, there is a gross vertical zonation from *association 3* at higher levels to *association 1* at depth. A key feature mapped across the deposit is the interface between bornite- (± chalcocite) and chalcopyrite-bearing assemblages. This interface undulates at a depth of ~100-300 m below the top of the deposit but locally traces subvertical pinnacle-like extensions, and dips towards the hematite-quartz core. The protruberances in this surface are interpreted to represent upflow zones of fluids responsible for *association 2* (Haynes *et al.*, 1995).

A summary of fluid inclusion and stable isotope data are given in Table 1. Ore deposition mostly occurred at temperatures of 150-250ºC (Oreskes & Einaudi, 1992; Cross *et al.,* 1993), and involved a wide range of fluid salinities. Two fluids were present, either during temporally separate stages (Oreskes & Einaudi, 1992) or synchronously (Haynes *et al.*, 1995), as discussed further below.

Wirrda Well and Acropolis Cu-Au Prospects

Brief descriptions of the Wirrda Well Cu-U-Au and Acropolis Cu prospects are given in Paterson (1986), Parker (1990), Cross (1993), and Daly *et al.* (1998). The Acropolis prospect comprises two main zones of iron oxide-rich alteration about 7 km apart. Most of the Cu (-U-Au) mineralisation occurs in the northwestern zone where magnetite, hematite, K-feldspar, quartz, and apatite occur in vein networks and massive replacements within sericitised GRV dacite. The volcanics overlie meta-sedimentary rocks correlated with the Palaeoproterozoic Wandearah Formation, foliated granite, and diorite. A breccia of granite clasts in a magnetite-hematite-rich matrix is developed in the southeastern alteration zone. Breccias and hematisation are more extensively developed at Wirrda Well and are hosted by granite of the Hiltaba Suite, foliated granite, and by Palaeoproterozoic metasedimentary rocks. Other minerals reported at Acropolis and Wirrda Well include pyrite, chalcopyrite, siderite, chlorite, barite, fluorite, phlogopite, and uraninite (Cross, 1993). Bornite is present at Wirrda Well. Oxygen isotope data for magnetite - K-feldspar pairs in veins at Acropolis were reported by Oreskes and Einaudi (1992; Table 1).

Oak Dam Cu-U Prospect

WMC Ltd discovered the Oak Dam prospect in 1976 by targeting coincident intense magnetic and 3-4 mgal gravity anomalies, 39 km west of Lake Torrens (Paterson, 1986). The prospect was described by Davidson (1991) and Davidson and Paterson (1993). Thirteen drill holes revealed two very large iron-oxide bodies (ironstones) whose tops were intersected below an unconformity at the base of 400-500 m of flat-lying Adelaidean cover (Fig. 2). Ironstone cobbles shed into the basal Pandurra Formation during weathering of the basement provides evidence of a minimum age of 1424±51 Ma (Fanning *et al.*, 1983) for the ironstone development. The eastern ironstone, Oak Dam East, was the source of the targeted coincident magnetic and gravity anomalies. Infill drilling delimited ore-grade U (Table 1) to a 200 m x 200 m x 60 m-thick zone within the overall 1200 m x 400 m x 300 m-thick ironstone zone. A second non-magnetic ironstone, termed Oak Dam West, forms a gravity anomaly about 4 km west of Oak Dam East. Limited drilling penetrated a thick sequence of barren hematite sandstones and conglomerates resembling the interpreted maar-fill volcaniclastic facies at Olympic Dam. The underlying rocks have not been drilled.

The Oak Dam East ironstone occurs on the northernmost tip of the regional north-south Pernatty Culmination; basement isopachs and the ironstone itself parallel the north-south trend. Intense brecciation, similar to that in the ODBC, is the dominant feature of Oak Dam East. Fragments of gneissic granite (possible equivalents of the Donington Suite; Creaser, 1989) and minor schist (Hutchison Group?) are common, variably replaced by the dominant hematite ± quartz assemblage. The lower limit of intense iron metasomatism and veining coincides with a distinct decrease in the intensity of brecciation, forming a flat 'base' to the host ironstone body. The lateral margins have not been intersected in drilling.

The basement and small areas of the ironstone are transected by 0.5-5 m-wide dykes of undeformed, weakly sericitised, coarse-grained to pegmatitic alkali granite (Hiltaba Suite?), medium-grained diorite (very altered), and altered thin mafic dykes with peperitic margins. This evidence indicates that felsic and mafic magmatism was contemporaneous with ironstone formation and brecciation, but did not form the main hostrock to ironstone.

Table 1. Characteristics of selected Cu-Au deposits and prospects of the Olympic Cu-Au province.

Deposit/ prospect	Tonnage-grade or intersections	Hostrock geology	Ore/alteration Paragenesis	Mineralisation textures, style	Mineral and metal zoning	Controlling Structure	Fluid properties	References
Olympic Dam	2320 Mt @ 1.3% Cu, 0.5 g/t Au, 0.4 kg/t U_3O_8, 2.9 g/t Ag (resource, 1999)	[1] ODBC hosted by Roxby Downs Granite; ODBC contains multi-stage hematitic breccias & minor volcaniclastics; minor felsic & mafic/ultramafic dykes	1. Mt ± Hm, Chl, Ser, Sid, Py, Cpy, Pit 2. Hm, Ser, Cc, Bn, Pit, Bar, Flu, Chl 3. Hm, Qtz, Bar	Disseminated sulphides in hematitic breccia matrix & clasts; also sulphides in veins	Gross zonation from assoc 1 at depth to 3 at higher levels; sulphide zonation upwards from Py to Cpy to Bn to Cc; higher Au at margin of barren Hm-Qtz core in ODBC	Long dimension of ODBC trends NW	Assoc. 1 fluid: T = 250-400°C, $\delta^{18}O_{fluid} \approx 10‰$; Assoc. 2 fluid: T = 150-400°C, $\delta^{18}O_{fluid}$ <9‰; 7-42 eq.wt% NaCl; $\delta^{34}S_{sulphides}$ = –6 to -10‰ (av.); $\delta^{34}S_{barite}$ =10‰ (av.)	Reeve et al. (1990), Oreskes & Einaudi (1992), Haynes et al. (1995), Eldridge & Danti (1994), Reynolds (2000), Conan-Davies (1987).
Acropolis	66m @ 0.7% Cu	Felsic GRV, granitoid, gniessic alkali granite	Mt and/or Hm, Sid, Qtz, Kfs, Ser, Chl, Bar, Flu, Ap, Phl, Py, Cpy, Uran	Vein networks & granite breccia; massive Fe-oxides		Fault-controlled breccia(?)	T = 440-550°C $\delta^{18}O_{fluid} \approx 10‰$	Parker (1990) Cross (1993) Oreskes & Einaudi (1992)
Wirrda Well		Burgoyne granite, breccia clasts of Palaeoproterozoic deformed granite, Hutchison Gp	Hm, Mt, Sid, Qtz, Kfs, Ser, Chl, Bar, Flu, Ap, Phl, Py, Cpy, Uran,	Breccia & vein networks		Fault-controlled breccia(?)		Parker (1990) Cross (1993)
Oak Dam	7 m @ 0.27% Cu & 63 m @ 0.32% Cu & 690 ppm U; ~ 560 Mt massive Fe; 216 m @1480 ppm La, 1615 ppm Ce.	Deformed Palaeoproterozoic granitoids and metasediments; cut by Hiltaba Suite granite dykes, minor diorites, and mafic dykes.	1. Mag-Qtz-Ap-Py 2. Colloform Hm 3. Hm after Mt; chalcedony, Qtz-illite, Chl, Ser, Mon, Cpy, Py, Car, Sp, Ap, Carb, Uran; 4. Vughy Qtz ± Bar.	Disseminated sulphides in hematitic breccia matrix & clasts; sulphides in veins; replacement of colloform bands	Upper ~100 m weathered to hem-limonite; below this, mineralisation forms 25-180 m thick blanket (Cpy after dissem Py only). Main REE-P-Mt zone underlies this.	Ironstone was exposed on Pandurra Fm unconformity at 1424 Ma; this process left an erosional remnant with a strong north orientation, parallel to "Pernatty Culmination"	Early fluids: CO_2-L-V T = 360-495°C, 46.4 wt % NaCl; Syn-Cu-U fluid (L-V; boiled): T = 160-205°C, 1.3-4.7 eq.wt% NaCl; $\delta^{34}S_{sulphides}$ = –14 to 0‰ (av.)	Davidson (1991), Davidson & Paterson (1993)
Emmie Bluff	Up to 2.8% Cu, 0.6 g/t Au	Wandearah Fm, granite (in north); GRV dacite (in south)	1. Mt (+Cpx, Amph, Gt, Qtz, Cal, Kfs, Py, Allan in south) 2. Cpy, Bn, Hm, Chl, Qtz, Cc (in north)	Disseminated sulphides in tectonic breccias	Upper Hm-Chl-Qtz, lower Mt-Chl-Py	?Shallow-dipping splays of major NW-striking fault	Early fluid: T = 490-550°C, $\delta^{18}O_{fluid}$ 6.5-7.5‰; later fluid: T <430°C, $\delta^{18}O_{fluid}$ <4.6-8.2‰	Gow (1996)

Deposit/ prospect	Tonnage-grade or intersections	Hostrock geology	Ore/alteration Paragenesis	Mineralisation textures, style	Mineral and metal zoning	Controlling Structure	Fluid properties	References
Moonta (including Wheal Hughes, Poona)	approx. 6.75 Mt @ 5% Cu, 1-4 g/t Au (Moonta-Wallaroo combined)	Metarhyolite (Moonta Porphyry)	Qtz, Kfs, Bt, Tm, Hm, Cpx, Chl, Cpy, Py, Bn	Fissure veins up to 8 m wide	Bn towards the surface; Cpy at deeper levels	Arcuate sets of steeply dipping veins. Mineral-isation along veins and at intersections of veins and fractures		Dickinson (1953) McBriar (1962) Hafer (1991)
Wallaroo		Phyllite, biotite schist (Doora Metasediments)	Qtz, Carb, Tm, Ap, Flu, Amph, Cpx, Mt, Kfs, Bt, Py, Po, Cpy	Replacement and dissem-inations along foliation and shears		En echelon ductile shears		Dickinson (1953) McBriar (1962)
Manxman, Joes Dam	Up to 1.7% Cu, 2.5 g/t Au; anomalous LREE, Co; 287m @ 0.23% Cu, (Manxman A1)	Mt- & cal-rich breccias of pelitic metaseds; I-type granitoid, felsic to intermediate gneisses, granulite	1. Alb, Scap, Cpx, Qtz, Act, Ap 2. Mt, Bt, Ap, Tit, REE mins, Hm 3. Po then Cpy, Py, REE & U & Th mins, Hm, Co-Ni-As-Pb mins, Amph, Chl, Cal, Alb, Flu, Kfs, Sti, Bar, Ser, Ep	Sulphides as vein fill, dissem. & in breccia matrix; massive Mt & Hm zones	Inner & early Po to outer/later Py-Cpy to outermost Py; inner Mt, outer Hm	Fault(?) control on sulphide & oxide zonation	1. <500ºC (?) 2. 400-500ºC (?) 3. 200-400ºC (?)	Hampton (1997)
Prominent Hill	107m @ 1.94% Cu, 0.65g/t Au, 1.6g/t Ag; incl 20m @ 3.0 g/t Au; & 17 m @ 2.35% Cu, 1.07g/t Au, 3.3 g/t Ag, 1398 ppm U	Hematitic breccias hosted by metasediments & 'felsic volcs'	1. Cpy, Bn, Cc, Hm, Ser, silica 2. Flu, Uran	Dissem sulphides in breccia	Upper Cc; Lower Cpy-Bn-Uran	East-West trending gravity anomaly		Minotaur Resources Ltd. (2002)

[1] ODBC: Olympic Dam Breccia Complex (Reeve et al., 1990)

Mineral abbreviations: Alb – albite, Allan – allanite, Amph – amphibole, Ap – apatite, Bar – barite; Bn - bornite, Bt – biotite, Car – carrolite, Carb – carbonate, Chl – chlorite, Cpx – clinopyroxene, Cpy – chalcopyrite, Dol – dolomite, Flu -fluorite, Gal – galena, Hm – hematite, Kfs – K-feldspar, Mar – marcasite, Mon – monazite; Ms – muscovite, Mt – magnetite, Phl – phlogopite, Pit – pitchblende; Po – pyrrhotite, Py – pyrite, Qtz – quartz, Scap – scapolite, Ser – sericite, Sid – siderite, Sp – sphalerite, Sti – stilpnomelane, Tm – tourmaline; Uran – uraniniite.

Ironstone textures provide evidence for an early high temperature magnetite - apatite - calc-silicate ± pyrite assemblage, which is still partly preserved near the base of the ironstone. Brecciation was followed by development of large-scale open space infill by colloform hematite and quartz in the upper part of the body, as well as isolated development of hematite oolite-filled fractures interpreted to have been deposited from boiling of fluids. Approximately synchronous with the onset of sulphide mineralisation, a second, very widespread, steely hematite phase then partially replaced earlier fabrics.

Chalcopyrite and pitchblende are concentrated in a blanket-like 20-180 m-thick subhorizontal layer about 100 m below the unconformity. Above the blanket, there is a rapid transition to a hematite-limonite oxide zone, with evidence of replacement of pre-existing pyrite and chalcopyrite. This is interpreted as pre-Pandurra Formation Proterozoic weathering (Davidson and Paterson, 1983). Within the 'blanket', hydrothermal chalcopyrite, sphalerite, pitchblende, and carollite (associated with illite replacement), sericite, quartz, and monazite, have commonly replaced disseminated pyrite adjacent to fractures and veins.

Emmie Bluff Cu-Au Prospect

The Emmie Bluff Cu-Au Fe-oxide deposit was discovered by drilling coincident gravity and magnetic anomalies in basement, under 800-900 m of Pandurra Formation and younger cover. The following summary is based on Gow (1996). Two major zones of Fe-oxide rich alteration have been located about 3 km apart, as follows.

1 The northern, stratabound alteration zone is up to ~150 m thick, ~3 km in diameter, and is hosted by chert, shale, and carbonate-bearing metasedimentary rocks of the Wandearah Formation. The alteration is characterised by magnetite, hematite, chlorite, and quartz, and hosts the principal zone of Cu-Au mineralisation.
2 The southern, discordant alteration zone contains veins and replacements within rhyodacite of the Gawler Range Volcanics, intersected at more than1 km depth. Veins contain skarn-like, high-temperature mineral assemblages with combinations of clinopyroxene, amphibole, magnetite (<10% vol.), garnet, quartz, calcite, K-feldspar, pyrite, and allanite. Magnetite occurs disseminated in alteration selvages adjacent to veins. Albite veins are found within the rhyodacite. Sulphides, other than pyrite, are rare.

The chemical meta-sedimentary host sequence and underlying medium- to coarse grained meta-arkosic rocks and Palaeoproterozoic metagranite are interpreted to have been faulted against the Gawler Range Volcanics along the Southern Arcoona Fault Zone (Gow, 1996). Initial movement on the northeast-trending, southwest-dipping, fault zone was normal. This was followed by inferred reverse reactivation along shallow-dipping splays that resulted in tectonic emplacement of meta-granite wedges within the Wandearah Formation.

Copper-gold mineralisation in the northern alteration zone is hosted by brecciated, laminated meta-sedimentary and meta-granitic rocks. Grades of up to 2.8% Cu and 0.6 g/t Au are reported. The Fe-Cu-Au deposit is crudely zoned downwards from breccia and cataclasite zones with intense hematite-chlorite-quartz alteration and containing chalcopyrite-pyrite-bornite-covellite, to less brecciated magnetite-chlorite-pyrite altered laminated metasedimentary zones with lower abundances of Fe and Cu sulphides. Gow (1996) interpreted the breccias in the northern alteration zone to be of tectonic origin, related to reverse reactivation of the Southern Arcoona Fault Zone. Hematisation of pre-existing magnetite, and accompanying Cu-Au mineralisation, were also envisaged to have occurred during the fault reactivation.

Moonta-Wallaroo Cu-Au District

The Moonta-Wallaroo district is situated in the southern part of the Olympic Cu-Au province (Figure 1). During the latter part of the 19^{th} century the Moonta and Wallaroo Mines were largely responsible for South Australia being one of the world's largest copper producing provinces at that time. The historic yield from the Moonta-Wallaroo district, mostly during that period, totalled approximately 355 000 tonnes of contained copper and 2 tonnes of gold (Conor, 1995).

Basement outcrop in the Moonta-Wallaroo district is very poor, and is typically covered by up to 100 metres of Neoproterozoic to Quaternary sediments. The basement comprises meta-sedimentary and meta-volcanic rocks of the Palaeoproterozoic Wallaroo Group, which were intruded by Mesoproterozoic granitoids of the Hiltaba Suite. Fine grained albitic meta-sedimentary rocks, in places scapolite-bearing, are common in the Wallaroo Group. Calcsilicate skarns were commonly developed within calcareous meta-sedimentary rocks. SHRIMP zircon U-Pb ages of felsic volcanic rocks in the Wallaroo Group range from 1737±5 Ma to 1763±14 Ma (Fanning *et al.*, 1988, Conor 1995). Regional upper greenschist to amphibolite facies metamorphism and deformation of the Wallaroo Group occurred during the Kimban Orogeny (ca. 1720 Ma; Ferris *et al.*, this volume).

Well-constrained ages of Hiltaba Suite magmatism within the Moonta-Wallaroo district range from 1575±7 Ma to 1598±7 Ma (compiled in Zang, 2002). Intrusion of these granitoids was accompanied by contact metamorphism, shearing, and high temperature Fe-Na-Ca±K metasomatism of the adjacent Wallaroo Group and, in places, of the granitoids themselves. Conor (1996) referred to these altered rocks as the Oorlano Metasomatites, although metasomatic mineral assemblages vary widely. At a regional scale, there is a strong spatial association of Fe-Na-Ca metasomatism with the contact aureoles of Hiltaba Suite granites. At a drillhole scale, metasomatic alteration zones emanate away from granite bodies and dykes, with fluids commonly focussed along foliation and shear zones within the host rocks.

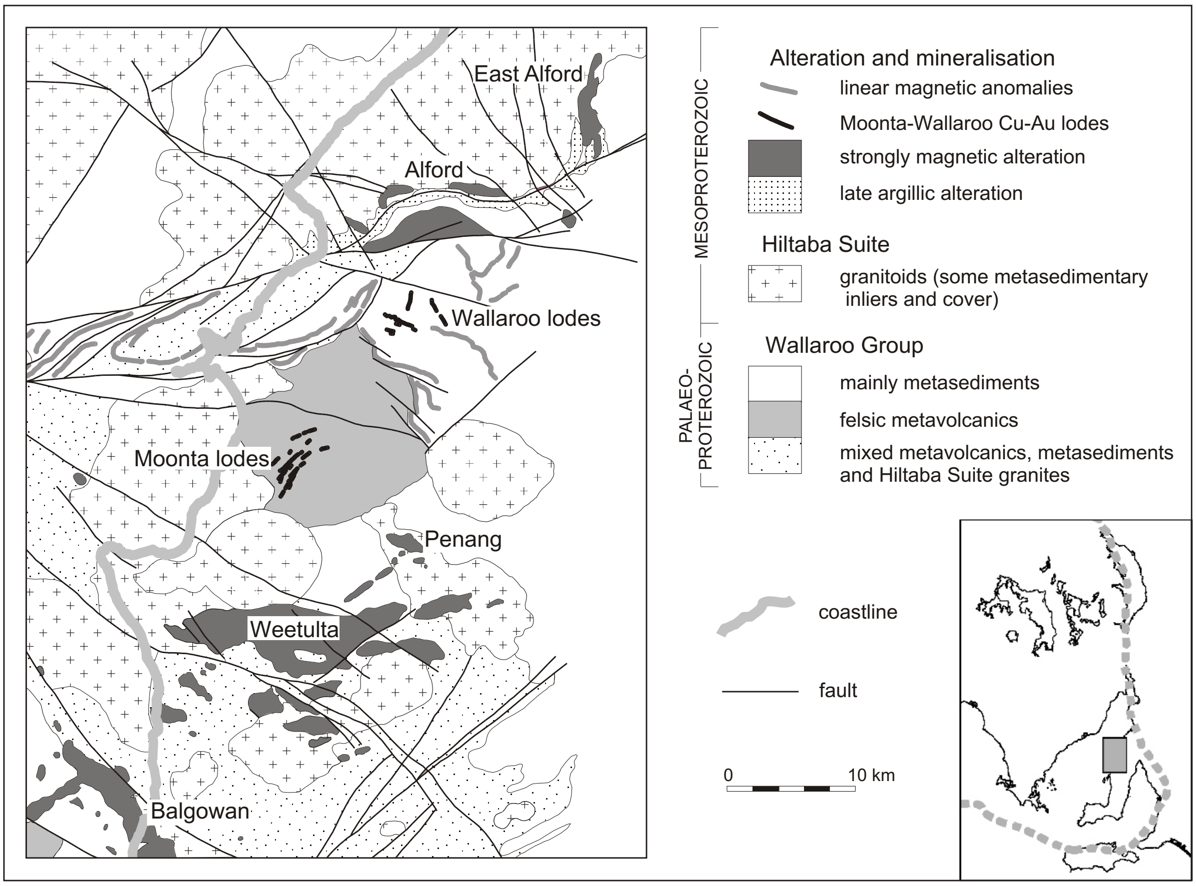

Figure 3: Basement geology sketch map of part of the northern Yorke Peninsula, showing the distribution of Hiltaba Suite granitoids and magnetic alteration. Inset shows location of map and the boundary of the Gawler Craton.

Albite-actinolite-magnetite ± carbonate ± pyrite replacement of metasedimentary rocks (i.e., the 'type' Oorlano Metasomatite) occurs primarily adjacent to Hiltaba Suite granites, notably the Tickera Granite in the Alford and Port Broughton areas (Fig. 3). More distal and widespread albitisation of metasedimentary and volcanic rocks is common. This alteration is not generally associated with significant sulphides.

Biotite-magnetite ± pyrite metasomatism in the Wallaroo mines district is focussed in brittle-ductile shear zones within metasedimentary rocks, forming strong magnetic anomalies and hosting the Wallaroo Cu-Au mineralisation (Fig. 4). A large area (~30 km x 40 km) of strongly magnetic rock, beneath the waters of Spencer Gulf west of Moonta, is interpreted to be a further zone of extensive biotite-magnetite metasomatism of Wallaroo Group metasedimentary rocks. South of Moonta, in the region between Penang and Balgowan, biotite-magnetite-albite ± K-feldspar ± amphibole ± pyrite veining and pervasive metasomatism forms irregular magnetic anomalies, including a major 5 km x 15 km alteration zone at Weetulta (Fig. 3). Apatite, monazite, allanite, and fluorite are locally important alteration components, indicating significant P, REE, and F in the hydrothermal fluids. Chlorite is locally significant - typically as a late alteration phase replacing biotite and/or actinolite and may occur with quartz ± K-

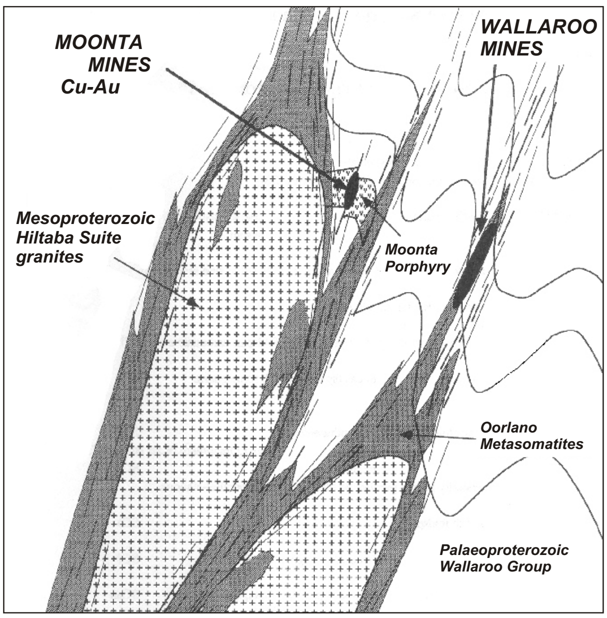

Figure 4: Diagrammatic cross section showing the geological setting of the Moonta and Wallaroo mineralisation associated with intrusion of Hiltaba Suite granites and syn-intrusive shearing (from Conor, 1995).

feldspar ± pyrite ± chalcopyrite. While magnetite is typically associated with broad alteration domains, it may show antithetic relationships with the more restricted chloritic alteration and/or Cu mineralisation.

Other metasomatic styles in the Moonta-Wallaroo district include minor carbonate breccias which may bear minor Cu mineralisation. Widespread hematite-quartz-chlorite-calcite alteration is generally a minor and late stage overprint, and is not associated with sulphides. Local kaolinite alteration and epithermal quartz-carbonate ± hematite veins overprint early albitic metasomatism, particularly within a major structural corridor along the southern margin of the Tickera Granite. The age and possible genetic relationship of this high-level alteration to the earlier higher temperature metasomatism is unclear, although some Moonta-style Cu mineralisation has kaolinitic wallrock-alteration.

Although the Moonta-Wallaroo district contains regional Fe-Na-Ca metasomatism typical of iron oxide-Cu-Au mineral systems, as well as deposits of this style (eg., Wallaroo), iron oxides do not constitute a major part of the mineralisation in the Moonta mines area. The Cu-Au mineralisation in the Moonta deposits occurs as steeply dipping quartz - K-feldspar - biotite - tourmaline ± hematite ± magnetite ± chlorite ± sericite, coarse-grained veins up to 8 m wide, developed within a competent metarhyolite host, the Moonta Porphyry. Chalcopyrite-pyrite-bornite mineralisation occurs in the veins, commonly at the intersection of cross structures.

Mount Woods Inlier

Archaean to Mesoproterozoic basement of the Mount Woods Inlier is mostly covered by 30-160 m of Permian to Cretaceous sediments, and by the Mesoproterozoic Pandurra Formation in the southeast. Basement comprises Archaean gneisses in the south and west and Palaeoproterozoic metamorphic rocks to the north and east, including paragneiss, orthogneiss, and extensive banded iron formation. Metamorphic zircons in the upper amphibolite to granulite facies rocks record a SHRIMP age of 1736±14 Ma (Fanning, 1997). The weakly deformed Engenina Granite (1691±2 Ma, Fanning, 1997) and undeformed Balta Granite (1584±18 Ma, Daly *et al.*, 1998) and related Hiltaba Suite equivalents, intruded the metamorphic rocks. Several large mafic intrusive complexes are believed to be Palaeoproterozoic in age (Daly *et al.*, 1998), but Hiltaba-aged mafic intrusions may also be present.

The Mount Woods Inlier is separated from high grade gneisses of the Coober Pedy Ridge to the north by shears associated with the Karari Fault Zone, which was active during the Kararan Orogeny. Tectonism in the Gawler Craton around 1650 Ma and in the period ~1565-1540 Ma has been ascribed to the Kararan Orogeny (Daly *et al.*, 1998). The Mount Woods Inlier appears to have escaped the high grade metamorphic event that affected basement rocks of the Coober Pedy Ridge at 1565±8 Ma (Daly *et al.*, 1998). Juxtaposition of the Mt Woods Inlier and Coober Pedy Ridge tectonic domains therefore probably occurred after about 1565 Ma, during the Kararan Orogeny. Although still poorly understood, this tectonic scenario may have important implications for the distribution of hydrothermal alteration and mineralisation in the Mount Woods region.

Iron-oxide-rich metasomatic rocks are widely distributed in the Mount Woods Inlier (PIRSA, 2000). For example, the Peculiar Knob iron ore prospect, which contains high grade hematite, has been interpreted to represent Palaeoproterozoic banded iron formation that was recrystallised and remobilised by the adjacent Balta Granite (PIRSA, 2000). The Skylark iron ore prospect, and Hawksnest prospect in the Wilgena Domain, to the south of the Mount Woods Inlier, both contain metamorphosed banded iron formation.

Magnetite- and hematite-rich alteration, breccias and 'skarns' have been widely reported in exploration drill holes. Only some of these Fe-oxide-rich alteration zones contain significant Cu or Au mineralisation. The most important are the recently discovered Prominent Hill prospect, the Manxman and Joes Dam prospects, described below, and the Cairn Hill prospect (Fig. 1).

Manxman and Joes Dam Cu-Au Prospects

Exploration by CRAE, Normandy Group and Burmine NL in the late 1980s to mid 1990s led to the discovery of major magnetite-rich alteration systems with anomalous Cu-Au-REE mineralisation in the southern part of the Mount Woods Inlier. The best intercepts occur in the vicinity of the White Hill mafic complex, and include 287 m @ 0.23% Cu and up to 1.7% Cu, 2.5 g/t Au at the Manxman A1 prospect, and 186 m @ 0.13% Cu at the Joes Dam South prospect (Table 1). Both prospects, described most recently by Hampton (1997), are highly anomalous in Co, Ce and La, whereas only Manxman is anomalous in U. The principal host lithologies at Joes Dam South are fine-grained, laminated, quartz - plagioclase - biotite meta-sedimentary rocks. Magnetite-rich breccias and lesser hematite-rich zones at the Manxman A1 prospect are hosted predominantly by various granitoid rocks and by subordinate fine-grained laminated quartz - albite - diopside ± biotite metasedimentary rocks (Hampton, 1997). Granitoids at Manxman A1 range from granitic gneiss and pegmatite gneiss to granite, microgranite and pegmatite. The granitoids are all I-type and range in composition from monzonite (similar to the Engenina Adamellite) to granite (similar to the Balta Granite; Hampton, 1997).

Granitoid and metasedimentary rocks have been overprinted by hydrothermal alteration during three main paragenetic stages which are observed at both Manxman and Joes Dam. Alteration styles include vein networks, infill of breccia matrix, and pervasive replacements. The stages proposed by Hampton (1997) are as follows:

1 Na-Ca metasomatism: albite - scapolite - clinopyroxene (diopside-hedenbergite) - quartz.
2 K-Fe metasomatism: magnetite - biotite - apatite - titanite - LREE minerals ± hematite.

3 ‘Regression’ and Cu-Au mineralisation: Na-amphibole - chlorite - LREE minerals - calcite - albite - fluorite - hematite - K-feldspar; mineralisation comprises early pyrrhotite and later chalcopyrite - pyrite - LREE minerals with a range of minor ore minerals such as uraninite, pyrosmalite, siengite, arsenopyrite, glaucodot, galena, tellurobismuthite and thorite. Other minor minerals reported for stage 3 include sericite, barite, zoisite, and stilpnomelane.

It is likely that stage 3 of Hampton (1997) includes several separate assemblages: for example, hematite and pyrrhotite would not have formed in equilibrium, nor is it likely that albite, K-feldspar and sericite grew in the same assemblage.

Fine hematite dusting of alkali feldspars has locally imparted a pinkish colouration (‘red-rock’) to some alteration assemblages and to most of the granitoid rocks at Manxman A1. Only very minor hydrothermal hematite is associated with sulphides at Manxman and Joes Dam. A hypogene, massive hematite zone at Manxman A1, apparently at the margin of the Fe-oxide rich alteration system, is low in Cu and Au.

In general, there is a strong spatial association between Cu, Fe, Co and Au contents, and most Cu (as chalcopyrite) occurs within magnetite-rich zones in veins, and as replacements of magnetite. Pyrite is widespread, whereas pyrrhotite at both Manxman A1 and Joes Dam South forms zones within which higher Cu±Au grades are commonly, but not exclusively, developed. Hampton (1997) suggested that these zones at Manxman A1 formed around faults, interpreted from geophysical data, near the centre of the hydrothermal system.

Prominent Hill Cu-Au-U Prospect

Significant copper and gold mineralisation was recently discovered at the Prominent Hill prospect in the southern Mt Woods Inlier (Fig. 5, Table 1) by Minotaur Resources Ltd in joint venture with BHP Billiton, Normandy Exploration Pty Ltd, Sons of Gwalia Ltd and Sabatica Pty Ltd. DDH URN1 (see Figure 5 for intersection widths and grades) was targeted on part of an E-W trending gravity ‘high’ about 2 km long, which has mostly low magnetic response; coincident gravity and magnetic ‘highs’ lie immediately to the north of the drilled gravity anomaly. Basement (from 108 m depth) comprises variably altered and brecciated metasedimentary rocks, underlain by a sequence described as amygdaloidal, felsic, volcanic rocks, agglomerate and silica-hematite breccia (Minotaur Resources Ltd, 2002). Mineralised hematitic breccia is developed within the metasedimentary rocks, which are cut by an unmineralised dolerite dyke. Clasts in the matrix-supported, ‘milled’ breccia are hematite-sericite-silica

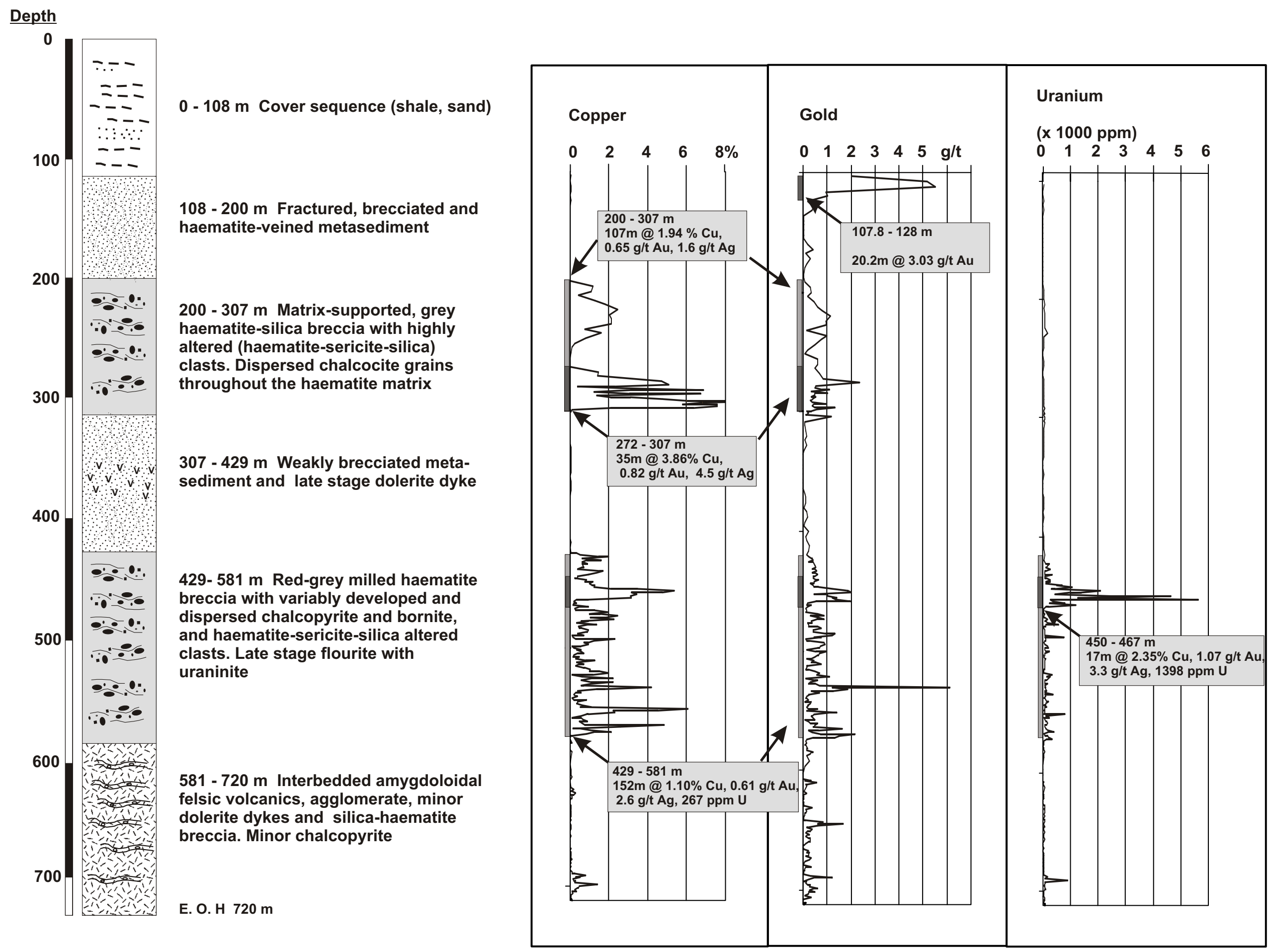

Figure 5: Prominent Hill prospect. Summary geological log and assay results, DDH URN1 (courtesy Minotaur Resources Ltd)

altered and are enclosed in a hematite-silica rich matrix containing disseminated copper sulphides.

Based on limited open file data (Minotaur Resources Ltd, 2002), mineralisation is zoned from an upper Au-rich zone, downwards through a Cu-Au zone containing chalcocite, to a lower zone of Cu-Au ±U containing chalcopyrite and bornite. Uraninite is reported with late-stage fluorite. Lanthanum and cerium are highly enriched, with REE grades of 0.2-0.6% throughout the Cu and Au mineralised zones. The copper sulphide zoning, Cu-Au-U-LREE association, brecciation and hematite-sericite alteration, bear strong similarity to the Olympic Dam deposit (Minotaur Resources Ltd, 2002).

Fe-oxide Cu-Au Ore Formation

Key geological criteria widely applied in exploration for Olympic Dam style Cu-Au deposits in the Gawler Craton include:

1. Broad temporal association of Cu-Au mineralisation with magmatism of the Hiltaba Suite and Gawler Range Volcanics, at ~1590 Ma; note that absolute age constraints on hydrothermal events are sparse.
2. Fe-oxide-rich alteration and Cu-Au mineralisation have a broad spatial associated with this magmatism, but evidently only in the eastern Gawler Craton. The Fe-oxide rich zones produce gravity anomalies, with or without major magnetic anomalies.
3. The presence of breccias (tectonic, hydrothermal, or magmatic-related) in localising mineralisation.
4. High crustal level of Cu-Au ore formation.
5. Strong (brittle) structural control on the location of breccias and ore.
6. Hematite-sericite-chlorite alteration accompanying higher grade Cu-Au mineralisation.
7. Association of Cu-U-Au with LREE, Ag, F, Ba, P, Co.

Several models of ore formation have been published for the Olympic Dam Cu-U-Au deposit in the past decade. The key differences between models relate to the role of granites versus other sources of metals and fluids, the timing of fluid-rock interaction, and which of two fluids carried the ore metals. The implications of the differences in the models for exploration are profound. Some of the components in the Olympic Dam style ore-forming system are shown schematically in Figure 6.

1 Reeve *et al.* (1990) proposed a model of near-surface formation of Fe-oxides and Cu-U-Au-Ag-REE mineralisation, within breccias of diverse phreatomagmatic, tectonic, and hydrothermal origin. Primary Cu-U-Au ore deposition resulted from

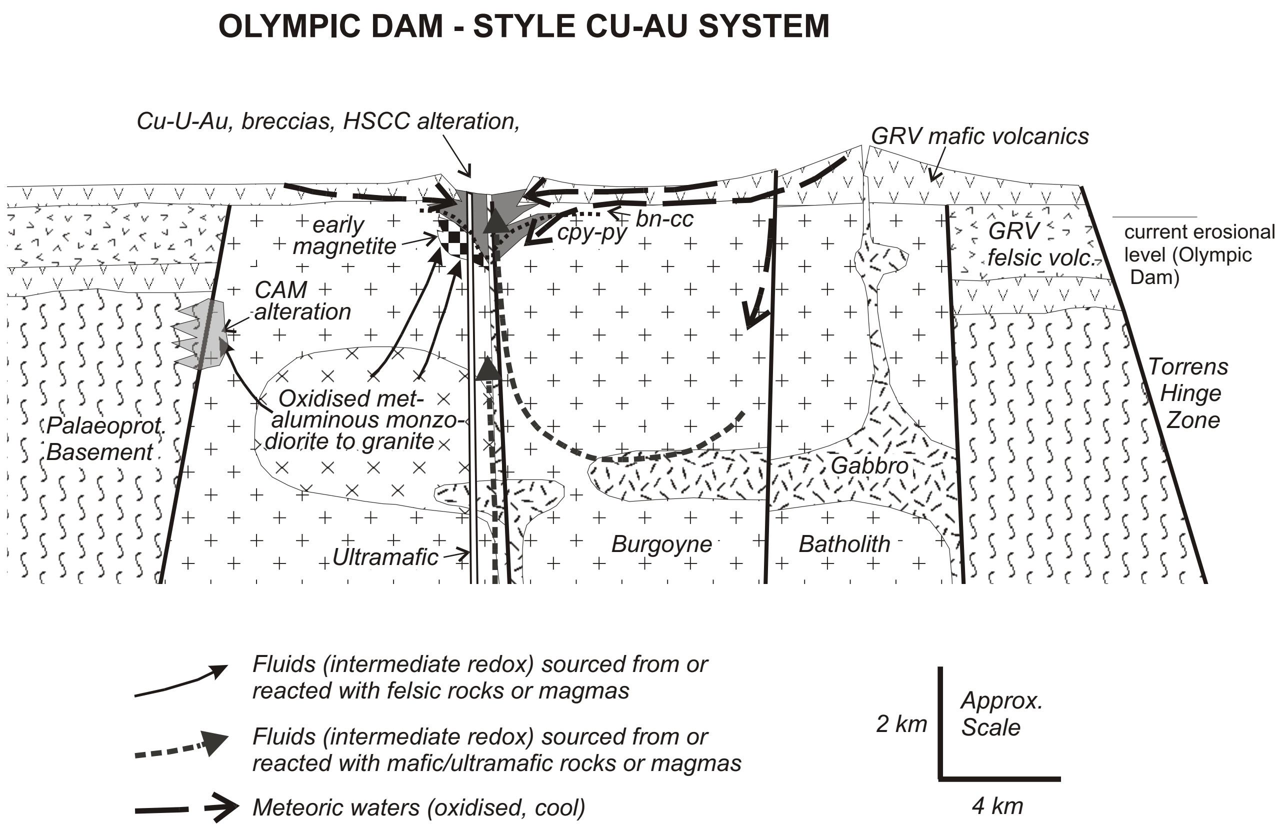

Figure 6: Schematic cross section of an Olympic Dam style hydrothermal system, showing Cu-U-Au mineralisation asssociated with hematite-sericite-chlorite-carbonate (HSCC) alteration. Deeper level and/or distal calcsilicate-alkali feldspar-magnetite alteration (CAM), and alternative fluid types that may have been active in the system, are also shown (see text). The interface between chalcopyrite-pyrite (cpy-py) and bornite-chalcocite (bn-cc) assemblages is indicated. Geology based on Reeve *et al.* (1990) and Haynes *et al*. (1995).

interaction of ascending hot, relatively reduced, metal-rich brines and descending cooler, oxidised, meteoric waters, producing a broad zonation from lower chalcopyrite ± pyrite to upper bornite ± chalcocite.

2 Based on the geological model in (1) and on thermodynamic modelling, Haynes *et al.* (1995) also advocated fluid mixing as a depositional mechanism for Fe-oxides and ores, but favoured Cu-U-Au transport in the cooler, descending, oxygenated meteoric waters (modelled at 150ºC). The authors acknowledged the alternative possibility that ore metals were introduced in the hotter fluid (250ºC in model). Basalts of the Gawler Range Volcanics were preferred as a source of the copper, leached by saline waters derived from a playa lake.

3 Oreskes and Einaudi (1990, 1992) postulated that the ODBC and associated Cu-Au-Au-Ag-REE mineralisation formed ~190 Ma later than the host Roxby Downs Granite, at and immediately below the palaeosurface following uplift and erosion of the granite. Brecciation was viewed as hydrothermal in origin, with major amounts of Cu-Fe sulphides introduced during the waning stages of brecciation. Like Reeve *et al.* (1990) and Haynes *et al.* (1995), two fluids were suggested by Oreskes and Einaudi (1990, 1992), but with hotter (~400ºC) deep-sourced fluids of possible felsic magmatic origin preceding rather than mixing with cooler oxidising surficial waters (seawater, groundwater, or closed-basin water). According to Oreskes and Einaudi (1990, 1992), the hotter fluid may have carried Fe, Cu and other metals but the oxidising fluids responsible for the formation of hematitic breccias were considered the key to the higher grade Cu mineralisation. Oreskes and Einaudi (1990, 1992) further proposed that Proterozoic surface weathering led to local development of supergene chalcocite ores.

4 Johnson and McCulloch (1995) suggested that the Cu-REE-enriched fluid may have been an ascending volatile phase exsolved from mafic/ultramafic magma chamber(s), and which post-dated the magnetite-forming fluid. They presented Sm-Nd isotopic evidence supporting involvement of two fluids in ore genesis, one of which was in isotopic equilibrium with Hiltaba Suite granites and which precipitated the early magnetite. The other fluid, responsible for introduction of at least some Cu, had a more primitive ε_{Nd} signature, which demanded a significant contribution of Nd (and by implication, Cu) from mafic/ultramafic rocks or magmas.

5 Reynolds (2000) alluded to magmatic sources for both ore fluids and metals at Olympic Dam. However, only limited supporting data have been published (eg., Eldridge and Danti, 1994)

At the Emmie Bluff deposit, Gow *et al.* (1994) and Gow (1996), proposed a two stage model resembling that of Oreskes and Einaudi (1990, 1992) for Olympic Dam. The calcsilicate - K-feldspar - magnetite vein networks in the southern alteration zone at Emmie Bluff were interpreted to be the product of contact metamorphism, and attributed the rock fracturing to high fluid pressures and volatile release associated with emplacement of Hiltaba Suite intrusion(s). Oxygen isotope compositions of quartz and magnetite in the veins are consistent with a magmatic source of fluids (Table 1). A shift towards lower temperatures and lower ($\delta^{18}O$) values of fluids associated with hematitic alteration and Cu-Au deposition (quartz-hematite pairs; Table 1) was interpreted to be from the influx of evolved meteoric-hydrothermal waters (Gow *et al.*, 1994; Gow, 1996). The proposed two-stage model involves early high-temperature magnetite-rich assemblages, that were overprinted by hematitic alteration possibly during the later stages of Hiltaba Suite magmatism (Gow *et al.*, 1994; Gow, 1996). In this model fluid flow was strongly controlled by northwest-trending faults.

At Oak Dam East, Davidson (1991) and Davidson and Paterson (1993) attributed brecciation to overpressuring during large-scale volatile release from underlying Hiltaba Suite magma. Some magnetite-calcsilicate skarn formed prior to brecciation and unroofing of the hydrothermal complex. Hot, saline waters of magmatic/meteoric origin (Table 1) formed magnetite, pyrite, and quartz near the base of the system. Colloform hematite-quartz formed towards the top of the system where cooler oxidised meteoric water dominated within 100-200 m of the Mesoproterozoic palaeo-surface. Minor brecciation occurred along narrow fracture zones during rapid 'gas-streaming' events, the results of phase separation at depth. Boiling of fluid almost to the top of the existing body produced widespread chalcedony and K-phyllosilicates. Late in the development of the iron-oxide body, an upwelling, boiling, Fe-Cu-U-bearing fluid mixed along a sub-horizontal boundary with oxidised, low-temperature meteoric water (Table 1), depositing oxidised metal assemblages and phyllosilicates. The processes of phase separation and fluid mixing in a high-level crustal setting are analogous to those forming some epithermal precious metal deposits. Prior to 1424±51 Ma, a weathering interface probably migrated downwards into the metal-rich blanket, potentially leaching a significant portion of the hydrothermal mineralisation.

Crustal Settings of Cu-Au Mineralisation

There are three major regions of hydrothermal activity broadly associated with Hiltaba Suite ± GRV magmatism (Fig. 1): Stuart Shelf basement, the Mount Woods Inlier and the Moonta-Wallaroo-Roopena region. Each of these regions contains high- to moderate-temperature Fe-oxide rich alteration as well as low temperature alteration, Cu-Au mineralisation and felsic Mesoproterozoic intrusions. At least two of the regions contain Mesoproterozoic intermediate or mafic intrusions. The three regions have a broad spatial correlation with regional-scale, positive gravity anomalies, and may represent the 'footprints' of separate crustal-scale thermal anomalies. To date, a world-class Cu-Au deposit has been identified only in the central region.

The crustal level of exposure of the hydrothermal systems may vary significantly between and even within the three regions of hydrothermal activity. This is suggested by (1) the temperature range of hydrothermal alteration from high (~450-500ºC, CAM assemblages, above) to low (HSCC assemblages), and (2) the variation in styles of structures controlling fluid flow, which range from brittle-ductile shear zones to breccias and brittle faults. Shear-hosted CAM and MB assemblages in the Moonta-Wallaroo district probably formed at deeper crustal levels than breccia and vein network styles of some CAM assemblages in the basement of the Stuart Shelf. The products of near-surface hydrothermal processes are also preserved (beneath sedimentary and regolith cover) in all three regions, particularly in the basement to the Stuart Shelf (eg., at Olympic Dam), and possibly at Prominent Hill. We suggest that uplift or unroofing of some of the hydrothermal systems occurred during and/or after their development, resulting in telescoping of deeper and shallower alteration patterns. The CAM, MB and HSCC assemblages and associated Cu-Au mineralisation, therefore, may represent a continuum from deeper, higher-temperature, shear-hosted settings to near-surface, low-temperature breccia and fault environments. The larger systems discovered, to date, in the Olympic Cu-Au province are of the higher-level style, but this does not rule out the presence of deeper-level styles of economic Cu-Au mineralisation similar to those in the Mt Isa Eastern Succession.

Ongoing investigations of the crustal structure, magmatism, fluid pathways, and timing of hydrothermal and tectonic events are aimed at elucidating the district- to crustal-scale controls on the location of major Cu-Au deposits in the Gawler Craton.

Acknowledgements

The authors wish to thank our colleagues at Geoscience Australia, CODES and at PIRSA for sharing the results of research, discussions, and reviews which have assisted us in the preparation of this paper. We also would like to acknowledge the cooperation of MIM Exploration, Minotaur Resources Ltd, Gunson Resources, WMC, and Adelaide Resources. Brian Logan at the PIRSA drill core facility is thanked for efficiently arranging core layouts.

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