THE PORTIA – NORTH PORTIA Cu-Au(-Mo) PROSPECT, SOUTH AUSTRALIA: TIMING OF MINERALISATION, ALBITISATION AND ORIGIN OF ORE FLUID

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Abstract - Cu-Au(-Mo) mineralisation at the Portia-North Portia prospect is located under cover on the eastern flank of the Benagerie Ridge Magnetic Complex, within the Curnamona Province and approximately 125 km WNW of Broken Hill. The mineralisation is located within rocks which have a SHRIMP U-Pb zircon age of 1703±6 Ma, which is similar to Willyama Supergroup ages obtained from the Broken Hill and Olary Domains. The meta-sedimentary unit that hosts the mineralisation is approximately 200 m thick and is overlain by carbonaceous phyllite, and underlain by a unit which is dominated by albite-magnetite-hematite. The host units contain numerous carbonate-rich domains intercalated with meta-evaporitic sediments. The sequence had undergone low-grade metamorphism and fabric development and was subsequently intensely albitised. Hydrothermal monazites formed during this albitisation event give SHRIMP II *in situ* U-Pb ages of ~1630 Ma. The albitised meta-sediments proved to be an excellent host to the later Cu-Au(-Mo) mineralisation. Abundant monazite associated with the mineralisation yield SHRIMP II ages of ~1605 Ma. It is possible that the numerous, highly fractionated and altered diorite bodies known to be present on the Benagerie Ridge, may have produced some of the metals. The "Hiltaba age" (~1585 to 1590 Ma) granites of the area cannot be considered as a source of the metals.

Introduction

The Portia-North Portia Prospect is located approximately 125 km WNW of Broken Hill (Figs. 1 and 2) on the southern segment of the Benagerie Ridge, a north-south trending, fault bounded Proterozoic basement structure which is almost fully concealed by younger cover. The Benagerie Ridge is sited approximately in the centre of the Curnamona Province (Robertson *et al.*, 1998) which includes the Curnamona Craton as defined by Teale and Flint (1993). The Curnamona Province (CP), shown in Fig. 3, is an aeromagnetically defined, sub-circular domain containing outcropping and buried Proterozoic rocks, including the Willyama Supergroup (Willis *et al.*, 1983). The latter contains the world class Broken Hill Pb-Zn-Ag deposit in the Broken Hill Domain (BHD; Fig. 3) as well as numerous other small Broken Hill Type (BHT) deposits which are uneconomic to sub-economic (e.g., the Pinnacles and Allendale mines). This mineralisation type within the BHD occurs in upper amphibolite to granulite facies rock-types with minor Cu-Au mineralisation (e.g., Copper Blow, cf Willis, 2000). The neighbouring and lower metamorphic grade Olary Domain (OD) contains numerous small copper prospects, but BHT Pb-Zn-Ag mineralisation tends to be a rarity. In the Mount Painter Inlier (Fig. 3) in the north-west CP, a probable Willyama Supergroup equivalent sequence (upper amphibolite metamorphic grade) contains quartz-gahnite and spessartine garnet-rich laminated rock-types but no Pb-Zn-Ag mineralisation is

known. A lower metamorphic grade sequence along the eastern flank of the Inlier contains Cu-Au-Mo(-Co-REE) mineralisation (Parabarana Prospect) and magnetite-rich Cu-Co-F-REE-U mineralisation (Gunsight Prospect; cf. Teale, 1993).

The Portia-North Portia Prospect is the most significant Cu-Au(-Mo) occurrence in the Curnamona Province. It is located within the Benagerie Ridge Magnetic Complex (BRMC; Fig. 4), a dome-like structure which contains numerous other prospects (Fig. 5). The Eurinilla and Lake Charles Magnetic Complexes to the east and north-east respectively also contain Cu-Au mineralisation. The large gravity and magnetic complex at Emu Dam (Fig. 4) is under approximately 500 m of cover making conventional exploration very difficult. The Portia-North Portia mineralisation is concealed by up to 80 m of Tertiary cover and intense saprolite development to 200 m is common. The history of discovery is complicated as many groups contributed. In 1982 Marathon Oil Australia intersected 79 m at 0.4% Zn in drillhole BD002 (Teale, 1985) and in 1986 Billiton intersected anomalous copper over approximately 30 m in highly carbonaceous meta-pelites (DDH-BH2). In 1996, Pasminco Exploration and Werrie Gold Ltd intersected gold mineralisation in aircore drilling over the Portia Prospect (e.g., 5 m at 15.4 g/t Au in BEN316; 1 m at 51.3 g/t Au in BEN320) and in 1997 aircore drilling
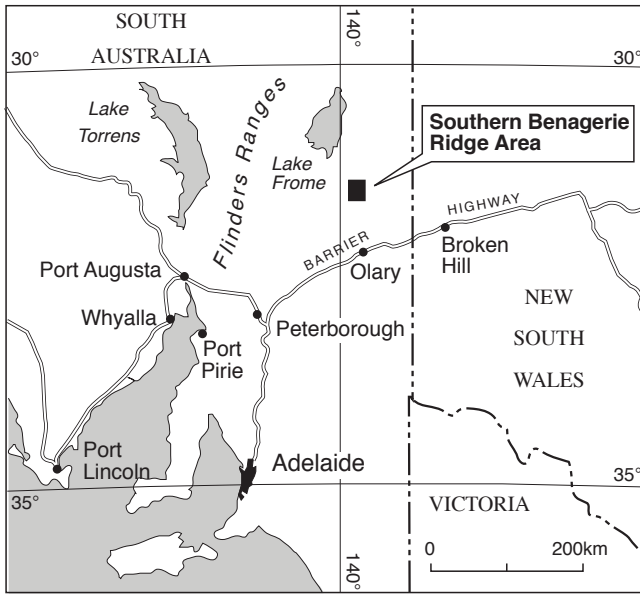
Figure 1: Location of the Southern Benagerie Ridge area, South Australia
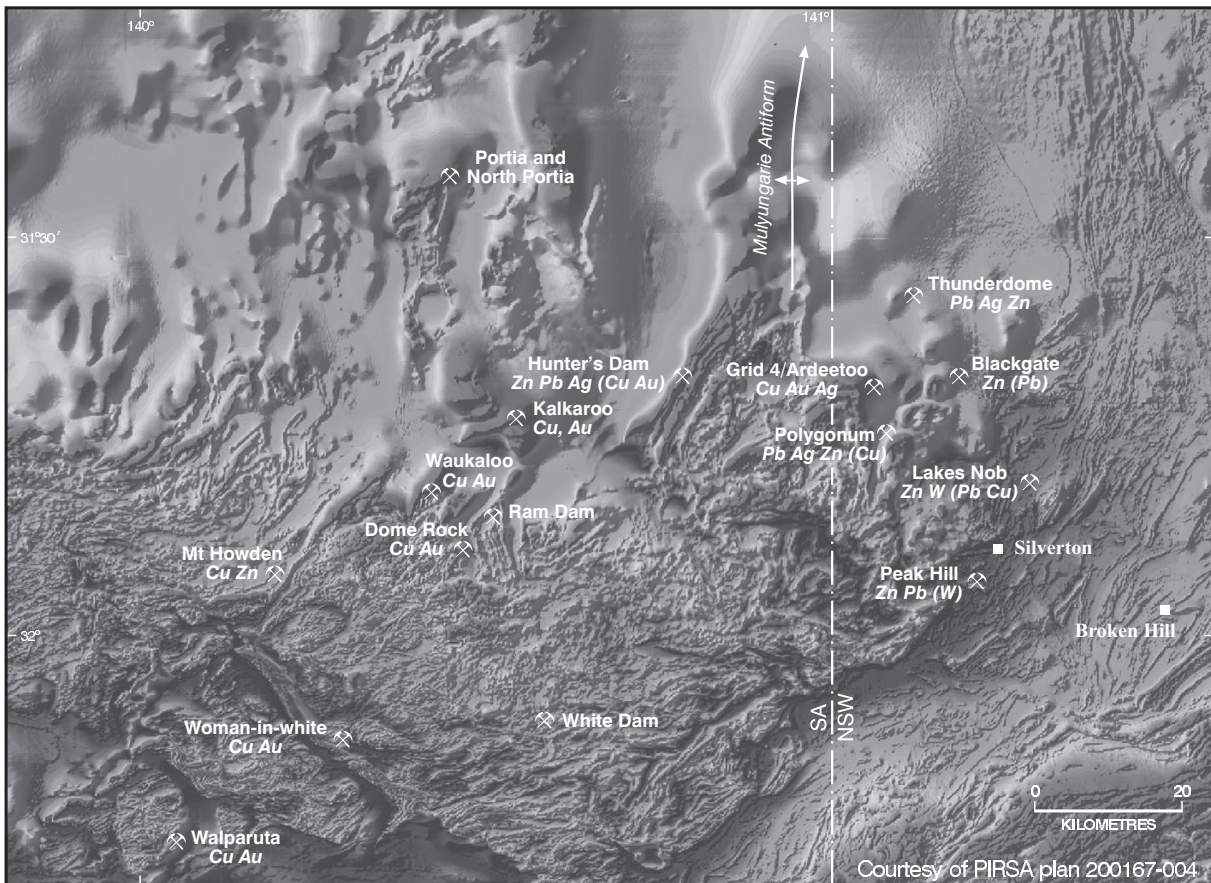

Figure 2: Total magnetic intensity image showing mineral prospects of the southern Curnamona Province

to the north of this prospect intersected copper and gold mineralisation at the North Portia Prospect (e.g., 47 m at 0.84 g/t Au and 0.94% Cu in BEN408). Over the next two years many spectacular Au and Cu-Au(-Mo) intersections were announced at both Portia (e.g., 9 m at 237 g/t Au in BEN478) and North Portia (e.g., 76 m @ 1.06% Cu, 1.21 g/t Au and 235 ppm Mo in BEN592, see Fig. 6) as well as in the numerous other prospects located around the BRMC (e.g., 5 m at 356 g/t Au in BEN677 at the Shylock prospect; see Fig. 5). Aeromagnetics, regional and local

gravity and reconnaissance aircore drill traverses proved most effective in locating mineralisation on the BRMC. Surface geochemical techniques were not successful.

The Portia-North Portia prospect has geochemical and mineralogical characteristics that allow it to be classified with the Proterozoic iron oxide, Cu-Au class of deposit. The element association of Fe-Cu-Au-Mo-REE-F-Ba-Co and the presence of highly oxidised, magnetite and hematite-rich footwall, and wallrocks confirm this classification.

Regional Geology

The Palaeoproterozoic rocks of the CP can be grouped into four sequences ranging from Palaeoproterozoic to Neoproterozoic. The oldest Palaeoproterozoic sequence, the Willyama Supergroup, has an age of 1690 to 1720 Ma (Page and Laing, 1992, Donaghy *et al.*, 1998; Page *et al.*, 2000, Teale and Fanning, 2000). This sequence is found in the OD and BHD and has correlatives in the Mount Painter and Mount Babbage Inliers (Fig. 3). Basement to this sequence has not as yet been located but detrital zircon studies (Cook *et al.*, 1994; Nutman and Gibson, 1998; Page *et al.*, 2000) yield provenance ages of Archaean, ~1860, ~1820, ~1770 to 1790 and ~1730 Ma. The apparent older basement proposed by Nutman and Ehlers (1998a) is considered to reflect inherited zircons rather than a true crystallistion age for the basement (see also Page *et al.*, 2000). A younger Palaeoproterozoic sequence sits (?) disconformably on the Willyama Supergroup and has been dated at 1656±5 and 1642±5 Ma by Page *et al.* (2000). Teale (1985) had earlier discussed the presence of a Mount Isa Group age sequence sitting unconformably on the Willyama Supergroup along the Benagerie Ridge.

The Palaeoproterozoic sequence on the Benagerie Ridge is the least metamorphosed and deformed in the CP, a consequence of its central location on the stable cratonic nucleus well away from the marginal mobile belts. Elsewhere the high T, low P metamorphic effects increase towards the CP margins, with metamorphic grade increasing to the south in the OD and to the south and south-east in the BHD. Metamorphic grade in the north west of the CP (Mount Painter and Mount Babbage Inliers) is similar to that at Broken Hill.

The most intense deformation superimposed on the Palaeoproterozoic sequences occurred during the nebulous Olarian Orogeny (see Drexel *et al.*, 1993 pp. 88-91 and references therein). More recently Page *et al.* (2000) confirm an age of ~1600 Ma, but find no isotopic support for any pre-1600 Ma metamorphic events. Evidence for older events has been discussed by Nutman and Ehlers (1998) and Teale and Fanning (2000). Laing (1996) had the Palaeoproterozoic of the CP forming part of a more intensive mobile belt (the Diamantina Orogen) which included the East Mount Isa and Georgetown Inliers in Northwest Queensland.

Mesoproterozoic volcanic sequences and cogenetic intrusives in the CP range in age from approximately 1550 Ma to 1590 Ma (Sheard *et al.*, 1992; Teale, 1993; Cook *et al.*, 1994; Teale and Fanning, unpublished data) with most having 'A-type' affinities. S-type anatectic granitoids in the OD share a similar age (Fanning *et al.*, 1998). The 'A-type' intrusives can often be extremely altered with hydrothermal biotite, K feldspar and hematite present.

Neoproterozoic, Adelaidean sequences are flat lying in the central domain of the CP and become more progressively deformed towards its margins. The Cambro-Ordovician Delamerian Orogeny reworked older Palaeo and Mesoproterozoic crust as well as the Adelaidean Sequence.
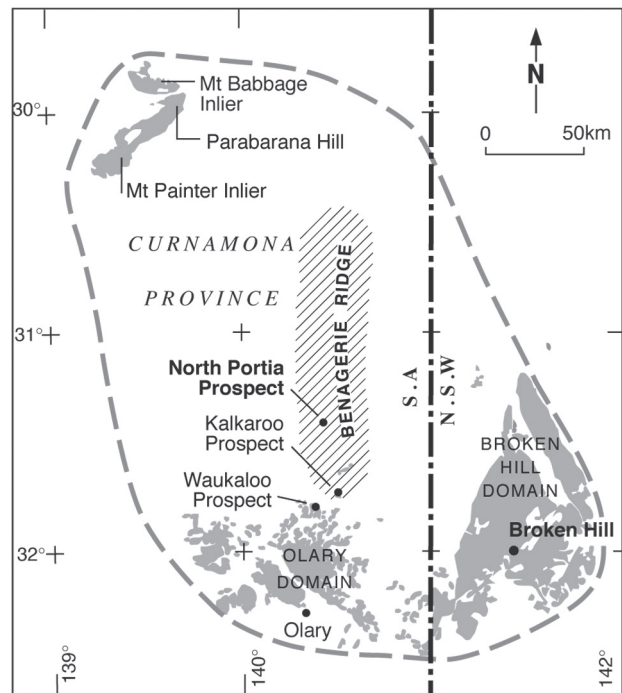

Figure 3: Exposed Palaeo- and Mesoproterozoic rocks of the Curnamona Province.

Geology of the Benagerie Ridge Area

Approximately 1600 drillholes, predominantly aircore, have been drilled into the BRMC over the last decade with additional drilling carried out on other magnetic complexes in the southern Benagerie Ridge region. Mineralisation encountered ranges from stratabound Pb-Zn-Ag (e.g., Lorenso prospect, Fig. 5) with an age of approximately 1680 to 1700 Ma (i.e., probable diagenetic) through to Tertiary (Au in palaeosols, roll-front uranium). The Palaeoproterozoic geology and stratigraphy of the BRMC and the southern Benagerie Ridge region, including Mesoproterozoic intrusive and extrusive activity can now be discussed with some authority.

At present the BRMC stratigraphy is subdivided into a minimum of nine Units (Fig. 7), with both Units one and nine needing further subdivision. In the Portia-North Portia area the meta-sediments and tuffs of the sequence have been albitised (see next section) with dark grey to black carbonaceous and/or biotite-rich shales now bleached white grey and/or brick red. The stratigraphy can however be traced through this albitised domain, which now hosts the Cu-Au(-Mo) mineralisation.

Unit one in the BRMC is dominated by white grey albitites which in some areas are darker grey due to the presence of carbonaceous matter. The meta-sediments can be finely laminated to massive and many contain scapolite porphyroblasts that have now been pseudomorphed by albite. Analyses of relict scapolite in the region indicate chlorine contents of 2 to 3%. Rare tourmalinites and kimberlitic sills are present and flaser cross-bedded siltstones (now albitised) suggest tidal depositional environments. The albitites can contain high modal percent magnetite with finer grained hematite often present. The latter phase can
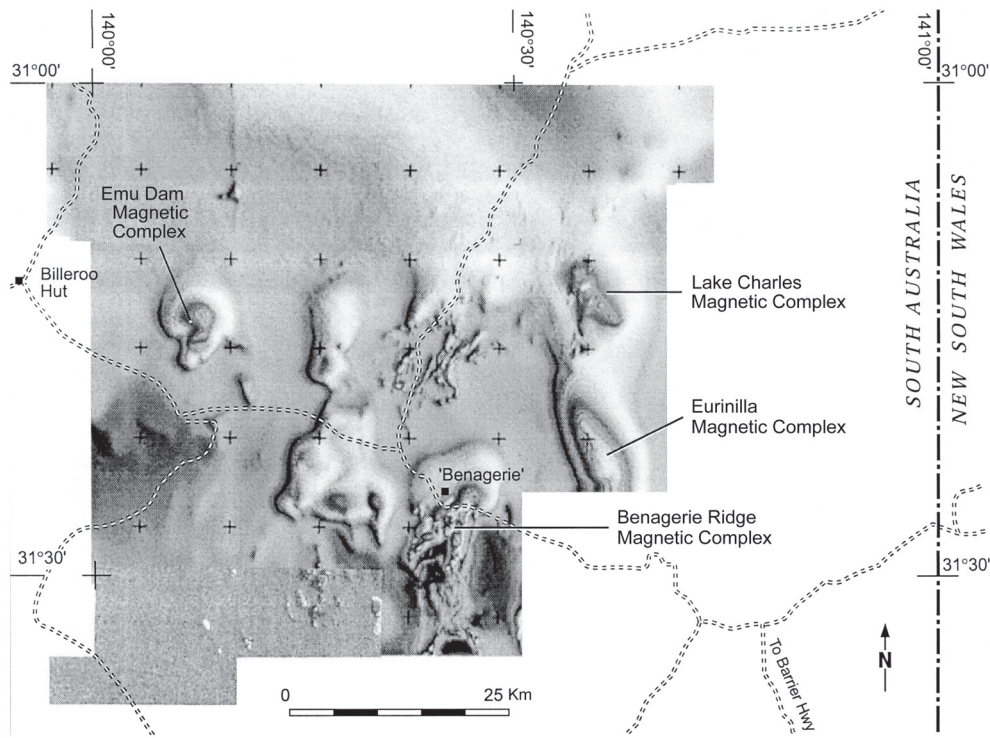
Figure 4: Magnetic complexes, southern Benagerie Ridge area

also replace porphyroblastic magnetite. Magnetite bands (up to 1 cm) are present as are crosscutting cobaltian pyrite ± magnetite veins. Massive magnetite is associated with intense albitisation in some areas of the CP.

Units two and three (upper and lower meta-evaporite units) mark a significant change in depositional conditions with abundant carbonates developed. A calcite-biotite ± albite marble is always observed at the base of Unit two as are pink albite (±calcite) ellipsoids and lenses which occur in carbonate beds. Probable stromatolitic horizons have been identified and albite ellipsoids also occur at the top of Units two and three and are excellent marker horizons.

The distinctive Unit four consists of intercalated biotite-albite marbles (up to ~10 cm thick) and finely laminated albitites and/or K-feldspar rock. Up to twenty-five marble beds per metre can be present. The presence of rhombohedral and six sided albite crystal forms in the carbonates argues for the presence of former evaporite phases and gypsum/anhydrite pseudomorphs have been recorded.

Unit five, designated the 'Pyritic Albite Unit', contains numerous marker horizons and is generally composed of finely laminated albitic and minor K-feldspar-rich bands. It can be divided into an upper sub-unit which contains carbonate ellipsoids (immediately below Unit six) and pyritic or pyrrhotitic nodules, and a lower sub-unit which commences with the first appearance of biotite-rich carbonate beds. The lower sub-unit also contains unusual anatase beds (up to 4 mm thick), which can comprise greater than 50% anatase (with quartz and rare apatite), and tuff marker beds. Zircons separated from a tuff marker yield a SHRIMP weighted mean $^{207}Pb/^{206}Pb$ age of 1703±6 Ma for

twelve concordant analyses (Fig. 8). This age is interpreted as giving the time of magmatic zircon crystallisation in this tuff. It is within uncertainty of published ages for metavolcanics (1699±10 Ma, Ashley *et al.*, 1996; 1692±3 Ma, Page *et al.*, 2000) and meta-granitic bands (1703±6 Ma, Ashley *et al.*, 1996) within the outcropping OD. It can be concluded therefore that the sequence on the BRMC not only shares a similar age with that in the OD, but also with the Broken Hill and Thackaringa Groups in the BHD.

A laminated to thinly bedded Fe and Mg-rich 'calc-silicate' forms Unit six. It contains quartz nodules within carbonate (actinolite + biotite + calcite) at its base and may have a disconformity separating it from the overlying Unit seven. It can contain monomineralic beds of actinolite, biotite, calcite and K-feldspar. Intercalated beds of biotite and K-feldspar typify the unit. A number of unusual rock-types are present, such as siderite-F biotite and siderite-K-feldspar. Another noticeable feature is the absence of tremolite-actinolite in the unit immediately above mineralisation.

The Units described above are blanketed by a thick succession of carbonaceous meta-shales/phyllites. In places these have been intensely albitised (Upper Albite, Unit seven; see Fig. 5). The shales also become more sodic towards their base. Mn-ilmenite is the dominant opaque oxide and abundant pyrite and/or pyrrhotite can be present. Sub-units containing abundant chloritoid or spessartine garnet porphyroblasts have been noted.

The sequence in the Portia-North Portia area dips shallowly to the ESE with dips ranging from approximately 20° to 50°. The area is strongly faulted and there is evidence for thrusting with bedding parallel shears and kimberlitic sills present.
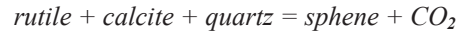
Albitisation

Albitisation within the CP has been the focus of many studies over the last decade (Cook and Ashley, 1992; Ashley *et al.*, 1998; Skirrow and Ashley, 1998; Davies and Anderson, 2000; Teale and Fanning, 2000; Ashley, 2000; Skirrow *et al.*, 2000). One of the major conundrums has been the timing of this albitisation and its relationship, if any, to Cu-Au(-Mo) mineralisation. Albite gneisses occur in the OD, the BHD and in the Mount Painter Inlier (Fig. 3) and well bedded to finely laminated albitites occur in the OD, the Mount Painter Inlier and under cover on the Benagerie Ridge. The latter domain with its low metamorphic grade (~400 to 450°; 2 Kb, P_{H_2O}), is ideal for the study of the albitisation process and its relationship to Cu-Au(-Mo) mineralisation (e.g., Portia-North Portia).

In the OD most workers agree upon an early albitisation probably associated with diagenesis (Ashley, 2000; Skirrow *et al.*, 2000) and a subsequent 'syn tectonic' Na + Ca + Fe metasomatic event with a mineralogy comprising albite, quartz, clinopyroxene, actinolite, epidote, magnetite, hematite, grossular-andradite garnet and sphene. Skirrow *et al.* (2000) bracketed this albitisation event between ~1595 and ~1583 Ma using SHRIMP (U-Pb zircon) dating work of Page *et al.* (2000) and their own SHRIMP U-Pb dating of sphene.

In the southern Benagerie Ridge and adjacent areas there is an early albitisation and K-feldspar enrichment that more than likely occurred over a period of time from diagenesis through to the earliest metamorphic or thermal event. It should be remembered that granitic sills were emplaced into the OD at 1703±6 Ma (Ashley *et al.*, 1996) and into the BHD at 1704±3 Ma (e.g., the Alma Gneiss, Page *et al.*, 2000) suggesting high heat flow and movement of probably saline groundwaters at an early stage in the development of both domains. Evaporitic minerals and possible early formed zeolite minerals provided sodium and potassium during dehydration and destruction of water soluble sodium carbonates.

The cross-cutting, invasive albitisation event in the southern Benagerie Ridge area is dominated by a mineralogy consisting of albite, quartz, calcite (and sometimes ankerite), magnetite-hematite and rutile. In addition fluorite, F-phlogopite, REE-fluocarbonates and monazite can be present with phlogopite often retrogressed to chlorite and fluorite sometimes replacing carbonate. The presence of these fluorine-bearing phases indicates a high a_{HF} during the albitisation process. Actinolite-tremolite, sphene, clinopyroxene, garnet and epidote are usually absent and are only observed at deeper levels in the hydrothermal system. For example, garnet + epidote can be found at approximately 500 m vertical depth in the centre of the BRMC (DDH-BD001). Actinolite and clinopyroxene form part of the albitisation assemblage along the western bounding fault of the Benagerie Ridge and in albitites under approximately 500 m of cover to the immediate west of the Benagerie Ridge (the Emu Dam Magnetic Complex, see Fig. 4).

Sphene is not present in the albitites of the low metamorphic grade Benagerie Ridge and is only found as an early vein phase within the mineralisation. Instead rutile-calcite-quartz is present within the albitites. The absence of sphene (and clinopyroxene and actinolite) may suggest that this phase is metamorphic, and not part of the hydrothermal event that formed the albitites. The low temperature stability limit of sphene, represented by the reaction:

$$rutile + calcite + quartz = sphene + CO_2$$

has been studied by Hunt and Kerrick (1977). This reaction (at P_{fluid} = 2Kb) occurs at ~500°C, X_{CO_2} = 0.5, well below PT effects superimposed upon the OD but above those imposed upon the Benagerie Ridge area. If the albitisation event was pre-syntectonic then sphene ages may represent a metamorphic and not a hydrothermal/metasomatic event. Alternatively, assuming that bulk compositions of the albitites are similar, the presence of sphene, epidote and muscovite in the OD albitites may suggest a more H_2O-rich composition to the hydrothermal/metasomatic fluid with Benagerie Ridge albitites forming under higher X_{CO_2} conditions. In addition, sphene and allanite are the main REE carriers in the OD and REE fluocarbonates and monazite are the dominant REE phases on the Benagerie Ridge suggesting major differences in X_{HF} in the two regions.

The Benagerie Ridge albitisation has been superimposed on rocks that exhibit two tectonothermal events, each with a distinct fabric. Early formed spessartine garnet, in carbonaceous shale for example, is totally replaced by albite during albitisation. Davies and Anderson (2000) discuss pseudomorphed andalusites in massive quartz-albite rock from the OD. The albitisation (invasive) has therefore been superimposed on a sequence that had been previously deformed and metamorphosed, and subsequently subjected to the major tectonothermal event, Olarian Orogeny, at approximately 1590 to 1600 Ma.
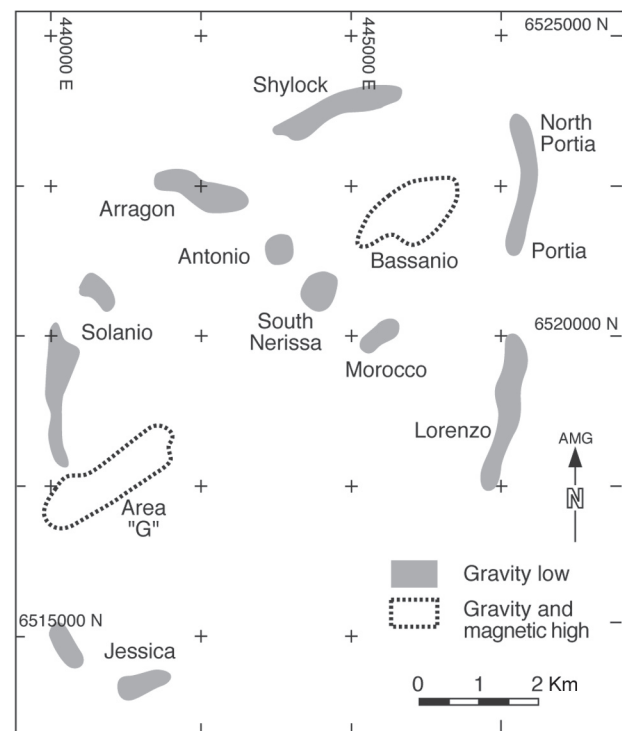

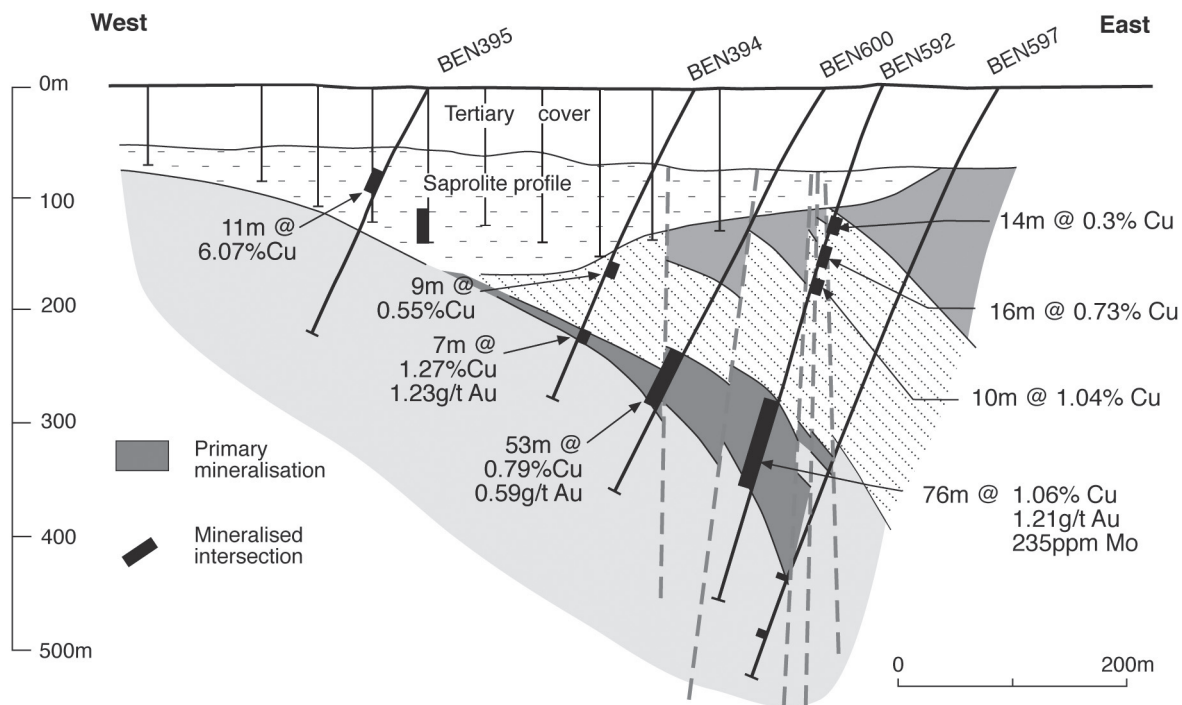**Figure 5:**   Benagerie Ridge magnetic complex and prospect localities.

Figure 6: North Portia mineralised intersections on section 22 600 mN

The presence of abundant hydrothermal monazite at the abitisation 'front' in the Benagerie Ridge area has allowed U-Pb age dating of the event. Monazite which formed during the albitisation is very distinctive and occurs as tabular to lenticular 'spongy' hydrothermal grains. These fragile grains have been analysed 'in situ' by SHRIMP II and give the timing of albitisation at ~1630 Ma. Albite-quartz-monazite veins occurring in the albitic footwall of the Portia prospect also have a SHRIMP II U-Pb monazite age of ~1630 Ma, confirming the timing of this post metamorphic invasive albitisation.

The Portia – North Portia Mineralised System

The Portia-North Portia mineralisation is confined to a large crosscutting albitised domain located on the eastern flank of the BRMC. Older Pb-Zn-Ag mineralisation (cf Teale, 1985), cut by the ~1630 Ma albitisation event has been removed, presumably by introduced and locally generated Cl (and F)-rich fluids during albitisation. Away from the Portia-North Portia area Pb-Zn-Ag prospects are present at, for example, Lorenso, Morocco and Jessica (Fig. 5). The Cu-Au (-Mo) mineralisation is similar to that at Kalkaroo (Fig. 2) and Parabarana Hill (Fig. 3) and shares some similarities with mineralisation at Waukaloo (Fig. 2). Both Waukaloo and Parabarana contain primary bornite, but no bornite is present at Portia-North Portia. Copper mineralisation to the south of Waukaloo, for example Dome Rock and Walparuta (Fig. 2), have some similarities (e.g., breccia development, gangue phases) but are essentially a different type of mineralisation.

Mineralisation at Portia-North Portia is developed predominantly in Units two, three and five (Fig. 7) above the oxidised magnetite-hematite-rich footwall (Unit one) and below the highly reduced hangingwall units (Unit 7 and above). The average thickness of the Units between

Units one and seven is approximately 200 m and up to 116 m of Cu-Au (-Mo) mineralisation has been intersected (BEN592, see Fig. 6) although some fault repetition may be present. The carbonate-rich lower units contain significant replacement and bedding parallel style mineralisation that emanates from crosscutting veins while Unit five tends to host infill mineralisation in veins and fractures. These veins tend to dip steeply to the southwest, although other vein orientations have been noted. Molybdenite replacement adjacent to quartz-carbonate veins on the margins of the albitised domain may have occurred at ~1630 Ma and so be the same age as the albitisation.

The vein and replacement system exhibits a zoning upwards from its structural/stratigraphic base. Early "calcic" veins (tremolite-actinolite, calcite, quartz, sphene ± biotite) give
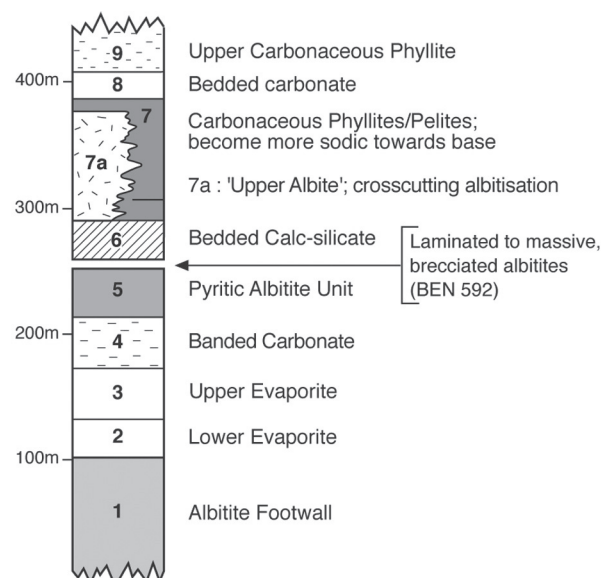

Figure 7: Generalised stratigraphic column, North Portia-Portia area.

way to biotite-K-feldspar veins (quartz, calcite, biotite, K-feldspar, chalcopyrite, pyrite, monazite) which become progressively more hematite-rich. In the upper parts of the system, barren calcite-hematite veins are present with barren K-feldspar ± biotite veins developed in the footwall albitite. Within the mineralisation, repeated movement on and opening of vein structures saw a continuum of crosscutting and replacement mineralogies and element associations which are summarised in Table 1 (Stages 5a to 5e). Some of the more interesting characteristics are outlined below in point form:

(1) The Cu-Au(-Mo) mineralisation post dates the ~1630 Ma albitisation. Brick red albitisation can be superimposed on existing albitites and K-feldspar selvedges, along some veins, replace albite. Chalcopyrite also replaces carbonate associated with the albitisation.

(2) Sphene and tremolite-actinolite in early 'calcic' veins are replaced by rutile + REE fluocarbonates + monazite ± quartz and quartz + carbonate respectively. Both sphene and allanite are attacked by presumably HF in the mineralising fluid with monazite and REE fluocarbonates the dominant REE-bearing phases in the hydrothermal system.

(3) Fluorite-bearing, quartz-chalcopyrite veins often contain trace telluride phases (e.g., hessite, altaite, coloradoite, wehrlite) which can crosscut and replace 'older' phases. Tellurides along with tetrahedrite and tennantite occur as inclusions in chalcopyrite, and are often associated with phyllosilicate gangue.

(4) Late replacement of biotite by chlorite, actinolite by talc + calcite and hematite by siderite + chlorite is often accompanied by an addition of copper mineralisation. In high grade Cu-Au areas of the prospect there is often an intense development of muscovite + calcite and talc + calcite reminiscent of phyllic-like alteration.

(5) Gold fineness increases overall from the structural/ stratigraphic base to the top of the system due to precipitation of hessite (Ag_2Te). Carbonates become progressively more Fe and Mn-rich from the base to the top and this zoning may be of use as a pathfinder to higher grade Au and Cu-Au in the system. Tourmaline becomes more vanadium-rich towards the top of the system with V_2O_3 and Cr_2O_3 sometimes up to 7% combined. It would appear that vanadium in the ore fluid increases with time.

(6) Bonanza gold grades tend to occur high in the structural/stratigraphic framework of the Portia-North Portia system, immediately below the carbonaceous meta-shales of Unit seven.

Monazite in the Cu-Au(-Mo) mineralisation can form a significant proportion of the gangue in some areas and is present in bedding parallel replacement mineralisation as well as in crosscutting infill sulphide veins. The monazite can be included in chalcopyrite and have inclusions of chalcopyrite. Molybdenite-monazite veins are also present. Detailed in situ SHRIMP II dating of monazites

associated with Cu-Au mineralisation gives an age of approximately 1605 Ma, although some grains are complex and a subordinate number of areas record an older age of ~1690 Ma. This older age is not as well defined and most probably reflects inheritance associated with an earlier phase of fluid activity which crystallised monazite, during the time of the major ~1700 Ma magmatism in the CP (Fanning *et al.*, 1998). Dating of rutiles from mineralised veins is ongoing with SHRIMP U-Pb rutile ages of ~1600 Ma being obtained when the grains are found to contain significant uranium.

Table 1: Timing and Stages of Mineralisation, North Portia - Portia Prospects

Mineralisation	Age	Comment
Stage 1	1680 - 1700 Ma (D1, M1)	Diagenetic to (?) D1 framboidal pyrite; Sphalerite ± galena ± REE-bearing phases; early albitisation
Stage 2	1640 - 1680 Ma (?)	Early bedding parallel pyrrhotite + cpy ± bornite ± REE-bearing phases
Stage 3	1640 - 1660 Ma (?) (D2, M2 ?)	Pyrite ± magnetite ± hematite; replaces Stage 2
Stage 4a	~1630 Ma	Invasive albitisation; Monazite abundant at albitisation "front"; possible pyrite-monazite veins; albite - quartz - monazite veins; replacement MoS_2 (±biotite)
Stage 4b	~1630 Ma	Breakdown of Cl- and F-bearing phases during albitisation and removal of Ag Pb (- Cl - F) and other metals from albitised lithotypes.
Stage 5a (Calcic vein type)	~1605 Ma	MoS_2 in veins and replacement domains; "calcic" veins structurally and stratigraphically low in system. Allanite and sphene as gangue phases.
Stage 5b (Biotite - Kspar - Fe type)	~1605 Ma	Development of hematite ± mt - calcite veins; Cu-Au in crosscutting veins; and replacing meta carbonate / evaporite beds; breccia zones; additional MoS_2 in calcite ± cpy veins; monazite abundant.
Stage 5c (F - rich type)	~1605 Ma	Cu - Au (- F - Bi - Te - Hg - Ag - Ba) introduction; can crosscut or replace "older" phases; reactivation of older min; REE - fluocarbonates peak
Stage 5d (Lower temp. addition)	~1605 Ma	Replacement of higher T. gangue by chlorite, talc - calcite, siderite - Fe chlorite; upgrading of existing mineralisation.
Stage 5e	~1605 Ma	Zeolite - pyrite veining
Stage 6	<1605 Ma (pre-Delamerian)	Late fault breccias; hematite - calcite -fluorite - barite - galena ± sphalerite ± MoS_2; reactivation and micro shearing. Probably generated outside of the North Portia hydrothermal system.
Stage 7	~ 500 Ma	Remobilisation of the above; crustiform galena - calcite ± marcasite ± sphalerite veins; Bi - Te - Au - Ag veins in Adelaidean; calcite - cpy veins, calcite - cpy infills
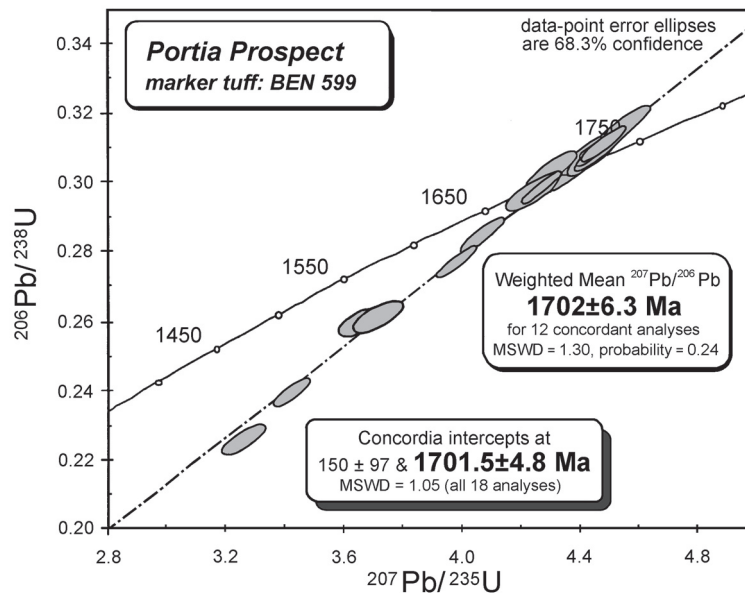
Figure 8: Standard concordia plot of SHRIMP U-Pb analyses of zircons from tuffaceous horizon in BEN 599, Unit 5. Analyses plotted as 1σ error ellipses; age uncertainties given t 95% confidence limits.

Skirrow *et al.* (2000) report Re-Os dating of molybdenite from three prospects on the BRMC, the Kalkaroo prospect, White Dam and the Waukaloo prospect (Fig. 2). This dating yielded ages ranging from ~1632 to ~1612 Ma, confirming the pre-1600 Ma age for mineralisation in the district.

Iron oxide minerals within and adjacent to the Portia-North Portia mineralisation include magnetite, hematite, titaniferous magnetite and hematite and specular hematite. Magnetite usually occurs as idioblastic porphyroblasts but can also be present as a pseudomorph after bladed hematite and as small rounded grains in footwall albitites. It can be replaced by hematite or intergrown, and in textural equilibrium, with hematite, indicating co-existence along the magnetite-hematite buffer. Magnetite can be replacive (skarn-like) occurring with pyrite and/or chalcopyrite within carbonate beds at their contact with albitic metasediments. Near massive magnetite (with pyrite) is present in drillhole BEN602 (North Portia) where it occurs at the base of Unit two and gradually grades into an actinolite marble. Although large bodies of massive magnetite/hematite occur elsewhere in the CP (e.g., Gunsight Prospect, Mount Painter Inlier), none exist in the Portia-North Portia area. Instead, abundant disseminated magnetite (up to 30% in places) is present, generally contained within the albitites. The invasive albitites which cut across stratigraphy are therefore capped, and in part enveloped, by highly reduced, carbonaceous meta-shales.

Mineralised veins contain evidence of a complex history, especially with regard to the iron oxides. High copper grades can be associated with feathery, bladed hematite that has been pseudomorphed by magnetite. Hematite and/or chalcopyrite can then replace this magnetite. Hematite can also be replaced by siderite and iron chlorite. The ore fluid would be quite oxidised (as it precipitates magnetite, hematite and lesser barite) however interaction with adjacent reduced rock-types would mean highly fluctuating oxygen fugacities and changes in X_{CO2}. The extreme gold grades which are contained structurally/stratigraphically high in the hydrothermal system (e.g., Portia, Shylock), may be present as a response to the oxidation of carbonaceous matter, creating a $CO_2 + CH_4$-rich fluid phase. This fluid phase, when mixed with the ore fluid, would decrease f_{O2} with concomitant deposition of gold.

Changes in f_{O2}, X_{CO2}, f_{HF}, temperature of ore fluid and probable constant addition of a compositionally changing ore fluid are more than likely to be responsible for the ore system observed. The abundance of magnetite-hematite in the system juxtaposed against highly reduced lithotypes, is perhaps the fundamental parameter for the deposition of Cu-Au (-Mo-REE). The presence of a highly fractured and 'brittle' host (albitite) combined with abundant meta-carbonates and evaporites was also important.

Cu-Au(-Mo) mineralisation in the region has often been related back to 'Hiltaba' age granitoids (~1590 Ma) with 'A-type' affinities (cf Robertson *et al.*, 1998 re the Parabarana prospect; see also discussion by Wyborn *et al.*, 1998). Recently, Ashley (2000) stated that "although the origin of the Cu-Au (-Mo) association could not be superficially attributed to magmatic hydrothermal processes, it is difficult to unequivocally prove such a link based on currently known field, geochronological, chemical and isotopic constraints". We agree, in part, with Ashleys' view. Unpublished data (Teale and Fanning) show that the 'A-type' intrusives of the Benagerie Ridge area cannot be responsible for the observed mineralisation as they were emplaced approximately 25 Ma after the development of that mineralisation (potentially up to 50 Ma after the deposition of some of the molybdenite mineralisation). They could have been responsible for the partial remobilisation of metals and as a source of heat creating late retrograde effects, but not as the ultimate source of metals.

The Benagerie Ridge region contains large bodies of fractionated, extremely altered gabbro/diorite. Attempts to date these bodies have failed due to the paucity of zircon. They contain minor disseminated chalcopyrite and molybdenite, fluorite-actinolite veining, development of hydrothermal biotite and K-feldspar, intense carbonate alteration and scapolite replacement and veining. The latter suggests an interaction between the meta-evaporitic host rocks and the diorite bodies. These bodies are potential candidates as the suppliers of Cu-Au-Mo metal. Further work on these fractionated mafics is being undertaken. Also, one cannot discount the potential addition of metal from the meta-black shales of the region which are excellent repositories for elements such as V, Cu, As, Ni, Mo, U, and Be.

Summary and Concluding Remarks

The Portia-North Portia Cu-Au(-Mo) Prospect can be classified as a member of the Proterozoic iron Cu-Au class of deposit. The mineralisation is zoned, being Cu-Mo-rich towards its structural/stratigraphic base and changes to Cu-Au and then Au-rich towards the top of the system. The interaction of mineralising fluids with an extremely iron-rich and oxidised "footwall", and a highly carbonaceous, reduced "hangingwall" is perhaps the dominant parameter for sulphide and gold deposition. The following are key features that should be considered in any discussion of the prospect.

(1) The prospect is located in the centre of the CP and is perhaps the least deformed and metamorphosed Palaeoproterozoic sequence in the CP.

(2) A small but prominent, stratigraphically well-constrained tuff marker in the host sequence has a SHRIMP U-Pb zircon age of 1703 ± 6 Ma. The sequence is therefore the same age as parts of the Willyama Supergroup in the BHD and OD, and is not part of a younger sequence (~1640 to ~1655 Ma, Page *et al.*, 2000) now known to overlie the Willyama Supergroup.

(3) The prospect lies on the eastern flank of the BRMC, which is cored by albite-magnetite rocks. Other magnetic complexes in the CP can be host to massive magnetite ± hematite.

(4) The prospect is hosted by an albitised, meta-carbonate/evaporite sequence. The potentially mineralised portion of this sequence can be 200m in thickness. Carbonate and albite nodules, gypsum/anhydrite pseudomorphs, abundant tourmaline, the presence of Cl-rich scapolite, carbonate beds and the finely laminated nature of the sediments are all distinguishing features of this part of the sequence.

(5) Albitisation was superimposed on these sediments during diagenesis. Detailed in situ SHRIMP U-Pb monazite dating of the albitites gives ~1630 Ma for this albitisation event, in agreement with SHRIMP U-Pb monazite dating of veins within the footwall albitites.

(6) The presence of abundant monazite in the mineralised veins at Portia-North Portia allows a reliable age for the mineralisation to be obtained. Detailed in situ SHRIMP II dating of these monazites constrains the emplacement of the mineralised veins at ~1605 Ma.

(7) Mineralisation, gangue mineralogy and vein development are complex. Earlier assemblages can be replaced by later fluids which are for example, more oxidised, or more CO_2-rich, or HF-rich, etc. Early sphene and allanite for example, give way to REE-fluocarbonates and monazite, and actinolite in vein assemblages has been almost totally pseudomorphed by a variety of phases.

(8) The "Hiltaba age" A-type granitoids of the region are not responsible for the Cu-Au(-Mo) mineralisation. They are approximately 25 Ma younger than the mineralisation. Intensely altered diorites, which are present under cover on the Benagerie Ridge, may be the source of some of the metals. These diorites are highly fractionated, in part granophyric, Fe-rich and contain some disseminated sulphide. The age of the diorites is not known at present.

Acknowledgements

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