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ALTERATION AND MINERALISATION IN THE MOONTA-WALLAROO COPPER-GOLD MINING FIELD REGION, OLYMPIC DOMAIN, SOUTH AUSTRALIA

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Abstract - The Olympic Copper-Gold Province of the eastern Gawler Craton of South Australia, in hosting the Olympic Dam, Prominent Hill, Carrapateena and Moonta-Wallaroo deposits, has the greatest known iron-oxide, copper, gold and uranium (IOCGU) metal endowment of any geological province on Earth. The historic Moonta-Wallaroo copper-gold mining field is within the Moonta sub-domain and is hosted by the ~1750 Ma Wallaroo Group that preserves some evidence of evaporitic sedimentation, similar to other major iron oxide-copper-gold (IOCG) provinces in Australia and North America. Observations in the Moonta-Wallaroo district indicate that mineralisation was broadly associated with intense metasomatic alteration, intrusion of granites and gabbros of the Hiltaba Suite, moderate grade metamorphism and intensely partitioned deformation. The driving force of this extensive ~1600 to 1500 Ma hydrothermal, magmatic and tectonic event was a major thermal pulse, the cause of which remains under debate. The vein-style mineralisation in the Moonta-Wallaroo district developed in ground prepared by ductile shearing. Widespread sub-economic copper mineralisation in the region is associated with intense regional magnetite-bearing skarn-like alteration of the Cloncurry type, with oxidation and hematite replacement of early magnetite. Targeting of structurally-controlled demagnetised zones and the oxidised margins of magnetic anomalies has been applied successfully in the northern Olympic Copper-Gold Province (e.g. Prominent Hill) and is also applicable to the Moonta-Wallaroo region. The recently discovered copper-gold mineralisation at the Hillside copper-gold deposit demonstrates the continued prospectivity of this southern portion of the Olympic Copper-Gold Province.

Introduction

Skirrow *et al.* (2002) defined the Olympic Copper-Gold Province, as a metallogenic belt encompassing all of the IOCG mineralisation in the eastern Gawler Craton of South Australia. Mineralisation took place at around 1600 to 1570 Ma, and generally shows an association of copper with the oxidation of early formed magnetite-bearing alteration. This province, which includes the Mount Woods and Moonta tectonic domains (Ferris *et al.*, 2002), hosts the giant Olympic Dam deposit, as well as those of Prominent Hill, Carrapateena and Moonta-Wallaroo, thus having the greatest known iron oxide, copper, gold, uranium (IOCGU) metal endowment of any geological province on Earth (Fig. 1). The deposits of the Olympic Copper-Gold Province follow a curvilinear trend, with the above first three being in the north and approximately equidistant from each other. The Moonta-Wallaroo mining field (Moonta-Wallaroo) of the Moonta sub-domain is situated to the south, in the northern part of Yorke Peninsula (Figs. 1 and 2).

The importance of Moonta-Wallaroo is two-fold. Firstly, the discovery of the Moonta and Wallaroo copper-gold lodes in 1861 was a great historic boon to the economy and social development of South Australia. Secondly, when in 1975 Western Mining Corporation extended its search northward along strike of the then unknown Olympic domain, it was the stepping-stone to the discovery of the giant Olympic Dam deposit, the world's greatest single copper-gold-uranium resource.

Production from the Moonta-Wallaroo mining field, firstly from 1861 to 1923 and then between 1988 and 1993, was over 355 000 tonnes of copper and associated gold at a grade averaging 5% Cu and 1 to 4 g/t Au (Daly *et al.*, 1998). Jack (1917) provided detailed descriptions of the Moonta mines following fifty years of mining, and Dickinson (1942, 1953) gleaned information from mine plans, records of Inspectors of Mines and from the personal accounts of former miners twenty years after mining ceased at the Wallaroo mines. The discovery by Western Mining and subsequent mining of the Poona mine and Wheal Hughes lodes provided the opportunity for geological mapping and modern geochemical studies (Janz, 1990; Hafer, 1991; Both *et al.*, 1993; Wurst, 1994; Morales-Ruano and Both, 1999; Morales-Ruano *et al.*, 2002; Skirrow *et al.*, 2007).

This article describes the alteration in the Moonta-Wallaroo district, and how aspects of alteration and mineralisation were controlled by the interaction of magmatism, metamorphism, metasomatism and deformation. Also included is an introduction to the recently discovered Hillside deposit in order to highlight a potentially new structural regime controlling mineralisation in the Moonta sub-domain. This discovery by Rex Minerals of a larger extension to the historic Hillside mine (Wade and Cochrane, 1954), has refocussed interest on the Moonta-Wallaroo district (Figs. 2 and 3), demonstrating that the potential remains for significant economic mineralisation in this southern part of the Olympic domain.

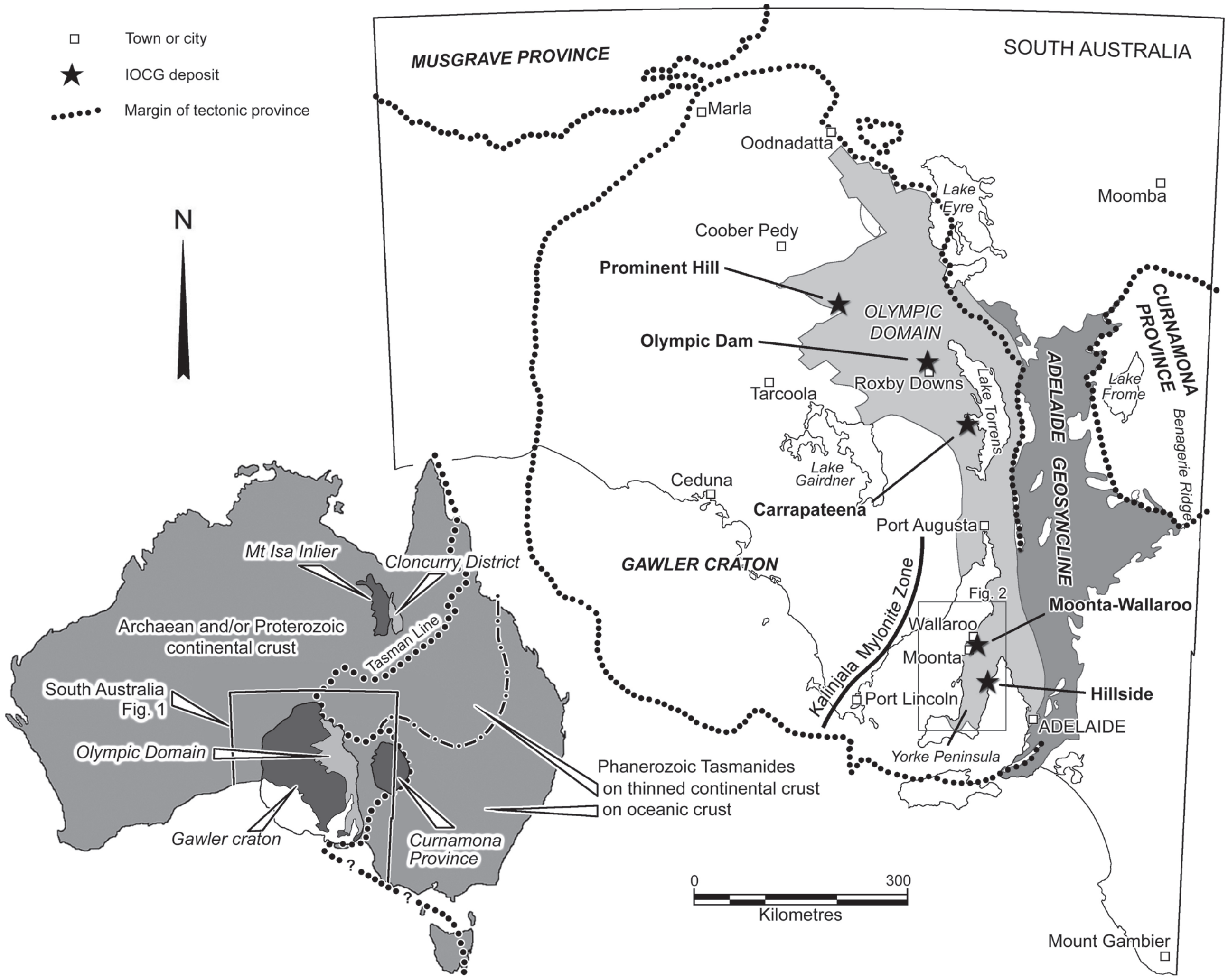


Figure 1: The tectonic framework and location of the IOCGU mineralised Archaean to Mesoproterozoic Gawler Craton and Curnamona Province of South Australia, highlighting the regular spacing of the main currently known deposits. **Inset:** Location and tectonic setting of the major Mesoproterozoic IOCGU provinces of Australia. These areas lie to the west of the Tasman Line (dotted line) which marks the boundary between the area dominantly occuppied by the Phanerozoic Tasmanides of Eastern Australia, and the western two thirds of the continent where coherent Archaean and/or Proterozoic continental crust is either exposed or occurs as basement to Phanerozoic cover sequences. The Tasmanides overlie Cambrian and younger oceanic crust to the south and attenuated Precambrian continental crust to the north (as indicated). A section of western North America, which includes the Mesoproterozoic Wernecke Mountains IOCG district of northwestern Canada, is believed to have been rifted from somewhere to the east of the Tasman line following the breakup of the Rodinia super-continent in the Late Neoproterozoic (Glen, 2005 and references quoted therein).

Regional Geological Setting

A major thermal event, or clustering of events, is reflected in alteration and IOCG(U) mineralisation in southern and northeastern Australia (Fig. 1 inset; Fig. 4), and northwestern Canada from approximately 1600 to 1500 Ma. Apart from the copper-gold dominated mineralisation, the thermal nature of this event was registered in: (1) the Gawler Craton by the intrusion of the Hiltaba Suite granites and the outpouring of the Gawler Range Volcanics; (2) in the southern Curnamona Province by the Olarian orogeny and intrusion of the Ninnerie Supersuite granites, and extrusion of the bimodal volcanics of the Benagerie Ridge; (3) in the Mount Isa Inlier by the Isan Orogeny and intrusion of the Williams and Naraku Granites; and (4) in the Wernecke Mountains of the Yukon (believed to have been located adjacent to eastern Australia prior to the late Neoproterozoic breakup of Rodinia; Fig. 1 inset) by brecciation accompanied by high temperature sodic and calcsilicate alteration. Of added significance are the depositional packages associated with these regions, the 1750 Ma Wallaroo Group of the eastern Gawler Craton (Cowley *et al.,* 2003), the 1720 to 1640 Ma Willyama Supergroup of the southern Curnamona Province (Conor and Preiss, 2008), Cover Sequences 2 (1780 to 1725 Ma) and 3 (1680 to 1610 Ma) in the Eastern Succession of the Mount Isa Inlier (Foster *et al.*, 2008), and the ~pre-1600 Ma Wernecke Supergroup of the Yukon (Hunt *et al.* 2007). These packages share similar sedimentary characteristics, including evidence for the presence of evaporites, which have been shown to be of significance as brine sources during formation of IOCG(U) deposits (Hunt *et al.*, 2007). Of additional interest, the Willyama Supergroup and Eastern and Western Successions of the Mount Isa Inlier are parts of the eastern Australia lead-zinc belt, one of the most highly mineralised successions for these commodities on Earth.

The Moonta-Wallaroo, Olympic Dam, Prominent Hill and Carrapateena copper-gold (uranium) deposits are hosted within Palaeo- to Mesoproterozoic rocks of the Olympic domain that extends along the eastern edge of the currently preserved Gawler Craton (Fig. 1). Underlying and to the west is Mesoarchaean to Palaeoproterozoic basement, partly overlain by the thick Mesoproterozoic Gawler Range Volcanics. Unconformably overlying these deposits are the Neoproterozoic sediments of the Stuart Shelf

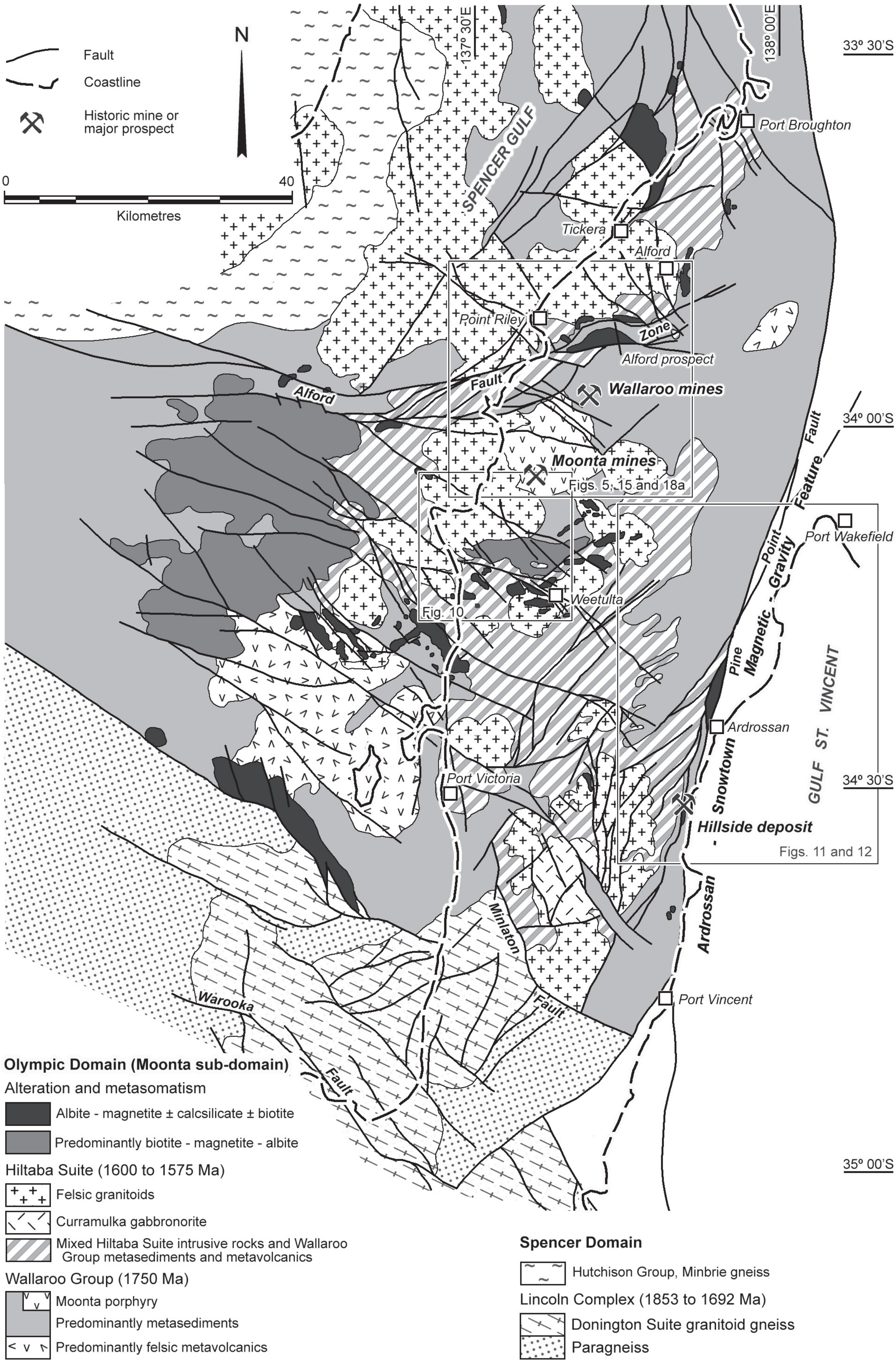


Figure 2: The interpreted solid geology of northern Yorke Peninsula and below the adjacent Spencer Gulf, showing the location of the Moonta and Wallaroo mines, the Hillside deposit on the east coast, Palaeoproterozoic metasediments and volcanics, Mesoproterozoic intrusions, and zones of intense magnetite-bearing alteration (Figure modified from Raymond, 2003). See Fig. 1 for location.

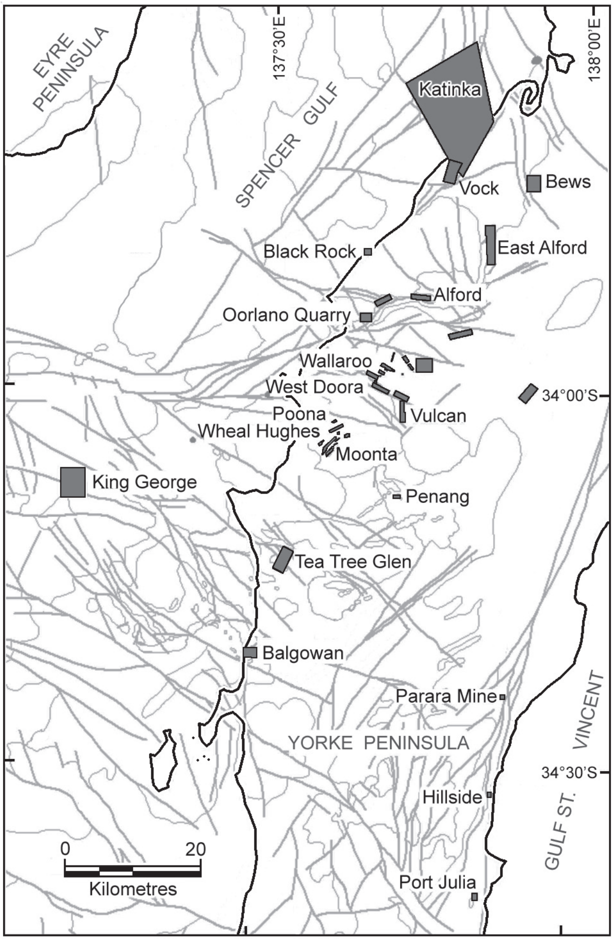


Figure 3: Metallic mineral occurrences, prospects and historic mines of northern Yorke Peninsula. The geological boundaries and faults from Fig. 2 are shown in the background.

marking the western flank of the Adelaide Geosyncline, an intracontinental rift-complex. The Olympic domain may reappear to the east as the deeply buried western part of the Curnamona Province. This contention is supported by the presence in the latter region of large magnetic and gravity anomalies, early Mesoproterozoic granites and volcanics, and deformation and alteration styles similar to those of the Gawler Craton. One such magnetic-gravity anomaly in the Gawler Craton forms a laterally extensive, deeply buried feature paralleling the eastern coast of Yorke Peninsula, immediately east of the Pine Point Fault, and is proximal to the Rex Minerals Hillside deposit (Figs. 2 and 3). In addition, the earlier history saw an eastward migration of similar sedimentation and bi-modal A-type volcanism from the eastern Gawler Craton (~1750 Ma Wallaroo Group) to the Curnamona Province (1720 to 1640 Ma Willyama Supergroup; Conor, 1995; Conor and Preiss, 2008). Hand *et al.* (2008) have highlighted this connection by suggesting that the Gawler Craton and Curnamona Province represent parts of an early Mesoproterozoic foreland basin that accommodated the voluminous bi-modal 1600 to 1590 Ma Gawler Range Volcanics and the 1600 to 1575 Ma Hiltaba Suite granitoids in the west, and 1600 to 1580 Ma Ninnerie Supersuite granites and Benagerie Ridge volcanics in the Curnamona Province in the east. Preceding this Mesoproterozoic magmatism, the 1620 to 1615 Ma intrusive and extrusive rocks of the mafic to granitic St. Peter Suite were emplaced in and on the western half of the Gawler Craton.

During this period, the contractional ~1620 to ~1575 Ma Olarian orogeny was responsible for greenschist to granulite grade metamorphism of the southern Curnamona Province and inliers within the Adelaide Geosyncline (Szpunar *et al.*, 2007). Further west, in the Gawler Craton, the Olarian orogeny was manifested by metamorphism and deformation that were partitioned by crustal-scale faults and shear zones (Conor, 1995 and 2002). These penetrating structures were critical to the formation of ore in that, not only did they allow ingress of metasomatic and mineralising fluids, but also provided the loci for deposition. The ultimate cause of the early Mesoproterozoic heating that drove the mineralising system is still under debate. However, the volume of crust involved was huge because the copper-gold-uranium mineralisation of the Gawler Craton, Curnamona Province and Cloncurry district, and possibly the Wernecke Mountains (Thorkelson *et al.*, 2001; Conor, 2003) was all broadly coeval with the mineralisation at Olympic Dam which formed at around 1590 Ma (Johnson and Cross, 1995).

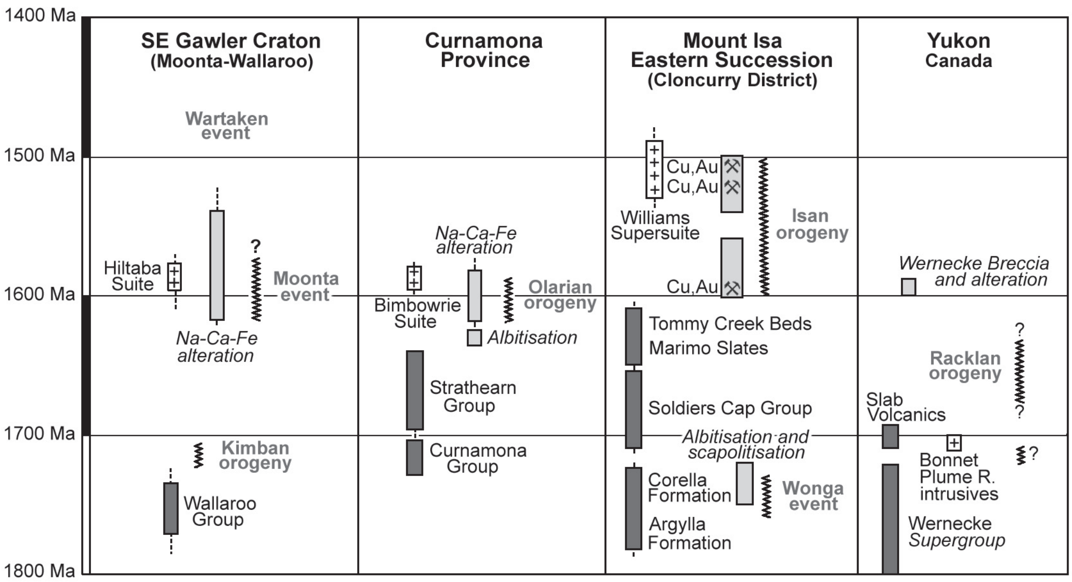


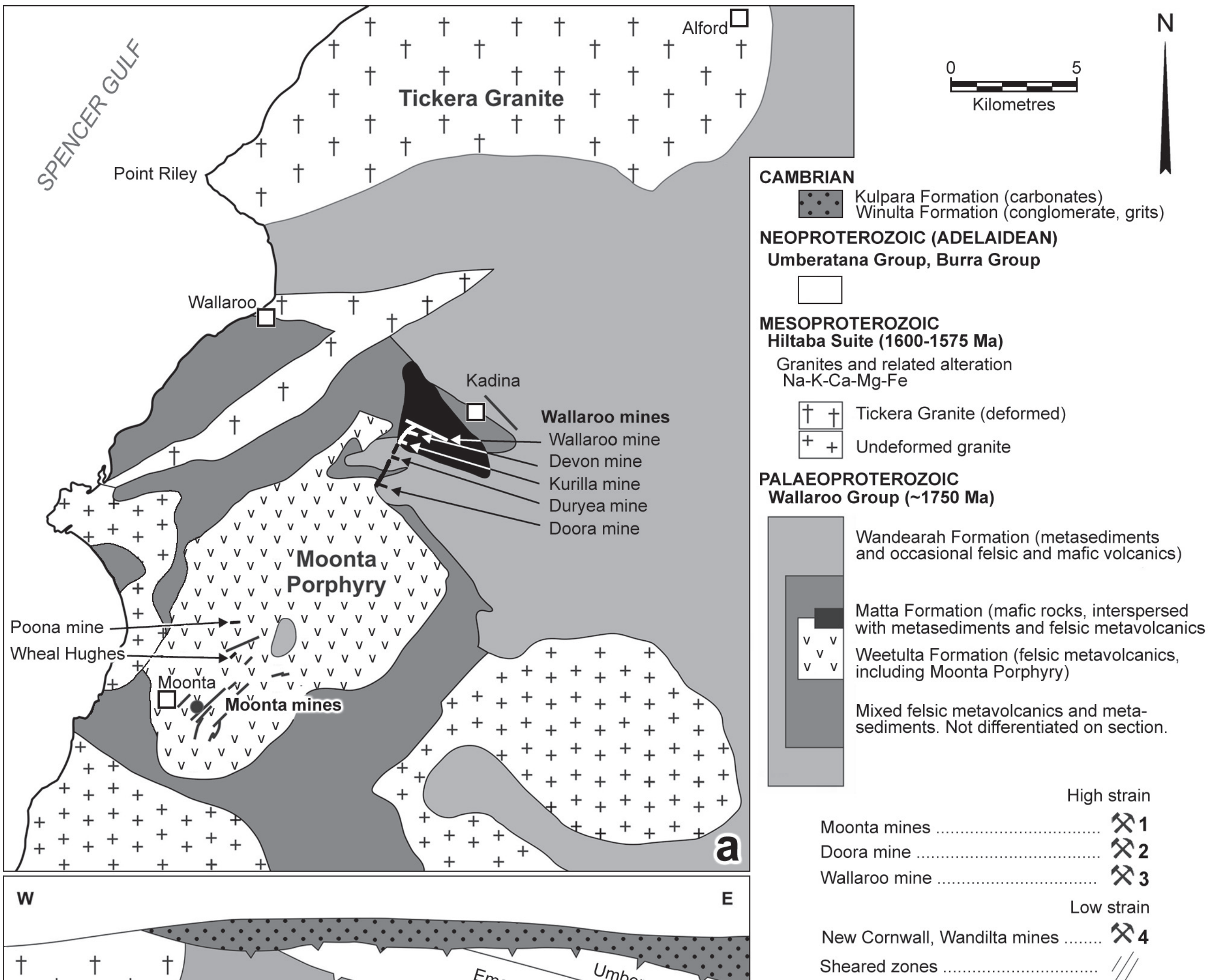
Figure 4: Summary time-space diagram of the Moonta-Wallaroo region, Curnamona Province, Cloncurry Belt and Yukon region, for the late Palaeoproterozoic to early Mesoproterozoic period, showing regional alteration, mineralisation and related deformation and magmatism. Age ranges represent available isotopic dating summarised in this paper and in Skirrow *et al.* (2007), Skirrow (2009), Betts *et al.* (2006), Mark *et al.* (2006b), Oliver *et al.* (2001) and Thorkelson *et al.* (2001).

Geological Setting of the Moonta-Wallaroo District

The largely sub-cropping host units of the Moonta-Wallaroo region comprise the Palaeoproterozoic Wallaroo Group volcano-sedimentary succession, and early Mesoproterozoic granites and mafics of the Hiltaba Suite (Figs. 5a and 5b). The underlying basement of the region is thought to include gneissic granitoids of the Donnington Suite (~1850 Ma), which are uplifted and exposed in the southern part of Yorke Peninsula by faulting that limits the southern extent of the Moonta sub-domain (Raymond, 2003). Being located on the western flank of the Adelaide Geosyncline rift, the Moonta-Wallaroo region is unconformably overlain and almost totally blanketed by thin, incomplete, successions of Neoproterozoic, Cambrian, Permian and Tertiary sediments upon which the present day regolith and soils reside (Fig. 5b).

Wallaroo Group (~1750 Ma)

The Wallaroo Group (Conor, 1995; Cowley *et al.,* 2003) is a diverse set of siltstone-dominated metasedimentary rocks extending from Yorke Peninsula northward below the Stuart Shelf and along much of the Olympic domain. Important facies include fine-grained psammites, zincian graphitic sediments, calcsilicates (e.g., east of Kadina), quartzites, iron-rich sediments (e.g., Wallaroo and New Cornwall mines) and perfectly planar, thinly interbedded sodium-rich calc-albitite sediments (e.g., north of Alford). This latter sodium-rich lithology, together with the large volume of metasomatic albite and also metamorphic scapolite, suggests the original presence of evaporites in the Moonta-Wallaroo region. The apparent absence of aluminosilicate minerals indicates that pelites are either uncommon or non-existent. Stratigraphically, the facies of the Wallaroo Group have been subdivided to member level, but due to poor exposure, sporadic drill hole distribution



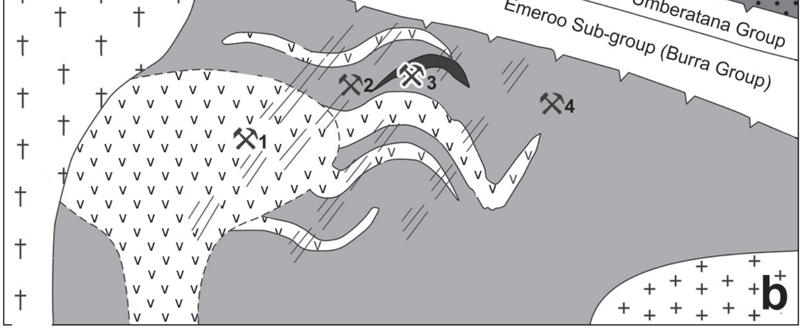


Figure 5: **a** - Generalised solid pre-Neoproterozoic geology of the Moonta-Wallaroo region, from Moonta in the south to Alford in the north. See Fig. 18b for detail of Moonta mines lode traces. **b** - Schematic rock relation section of the geology of the Moonta sub-domain (Olympic domain) showing the interfingering components of the Wallaroo Group, deformed and undeformed Hiltaba Suite granite intrusions, mineral deposits associated with ductile high strain zones (Moonta, Doora and Wallaroo mines), and brittle fractures (New Cornwall and Wandilta) (adapted from Parker, 1993).

and complex structure, the spatial and temporal relationship between stratigraphic units is not clearly understood.

Importantly, the sediments of the Wallaroo Group were deposited synchronously with bimodal A-type felsic volcanism, which supports crustal attenuation and a rift setting as the environment of deposition. This is in agreement with Plimer (1980), who suggested Lake Magadi of East Africa as an analogue for the formation of the banded magnetite-albite metasediments of the East Kadina mines area. Where outcropping at Port Victoria and Wardang Island, felsic volcanics show good evidence of subaerial to subaqueous deposition in that flow banding and folding, and peperitic textures are well displayed. The main Moonta Porphyry body is a large oval mass of feldspar porphyry, extending north-northwest from Moonta to near Kadina, where drilling shows interdigitation with the iron-rich psammites of the Doora Member of the Wallaroo Group. Drilling within the bounds of the porphyry body near Wheal Hughes intersected a sediment-supported feldspar porphyry-clast breccia, which grades upwards through graded-bedded volcaniclastics and calcic-sediments, and hosts significant disseminated chalcopyrite mineralisation. The above, together with the local preservation of layering within the main Moonta Porphyry, provides evidence for an eruptive environment, perhaps of the rhyodacite-dome-style proposed by Hafer (1991) at Port Victoria.

Hiltaba Suite Granites and Related Intrusions (~1600 to 1575 Ma)

Jack (1917), in recognising that the granite complex in the vicinity of Point Riley and Tickera was deformed, called it the Tickera Granite and considered it to be older than the undeformed granites south of Moonta (Figs. 5a and 5b), which he named the Arthurton Granite. However, U-Pb dating has indicated both granites to be of similar age and part of the Hiltaba Suite (Creaser and Cooper, 1993; Fanning in Conor, 1995). Consequently, no distinction will be made in this contribution, except that the name 'Tickera Granite' will be used in a restricted sense for R. L. Jack's 'type' Tickera Granite that is exposed along the Tickera coastline. The introduction of the Hiltaba Suite granites, and temporally related mafic rocks (e.g., Curramulka Gabbronorite, Zang *et al.*, 2007), was the second bimodal igneous event that affected northern Yorke Peninsula (Fig. 2). Granite chemistry varies across the A-, I- and S-type range, with both brick red oxidised and more reduced white granites being common (Wurst, 1994). The granites exhibit a considerable diversity in grain size and texture, and there is evidence for great variation in depth of emplacement, from deep, where some examples are foliated and lineated, to near surface as exemplified by a late non-foliated granite at Point Riley containing miarolitic cavities (A. White, *pers. com.*, 1996). Also in the vicinity of Point Riley, variation in timing is displayed by pegmatite veins, some being deformed and others not. In addition, the coincidence in timing of granite emplacement and alteration is demonstrated by a feldspar-dominated felsic intrusion of intermediate composition south of Alford, which is intensely affected by calcsilicate alteration (i.e., endoskarn), while a partly deformed intrusion of similar composition is exposed intruding altered Wallaroo Group metasediments in the deep excavation that drains eastern Kadina (Fig. 5a). Additionally, as described below, both exoskarn and endoskarn development is reported in the vicinity of the Hillside deposit. Since the granites are variably deformed but locally bear a metamorphic foliation, and either intrude metasomatically altered assemblages, or are themselves altered, the timing of granite crystallisation over the period ~1600 to ~1575 Ma indicates coincidence with deformation, metamorphism and metasomatism.

Geochronological Summary

Considerable isotopic dating, using several methods and target minerals, has been carried out in northern Yorke Peninsula. Significant mobility of Rb and Sr during metamorphism and/or hydrothermal alteration has meant that attempts to use Rb-Sr dating in the Moonta district (e.g., Webb, 1978; Webb *et al.*,1982) resulted in little geologically useful data. K-Ar dating of biotite, muscovite and hornblende from Wallaroo Group metasediments, metavolcanics, skarns and pegmatite veins (Webb, 1978; Webb *et al.*, 1982) show a wide range of interpreted ages (Fig. 6). For instance, hornblende K-Ar data ranges from 1634 to 1241 Ma. The majority of K-Ar data from northern Yorke Peninsula lie between 1500 and 1400 Ma, suggesting that hornblende, biotite and muscovite

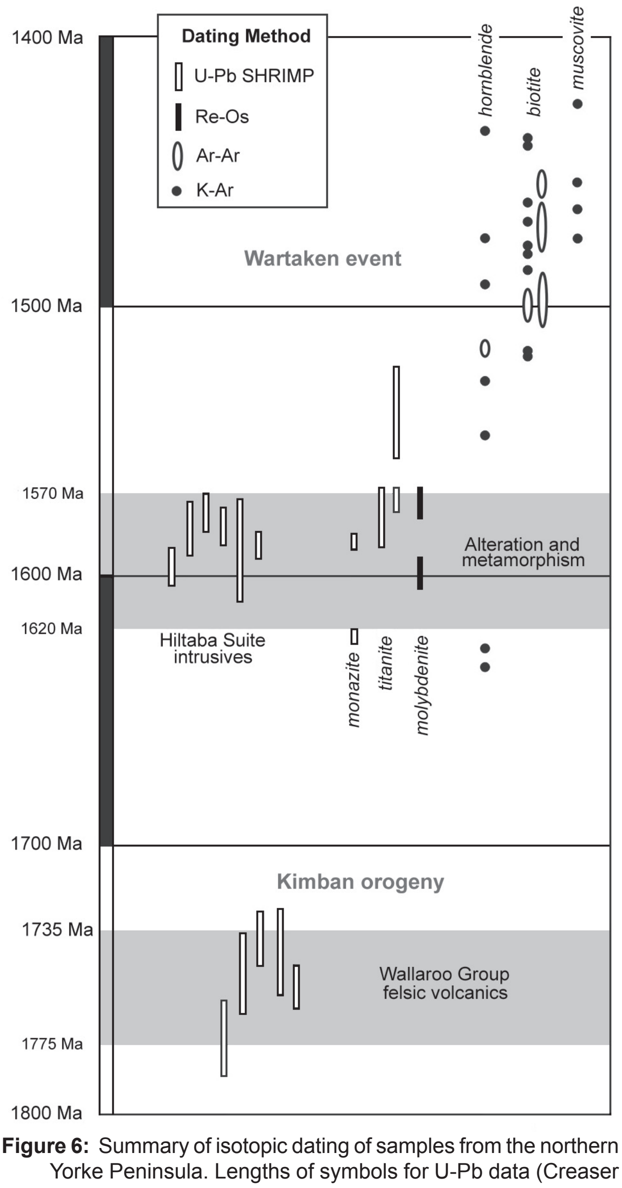


Figure 6: Summary of isotopic dating of samples from the northern Yorke Peninsula. Lengths of symbols for U-Pb data (Creaser and Cooper, 1993; Raymond *et al.*, 2002; Fanning *et al.*, 2007; Zang *et al.*, 2007; C.M. Fanning, pers. comm.), Re-Os data (Skirrow *et al.*, 2007), and Ar-Ar data (G. Fraser, pers. comm.) indicate interpreted error range. K-Ar data (Webb, 1978; Webb *et al.*, 1982) were not reported with errors.

K-Ar systematics have been thermally reset during the regional Wartakan Event after 1500 Ma. This thermal resetting is also supported by Ar-Ar analyses (G. Fraser, Geoscience Australia, unpublished data) of biotite and hornblende from hydrothermally altered Wallaroo Group metasediments.

U-Pb SHRIMP dating of zircon, monazite and titanite defines two periods of magmatism and hydrothermal alteration (Fig. 6). The tight grouping of most of the U-Pb analyses suggests that the U-Pb isotopic system has preserved primary closure ages, and has not been adversely affected by later events. Wallaroo Group magmatism is approximated by five zircon ages (Fanning *et al.*, 2007), ranging from 1772±14 to 1735±10 Ma. Hiltaba Suite magmatism is defined by five dates from felsic to mafic intrusives ranging from 1591±19 to 1570±8 Ma (Creaser and Cooper, 1993; Fanning *et al.*, 2007; Zang *et al.*, 2007; Reid, 2010). This is consistent with the period of Hiltaba Suite magmatism defined elsewhere in the Gawler Craton (Fanning *et al.*, 2007; Reid, 2007).

Nine analyses of monazite (Raymond *et al.*, 2002), titanite (Raymond *et al.*, 2002; Fanning, unpublished data; Reid, 2010) and molybdenite (Skirrow *et al.*, 2007) from alteration zones in the Wallaroo Group define a period of hydrothermal alteration broadly coincident with Hiltaba Suite magmatism. The oldest hydrothermal monazite date (1623±3 Ma) is around 10 Ma older than the oldest dated granite in the Moonta region, and suggests crustal heating and hydrothermal activity prior to granite intrusion. The youngest titanite date (1539±17 Ma; Fanning, unpublished data) is the least well constrained statistically of all the U-Pb alteration dates, due to low U and high common Pb concentrations.

Structure and Metamorphism

It is well known that the Olympic Dam (Roberts and Hudson, 1984: Reeve *et al.* 1990, Reynolds, 2001), Prominent Hill (Belperio *et al.*, 2007) and Carrapateena (Primary Industries and Resources South Australia, 2010) deposits are to a large degree structurally controlled. However, prior to the discovery of these major deposits, both Jack (1917) and Dickinson (1942 and 1953) had demonstrated the relationship of mineralisation at the Moonta and Wallaroo mines to structures that deform the ~1750 Ma volcano-sedimentary Wallaroo Group. Studies since then, highlight the connectivity of deformation, magmatism, metamorphism and metasomatism in controlling alteration and mineralisation (Conor, 1995; Raymond *et al.*, 2002).

Observations from excavations (e.g., Wheal Hughes), drill core from mines, regional exploration, and coastal outcrop (e.g., Wallaroo North Beach to Point Riley) show that the Wallaroo Group is highly deformed and metamorphosed. Regional metamorphism varies from upper greenschist to mid-amphibolite facies grade. However, the degree of metamorphic mineral growth and fabric intensity is highly variable. Bedding is generally steeply inclined, and interpretation of aeromagnetic imagery indicates that, at least in places, isoclinal fold limbs are several kilometres long.

Metamorphic textures are displayed as foliations and/or mineral lineations. Locally, the latter may be of sufficient intensity to dominate the rock fabric, being most obvious in homogenous rocks such as felsic volcanics and amphibolites, and the finer grained Mesoproterozoic granites. This distinctive, generally steeply plunging, L-S metamorphic fabric is shared, at least locally, by such diverse non-layered rocks as felsic volcanics and mafic rocks of the Wallaroo Group at Port Victoria and Wardang Island in the south, the Moonta Porphyry, a granite of presumed Mesoproterozoic age near Wallaroo, and different varieties of the Tickera Granite exposed at Point Riley and northward along the coast to Tickera (Fig. 2).

The northeasterly orientation of the highly strained domain of northern Yorke Peninsula is paralleled by the trend of the shore-line north of Point Riley (Figs. 2 and 5a). Partitioned strain is demonstrated by the intensity of foliation within the Tickera Granite, varying from incipient, to intensely lineated, to protomylonite, and clear examples from diamond drill holes show the relatively abrupt change from apparently undeformed granite to granitic augen gneiss. The mineral lineation, present in all but the latest granite intrusions, plunges consistently steeply. The shoreline southeast of Point Riley provides a section across structural strike, thereby exposing migmatitically altered metasediments of the Wallaroo Group that dip vertically. Mesofold-planes in metasediment enclaves are orientated in the same northeasterly striking plane, but fold axes in the metasediments plunge at various angles. The metamorphic fabric in the containing granite suggests that strain was not of sufficient intensity for the folds to have been rotated during the shearing event. It is therefore probable that the variation in orientation of the fold axes indicates the prior rotation of enclaves during intrusion. The same applies to pegmatite sheets where the orientation of fold axes reflect the original orientation of the vein sets. As will be discussed later, the same northeasterly trend is followed by the mineralised structures of the Moonta and Wallaroo mines.

The orientation of the eastern coast of Yorke Peninsula is controlled by the more northerly trending Pine Point Fault, with which the Hillside deposit is associated.

That the degree of strain, metamorphism, and metasomatism can vary abruptly is exemplified by the sharp divide between the highly deformed rocks of the Wallaroo mines and the barely deformed sediments east of Kadina. This divide has been responsible for division of opinion, with on the one hand the change in deformational state being attributed to the overlap of two supercrustal successions, the 'Doora Schist' and 'Wandearah Metasiltstone' of Parker (1993), and on the other to variations in strain and metasomatism (Lynch, 1982; Conor, 1995). Elsewhere, drill core displays in detail the rapid passage from undeformed homogeneous felsic rocks like meta-rhyodacite and granite to mylonite and augen gneiss.

Timing of Deformation and Metamorphism

No detailed, and therefore definitive, study of deformation and metamorphism has been attempted on northern Yorke Peninsula, so that even though there is a common steeply dipping L-S fabric, it is not known if this can be attributed to one or more separate events. It is certain that partitioned deformation and metamorphism, and metasomatism broadly accompanied intrusion of the Hiltaba Suite granites giving a Mesoproterozoic timing approximating the Olarian orogeny of the Curnamona Province. However, sedimentation at ~1750 Ma and proximity to the Kalinjala Mylonite Zone (Fig. 1) give the expectation for the Moonta-Wallaroo region to have been affected by the 1720 Ma Kimban orogeny.

It seems likely that the previously mentioned large-scale, apparently isoclinal, folding is the result of this regional deformation rather than of aerially restricted partitioned shearing. In support, an exposure at Wallaroo North Beach on the western coast of Yorke Peninsula exhibits examples of polyphase folding, where earlier-formed isoclines are refolded by open upright folds. That these upright folds, but not the earlier folds, have focussed amphibole-rich calcsilicate alteration supports the notion that deformation occurred on two separate occasions, rather than as a single progressive event. Therefore it is possible that the earlier isoclines are of Kimban age, and the later upright folds are more certainly related to the 1600 to 1575 Ma syn-Hiltaba Suite event. These observations are supported by the initial structural interpretation of Rankin (2009) at the Hillside deposit on the opposite coast of Yorke Peninsula. Here, long-limbed northeasterly trending folds suggest sinistral drag displacement along the associated Pine Point Fault, possibly the controlling eastern shear of a regionally extensive shear duplex.

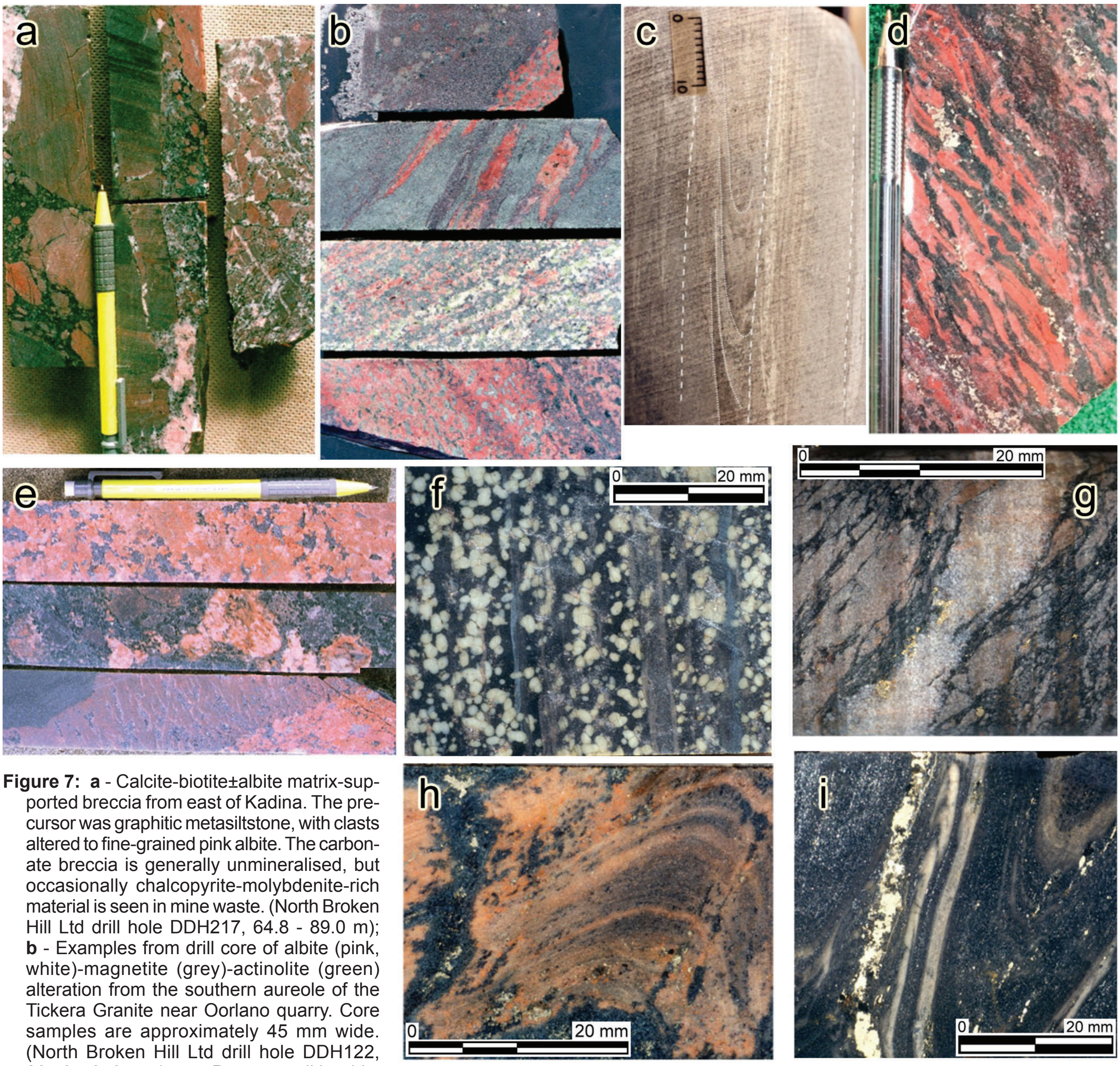


Figure 7: **a** - Calcite-biotite±albite matrix-supported breccia from east of Kadina. The precursor was graphitic metasiltstone, with clasts altered to fine-grained pink albite. The carbonate breccia is generally unmineralised, but occasionally chalcopyrite-molybdenite-rich material is seen in mine waste. (North Broken Hill Ltd drill hole DDH217, 64.8 - 89.0 m); **b** - Examples from drill core of albite (pink, white)-magnetite (grey)-actinolite (green) alteration from the southern aureole of the Tickera Granite near Oorlano quarry. Core samples are approximately 45 mm wide. (North Broken Hill Ltd drill hole DDH122, 264.0 - 359.4 m); **c -** Psammopeliticschist showing transposed bedding (fine dotted lines) that is folded and with an intense penetrative axial planar foliation (dashed lines), Alford prospect. Scale bar is one cm. (MIM Exploration drill hole MALD1, 103.7 m); **d** - Early albite-actinolite-magnetite alteration, developed along the intense penetrative foliation shown in Fig. 7c, is overprinted by chlorite (green, replacing actinolite), deep pink K feldspar (replacing pale pink albite), hematite (maroon, replacing magnetite), calcite and pyrite (Alford prospect. MIM Exploration drill hole MALD1, 208.6 m); **e** - Examples of albite-magnetite-actinolite alteration from the Weetulta area, south of Moonta. Top: Complete replacement of a metasiltstone by an albite-magnetite rock; Middle: An alteration pseudo-breccia formed by domains of intense albite-rich and actinolite-rich alteration of a metasiltstone; Bottom: A selvage of albite-magnetite-actinolite surrounds a granite vein intruding an unfoliated metasiltstone (dark grey rock on the left of the sample), (North Broken Hill Ltd drill hole DDH203, 242.3 - 244.1 m); **f** - Scapolite porphyroblasts developed in metasiltstone of the Wallaroo Group (Western Mining Corporation Ltd drill hole DDH3, 34.7 m); **g** - Spall or implosion breccia showing the long orientation of jig-saw fit clasts. Biotite in the matrix (biotite-magnetite-pyrite) tends to be oriented parallel to both the clasts and the overall L-S metamorphic fabric, indicating that the host Moonta Porphyry was brecciated under moderate grade metamorphic conditions. A later, sub-parallel carbonate vein is chalcopyrite mineralised (SADME drill hole Yorke DDY4, 147.9 m); **h** - Folded albitised metasiltstone, with biotite-magnetite-pyrite alteration invading axial plane structures (SADME drill hole North Kadina KND3, 30.8 m); **i** - Biotite-magnetite and albite alteration of metasiltstone of the Doora Member. Mineral growth and pyrite (chalcopyrite) mineralisation is aligned parallel to the axial plane metamorphic L-S fabric (Western Mining Corporation Ltd drill hole DDH7, 101.5 m).

Brecciation

Brecciation is widespread in northern Yorke Peninsula, with such competent quartzo-feldspathic rocks as the Moonta Porphyry, feldspar-indurated metasediments and granite being the most susceptible. Matrices vary from rock gouge to introduced hydrothermal assemblages of carbonate-albite (Fig. 7a) or biotite-magnetite-apatite-pyrite (Fig. 7g).

One style of breccia provides evidence for the coincidence of deformation, metamorphism and the introduction of metasomatic K-Fe-S-bearing fluids, wherein clasts of brecciated leucocratic rock are supported in an introduced black biotite-rich matrix. At least in some places, the consistent jigsaw-fit of tectonic breccias indicates that elongate angular clasts have not rotated, but have simply spalled into voids to be locked in place by the introduced matrix. Clast orientation apparently parallels the metamorphic mineral lineation shared by both the matrix and country-rock (Fig. 7g). If this parallelism could be shown to be regionally consistent then it would confirm that brecciation took place under the same moderate dynamic and metamorphic conditions that affected northern Yorke Peninsula, at a time approximating the 1620 to 1575 Ma Olarian Orogeny. The present interpretation is that, coincident with metamorphism, brecciation was a result of shear deformation that induced decompression-spalling or implosion into jogs, with fracture orientation, hence clast shape, being controlled by the pre-existing elastic strain of the rock mass. This was a stage when both iron and sulphur were introduced hydrothermally, to form biotite, magnetite and pyrite. Similar forms and associations of breccias are observed in the Cloncurry district (Williams and Blake, 1993; Marshall and Oliver, 2001).

Regional Alteration Styles

A large proportion of the Moonta-Wallaroo region is metasomatically altered, with alteration styles in many respects being similar to those of the northern Olympic Copper-Gold Province, the Curnamona Province, and the Cloncurry district of the Mount Isa Inlier in Australia (Conor, 1998; Oliver *et al.*, 2001; Raymond *et al.*, 2002, Mark *et al.*, 2006a), and also to other iron oxide copper-gold districts world wide (Corriveau, 2009). However, differing from the northern Olympic Copper-Gold Province, where hematite and magnetite bodies are highly developed, the regional alteration assemblages in the Moonta-Wallaroo region are sodium- and calcium-rich with calcsilicate skarn-like assemblages being considerably more common than those dominated by iron. Rarely, late-stage alteration is marked by dissolution and the formation of vughs (e.g., Alford prospect area), and amphibole+pyrite filled geodes have been noted (e.g., east of Kadina).

Fig. 8 provides a schematic view of ingredients associated with the alteration and mineralisation. The main components are Fe in magnetite, hematite, biotite, chlorite and amphibole, Na in albite, K in microcline and biotite, and Ca and Mg in carbonate and calcsilicate minerals such as actinolite, diopside and epidote. Magnetite and albite are the dominant iron-oxide and alkali feldspar respectively. While all three main element sets (i.e., Fe^{2+}+Fe^{3+}, Na+K and Ca+Mg) are generally present in altered rocks, the proportion of each varies from place to place. At some sites, the sourcing of metasomatic elements is potentially local (e.g., carbonate from the calcareous metasediments east of Kadina), but more often it is less obvious. The predominant mineral assemblages are consistent with the high temperatures that are characteristic of upper greenschist to lower amphibolite facies metamorphism.

Calcsilicate-albite-magnetite and biotite-magnetite-albite, the early-formed alteration assemblages (described below), are commonly developed in discrete areas, but can also co-exist. Thus the presence of magnetite and albite in both these assemblages makes it difficult to interpret the overprinting relationship. Also preventing confident interpretation of the relative timing of overprinting is the overlap and lack of precision of isotopic dating of monazite and titanite in these alteration assemblages. In contrast, chlorite-quartz-hematite-K feldspar alteration is observed to always overprint earlier albite- and magnetite-bearing assemblages, followed by later argillic alteration.

While overall, the alteration of the Moonta-Wallaroo region does form the compositional continuum represented in Fig. 8, it can be subdivided depending upon the dominance of a particular mineral or mineral assemblage such as:

Scapolitisation: Scapolite is a common metamorphic mineral which is present as intense spotting (Fig. 7f), pisolite-like growths, disseminated crystals, and locally as pervasive replacement where it is not easily distinguishable from alkali-feldspar alteration. As in the Cloncurry district of the Mt Isa Inlier (Oliver *et al.*, 2001), scapolite is interpreted as a metasomatic product involving local sourcing of saline fluids from precursor evaporitic beds, although these beds are not obvious from the available drilling and sparse outcrop in the Moonta-Wallaroo district. Scapolite is commonly replaced by such minerals as epidote and chlorite.

Alkali-feldspar alteration: Regional albitisation is the most widespread alteration type in the Moonta-Wallaroo region. It varies from pervasive replacement, to foliation-controlled alteration, to veining, and as a component of the other types of alteration described below. Microcline is more sporadic and does not have the regional prevalence of albite. Where microcline is present pervasively with no obvious veining or alteration, it probably reflects primary potassic feldspar in felsic volcaniclastic sediments of the Wallaroo Group rather than potassic metasomatism. The predominance of albitisation in regional alteration in the Moonta-Wallaroo region is similar to the albitisation evident in the Cloncurry district, Curnamona Province and Mt Woods Inlier (Conor, 1998; Raymond *et al.*, 2002,

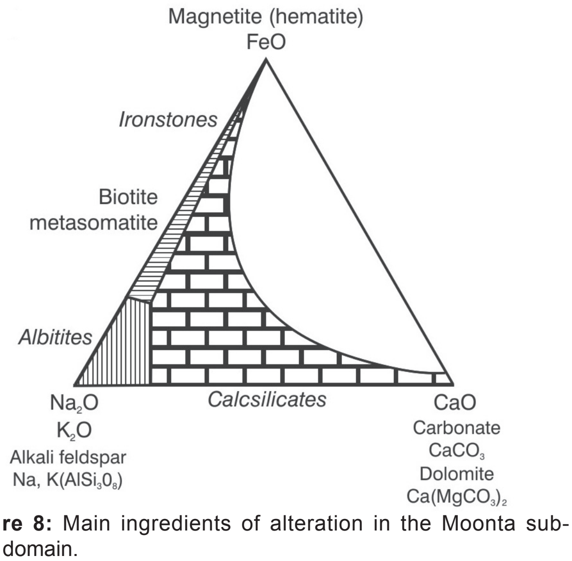
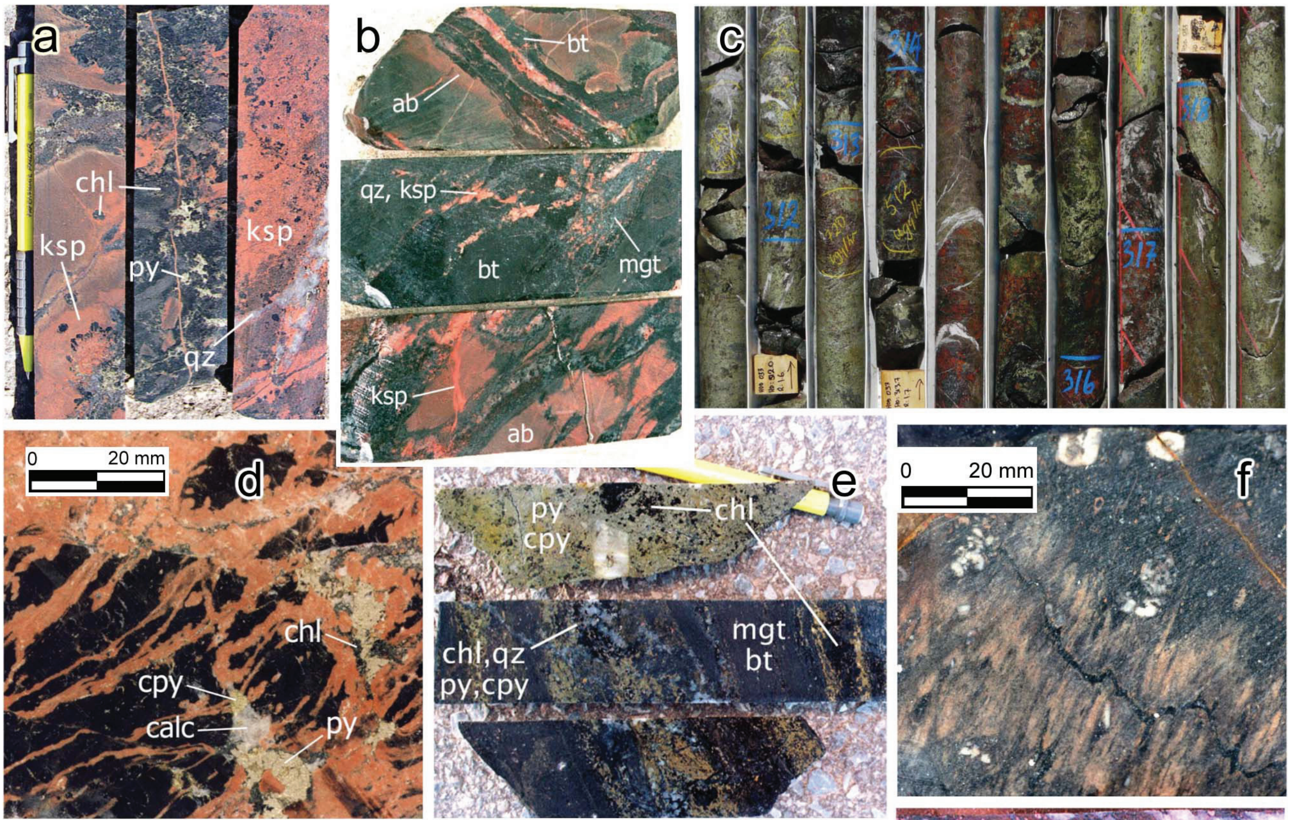


Figure 8: Main ingredients of alteration in the Moonta sub-domain.

Oliver *et al.*, 2004, Skirrow *et al.*, 2002, 2007). In contrast, albite is not as common in the Olympic Dam region, where alkalic alteration occurs as widespread anhydrous potassic alteration of feldspar in the host granite, and intense hydrous sericite development within the Olympic Dam deposit itself (Skirrow, 2009).

Calcsilicate-albite-magnetite alteration: This assemblage is one of the two most common types of 'poly-minerallic' alteration in the Moonta-Wallaroo region, the other being characterised by the assemblage: biotite-magnetite-albite. Intense albite-actinolite-magnetite ±diopside ±epidote ±carbonate ±titanite ±allanite alteration of Wallaroo Group host rocks is preferentially associated with the proximal contact zones of Hiltaba Suite granites, particularly the Tickera Granite. Sulphides do not accompany this alteration event. In cases where minor pyrite ±chalcopyrite are present within this assemblage (such as at the Alford prospect, 25 km northwest of Moonta) it is clear that sulphides were introduced by a later alteration overprint, typically chlorite-quartz-hematite-K feldspar, or the biotite-magnetite alteration assemblage described below.

Calcsilicate-albite-magnetite alteration commonly has a distinctive pink and green colour reflecting domains of albite- and actinolite-rich alteration (Fig. 7b). Typically, these alteration zones form prominent, high intensity



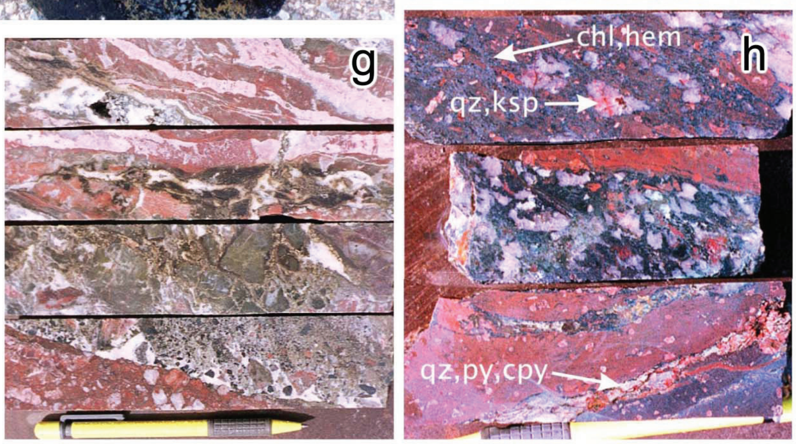


Figure 9: **a** - Chlorite(chl)-quartz(qz)-K feldspar (ksp)-pyrite(py) veining with K feldspar wall rock alteration in a metasiltstone from the Tea Tree Glen prospect. The lack of early magnetite alteration in the host rock may account for the absence of significant hematite in the later chloritic alteration assemblage. (North Broken Hill Ltd drill hole DDH178, 125.0-132.0 m); **b** - Foliated and folded veins of biotite(bt)-magnetite(mgt)-quartz with selvages of fine-grained pink albite (ab) in an altered metasiltstone of the Wallaroo Group in the southern aureole of the Tickera Granite, Alford prospect. Late Kfeldspar(ksp)±quartz(qz) veins cut the earlier biotite-magnetite alteration. Core samples are approximately 45 mm wide. (North Broken Hill Ltd drill hole DDH130, 101.2 - 282.5 m); **c** - Hillside deposit, eastern Yorke Peninsula. Rex Minerals Ltd drill hole HDD033, 311–319 m averaging 10.0% Cu and 0.9 g/t Au from massive chalcopyrite-pyrite mineralisation hosted in garnet-hematite-magnetite-alkali feldspar-epidote-clinopyroxene skarn; **d** - Late calcite(calc)-chlorite(chl)-pyrite(py)-chalcopyrite(cpy) veining overprints earlier albitisation at the Alford prospect. The sulphide-bearing veins both cross-cut and re- use structures which have localised the earlier pink albite alteration (MIM Exploration drill hole MALD1, 143.2 m); **e** -. Chlorite(chl)-quartz(qz)-hematite-pyrite(py)-chalcopyrite(cpy) mineralisation in a biotite(bt)-magnetite(mgt) schist from the Tea Tree Glen prospect. (Western Mining Corporation Ltd drill hole DDH88, 190.5 - 192.0 m); **f** - Pink albite and dark biotite alteration emanating from a biotite vein. The alteration has preferentially infiltrated into the Moonta Porphyry along the foliation (SADME drill hole Moonta mines (Hoggs) DDE 2, 45.6 m); **g** - Epithermal-style quartz-carbonate-hematite-pyrite veining and brecciation of an albitised metasediment, Katinka prospect. (Phelps Dodge drillhole KD18, 360.1 - 376.3 m); **h** - Brecciation and veining of the Moonta Porphyry with chlorite(chl)-quartz(qz)- hematite(hem)-Kfeldspar(ksp) alteration and pyrite(py)-chalcopyrite(cpy) mineralisation adjacent to the Elders Lode, Moonta mining field. (North Broken Hill Ltd drill hole DDH192, 82.9 - 92.0 m).

magnetic anomalies, close to the margins of Hiltaba Suite granites. These anomalies range from small, discrete zones (e.g., along the southern and eastern margins of the Tickera Granite at the Oorlano, Alford and Bews prospects) to broader areas of high magnetic intensity (e.g., on the northern margin of the Tickera Granite, at the Katinka prospect, west of Port Broughton).

The albite-actinolite/epidote-magnetite mineral assemblage represents the "type" Oorlano Metasomatite (Conor, 1995; Cowley *et al.*, 2003), exposed at Wallaroo North Beach and in the Oorlano quarry where it is quarried as "Harlequin Stone" (Cooper, 1999). The alteration generally forms as pervasive replacement that may have a distinct banded texture imparted by intense development of alteration along foliation (Figs. 7b and 7d). Additionally, it is locally present as veins. Away from the foliated high strain zones, magnetite-albite±actinolite alteration may preserve primary sedimentary structures in iron-rich replacement of laminated fine-grained metasediments ("taconites"). Equally however, coarse-grained alteration may completely destroy the primary host rock (Fig. 7e), or form magnetite-rich breccias of albitised metasediments (e.g., Bews, Port Julia and Katinka prospects).

Biotite-magnetite-albite alteration: Fine-grained, regional metamorphic biotite is common throughout the Wallaroo Group. However, hydrothermal metasomatic biotite with associated magnetite forms wide areas of regional metasomatism and prominent magnetic anomalies. This assemblage consists primarily of biotite, magnetite and albite with minor apatite ±quartz ±monazite ±titanite ±tourmaline ±allanite and fluorite. Accessory pyrite, rarer pyrrhotite, and trace chalcopyrite mineralisation may accompany biotite-magnetite alteration. The apatite, monazite, allanite and fluorite are important components, indicating significant P, REE and F locally in the alteration fluids. This mineral assemblage is similar to pre-ore alteration found proximal to iron oxide copper-gold deposits in the Mt Isa Inlier, such as Ernest Henry (Mark *et al.*, 2006b). However the lack of copper mineralisation associated with magnetite-bearing alteration in the eastern Gawler Craton suggests that there was no effective mechanism for the precipitation of copper minerals from these relatively hot, reduced hydrothermal fluids even if they did contain significant dissolved copper (Bastrakov *et al.*, 2007).

The albite-calcsilicate-magnetite and biotite-magnetite-albite alteration assemblages appear to have developed broadly concurrently. Mutually crosscutting relationships and mixtures of the two end-member assemblages exist in highly altered zones, making paragenetic interpretation complex. U-Pb isotopic dating of accessory monazite and titanite from both the albite-calcsilicate-magnetite and biotite-magnetite-albite assemblages revealed ages ranging from 1623±3 Ma to 1539±17 Ma. The wide range in ages and significant errors in some samples indicate that it is not possible to determine paragenetic timing from available isotopic dating, other than to say that these alteration assemblages are broadly coeval with Hiltaba Suite magmatism.

Biotite-magnetite alteration may be manifested as pervasive replacement, often parallel to foliation (Fig. 9f), preferentially developed along axial plane foliation (Fig. 7h), in narrow veins with albitic selvages in metasedimentary schists (Fig. 9b), as fracture-controlled vein networks in more competent meta-volcanic rocks, and as biotite-carbonate-rich breccia matrices (Fig. 7a). The close association of this style of alteration with structural features and metamorphic fabrics indicates coincidence with deformation. The alteration is also demonstrably associated with granite intrusion as it is seen to emanate into Wallaroo Group host rocks along foliation from some granitic veins (Fig. 7e). However, biotite-magnetite alteration appears to be less closely associated with the proximal contact zones of Hiltaba Suite granites than the albite-calcsilicate-magnetite assemblage, and possibly forms broader areas of more distal alteration.

Biotite-magnetite alteration is particularly widespread south of Moonta where numerous magnetic and non-magnetic Hiltaba Suite plutons (previously described as the Arthurton Granite) intrude the Wallaroo Group. The alteration forms a broad 5 × 15 km magnetic anomaly near Weetulta, as well as numerous smaller magnetic highs between the Penang and Balgowan prospects (Figs. 3 and 10).

In the area between the West Doora and Vulcan prospects, about 4 km south of the Wallaroo mine, a strong curvilinear magnetic anomaly reflects biotite-magnetite alteration developed along the sheared contact between the main body of the Moonta Porphyry and the less competent metasediments of the Doora Member (Fig. 14 and 15). Textural characteristics of this alteration vary widely from intensely foliated biotite-magnetite-albite±apatite-scapolite-monazite-pyrite schists, to delicate foliation-parallel biotite-rich lamellae and flecks in less intensely metasomatised rocks. Coarser grained biotite alteration is generally concentrated in fold hinges and locally in narrow high strain zones.

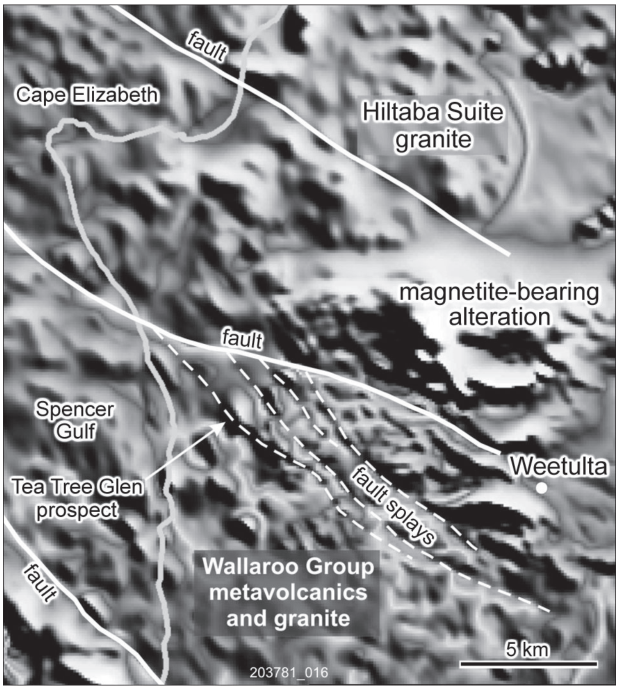


Figure 10: Image of total magnetic intensity with a north-east sun-angle filter of the Weetulta area, south of Moonta. Many strong magnetic anomalies reflect irregular magnetite-bearing alteration of Wallaroo Group metasediments and metavolcanics. Late hydrothermal fluids, focused along regionally extensive southeast-trending faults, have de-magnetised earlier magnetite-altered rocks. At the Tea Tree Glen prospect, several splays off a major southeast-trending fault appear to have further localised magnetite-destructive alteration associated with copper mineralisation.

A large area (~30 × 40 km) of strongly magnetic rock, concealed beneath the waters of Spencer Gulf west of Moonta, is also interpreted to be an extensive zone of biotite-magnetite metasomatism of Wallaroo Group rocks. A single hole drilled into this zone at the King George prospect (Fig. 3) intersected very intensely foliated biotite-magnetite-apatite-albite schists containing deformed quartz-feldspar-apatite-clinopyroxene-tourmaline-pyrite-?scapolite veins and trace disseminated pyrite-chalcopyrite, similar to iron-rich metasediments of the Doora Member in the Wallaroo district.

Chlorite-quartz-hematite-K feldspar-pyrite ± chalcopyrite: The introduction of significant sulphides and copper in the Moonta-Wallaroo region is characterised by a late alteration assemblage containing mainly chlorite, quartz, hematite, K feldspar and pyrite, with accessory calcite, chalcopyrite, tourmaline, sericite and fluorite (Fig. 9a). One or more of the main minerals may locally be absent in this alteration stage. Some mineralised quartz-chlorite veins contain very little iron oxide (e.g., in the Wallaroo mines area), and therefore may reflect a lack of early-formed magnetite in the host rock. It is likely that this alteration assemblage and copper mineralisation were associated with a cooler and more oxidised hydrothermal fluid than earlier regional alteration, as observed in the Olympic Dam district (Bastrakov *et al.*, 2007). However, unlike in the Olympic Dam district (Skirrow *et al.*, 2002) and at the Prominent Hill deposit (Belperio *et al.*, 2007), sericite is not a significant phase developed with this regional copper mineralisation, although it is present as an accessory mineral associated with copper mineralisation in the Moonta mining field (Morales-Ruano *et al.*, 2002). Additionally, the presence of significant quartz in association with copper in this event is not typical of IOCG mineralisation across the world.

Generally, chlorite, hematite and K feldspar replace earlier-formed biotite and actinolite, magnetite, and albite respectively. Where there are sulphides within early magnetite-rich mineralisation, there is almost always a chlorite-quartz-hematite-K feldspar overprint (Figs. 7d and 9e). Earlier regional metallogenic studies (e.g.; Skirrow *et al.*, 2002) did not recognise the importance of the chlorite-quartz-hematite-K feldspar mineral assemblage and its relationship to copper mineralisation, due to its generally weak and localised development compared to the more prevalent Na-Ca-Fe alteration. More recent work (e.g., Raymond *et al.*, 2002; Skirrow *et al.*, 2007) has established a strong association of copper mineralisation with this late chlorite-quartz-hematite-K feldspar alteration stage.

In the vicinity of the Moonta and Wallaroo mines, quartz-chlorite-hematite-K feldspar-pyrite-chalcopyrite veining is commonly associated with brecciation of more competent host rocks, particularly the Moonta Porphyry (Fig. 9h). Brecciation of quartz veins and wall rocks, and dismemberment of vein sets along foliation, indicates multiple phases of brittle-ductile deformation coincident with quartz-chlorite-hematite-K feldspar-pyrite alteration and copper mineralisation. The association with late brittle structures is a significant difference from much of the earlier albite-calcsilicate-magnetite and biotite-magnetite-albite regional alteration which is more typically controlled by bedding, and earlier penetrative ductile structures such as foliations and shear zones. Morales-Ruano *et al.* (2002) described three phases of veining and fracturing in the development of the Wheal Hughes and Poona mine mineralised vein sets. The ore paragenesis indicated a progression from quartz-magnetite to quartz-hematite, then to quartz-chlorite-pyrite-tourmaline and chalcopyrite.

Chloritic alteration most typically overprints earlier calcsilicate and magnetite alteration, but does not generally occur as separate alteration zones. This suggests that the later alteration fluids have re-used pathways established by earlier hydrothermal fluids. The ubiquitous replacement of precursor minerals such as magnetite, biotite and calcsilicates suggests that early formed magnetite-bearing alteration zones probably acted as chemical traps for later cooler and more oxidised fluids to deposit the chlorite-quartz-hematite-K feldspar mineral assemblage. A lack of precursor magnetite in some localities may account for the development of chloritic alteration without significant hematite (Fig. 9a). The oxidation of pre-existing magnetite bodies commonly accompanies copper mineralisation in the Olympic Copper-Gold Province in the eastern Gawler Craton (e.g., Prominent Hill, Belperio *et al.*, 2007).

Re-Os isotopic dating of molybdenite from quartz-pyrite±calcite±chlorite veining revealed ages of between 1599±6 and 1574±6 Ma (Skirrow *et al.*, 2007), which overlap with the range of monazite and titanite U-Pb ages from clearly paragenetically earlier albite- and magnetite-bearing alteration (Fig. 6). The isotopic dates suggest that all these alteration styles were developed within one broad thermal event, although it is clear that the isotopic data are not precise enough to establish paragenetic timing between alteration styles.

In the Moonta-Wallaroo region, examples of local replacement of early magnetite-bearing alteration and coincident introduction of sulphides are displayed by drilling of many magnetic anomalies (e.g., Alford, Vock and Port Julia prospects). At the Tea Tree Glen prospect, west of Weetulta, a broad area of magnetic alteration is transected by a series of splays off a major southeast trending fault. Regional magnetic data show linear zones of interpreted demagnetisation, and suggest that the faults have been the loci for late magnetite-destructive alteration (Fig. 10). Drilling in the Weetulta area, located primarily on magnetic highs, intersected zones of intense calcsilicate-albite-magnetite and biotite-magnetite alteration, with narrow zones of chlorite-hematite-quartz-K feldspar-pyrite alteration and chalcopyrite mineralisation (Fig. 9e). Previous emphasis in exploration drilling on targeting magnetic "bulls eye" anomalies has most probably resulted in an under-sampling of copper-bearing non-magnetic alteration in the Moonta-Wallaroo region. Targeting structurally-controlled demagnetised zones and high density features at the margins of magnetic anomalies, which resulted in success at Prominent Hill, may prove more successful in locating copper-gold mineralisation in the Moonta-Wallaroo region.

Carbonate alteration: Carbonate alteration is present in a number of guises, as pervasive replacement of calcareous metasediments, in calcsilicate skarns with amphibole, diopside, magnetite and albite, as an accessory phase in chlorite-hematite-sulphide-bearing alteration (Fig. 9d), as breccia matrix (Fig. 7a), or as late stage veining (Fig. 9g). Carbonate may generally be derived from local sources, with secondary carbonate most intensely developed within or near calcareous host rocks of the New Cornwall and Wokurna Members of the Wallaroo Group. While typically barren, occasionally carbonate veins may be copper, zinc and molybdenum mineralised (e.g., east of Kadina).

Locally developed filamentous carbonate textures (with chalcopyrite) are similar to those associated with the Ernest Henry deposit in the Cloncurry district. In addition, late-stage widely distributed thin carbonate veinlets frequently carry minor chalcopyrite.

Epithermal-style alteration: The presence of late epithermal style quartz-carbonate (±hematite ±adularia) veining and brecciation in the Moonta-Wallaroo region indicates a progression towards significantly cooler and higher crustal levels in the latest stages of hydrothermal activity. The epithermal-style veins cut all other alteration assemblages and structures, but no minimum age has been established. The quartz-carbonate veining contains massive, crustiform, bladed, banded and vuggy textures, and is widespread but generally a minor component of the regional alteration paragenesis. It is exposed on the coast at Black Rock, where veins are developed in intensely chloritised Tickera Granite. Also, the walls of a large, zoned, three metre wide amethyst-bearing vein, which parallels the southeasterly trending part of the coastline south of Point Riley, are locally brecciated and hematitic. Epithermal alteration is notable at the Katinka prospect west of Port Broughton (Fig. 9g), and at the Bews prospect, where epithermal style veining and brecciation overprints an earlier strong albite-magnetite-actinolite alteration. Accessory pyrite, chalcopyrite and bornite occur with the quartz-carbonate veining, but no significant copper or gold mineralisation has so far been identified. Argillic alteration is also locally developed in the host rocks to epithermal veining and brecciation.

Argillic alteration: Kaolinite alteration is widespread, but not common, in the Moonta-Wallaroo district as a late stage overprint within and surrounding fault zones and pre-existing veins of earlier alteration phases. In and around chalcopyrite-mineralised veins, there may be malachite and other supergene copper minerals developed with late stage kaolinite and halloysite (e.g., Wheal Hughes; Keeling *et al.*, 2003). Intense kaolinite alteration is observed in the vicinity of the Hillside deposit, and along the southern and eastern aureole of the Tickera Granite where a zone of intense kaolinisation is developed along the interpreted sheared margin of the granite (i.e., the Alford Fault Zone).

The argillic alteration along the Alford Fault Zone forms a broad, swampy, east-west-trending, topographic low. Here, kaolinite partially to completely replaces all previously described alteration assemblages, so that the loss of magnetite results in a significant magnetic-low anomaly in regional magnetic data (Figs. 14 and 15). Accessory quartz, pyrite, chalcocite, alunite and siderite may occur with the argillic alteration. Small sub-horizontal, augen-like voids might represent carbonate or some other mineral that has been dissolved. Sulphides and copper mineralisation appear to have been remobilised rather than introduced by this alteration phase, with chalcocite being observed as rims on disseminated pyrite grains south of the Tickera Granite, and as veins elsewhere. There is also, spatially associated, sporadic subeconomic gold, molybdenum and uranium anomalism.

Keeling *et al.* (2003) interpreted the argillic alteration at the Poona and Wheal Hughes deposits in the Moonta mining field to have resulted from acid sulphate weathering in and around the mineralised structures to a depth of up to 80 m. However, elsewhere the intensity and depth of kaolinite alteration suggests a hydrothermal origin for the argillic alteration. Examples of such extensive alteration are the Alford Fault Zone and at the Katinka prospect. At the latter locality, there is a local association of argillic alteration with late epithermal quartz veining to depths exceeding 200 m below surface. Locally vughy alteration of calcsilicate skarn adjacent to kaolinite rock along the Alford Fault Zone indicates dissolution, and in spite of much drilling, the full depth of argillic alteration is unknown. Additionally, in the vicinity of the Alford prospect, drilling has shown a locally auriferous goethite horizon to form the base of a regolith profile developed upon the earlier formed kaolinite alteration.

Mineralisation

Chalcopyrite-bornite mineralisation at the Moonta and Wallaroo mines was controlled by curving northeasterly-trending sheared zones, but with the vein styles of the Moonta mines and the Kadina area varying due to different host lithologies. The Moonta lodes are in the deformed Moonta Porphyry rhyodacite dome where prior shearing provided a penetrative fabric for a later stage of brittle veining. The main controlling structure northeast of the Moonta mines in the Kadina area continues the trend of the northeasterly oriented Moonta lodes, but links a number of spaced lodes striking eastsoutheast (Fig. 5a). The northernmost Wallaroo mines lode-set is the most intensely mineralised. These lodes in the Kadina area are at the deformed northern periphery of the Moonta Porphyry where rhyodacite interfingers with amphibolite and iron-rich metasediments of the Wallaroo Group (Figs. 5a, 14 and 15), mainly the Doora Member of Cowley *et al.* (2003) (Doora Schist of Parker, 1993). Thus the east-southeast strike of the individual lodes appears to relate to the combination of bedding and shearing.

Significant chalcocite mineralisation is now known from the Hillside deposit, and in the kaolinite body of the Alford Fault Zone where it represents a late-stage of pyrite-associated mineralisation. Quartz-chalcocite-pyrite veining is also present within fine-grained graphitic metasediments of the Wallaroo Group adjacent to the eastern margin of the Tickera Granite at the East Alford prospect, where it may represent the potential for Manto style mineralisation adjacent to the some Hiltaba Suite stocks.

Fluid inclusion data indicate that both weakly and highly saline, multi-cation fluids were associated with the mineralisation and regional alteration, a situation similar to other IOCGU regions, such as in the northern part of the Olympic Copper-Gold Province (Bastrakov *et al.*, 2007), the Cloncurry district (Baker *et al.*, 2008), and the Wernecke Breccias (Hunt *et al.*, 2005). Janz (1990) and Hafer (1991) recognised two fluid phases of low to high salinities from the mineralisation of the Poona mine and Wheal Hughes, while Morales-Ruano *et al.* (2002) determined that the Moonta ores were deposited in four hydrothermal stages, the first two being dominated by iron oxides, the third by iron sulphides, and the final stage by a Cu-Fe-Co-Au-Zn-Pb-S assemblage. The fluid inclusion data reflect a complex history involving variable amounts of boiling, cooling and mixing in the vein system. Salinity-homogenisation relationships indicate variable temperatures up to 475°C, and mixing of the hypersaline and vapour-rich fluids with a surface-derived fluid of low temperature and low to moderate salinity. Hence the data broadly support a genetic relationship between the Moonta-Wallaroo ores and possibly granite-derived fluids, with some influence of surface or metasediment-derived fluids (Morales-Ruano *et al.*, 2002).

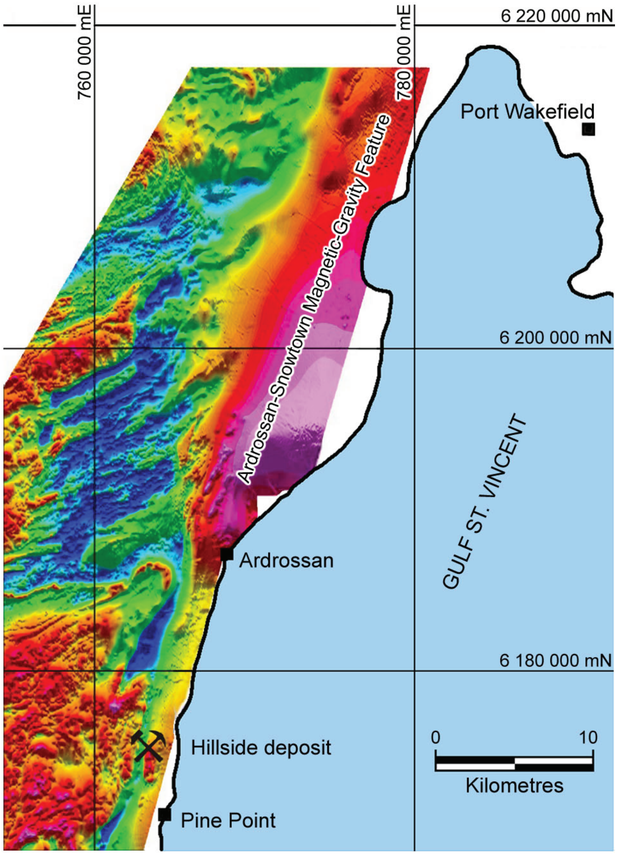


Figure 11: Eastern Yorke Peninsula TMI image of the Rex Minerals project areas, reflecting the location of the Pine Point Fault Zone and showing the Hillside deposit area.

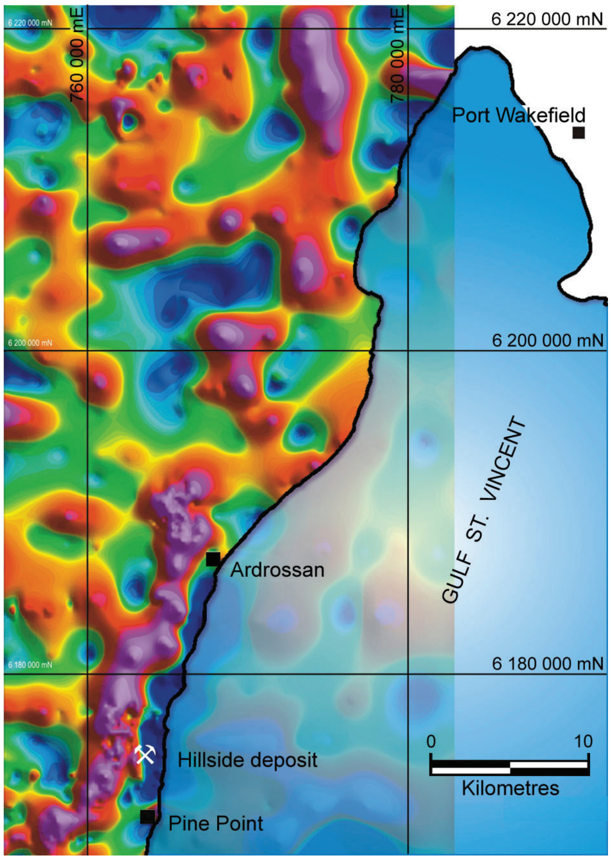


Figure 12. Eastern Yorke Peninsula gravity image of the Rex Minerals project areas, reflecting the location of the Pine Point Fault Zone and showing the Hillside deposit area.

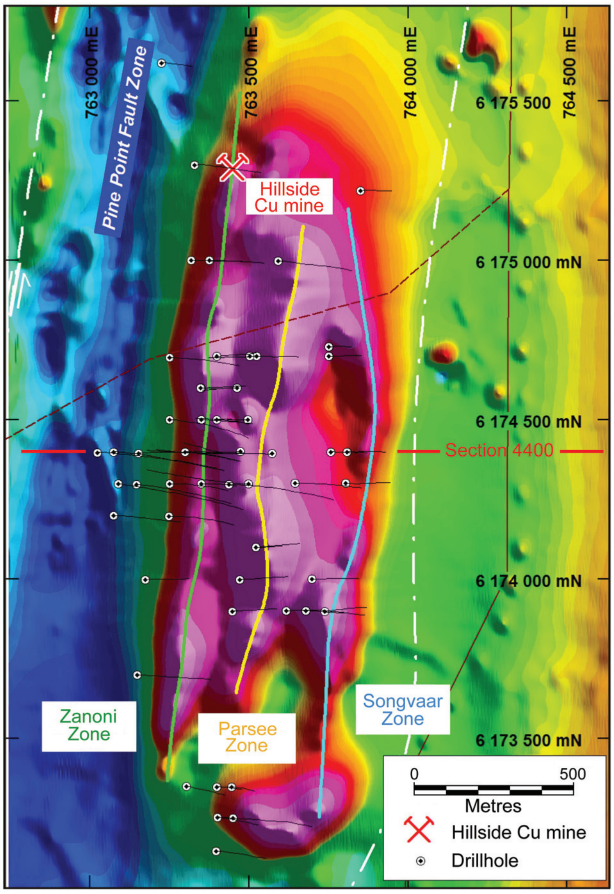


Figure 13: Hillside copper-gold project residual magnetic image showing the location of drilling, and the interpreted Zanoni, Parsee and Songvaar mineralised structural zones.

Oxygen isotope data also support mineralisation from a hot saline brine of magmatic origin mixing with a cooler low salinity, possibly meteoric fluid (Morales-Ruano and Both, 1999), although $\delta^{34}S$ values of ore sulphides (-2.3 to +6.4‰) and disseminated sulphides in the Moonta Porphyry and interdigitated metasediment (-1.5 to +4.6‰) suggest assimilation of crustal sulphur by the granitic magma or ore fluids (Morales-Ruano *et al.*, 2002).

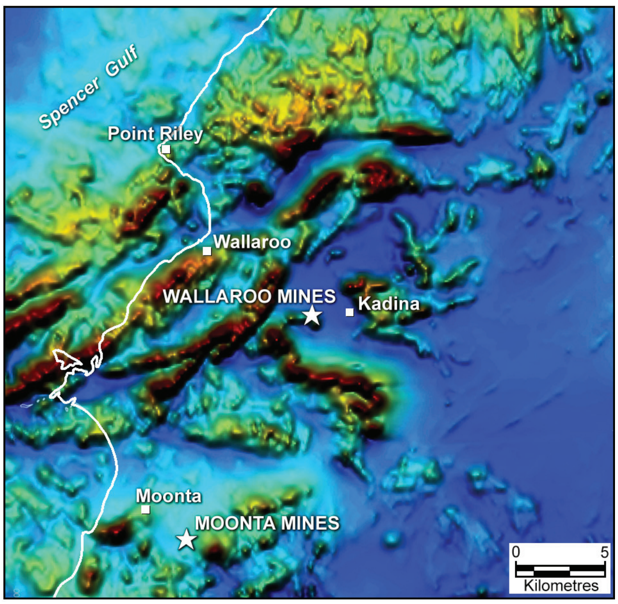


Figure 14: TMI of the Moonta-Wallaroo area processed to show magnetite-rich alteration zones. The set along the southern part of the Tickera Granite aureole is dominantly pink feldspar-rich calcsilicate, which has been largely overprinted and obliterated by kaolinite-dominated alteration.

Thermal pulsing, including the emplacement of Hiltaba Suite intrusions, was the likely driver of alteration and mineralisation in the region, and Lynch (1982) considered that the Moonta-Wallaroo region comprised a major granite batholith and its altered and mineralised metasedimentary carapace. Pegmatite veins intimately associated with mineralised structures, and the metal suite including Cu, Au, Mo, Pb, Zn, U and Ce are supportive of intrusion related sourcing. The proximity of granite intrusions to mineralisation of the Moonta and Wallaroo mines has also encouraged the notion that metals were derived from the Hiltaba Suite (Jack,1917; Both *et al.*, 1993; Morales-Ruano and Both,1999).

However, there is evidence that the Wallaroo Group was significantly mineralised prior to deformation. Graphitic metasiltstones east of Kadina are zinc-bearing, and volcaniclastic metasedimentary rock overlying the Moonta Porphyry near Wheal Hughes contains disseminated copper-mineralisation that is likely to be of syngenetic origin. The highly magnetic iron-rich Doora Member that interfingers with the Moonta Porphyry along its northern boundary (Figs. 5a, 14 and 15) may represent a similar zone of possible syngenetic metal enrichment that was the source of the Wallaroo mines ore. While Morales-Ruano *et al.* (2002) demonstrated the derivation of sulphur from the sediment pile, their detailed investigation provided no proof of magmatic metal sourcing. Thus the question of metal sourcing remains equivocal, and it is possible that fluids and metals of the Moonta-Wallaroo area originated from various sources, including evaporitic sediments and bi-modal ~1750 Ma volcanics within the Wallaroo Group, and the later chemically similar felsic and mafic rocks of the ~1600 Ma Hiltaba Suite. Even in the highly mineralised northern Olympic Copper-Gold Province, Bastrakov *et al.* (2007) interpreted some non-magmatic input into hypersaline hydrothermal fluids.

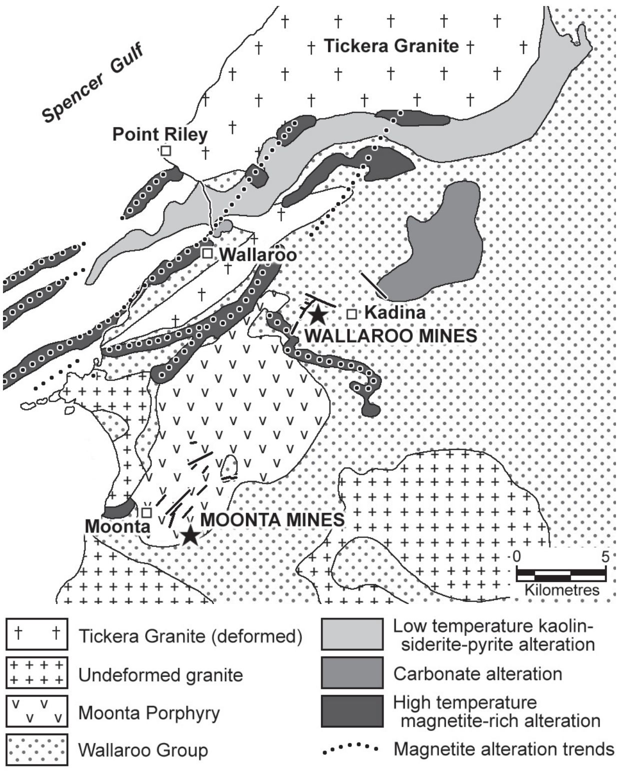


Figure 15: Geology and alteration in the Moonta-Wallaroo area, refelected by the TMI data displayed on Fig. 14, which covers the same area, highlighting the main zones of high temperature magnetite-bearing alteration following northeasterly structural trends. Alteration appears to have been enhanced where two structures (shown by dotted lines) intersect the southern part of the Tickera Granite aureole and Alford Fault Zone (Fig. 2).

Hillside Cu-Au (-U) Deposit

Mineralisation in the Moonta sub-domain is not restricted to the Moonta-Wallaroo mining field, but is known from numerous prospects discovered during the nineteenth and twentieth centuries (Fig. 3). In modern terms, most of these are sub-economic. However, the Yorke Peninsula has received renewed exploration interest since the discovery by Rex Minerals Ltd early in 2008 of the Hillside IOCG (LREE-U) deposit (Figs. 1, 2 and 3). The inferred mineral resource at 30 November, 2010 was estimated at 170 Mt @ 0.7% Cu and 0.2 g/t Au (ASX Release, 6 December, 2010).

The discovery was made as a result of exploration drilling of discrete magnetic (Fig. 11) and gravity (Fig. 12) features spatially associated with the regional north-northeasterly trending Pine Point (Ardrossan) Fault and adjacent to the historic Hillside copper mine. The newly discovered deposit is located approximately 15 km south of Ardrossan, on the east coast of Yorke Peninsula (Figs. 2 and 3). It represents the southern extension of the mineralisation exploited by the Hillside mine (Fig. 13). Records indicate that the historic mine, which was active prior to 1916 and between 1929 and 1932, produced around 50 tonnes of ore for 8 tonnes of recovered copper (Wade and Cochrane, 1954), with grades varying from 0.5% to 44% Cu. Two northeasterly-striking, steeply (70 to 80°) westerly dipping lodes that were originally mined, varied from <0.5 to 3 m in thickness. The ore comprised chalcopyrite, bornite, malachite, chalcocite, atacamite and covellite, hosted in brecciated and sheared schist with quartz stringers.

The Hillside deposit is masked by a sequence of calcareous Tertiary sediments ranging from <1 to 30 m in thickness, and local, up to 30 m thick channel-fill alluvium in north-northwesterly trending palaeochannels (Fig. 16). The gravity and magnetic features confined to the Pine Point Fault structure most likely represent gabbroic intrusives emplaced within this structural corridor, while immediately to the east and parallel to the Pine Point Fault, there is a large, deep seated geophysical anomaly (Ardrossan-Snowtown Magnetic-Gravity Feature; Figs. 2 and 11). This feature may have some bearing on mineralisation along the Pine Point Fault trend.

Drilling has shown that the Hillside deposit is hosted by a highly deformed and folded sequence of metasediments of the Wallaroo Group intruded by Mesoproterozoic igneous rocks. The metasediments are invariably intensely altered within the Pine Point structural corridor with late retrogression common. The Mesoproterozoic intrusions comprise numerous phases of granite, micro-gabbro, porphyritic gabbro and gabbro-diorite that are presumed to be related to the Hiltaba Suite. All intrusions, including numerous pegmatites that have been emplaced along minor structures, have been intensely altered with both endoskarns and exoskarns being present. The gabbroic rocks in the Hillside area contain an early high temperature alteration, which is potassic and shows the development of magnetite-biotite-K feldspar±bornite. The late replacement of plagioclase by K feldspar is common.

The copper-gold-(uranium) mineralisation tends to develop as north-trending sub-vertical to steeply west dipping bodies that are intimately associated with prograde and retrograde skarn assemblages and steeply west-dipping 'breccia' structures (Fig. 16). Mineralisation associated with metasediments is also present in the immediate footwall of the western branch of the Pine Point Fault structure.

Table 1: Significant drill hole assay results from the Hillside deposit

HOLE ID	FROM (m)	TO (m)	INTERVAL (m)	Cu (%)	Au (g/t)	Structure
HDD024	**413**	**499**	**86**	**0.6**	**0.1**	**Zanoni (p)**
including	*426*	*433*	*7*	*3.1*	*0.6*	*Zanoni (p)*
including	*447*	*449*	*2*	*1.5*	*0.3*	*Zanoni (p)*
including	*484*	*488*	*4*	*2*	*0.8*	*Zanoni (p)*
including	*497*	*499*	*2*	*0.8*	*1.4*	*Zanoni (p)*
HDD024W2	**400**	**498**	**98**	**0.5**	**0.1**	**Zanoni (p)**
	513	**522**	**9**	**0.9**	**0.3**	**Zanoni (p)**
	609	**660**	**51**	**1.5**	**0.1**	**Zanoni (p)**
including	*617*	*672*	*10*	*3.4*	*0.3*	*Zanoni (p)*
including	*633*	*639*	*6*	*2.4*	*0.2*	*Zanoni (p)*
HDD026	**257**	**525**	**268**	**0.7**	**0.2**	**Zanoni (p)**
including	*258*	*265*	*7*	*1*	*0.2*	*Zanoni (p)*
including	*297*	*298*	*1*	*1.1*	*0.2*	*Zanoni (p)*
including	*350*	*372*	*22*	*3.2*	*0.7*	*Zanoni (p)*
including	*387*	*397*	*10*	*1.9*	*1*	*Zanoni (p)*
including	*417*	*421*	*4*	*3.4*	*1.4*	*Zanoni (p)*
including	*515*	*522*	*7*	*2.3*	*0.3*	*Zanoni (p)*
HDD033W1	**275**	**426**	**151**	**1.5**	**0.3**	**Zanoni (p)**
including	*275*	*335*	*60*	*1.2*	*0.2*	*Zanoni (p)*
including	*374*	*426*	*52*	*3*	*0.6*	*Zanoni (p)*
HDD-037	**244**	**297**	**53**	**1.7**	**0.2**	**Zanoni (p)**
including	*263*	*273*	*10*	*4.7*	*0.8*	*Zanoni (p)*
including	*279*	*282*	*3*	*6.8*	*0.6*	*Zanoni (p)*
HDD-039	**33**	**141**	**108**	**0.2**	**0.3**	**Songvaar (s)**
including	*83*	*117*	*34*	*0.4*	**-**	*Songvaar (s)*
	54	**69**	**15**	**-**	**2**	**Songvaar (s)**
	28	**72**	**44**	**-**	**-**	**Songvaar (s)**
HDD-044	**272**	**304**	**24**	**0.7**	**0.3**	**Parsee (p)**
including	*278*	*282*	*4*	*1.4*	*0.8*	*Parsee (p)*
	302	*304*	*2*	*1.5*	*1.1*	*Parsee (p)*
HDD-045	**193**	**218**	**25**	**0.8**	**0.3**	**Songvaar (p)**
including	*195*	*206*	*11*	*1.3*	*0.4*	*Songvaar (p)*
HDD-047	**15**	**48**	**33**	**0.7**	**0.9**	**Songvaar (s)**
including	*33*	*45*	*12*	*1.1*	*1.6*	*Songvaar (s)*
HDD-048	**101**	**172**	**71**	**1.5**	**0.4**	**Songvaar (s & p)**
including	*118*	*147*	*29*	*2.2*	*0.5*	*Songvaar (s)*
including	*154*	*168*	*14*	*2.1*	*0.5*	*Songvaar (p)*
HDD050	**71**	**99**	**28**	**1.1**	**0.46**	**Songvaar (s & p)**
HDD053	**173**	**198**	**25**	**1.1**	**0.1**	**Songvaar (p)**
HDD054	**92**	**110**	**18**	**0.7**	**0.3**	**Parsee (p)**
	149	**167**	**18**	**0.6**	**0.1**	*Parsee (p)*
	203	**226**	**23**	**0.6**	**0.3**	*Parsee (p)*
	237	**277**	**40**	**0.6**	**0.3**	*Parsee (p)*
	301	**380**	**79**	**0.4**	**0.1**	*Parsee (p)*
including	*317*	*337*	*20*	*0.8*	*0.3*	*Parsee (p)*

(p) = Primary Mineralisation (s) = Supergene Mineralisation * All intercepts reported are down hole

Three major anastomosing structures have been defined, with individual copper-mineralised strike lengths of 1.5 km and a combined copper-mineralised strike length in excess of 4 km (Fig. 13). Copper mineralisation remains open along strike and at depth, and has been observed from as shallow as 5 m below surface to 700 m in depth.

The structural style of the Hillside mineralising system displays some characteristics which are similar to the Moonta-Wallaroo mines, the deeper Cloncurry-style IOCG(U) deposits (e.g., Starra; Williams *et al.*, 2005; Mt. Elliott; Fortowski & McCracken, 1998; and Wang and Williams, 2001) and some of the IOCG-style deposits from the Curnamona Province (e.g., Kalkaroo; Teale, 2006) in that the mineralisation is hosted within discrete, but apparently laterally and vertically continuous, structures. This structural style is quite different from the Olympic Dam and Prominent Hill-style IOCG(U) deposits that are characterised by large polygonal to circular hematite-dominant breccia bodies containing high tonnages of mineralisation.

Primary copper mineralisation at the Hillside deposit is dominated by chalcopyrite with lesser bornite and chalcocite. The latter two phases are often intergrown with apparent unmixing textures common. Some zones of the deposit contain significant primary bornite and chalcocite. These sulphides are associated with extremely oxidised domains within the deposit and bornite is often found with carbonate and hematite. Pyrite is abundant in some domains but is usually replaced by chalcopyrite during skarn retrogression. There are numerous high to low temperature skarn types developed in the Hillside deposit. Earliest, higher temperature skarns are dominated by magnetite±quartz±pyrite±garnet and almost monomineralic garnet skarn. Replacement of the earlier skarns by clinopyroxene, K feldspar, epidote, actinolite, allanite and biotite-rich skarns occurs with, for example, clinopyroxene-bearing skarn often developed on the margins of and replacing garnet skarn. Introduction of copper is associated with highly oxidising fluids with replacement of magnetite by hematite±chalcopyrite. Late carbonate and silica flooding creates extreme increases in copper grade in many areas and is associated with the development of chlorite+chalcopyrite which replace clinopyroxene, actinolite and garnet.

Secondary copper mineralisation is dominated by chalcocite with lesser malachite azurite, native copper and rare cuprite, atacamite and chrysocolla. Current understanding indicates that there is a development of supergene chalcocite overlying primary copper mineralisation along the eastern domains of the deposit ('Songvaar' and 'Parsee' structures; Figs. 13 and 16). Additional chalcocite development may be present overlying primary mineralisation elsewhere in the deposit. Primary copper mineralisation, which is developed within and adjacent to skarn lithotypes, comprises parallel, steeply-dipping domains that are extremely copper-rich, and may be flanked by lower grade vein, blebby and lace-like chalcopyrite accumulations. Table 1 lists a selection of significant drill intersections and assay results for the project.

Detailed structural, geological, mineragraphic and petrological investigation of the deposit is ongoing and a comprehensive structural and lithological model is being established. A number of preliminary observations from key drill holes within the mineralised system have been made, and are summarised below (Rankin, 2009; Teale, 2009):

- The copper mineralisation is hosted within metasediments and meta-mafic rocks and can develop within and adjacent to gabbros and A-type felsic intrusives. The metasediments are folded by pre-intrusion open to tight, south-plunging folds, including both upright folds (local F_2), and a series of recumbent to strongly inclined folds (local F_1). The local F_1 folds are also associated with possible early thrusts in some sections.
- Folds trend north to northeast, with some evidence for later northwest cross-folding in some areas. The folding varies from parallel-coincident, to acutely discordant to the north-south trending skarn and breccia bodies.
- The copper-gold mineralisation is focussed in numerous steeply dipping, sub-vertical skarn and associated breccia bodies. The overall depth extent of the individual high-grade mineralised zones suggests mineralisation was emplaced over a vertical dimension of greater than 700 m. Mineralisation and associated skarn development can vary both laterally and vertically. Stratabound replacement of layering occurs adjacent to the skarns.

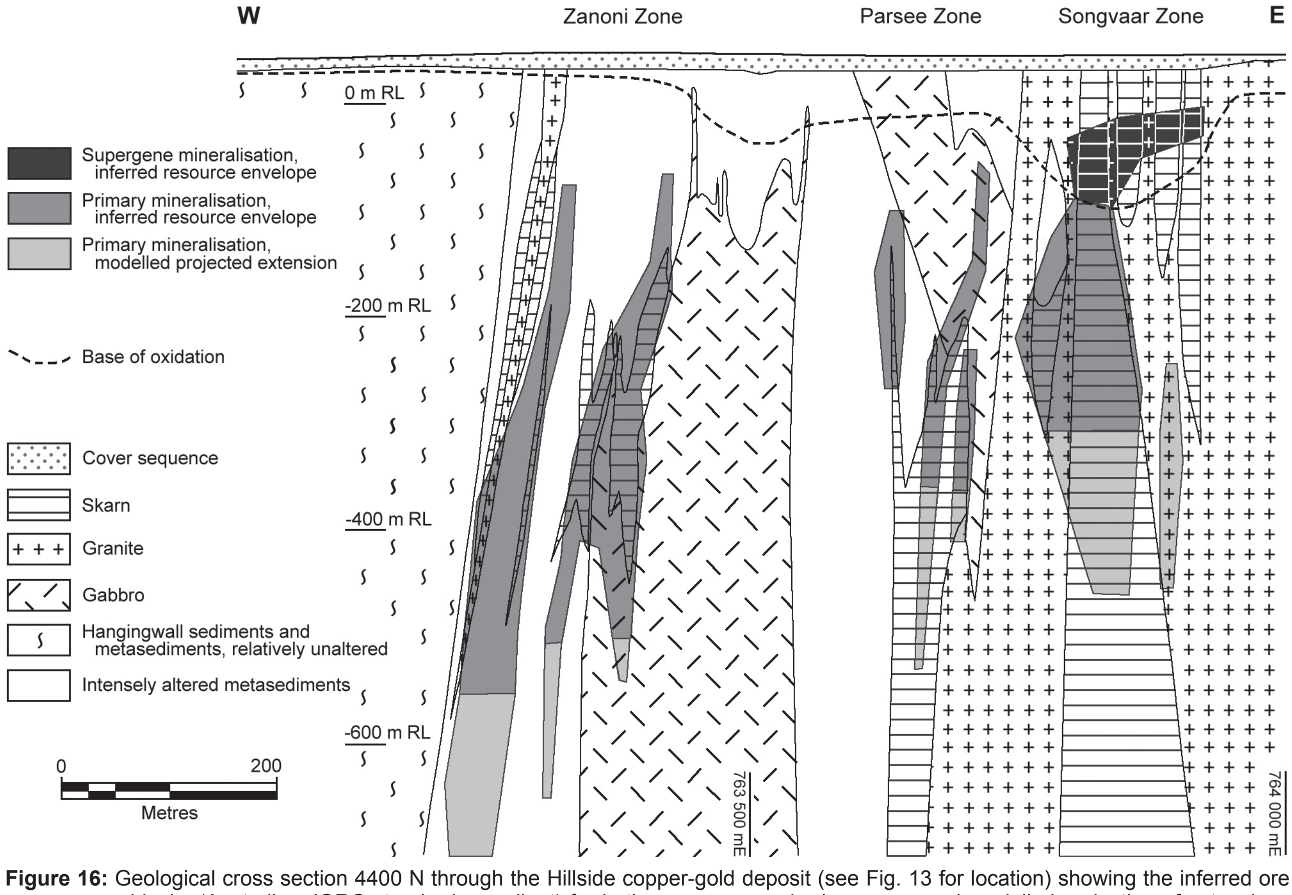


Figure 16: Geological cross section 4400 N through the Hillside copper-gold deposit (see Fig. 13 for location) showing the inferred ore resource blocks (Australian JORC standard compliant) for both supergene and primary ore, and modelled projection of extensions based on a drill density less detailed than required for inferred status (Rex Minerals Ltd., ASX release, July 2010).

- Copper mineralisation is dominated by chalcopyrite with lesser primary chalcocite and bornite. Pyrite tends to be partially replaced by chalcopyrite and gold appears to be hosted in chalcopyrite. Rare galena, tennantite, bismuthinite and aikinite are present and uraninite and pitchblende are often associated with carbonate-rich zones. LREE are contained within allanite.
- Post-mineralisation faulting is evident, particularly north-trending, steep to sub-vertical structures, and others that are moderate to shallow and northwest-trending.

Recent U-Pb isotopic dating of two titanite samples from alteration at Hillside indicate that the alteration is broadly coeval with granite emplacement (1570±8 Ma; Gregory in Reid, 2010), which relates to the latest stage of Hiltaba Suite magmatism in the wider Olympic Copper-Gold Province.

Although differing in structural style to the Olympic Dam and Prominent Hill deposits, the Hillside mineralisation shares features such as (1) the age of alteration is coeval with late stages of Hiltaba Suite magmatism, and alteration and mineralisation in the other major deposits of the Olympic Copper-Gold Province; (2) the introduction of copper mineralisation is associated with hematite replacement of a pre-existing magnetite-altered host; (3) proximity to a major magnetic-gravity structure (albeit linear); (4) mineralisation is controlled by a major fault system; and (5) association with the northwest-trending G2 Corridor (O'Driscoll, 1983).

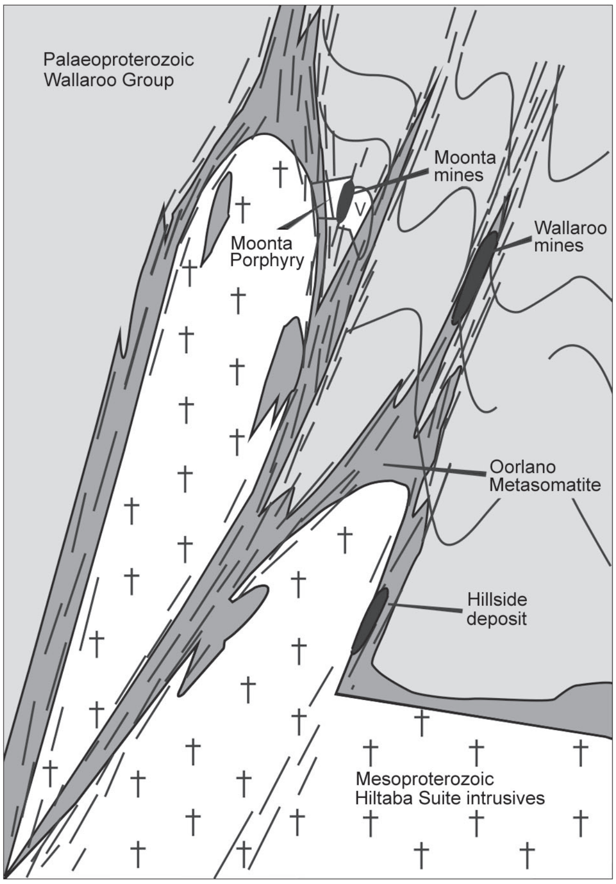


Figure 17: Schematic diagram illustrating the main ingredients in the Moonta sub-domain of the Mesoproterozoic IOCGU thermal event; hot oxidised A, I and S-type Hiltaba Suite granites, regional amphibolite-greenschist facies metamorphism, intensely partitioned deformation, intense metasomatic Na-K-Ca-Fe (magnetite) alteration, and polymetallic, Cu-Au dominated mineralisation.

The Hillside deposit is also significant because: (1) it is economically promising; (2) it is controlled by elements of the Pine Point Fault structure, hence adding potential to that laterally extensive zone; (3) it demonstrates, that in spite of considerable unsuccessful exploration expenditure in the recent past, potential remains on Yorke Peninsula for significant economic mineralisation.

Spatial and Temporal Associations

As described above, metasomatic alteration and mineralisation are related to deformation and metamorphism in the Moonta sub-domain. Additionally, alteration is broadly synchronous with the emplacement of the Hiltaba Suite intrusions. The interaction of all these elements (i.e., Mesoproterozoic intrusions, deformation, alteration and mineralisation) are represented in Fig. 17. Observations at hand, outcrop and mine scales can be extended to the regional scale via geophysical imagery, thus adding confidence to exploration targeting.

Geophysical Character of Alteration

Definition of a lithostratigraphy and production of lithostratigraphic maps were two objectives of a study of the Moonta-Wallaroo region, where it was hoped that the combination of drill hole information and regional geophysics would provide the means of achieving these aims (Conor, 1995). This hope was not fully realised because it became apparent that the magnetic patterning was related as much, if not more, to the vagaries of metasomatism than to the composition of the original strata. However, because magnetite is one of the principal minerals of early high-temperature metasomatism, and with its destruction being a characteristic of a later lower temperature event, the shallowly buried Moonta-Wallaroo region is ideal for the study of structurally-controlled alteration using magnetic data.

At the regional scale, the distribution of magnetite relates to a number, or combination of causes. In their simplest form, magnetic anomalies appear as:

- linear to curvilinear trends related to iron-rich sedimentary accumulations, either syngenetic or epigenetic,
- curved features adjacent to granite stocks, their origin presumably due to alteration within the aureoles,
- linear trends that are interpreted to be structurally controlled, along either faults or shear zones, some perhaps related to axial plane structures of large folds,
- discrete equant bodies that give rise to 'bull's-eye' anomalies, possibly representing iron-rich pipes, or the steeply plunging lines of intersection of planar structures.

Fig. 2 shows the distribution of magnetite-rich alteration on northern Yorke Peninsula, with the information being derived from interpretation of airborne geophysics, and where possible confirmed by direct observations from outcrop or drill core. The spatial relationship of alteration to granite stocks and direct observation of drill core show that the principal cause of introduction of metasomatic iron was the intrusion of the Hiltaba Suite. However the morphology of accumulations is controlled by a number of factors, such as intrusion margins, the reactive nature of the host lithologies of the Wallaroo Group, and penetrating structures. Matters are further complicated by de-magnetisation, either by oxidation of magnetite to non-magnetic hematite, or by metasomatic stripping of iron.

The Tickera Granite body north of Wallaroo is a notable example of a semi-circular magnetic and gravity feature coinciding with the margin of a large Hiltaba Suite granite stock. Intense irregular shaped magnetic highs near the margin of the main Tickera Granite body (Figs. 2, 14 and 15) have been investigated by exploration drilling, potentially either as sources of iron ore, or as hosts of copper-gold mineralisation. Examples of prospects are Katinka, East Alford, Alford and West Alford (Figs. 2 and 3), the latter two being situated at the southern margin of the Tickera Granite and associated with the Alford Fault Zone.

Drilling and outcrop have shown high magnetic responses to be from albite-magnetite-calcsilicate and lesser biotite-magnetite-albite alteration, which, on the gross scale was controlled by the interface of the granite body with metasediments of the Wallaroo Group, but in detail was influenced by the presence of sheared zones. An example, given later, demonstrates how the penetrative fabric of these sheared zones allowed ingress of fluids to then migrate further into the host metasediments.

That the magnetic highs are sporadic is explained by outcrop at Wallaroo North Beach where altered metasediments and magnetite-bearing calcsilicate metasomatites are replaced by kaolinite dominated assemblages. This later argillic alteration can be traced in magnetic imagery as a major demagnetised zone along the southern and, to a lesser extent, the southeastern part of the aureole of the Tickera Granite where sporadic pyrite-chalcocite mineralisation has been investigated by drilling (Figs. 14 and 15). Demagnetisation was due to stripping of iron and other elements during the late low-temperature kaolinite-dominated alteration, which Raymond (2003) interpreted to be controlled in part by the Alford Fault Zone, a major east-west structural corridor partially coincident with the Tickera Granite aureole and extending westward beneath the waters of Spencer Gulf (Fig. 2).

Similar examples of structurally-controlled de-magnetisation of earlier magnetite alteration exist to the south in the Weetulta-Balgowan area involving numerous stocks which are smaller than the Tickera Granite mass (Figs. 2 and 3). In the Tea Tree Glen area near Weetulta, drilling intersected significant Cu-Ce-rich mineralisation associated with hematite-chlorite-K feldspar-quartz alteration overprinting earlier biotite-magnetite. The mineralisation is represented in the magnetic imagery by apparent de-magnetisation along a series of late southeasterly-striking fault splays (Fig. 10; Raymond, 2002). These regional-scale southeasterly-striking faults could relate to the Moonta mines cross-faults, and also the major fault controlling the southeasterly trending coastline south of Point Riley (Fig. 18). This fault strikes towards the Wallaroo mines, and possibly had some control over the mineralisation.

Hand Specimen- and Outcrop-scale Evidence

At drill core- and outcrop-scale there is much evidence for the spatial relationship of alteration and mineralisation with deformation. The two following examples demonstrate that the development of penetrative metamorphic fabrics aided the ingress of both metasomatic and mineralising fluids.

Firstly, drilling along the southern part of the aureole of the Tickera Granite (Figs. 2 and 5) demonstrates that strain is highly partitioned. Fine-grained, graded-bedded psammitic-psammopelitic sediments of the Wallaroo Group have, over a wide zone, been converted to psammopelitic schistose tectonite, with the schistosity being an intense penetrative fabric in which bedding remains only as rare transposed mesofolds (Fig. 7c). Alteration parallel to foliation is evidence of the ingress of alkali, iron and calcsilicate material that eventually replaced the tectonite to form a skarn-like rock more commonly associated with contact metamorphism of carbonate rocks (Fig. 7d). Iron is present in amphibole, magnetite, locally pyrite and as hematite dusting in feldspar. Carbonate, accompanied by chalcopyrite, was introduced during the final stages of alteration (Fig. 9d), partly as late discordant veining.

In a second example, from drilling in the vicinity of the Wallaroo mines, the coincidence of tectonically induced structures and metasomatic alteration is striking where shear zones are developed in metasediments of the Wallaroo Group (Doora Member). A penetrative metamorphic foliation, which is distinctly lineated, is developed in these planar-bedded, thinly interlayered psammitic and psammopelitic metasedimentary rocks. With increasing proximity to shear zones, bedding becomes progressively more tightly folded, and biotite (plus magnetite) increases in both grain-size and proportion of the rock. Significantly, the orientation of foliation and lineation is maintained, with the latter apparently paralleling mesofold axes (Fig. 7i). Proximal to the core of the shears, the original quartzo-feldspathic bedding is totally replaced by the foliated and lineated biotite-magnetite-pyrite assemblage. The evidence points to progressive metasomatic replacement under tectono-metamorphic conditions. The final stage of deformation in the core zones of many of these structures resulted in disruption, with the rock characterised by transposed folded quartz and quartz-rich pegmatite veins, and increase of pyrite-pyrrhotite and chalcopyrite, locally presumably to ore grade (verification is difficult because flooding prevents access to the Wallaroo mines workings).

The examples from the Wallaroo mines and Tickera Granite aureole demonstrate that metasomatism was synchronous with moderate-grade metamorphism and with both ductile and brittle deformation. These observations, and those of brecciated zones, suggest development of fault zones that contained compartments characterised by either shearing or, in the case of spall breccias, dilation. The ore from Wheal Hughes was mined from a complex comprising a linking structure obliquely connecting two *en-echelon* shear zones. This situation is similar to the brittle-ductile behaviour noted in the Cloncurry district (Marshall and Oliver, 2001). The mineralogy of alteration assemblages indicates that shearing took place at depths favouring upper greenschist to lower amphibolite facies conditions, and was accompanied by the introduction of Fe-K-S-rich fluids from which alkali feldspars, amphibole, biotite, magnetite and pyrite crystallised, either by metasomatic replacement, or as void fill (breccia matrices and veins).

Elsewhere, at both hand specimen- and outcrop-scale, structurally controlled alteration is commonly visible following the axial planes of folds (Fig. 7h). This suggests that the axial planar zones of regional scale folds could focus both alteration and mineralisation. It is also possible that metamorphic mineral lineation would indicate the attitude of axes of much larger folds, and hence potentially the plunge of ore shoots.

Regional-scale Structural Control of Alteration

Giving consideration to the origin of linear aeromagnetic features, evidence has been presented at the mesoscopic scale (hand specimen to outcrop) for penetrative structures such as foliation (Figs. 7c and 7d), fold plane structures (Figs. 7h and 7i), zones of brittle fracture (Figs. 7a and 7g) and fault jogs, to have promoted the ingress of metasomatic and mineralising fluids. Therefore it is possible to reason that these structural controls were also operative at the regional scale (hundreds of metres to kilometres). Length-weighted frequency and orientation plots of linear magnetic features highlight northeast-, east-west-, and southeast-trending clusters that correspond to structural elements that either crop out or are exposed in mine workings (Figs. 14, 15 and 18a). The prominent northeasterly trend corresponds to the foliation displayed by the Tickera Granite and the orientation of the shoreline northeast of Point Riley. Both appear to relate to a major northeasterly trending structure situated just off-shore (Fig. 2).

Similar to the northeasterly striking foliation and lineation in the granites at Point Riley, an intense down-dip mineral elongation reflects pre-mineralisation syn-metamorphic ductile shearing at Wheal Hughes and the Poona mine. The same northeasterly structural trend corresponds with the orientation of the mineralisation-controlling West Lode Shears of the Moonta mines and the main linking Eastern Shears of the Wallaroo mines (Fig. 18c; Jack, 1917; Dickinson, 1942 and 1953). The north-northeasterly trending Moonta Mines Main Lode Shears, an element of which linked West Lode Shears in the Wheal Hughes open-cut, were not resolved by the available aeromagnetic imagery in the immediate Moonta-Wallaroo mines area. However, this north-northeasterly trend appears to approximate elements of mineralisation at the Hillside deposit, and the associated Pine Point Fault Zone that controls the eastern coastline of Yorke Peninsula (Figs. 2, 11 and 18c). The Moonta Mines Main Lode Shears, West Lode Shears and the slightly later Strike Faults

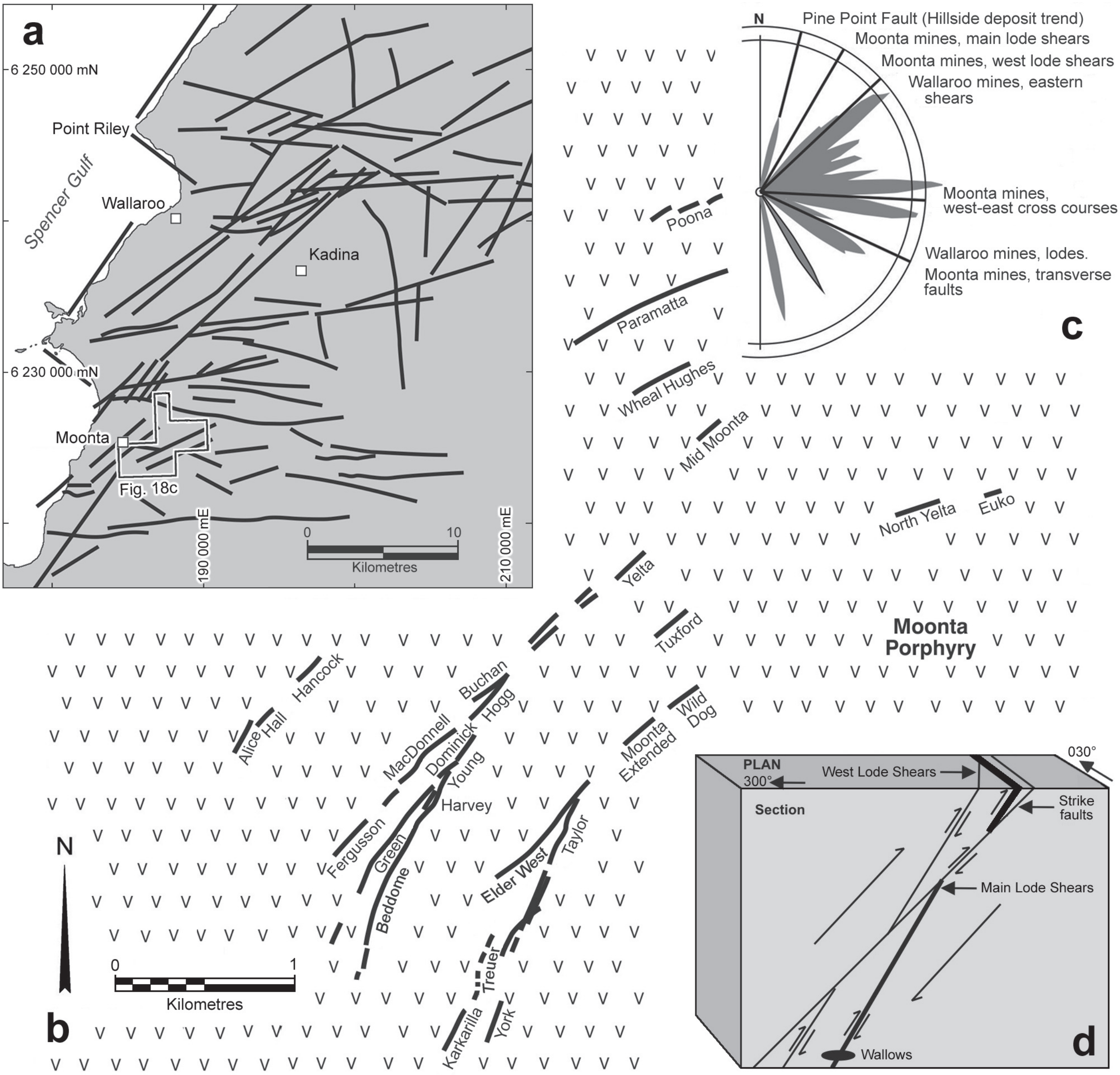


Figure 18: **a** - Moonta-Wallaroo area showing the main structural trends interpreted from 1VD aeromagnetic image; **b** - Distribution and strike of Moonta copper-gold lode structures hosted in the Moonta Porphyry dome (adapted from Dickinson 1942); area shown on Fig. 18a; **c** - Length weighted rose diagram showing strike of the trends and main structural sets interpreted from magnetic data, with the main trends of Moonta and Wallaroo mines lodes superimposed (black lines); **d** - Block diagram showing relationship of the main mineralised structures of the Moonta mines (adapted from Dickinson, 1942).

have been interpreted to show northwest over southeast thrust displacement (Fig. 18d). From observations at Wheal Hughes and the Poona mine, it would appear that the lodes are composite structures with mineralisation developed in a system of well developed brittle veins controlled by the orientation of the earlier ductile shear foliation. Pipe-like thickenings appear to follow the orientation of the original mineral lineation, and are also controlled by shear-set intersections. This progression of structures evolving from tight shears to open fractures, either conforms with the notion of thrust displacement of the Moonta rocks upwards across the ductile-brittle boundary, or simply local development of brittle zones within a regionally ductile setting due to fluid pressure perturbations and structural heterogeneity, as shown in the Cloncurry district of the Mount Isa Inlier (Marshall and Oliver, 2001).

In summary, structurally-related alteration in the Moonta-Wallaroo region has been described at two scales:

- *Local:* where drill hole and outcrop observations indicate that alteration coincided with deformation occurring under moderate metamorphic conditions. These fabrics and structures are commonly the loci of magnetite-bearing, and locally of magnetite-destructive alteration.
- *Regional:* where interpretation of aeromagnetic data can be used to reveal the location and orientation of both magnetite-bearing and magnetite-destructive structures and zones (e.g., alteration in granite aureoles, Alford Fault Zone), thus adding dimension to drill hole and field observations of intrusive and extrusive boundaries (e.g., Tickera Granite and Moonta Porphyry), mineralised structures (e.g., at Moonta and Wallaroo mines, Hillside deposit) and regions of high strain indicated by metamorphic fabrics.

Discussion and Conclusions

Many magnetite-bearing features apparent from aeromagnetic data, are interpreted to represent structures that were former conduits for fluids generated by metamorphism and magmatism. In the Moonta sub-domain, the distribution of alteration assemblages shows that fluids were able to either migrate away from fractures along reactive stratigraphy, or pervasively replace the surrounding rock. More complex channel-ways and traps formed at the intersections of fractures or along the penetrating margins of intrusions.

The massive extent of alteration indicates that a great volume of fluid has flowed through the rock mass, and the quantity of iron present, mainly as magnetite, suggests the potential for movement of other metals. Early hydrothermal fluids included (1) a sulphur-poor, Ca-Na-Fe-rich fluid which produced albite-magnetite-calcsilicate alteration, and (2) a sulphur-bearing K-Fe-rich fluid which produced biotite-magnetite-albite-pyrite alteration. However, despite the availability of sulphur, it appears that early hydrothermal conditions were generally not conducive to precipitation of copper-bearing sulphides, mineralisation being focussed during a later, cooler, and more oxidised hydrothermal stage.

Examination of fabrics at the Poona mine and Wheal Hughes in the Moonta Field indicates that mineralisation was imposed upon earlier formed structures, an observation consistent with the findings of Jack (1917) and Dickinson (1942). They showed mineralisation to be strongly controlled by thrust-related structures responsible for northwest over southeast displacement. The potential for rapid uplift during Hiltaba Suite times is supported by the apparent intrusion of miarolitic cavity-bearing unstrained granite into deformed and altered granite. In addition, the conclusions of Janz (1990) and Morales-Ruano *et al.* (2002) suggest the possibility that economic mineralisation at the Poona mine and Wheal Hughes took place at shallow depths where boiling was possible. These observations support the conclusion that northwest-southeast oriented compression resulted in the development of structures that, initially at depth, allowed the passage of high temperature metal-bearing fluids from which iron was deposited as magnetite. However, it was the later, possibly higher level, cooler, hematite-stable conditions, which favoured the chlorite-hematite-quartz-K feldspar-carbonate overprinting assemblage, that promoted the deposition of copper, gold and molybdenum to form the lodes of the Moonta mining field.

Many decades of exploration drilling of magnetic targets in the Moonta-Wallaroo region have had little success in locating magnetite-related copper-gold mineralisation. However recent discoveries in the Olympic Copper-Gold Province (e.g. Prominent Hill, Carrapateena, Hillside) highlight the importance of the association of copper mineralisation with oxidation, which is manifested by hematisation and demagnetisation of early magnetite-altered host rocks. Modelling by Bastrakov *et al.* (2007) suggests that the gradient between magnetite and hematite stability is the most favourable location for copper mineralisation. Likewise, in the majority of Cloncurry-style IOCGU systems, there is typically an early high temperature magnetite phase that is overprinted by the main copper sulphide mineralisation stage (Williams and Pollard, 2001). The notable exception is the Ernest Henry deposit in the Cloncurry district, which does maintain the potential for magnetite-associated copper mineralisation in deeper high temperature environments.

While magnetite alteration is not necessarily an indicator of copper mineralisation, it does mark the position of early formed fluid conduits and late chlorite-hematite-quartz-K feldspar alteration, and copper mineralisation is typically found within previously magnetite-altered structures. These structures have the potential for the accumulation of economic mineralisation, either within the primary structure, or in splays and associated dilatant zones (e.g., breccias), or in adjoining favourable lithological units. Hence, exploration around magnetite-bearing structures remains worthwhile, although detailed targeting requires data from other sources such as gravity and electrical methods. Additionally, targeting must be constrained by a good understanding of geological factors such as host rock composition and rheological contrasts, the location of penetrative discontinuities such as faults, intrusive contacts and metamorphic fabrics, and the controls upon mineralisation in the district.

The recent discovery of mineralisation in the vicinity of the historic Hillside mine is of great importance because, not only was it a technical success, but also the discovery provides confidence for increased exploration in northern Yorke Peninsula. It is important to note that Hillside is just one prospect among many that deserve renewed attention. The improved understanding of the regional mineral system, the recognition that alteration and mineralisation share similar structural controls, and that the controlling structures are readily visible in updated regional geophysical datasets, should allow the definition of hitherto untested targets in northern Yorke Peninsula.

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