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GEODYNAMIC SETTING AND CONTROLS ON IRON OXIDE CU-AU (±U) ORE IN THE GAWLER CRATON, SOUTH AUSTRALIA

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Abstract - The Olympic IOCG (iron oxide copper-gold) Province occurs along the eastern margin of the Gawler craton nucleus where oxidised (magnetite-series), A-type granitoid plutons of the 1595 to 1575 Ma Hiltaba Suite were emplaced into an accreted Palaeoproterozoic terrane, and where mafic volcanic rocks of the lower Gawler Range Volcanics are most abundant. This magmatism comprises the central part of a diachronous corridor of bimodal I-, A- and subordinate S-type intrusions that extends across the Gawler and Curnamona cratons, and was emplaced in a distal continental retro-arc setting during amalgamation of the North and South Australia cratons. IOCG mineralisation mostly formed during a short lived episode of northnorthwest-southsoutheast extension that approximately coincided with eruption of the Gawler Range Volcanics (ca. 1595 to 1590 Ma), but was preceded and followed by more protracted northwest-southeast to northnorthwest-southsoutheast contraction. The deposits were emplaced along eastnortheast- to northeast-trending extensional faults near their intersections with major northnorthwest- to northwest-trending faults in the hangingwall of first-order terrane boundary faults, such as the Elizabeth Creek and Pine Point Fault Zones.

The 3D crustal-scale architecture of the supergiant Olympic Dam ore system comprises a discrete lower- to mid-crustal zone of seismic transparency that may relate to voluminous Hiltaba-age migmatites and altered felsic batholiths, localised above a crust-penetrating fault zone at the edge of an inferred mafic underplate. Inversions of geophysical data suggest that magnetite-rich alteration extends several kilometres beneath the Olympic Dam deposit to near the top of these interpreted batholiths. A zone of low resistivity in the mid-crust beneath the deposit, imaged in magnetotelluric data, may be associated with conductive mineral seams, probably graphite, related to this alteration event. Large scale IOCG-related alteration systems in the province are generally zoned from distal, high-temperature, deep level albite-actinolite±magnetite assemblages, through biotite-magnetite and then magnetite-K feldspar±carbonate assemblages, to proximal lower temperature, shallow hematite-sericite-chlorite-carbonate alteration. IOCG mineralisation typically occurs at the Fe^{2+} to Fe^{3+} redox boundary which frequently has a distinct geophysical expression. Magnetite-rich alteration assemblages were deposited from high-temperature, hypersaline, CO_2-bearing brines of magmatic and deeply circulated bittern origin that isotopically equilibrated with metasedimentary and meta-igneous units. Although these high-temperature brines commonly transported significant copper (>300 ppm), their low sulphur (plus high iron and chlorine) contents severely limited their capacity for sulphide saturation and copper-gold mineralisation. Ore deposition only occurred where mixing or overprinting occurred with lower temperature, more oxidised, SO_4-rich brines, derived from either playa lake (bittern) sources or evolved from cooled and extensively equilibrated magmatic brines. In either case, external leaching of copper, gold and sulphur from buried basaltic units, and/or uranium from exposed felsic volcanics and radiogenic granites, is deemed essential for supplying sufficient metals to form economic IOCG(±U) deposits in the Olympic IOCG Province, and explains the spatial restriction of IOCG deposits to only a small portion of the broader magmatic province. Area selection guidelines for further discoveries beneath the extensive cover are considered at subprovince, district and deposit scales.

Introduction

The Gawler craton in South Australia hosts the world's most richly endowed iron oxide copper-gold (IOCG) ore province, the Olympic IOCG Province, containing the supergiant Olympic Dam copper-gold-uranium-silver deposit, and the major Prominent Hill, Carrapateena and Wirrda Well IOCG deposits (Fig. 1). Available geochronological data suggest that IOCG hydrothermal activity occurred during a widespread early Mesoproterozoic (1600 to 1575 Ma) magmatic event that produced the Hiltaba Suite I- and A-type plutons and the extensive Gawler Range Volcanics (e.g., Creaser and White, 1991; Johnson and Cross, 1995; Daly *et al.*, 1998; Skirrow *et al.*, 2002, 2007). This event is also temporally and spatially associated with gold mineralisation in the central Gawler craton (Ferris and Schwarz, 2003; Fraser *et al.*, 2007) and possibly with a range of other iron oxide deposits. Although the timing of major IOCG activity in the earliest Mesoproterozoic is widely accepted, models of ore formation post-dating the magmatism by at least 160 m.y. have also been proposed (e.g., Oreskes and Einaudi, 1992; McPhie *et al.*, 2010; Meffre *et al.*, 2010).

The extraordinary mineral wealth and exploration potential of the province has been the subject of intense multidisciplinary research involving collaboration between industry, government agencies and universities (e.g., Daly *et al.*, 1998; Ferris *et al.*, 2002; Betts *et al.*, 2003; Hand *et al.*, 2007; Skirrow *et al.*, 2002, 2007). For example, a recent special issue of Economic Geology (Volume 102, No. 8) was entirely devoted to the IOCG and gold systems of the Gawler craton. Understanding of the gross architecture of the province has benefited from regional seismic reflection and magnetotelluric data acquisition, as well as detailed aeromagnetic and ground gravity data coverage (e.g., Lyons and Goleby, 2005; Drummond *et al.*, 2006; Heinson *et al.*, 2006; Direen and Lyons, 2007). However, there remain many uncertainties on the controls on ore distribution due to the extensive burial by post-mineralisation sedimentary cover sequences. Much of the detailed knowledge on ore deposit controls has been acquired from prospect drilling and mine studies in the northern half of the Olympic IOCG Province.

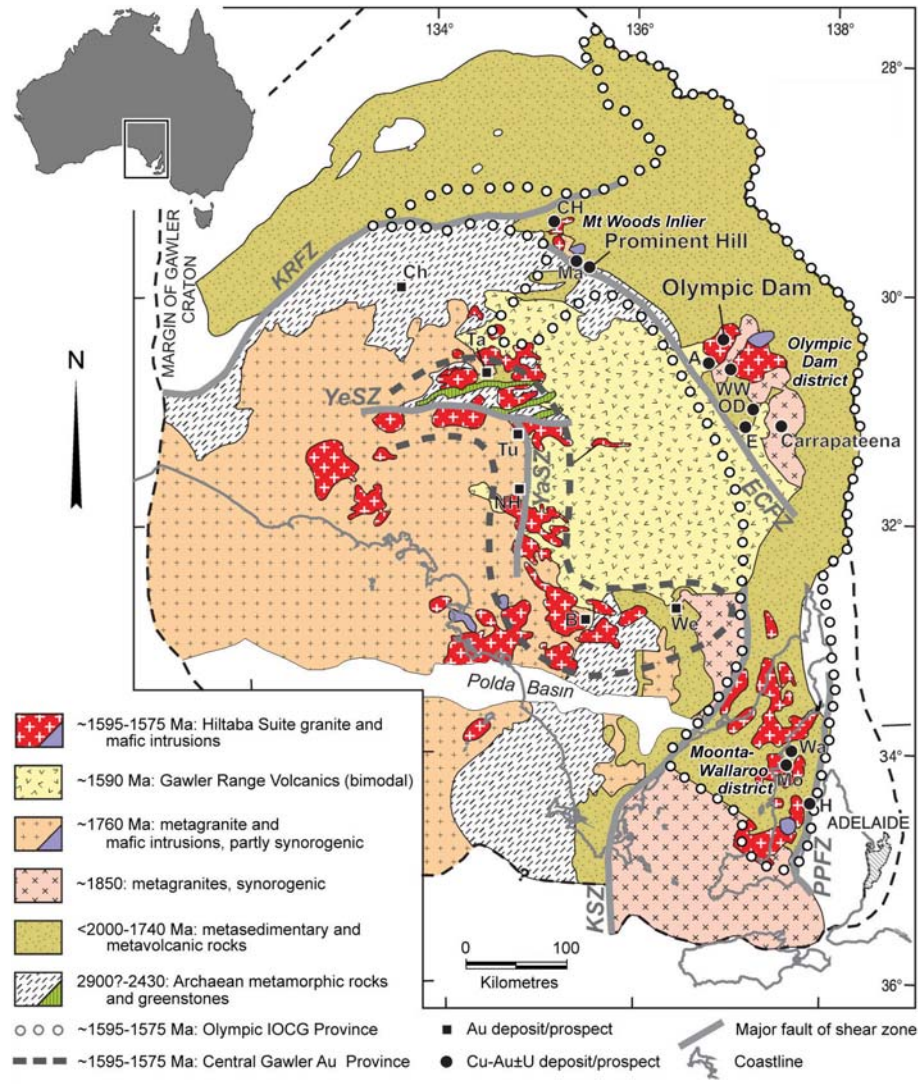


Figure 1: Geology of the Gawler craton (pre-Neoproterozoic, and excluding the Mesoproterozoic Pandurra Formation), regional fault zones, and principal IOCG±U and Au deposits and prospects in the Olympic IOCG Province and Central Gawler Gold Province. Regional faults: ECFZ: Elizabeth Creek Fault Zone, KSZ: Kalinjala Shear Zone, KRFZ: Karari Fault Zone, PPFZ: Pine Point Fault Zone, YaSZ: Yarlbrinda Shear Zone, YeSZ: Yerda Fault Zone. IOCG deposit abbreviations from north to south: Ch – Cairn Hill, Ma – Manxman, A – Acropolis, WW – Wirrda Well, OD – Oak Dam, E – Emmie Bluff, Wa – Wallaroo, Mo – Moonta, H – Hillside. Gold deposit abbreviations: Ch – Challenger, Ta – Tarcoola, Tu – Tunkillia, NH – Nuckulla Hill, B – Barns, We – Weednanna. Modified after Skirrow (2009).

This contribution provides a review of the ore systems and their geological controls in the Olympic IOCG Province. Special emphasis is given to the geodynamic setting, the structural controls on ore location, and province to camp scale alteration zonation patterns. From this updated geological framework, guidelines for exploration are developed and discussed in the context of residual potential for both iron oxide copper-gold(-uranium) and related iron oxide-poor gold, uranium and copper deposits.

Gawler Craton Geological Setting

The geological framework and evolution of the Gawler craton was recently summarised by Hand *et al.* (2007), building on previous studies and recent new data (e.g., Drexel *et al.*, 1993; Daly *et al.*, 1998; Ferris *et al.*, 2002; Fanning *et al.*, 2007). The major features are outlined below, with emphasis on new findings since the reviews published in Porter (2002) on IOCG settings in the Gawler craton (Ferris *et al.*, 2002; Skirrow *et al.*, 2002).

The Mesoarchaean to Mesoproterozoic Gawler craton is composed of fourteen geological domains that are defined by their tectono-stratigraphic history and geophysical characteristics (Parker, 1990; Daly *et al.*, 1998; Ferris *et al.*, 2002). The core of the Gawler craton comprises Neoarchaean to early Palaeoproterozoic metamorphic and igneous rocks of the Sleaford and Mulgathing Complexes, predominantly in the Coulta and Christie domains (Figs. 1 and 2). The Harris domain contains Neoarchaean komatiites in a granite-greenstone belt (Daly *et al.* 1998). The Sleafordian orogeny (2480 to 2420 Ma) attained granulite facies metamorphic conditions (Hand *et al.*, 2007). Recent geochronological studies have identified Mesoarchaean granitoid rocks in the Spencer domain, the oldest known Australian rocks east of the Yilgarn and Pilbara cratons (Fraser *et al.*, 2010a). The extent of Archaean rocks between the Coulta and Harris domains, and to the east of the Cleve domain, is unknown. However, evidence from seismic, magnetotelluric and Sm-Nd isotopic data suggest that Archaean rocks may extend eastwards beneath younger sequences of the Spencer and Olympic geological domains, at least as far as the northeast-dipping Elizabeth Creek Fault Zone, and westward under the Nuyts domain (Figs. 1and 2; e.g., Daly & Fanning, 1993; Creaser, 1995; Lyons and Goleby, 2005; Heinson *et al.*, 2006). Results of new seismic transects across the eastern margin of the Gawler craton recently published by Fraser *et al.* (2010b) have shed further light on the extent of Archaean crust. The eastern boundary between Archaean and Proterozoic

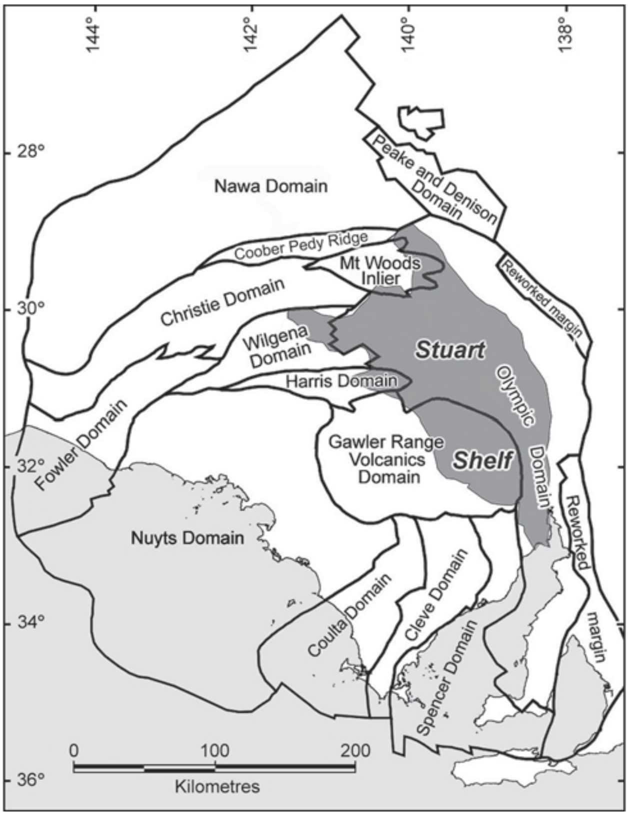


Figure 2: Tectono-stratigraphic basement domains of the Gawler craton (from Ferris *et al.*, 2002), and area of Mesoproterozoic to Neoproterozoic sedimentary cover rocks of the Stuart Shelf.

crustal domains appears to be a fundamental control on the distribution of IOCG systems, as discussed further below.

The Hutchison Group is a sequence of subaerial to shallow marine clastic and chemical metasedimentary rocks, with minor felsic and mafic volcanic rocks that were deposited after ~2000 Ma on a continental passive margin (Parker, 1993; Daly *et al.*, 1998). Although Hutchison Group units are inferred from seismic data to be present in the Olympic Dam district (Lyons and Goleby, 2005) there is scant direct evidence available (Jagodzinski, 2005). The eastern margin of the cratonic core, including the Olympic Dam district, was intruded by granitoids of the Donington Suite at ~1850 Ma during the Cornian orogeny (Hand *et al.*, 2007; Reid *et al.*, 2008). This suite is dominated by granodiorite gneiss, with subordinate metamorphosed alkali-feldspar granite, gabbronorite, tonalite and quartz monzonite intrusions with mafic dykes (Ferris *et al.*, 2002). Post-Donington extension along the eastern margin of the craton, but also on the northern and western margins, resulted in a series of basins between ~1770 and 1740 Ma, some of which contain bimodal volcanic rocks. These include the Wallaroo Group, an important host to IOCG alteration and mineralisation in the Moonta-Wallaroo and Olympic Dam districts.

The period between ~1730 and ~1630 Ma included the Kimban orogeny (1730 to 1690 Ma), Ooldean Event (1660 to 1630 Ma), widespread emplacement of various felsic igneous rocks, including the Tunkillia Suite, and formation of several small intracontinental sedimentary basins (Hand *et al.*, 2007). The Kalinjala Shear Zone (KSZ, Fig. 1) is a key manifestation of the Kimban orogeny. The close of the Palaeoproterozoic was marked by the emplacement of the Nuyts Volcanics and St Peter Suite bimodal magmas in the southwestern part of the Gawler craton at ~1630 to 1615 Ma (Fanning *et al.*, 2007). Although not well exposed, these igneous rocks have been interpreted to occupy much of the Nuyts domain (Fig. 2).

The geological history of the Gawler craton between ~1600 and ~1575 Ma includes the formation of the Olympic IOCG Province, Central Gawler Gold Province (e.g., Skirrow *et al.*, 2002; Ferris and Schwarz, 2003; Fraser *et al.*, 2007), and the high-volume magmatism of the Hiltaba Suite and co-magmatic Gawler Range Volcanics (Fig. 1). The distributions of the Hiltaba Suite and Gawler Range Volcanics spatially and temporally overlap with the formation of the Olympic IOCG Province and Central Gawler Gold Province, as noted above. However, the magmatism is considerably more extensive than either of these metallogenic provinces, and volcanic rocks of equivalent composition and similar age have been identified in the Curnamona Province to the east of the Gawler craton, and in the Terre Adélie craton in east Antarctica (Fanning *et al.*, 1998; Peucat *et al.*, 2002). The Hiltaba Suite was emplaced between ~1600 and ~1575 Ma, with some of the earlier phases intruded during regional deformation (Conor, 1995; Ferris *et al.*, 2002; Jagodzinski, 2005; Hand *et al.*, 2007). The recognition of widespread tectonism in the Gawler craton during the early Mesoproterozoic has led to a re-evaluation of the geodynamic and tectonic setting of the Hiltaba Suite, co-magmatic Gawler Range Volcanics and IOCG systems, as discussed further below.

Hiltaba Suite plutons comprise relatively oxidised, silicic (mostly >70 wt.% SiO_2) I- and A-type, generally metaluminous granitoids, ranging from granite to quartz monzodiorite, with strong enrichment in uranium, fluorine and other HFSE (Creaser and White. 1991; Johnson and Cross, 1995; Jagodzinski, 2005; Budd, 2006; Zang *et al.*, 2007). Hiltaba Suite plutons of the eastern Gawler craton are predominantly A-type and more oxidised and evolved than those in the central Gawler craton, with average εNd_{1595} of -5.9 indicating a significant crustal contribution (Budd, 2006). Plutons of the same suite in the central and west Gawler craton are predominantly less evolved I-type plutons with average εNd_{1595} of -3.4 (Budd, 2006; Hand *et al.*, 2007). The magmatic suite is interpreted to have formed via a combination of extensive fractionation and crustal contamination of mantle-derived mafic magmas, plus mixing with voluminous silicic crustal melts (Stewart, 1994). The co-magmatic and bimodal Gawler Range Volcanics represent a large felsic igneous province (>70 000 km^3, McPhie *et al.*, 2008). In contrast to the ~25 m.y. duration of Hiltaba Suite plutonism, the few available high-precision geochronological constraints for the Gawler Range Volcanics indicate a relatively short period of volcanism of a few million years around ~1592±3 Ma (Fanning *et al.*, 1988; Johnson and Cross, 1995). The lower Gawler Range Volcanics have moderate dips (10 to 30º; Allen *et al.*, 2008) and are dominated by dacite and rhyolite but with locally thick successions of basalt and andesite (e.g., >1000 m thickness in the Chitanilga Volcanic Complex, and >450 m thickness of Roopena Volcanics, Drexel *et al.*, 1993). The preserved area of upper Gawler Range Volcanics exceeds 25 000 km^2 and is dominated by large-volume dacite and rhyolite flows and ignimbrites with low dips (<5º; Creaser and Cooper, 1993; Allen *et al.*, 2008; McPhie *et al.*, 2008). The extensive outflow of the upper Gawler Range Volcanics is attributed to high eruption temperatures (900 to 1100ºC, Creaser and White, 1991), low water content and high fluorine activity (Allen *et al.*, 2008).

The locus of tectonism appears to have shifted northwards and westwards after Hiltaba Suite magmatism, with the high grade Kararan orogeny affecting the Coober Pedy Ridge and Fowler domains between ~1570 and ~1540 Ma (Hand *et al.*, 2007). Finally, the Coorabie orogeny at 1470 to 1440 Ma in the western parts of the craton resulted in transpressional movement along major shear zones (Fraser and Lyons, 2006; Hand *et al.*, 2007) and resetting of some isotopic systems (e.g., K-Ar in the Moonta-Wallaroo district, Skirrow *et al.*, 2007). The Archaean to early Mesoproterozoic rocks of the Gawler craton are partly concealed beneath a series of basins, including the Cariewerloo Basin (Mesoproterozoic), Adelaidean (Neoproterozoic) strata of the Stuart Shelf along the eastern margin of the Gawler craton, and Palaeozoic and younger basins.

Olympic IOCG Province

The Olympic IOCG Province along the eastern margin of the Gawler craton was defined by Skirrow *et al.* (2002) by the distribution of IOCG alteration and mineralisation, which is now known to have formed broadly coevally along the length of the province at ~1600 to 1570 Ma (Skirrow *et al.*, 2007; see also below). Boundaries of the IOCG metallogenic province remain uncertain, particularly in the north. This metallogenic province encompasses three known districts containing IOCG deposits (from north to south): Mt Woods Inlier with the Prominent Hill deposit on its southern margin; Olympic Dam district hosting the Olympic Dam, Carrapateena and Wirrda Well deposits and numerous prospects; and the historic Moonta-Wallaroo copper-gold mining district (Fig. 1). The Olympic IOCG Province is superimposed on older geological domains (Fig. 2). From north to south these geological domains include the Peake and Denison, Coober Pedy Ridge, Mt Woods Inlier, Olympic and Spencer geological domains. Not to be confused with the Olympic IOCG Province, the Olympic geological domain is the largest and hosts most of the known IOCG deposits. The western boundary of the Olympic IOCG Province is marked by the Elizabeth Creek Fault Zone (ECFZ), and by the Kalinjala Shear Zone (KSZ) in the central and southern portions of the IOCG province, respectively. The eastern boundary, believed to be the suture with the Curnamona craton which collided with the Gawler craton during the Palaeoproterozoic, is defined as a major linear discontinuity in magnetic and gravity data that is entirely buried beneath Neoproterozoic and younger cover sequences. This discontinuity has been commonly identified as the eastern margin of the Gawler craton. In the southern Olympic and Spencer domains, the eastern boundary of the Olympic IOCG Province is defined by the Pine Point Fault Zone along the eastern shore of Yorke Peninsula, although in this region the boundary is inboard of the craton margin.

Oxidised (magnetite-series), 1600 to 1575 Ma Hiltaba Suite granitoid intrusions and related mafic intrusions are present in each district, although this suite and comagmatic Gawler Range Volcanics are also present elsewhere in the Gawler craton. The Olympic IOCG Province is generally very poorly exposed and Neoproterozoic to Cenozoic cover sediments and regolith commonly exceed several hundred metres in thickness (e.g., >350 m at Olympic Dam, Reeve *et al.*, 1990).

Geodynamic and Tectonic Evolution

The geological domains hosting the Olympic IOCG Province comprise one or more extensively reworked terranes that likely accreted to the Meso- to Neoarchaean nucleus of the Gawler craton in the Palaeoproterozoic (Betts and Giles, 2006; Howard *et al.*, 2006). The craton nucleus stabilised between 2480 and 2420 Ma with the Sleafordian Orogeny (Hand *et al.*, 2007) and is near circular in shape, encompassing the Sleaford and Mulgathing Complexes in South Australia, as well as Neoarchaean basement gneisses at Terre Adélie in East Antarctica (Ménot *et al.*, 2007). The southeast margin of the craton nucleus was previously understood to be marked by the Kalinjala Shear Zone (Fig. 1), a subvertical to steep eastsoutheast-dipping transcrustal shear zone that recorded intense dextral transpressional deformation during the Kimban Orogeny (1730 to 1690 Ma; Thiel *et al.*, 2005; Betts and Giles, 2006; Howard *et al.*, 2006; Hand *et al.*, 2007). However,

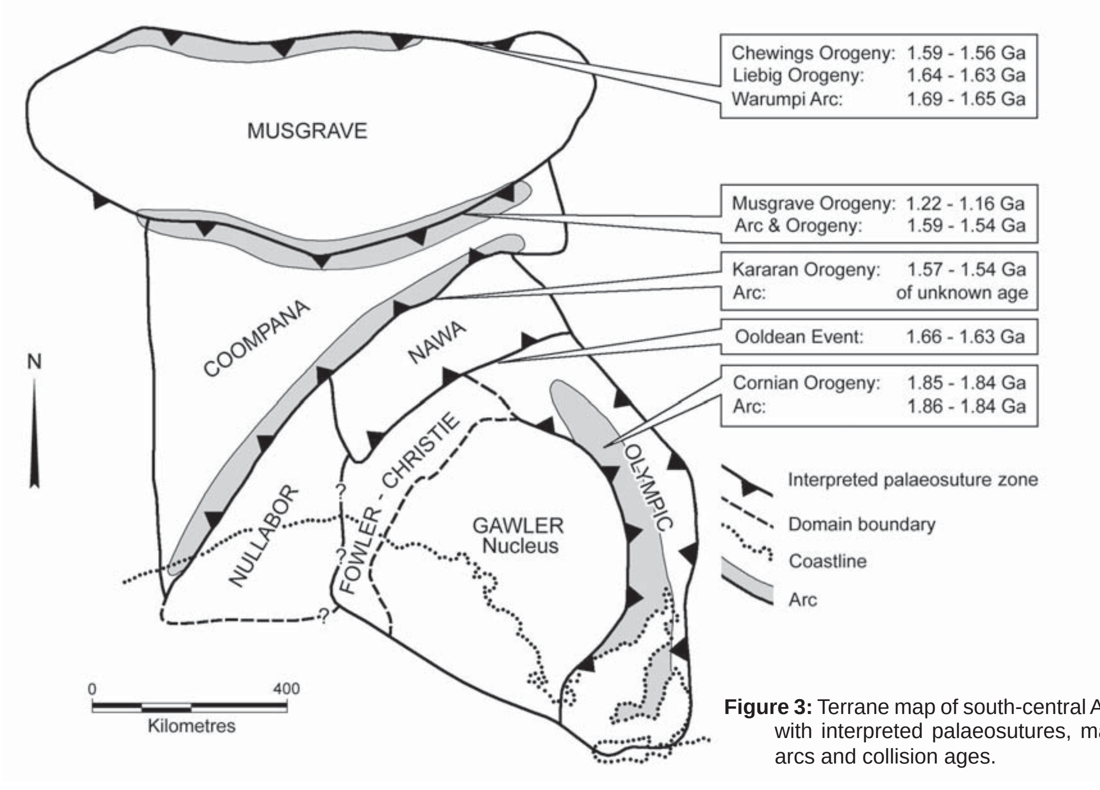


Figure 3: Terrane map of south-central Australia with interpreted palaeosutures, magmatic arcs and collision ages.

a domain of Mesoarchaean (~3125 Ma) granitic rocks was recently discovered east of the Kalinjala Shear Zone (Fraser *et al.*, 2010a), indicating that whereas this boundary separates basement rocks of different age, it does not define the eastern limit to Archaean sequences. The Elizabeth Creek Fault Zone located further north (Fig. 1) is possibly also a major terrane boundary separating Archaean from Palaeoproterozoic successions, and is shown in seismic reflection data to dip eastnortheast at a moderate angle down to the lithospheric mantle (Lyons and Goleby, 2005; Drummond *et al.*, 2006). It is possible that both of these regional fault zones are similar manifestations of the original eastern margin of the Neoarchaean craton nucleus, even though they record different reactivation histories due to differences in their strike direction. Thus, on the basis of limited evidence we speculate that much of the western margin of the Olympic IOCG Province comprises an E-dipping transcrustal boundary zone (Fig. 3).

Early to Middle Palaeoproterozoic

The timing of possible amalgamation of the Olympic geological domain with the Archaean nucleus of the Gawler craton is poorly constrained. The oldest stratigraphic unit interpreted to occur on both sides of the terrane boundary is the Hutchison Group, deposited between <2000 and 1857 Ma (Reid *et al.*, 2008). If this unit is correctly correlated across the terrane boundary, then the amalgamation age would be constrained to between 2450 and 1880 Ma.

No evidence has yet been found for a magmatic arc in the Olympic domain that fits within this age bracket, so the interpretation remains speculative. The oldest known candidate for a magmatic arc is the 1860 to 1845 Ma Donington Suite, which extends in a narrow north-south belt for over 700 km and was emplaced immediately prior to and during the Cornian Orogeny (1850 to 1840 Ma; Reid and Hand, 2008). Neodymium isotope geochemistry indicates that the intrusions were derived from a mixture of moderately juvenile mafic parent and Archaean crust (Mortimer *et al.*, 1988). The suite has been interpreted as rift-related (e.g., Schaefer, 1998). Alternatively, geochemical data are permissive, but somewhat equivocal, of a suprasubduction arc setting, comprising the highly fractionated batholithic roots of a continental magmatic arc or back-arc (Ferris *et al.*, 2002; Betts and Giles, 2006). We favour the latter alternative and suggest that Donington Suite magmatism was related to late Palaeoproterozoic subduction under the eastern margin of the Olympic domain, in association with a poorly studied terrane boundary located at or near the Torrens Hinge Zone under thick Neoproterozoic sediment cover of the Stuart Shelf.

Much of the Olympic Province has a doubly divergent structural geometry with inward dipping fault margins. In the northern half of the province there is a high frequency of northwest-trending faults that transgress and displace older north-trending faults extending northward from the Kalinjala Shear Zone and Pine Point Fault Zone (Figs. 1, 4 and 8). These faults show apparent reverse offsets in seismic reflection data (Drummond *et al.*, 2006). Although the geometry and interpreted kinematics of the northwest-trending fault set may be attributed to strong northeast-southwest compressive strain along the northeast margin of the craton, this deformation event is not well documented. These faults have experienced a long history of reactivation, including possible extension during emplacement of the 825 Ma Gairdner Dyke Swarm, and inversion during the 515 to 485 Ma Delamerian orogeny (Preiss, 2000). They likely originated during the Kimban orogeny between 1730 and 1690 Ma, possibly in response to collision between the Curnamona and Gawler cratons, although the timing of Curnamona docking also remains poorly constrained. Evidence for a comparatively early (Palaeoproterozoic) timing of northeast-southwest compression is recorded in the reactivation of the northnortheast-trending Kalinjala Shear Zone as a major dextral transpressional wrench during the Kimban Orogeny. Furthermore, from our aeromagnetic structural geology interpretations, we interpret that fault reactivation in the central Gawler craton involved dextral strike-slip along major north-trending faults, such as the Yarlbrinda Shear Zone, and conjugate sinistral strike-slip along major east-trending faults, such as the Yerda and Oolabinna Shear Zones, prior to overprinting by regional northeast-trending faults (Fig. 4).

Betts and Giles (2006) linked the Kimban Orogeny to collision between the Gawler craton and North Australia craton and argued that the Gawler craton was subsequently detached and rotated 52° clockwise during the Neoproterozoic (~1100 Ma) collision between the South Australia and West Australia cratons. This interpretation remains controversial, followed by some recent authors (e.g., Payne *et al.*, 2009) but questioned by others (e.g., Fraser and Lyons, 2006). It is beyond the scope of this paper to discuss this model further and all relative convergence directions listed are given in present day, rather than pre-rotation coordinates.

Late Palaeoproterozoic to Early Mesoproterozoic

After the Kimban Orogeny, subduction and orogeny switched to the west and northwest margins of the Gawler craton and commenced with calc-alkaline I-type intrusions of the Tunkillia and St Peter Suites (1630 to 1610 Ma; Hand *et al.*, 2007). Swain *et al.* (2008) proposed that the St Peter Suite formed outboard of the Gawler craton on a microcontinent above a west-dipping subduction zone (specified as south dipping prior to rotation), which then accreted to the western Gawler craton during collision between East Antarctica and the Gawler craton. Betts *et al.* (2009) proposed that the St Peter Suite resulted from arc magmatism above a shallow ("flat") east-dipping subduction zone, that was terminated by ocean plateau collision between 1610 and 1595 Ma before slab rollback. Both of these models place subduction at the west (originally southwest) margin of the Gawler craton and consider the St Peter Suite in isolation from the Hiltaba Suite and other orogenic episodes. However, the St Peter Suite does not form a linear arc and there is no clear evidence for an associated arc-parallel orogenic zone along the west margin, which could be expected to have formed from highly compressive flat slab subduction (e.g., Andes), ocean plateau collision, or microcontinent collision. An alternative explanation is that the St Peter Suite is the first stage of a diachronous eastnortheast-trending corridor of continental I- and A-type magmatism that extends across the Gawler and Curnamona cratons. In this scenario, the magmatic succession began with the western 1620 to 1610 Ma St Peter Suite I-type plutons, followed by the central 1600 to 1575 Ma Hiltaba Suite I- and A-type plutons (with rare S-types), and in turn followed by the eastern 1580 to 1550 Ma Bimbowrie Suite I- and S-types in the Curnamona Province. Each of these continental I-/A-type intrusive suites is bimodal and shows evidence for mingling of mantle mafic melts with silicic crustal melts (Stewart, 1994; Skirrow, 2009; Swain *et al.*, 2008). In this scenario, magma chemistry varied according to lithospheric composition of the host terranes, heat flow (temperature and depth of crustal melting), and with the degree of involvement of metasomatised subcontinental lithospheric mantle (SCLM), which was highest in the west margin. Involvement of metasomatised SCLM in the melt source does not require contemporaneous subduction, as it could have been derived from a much older subduction event, but this may be the simplest explanation. A-type intrusions mostly occur in the east central part of the craton where the highest temperature crustal melting occurred (Creaser and White, 1991; Budd, 2006).

These intrusive suites comprise a broad eastnortheast-trending magmatic belt which could be related to the distal subduction and terrane accretion events associated with amalgamation of the South Australia and North Australia

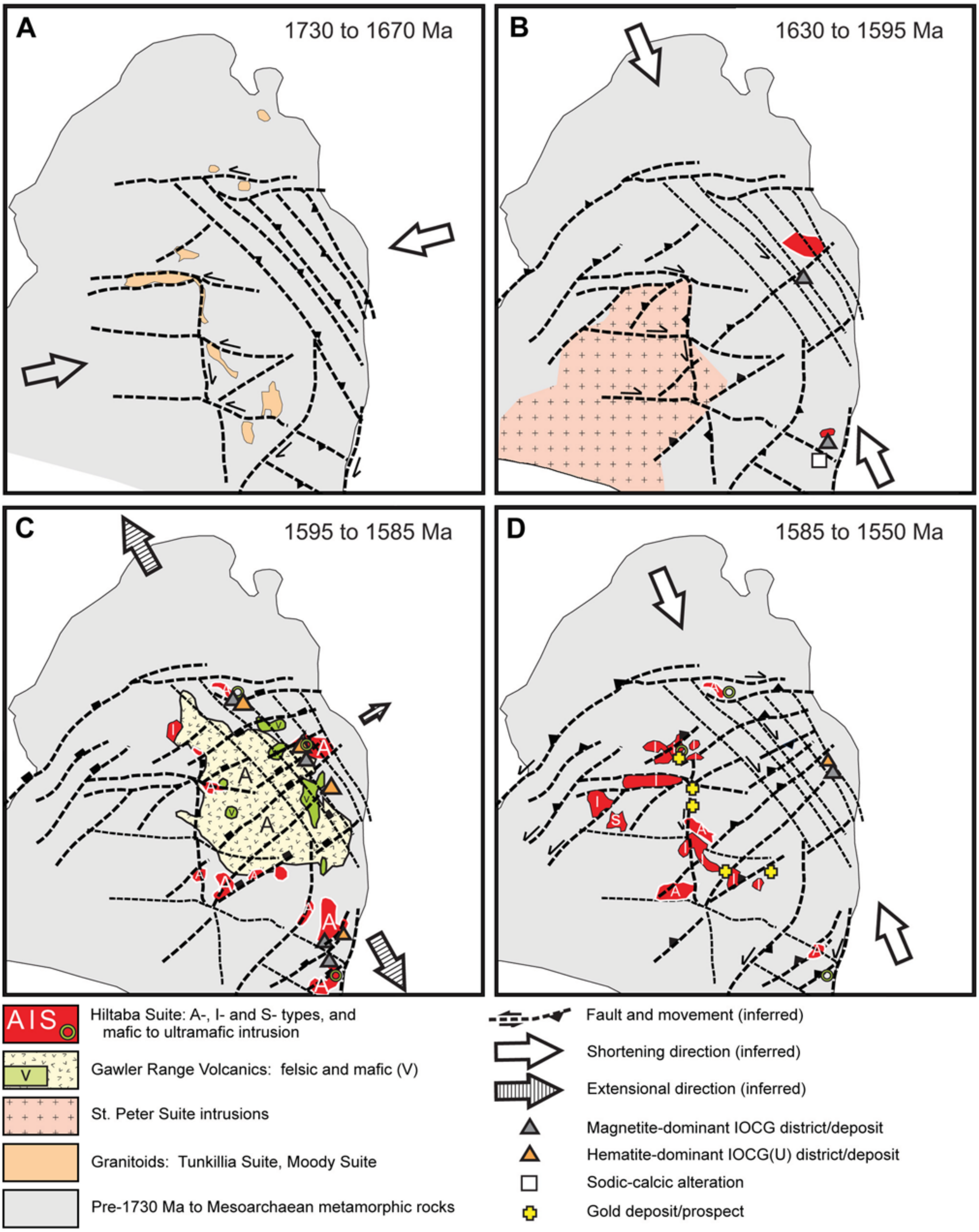


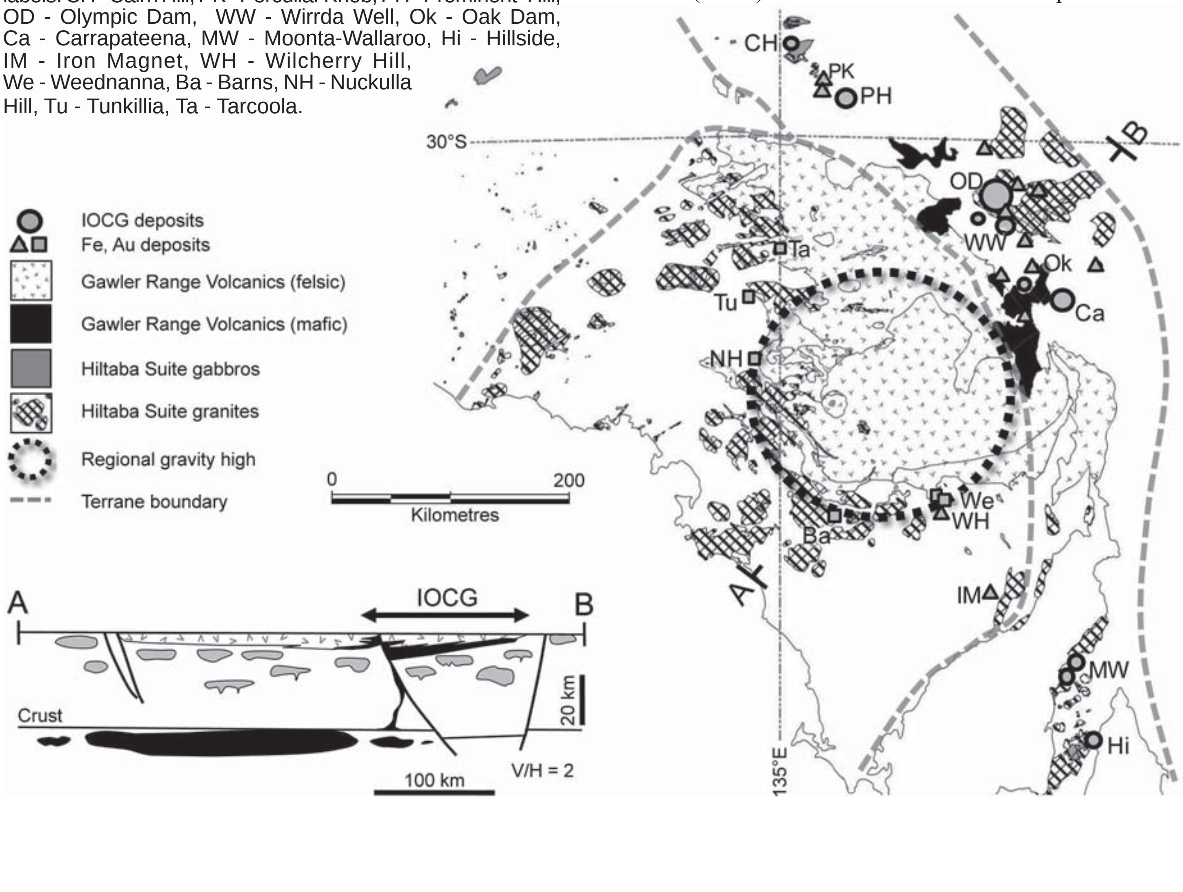
Figure 4: Interpreted time-slice geodynamic maps for evolution of the Gawler craton. **(A)** Kimban orogeny, ca. 1730-1670 Ma. **(B)** St Peters Suite age, initial Hiltaba Suite and earliest IOCG ca 1630-1595 Ma. **(C)** Hiltaba Suite + Gawler Range Volcanics + IOCG ca 1595-1585 Ma. **(D)** Late Hiltaba Suite and Kararan orogeny age ca. 1585-1550 Ma. Modified from Skirrow (2009).

cratons between 1690 and 1550 Ma (Fig. 3). In Central Australia, collision events along east-west- to eastnortheast-trending suture zones resulted in the Liebig Orogeny (1640 to 1630 Ma; Scrimgeour, 2006), the Chewings (1590 to 1560; Scrimgeour, 2006) and Musgrave Orogenies (ca. 1555 Ma, 1220-1160 Ma; Wade *et al.*, 2006), all 300 to 600 km further north of the magmatic belt. The Warumpi and Musgrave orogenies were each preceded by subduction and calc-alkaline arc magmatism. Furthermore, Geoscience Australia regional aeromagnetic data show a linear belt of subcircular magnetic features that can be interpreted as evidence of a possible buried magmatic arc along the southern margin of the Coompana Block: this is a key piece of the puzzle but it has not been studied in detail because of the deep Neoproterozoic to Phanerozoic sediment cover. Closer still, the northern margin of the Gawler craton shows northeast- to east-trending, generally northwest-dipping, high strain deformation zones that thrust over rocks with metamorphic peak assemblages recorded for the Ooldean event (1660 to 1630 Ma) and Kararan Orogeny (1570 to 1540 Ma; Fraser and Lyons, 2006; Hand *et al.*, 2007), followed by retrograde fault reactivation during the Coorabie Orogeny (1470 to 1450 Ma; Fraser and Lyons, 2006). The Curnamona craton similarly records northwest-southeast compression associated with the Olarian Orogeny during the interval ~1620 to ~1590 Ma (Preiss, 2006). The subduction zone along the southern margin of the North Australia craton associated with the Warumpi orogeny was south dipping (Scrimgeour, 2006, Selway *et al.*, 2009), whereas subduction zones along the northern margin of the Gawler craton were north-dipping. Collectively, these events indicate that the leading edge of the South Australia craton, which includes the Gawler and Curnamona cratons, experienced a protracted but somewhat episodic history of northwest/southeast- to north-south-directed compressive strain between 1660 and 1450 Ma (Fig. 4), spanning the diachronous emplacement of I-/A-type continental magmatism. Hand *et al.* (2007, 2008) interpreted that the Hiltaba and Gawler Range magmatic suites formed in a distal backarc to foreland setting, but this interpretation may be inconsistent with a lower plate position if a younger northwest-dipping suture(s) exists under cover between the Coompana and Nawa-Nullarbor cratons (Fig. 3).

The Gawler Range Volcanics are recognised as one of the world's largest felsic volcanic systems at >25 000 km^2, >1 km thick, emplaced in just 1 to 3 million years (1593±2 Ma, e.g., Allen *et al.*, 2008). The intensity of the Hiltaba and Gawler Range Volcanics magmatic event may be linked to mafic underplating of the crust with concomitant high temperature metamorphism and extensive lower crustal anatexis. There is little evidence for a mafic underplate in seismic reflection traverses in the Olympic Dam area (Direen and Lyons, 2007), but west of the Elizabeth Creek Fault Zone, Huynh *et al.* (2001) modelled from Bouguer gravity data the presence of a ~5 km thick, high density (~3.0 g/cm^3) mafic sheet at the base of the crust beneath the Gawler Range Volcanics (Fig. 5). This sheet is interpreted to be the product of decompression melting of ascending mantle that drove the most intense part of the 1600 to 1575 Ma crustal anatexis event.

Interpretations of the geodynamic driver for this mantle melting event are divided between two end-member models: (a) hot-spot plume impact (e.g., Creaser, 1996; Betts *et al.*, 2007, 2009) and (b) lithospheric detachment (Skirrow, 2009). Chemical data available for basalts in the central Gawler craton do not differentiate between these two models as they show evidence of significant crustal contamination. For example, the Roopena Volcanics display εNd_{1592} values between -5.67 and +2.50 (Fricke, 2005). The hot-spot plume model was proposed by Betts *et al.* (2009) to have evolved from a plume-modified

Figure 5: Simplified basement map of the Gawler craton showing terrane boundaries, Hiltaba Suite, Gawler Range Volcanics, interpreted mafic underplate and IOCG and related deposits. Schematic cross-section A-B shows the upper lithosphere with interpreted basin geometry in the Olympic IOCG Province and mafic underplate and mafic igneous rocks (black). Deposit labels: CH - Cairn Hill, PK - Perculiar Knob, PH - Prominent Hill, OD - Olympic Dam, WW - Wirrda Well, Ok - Oak Dam, Ca - Carrapateena, MW - Moonta-Wallaroo, Hi - Hillside, IM - Iron Magnet, WH - Wilcherry Hill, We - Weednanna, Ba - Barns, NH - Nuckulla Hill, Tu - Tunkillia, Ta - Tarcoola.



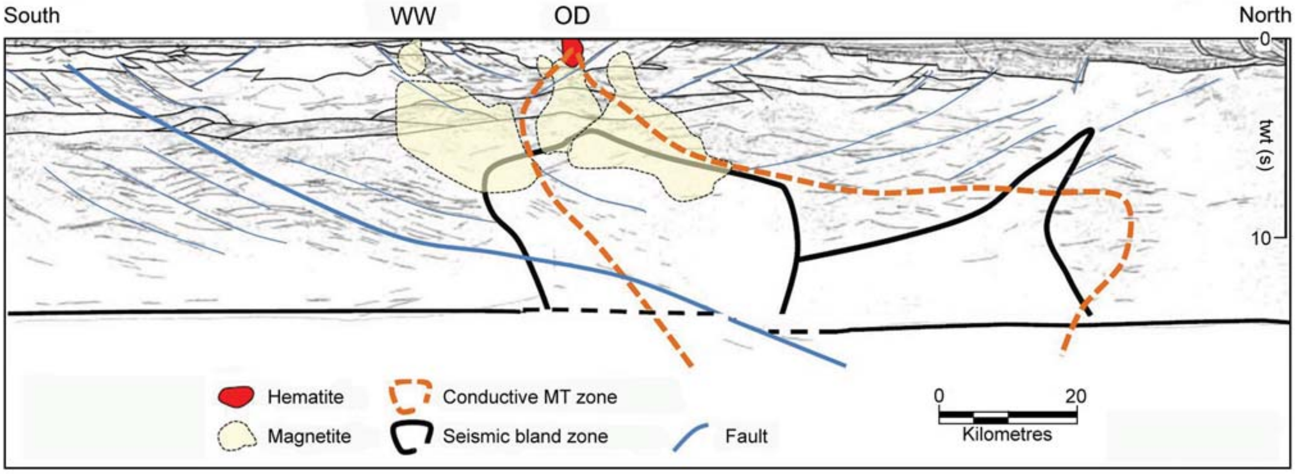


Figure 6: Interpreted north-south seismic line, 03GA-OD1 (modified after Lyons and Goleby, 2005, and Drummond *et al.*, 2006), showing seismic transparent zone, the low resistivity (conductive) zone from a regional magnetotelluric (MT) transect (Heinson *et al.*, 2006), and sections through inversion isosurfaces of inferred magnetite distribution from magnetic susceptibility (WMC unpublished data). OD = Olympic Dam, WW = Wirrda Well, Twt = two way travel time in seconds.

subduction setting, associated with the 1620 to 1610 Ma St Peter Suite (continental arc), into a continental hot spot trail across the Mesoproterozoic terranes of eastern Australia. The plume model is consistent with the subcircular extent of the Gawler Range Volcanics and their extraordinary high flux rate. Skirrow (2009) argued that the plume model does not readily explain the temporal and spatial association of magmatism with orogenesis unless this was coincidental. Additionally, the proposed plume impact area may have been smaller (~500 km diameter) than typical plumes (~1000 km) and did not lead to extrusion of extensive continental flood basalts, nor radial dyke swarms. This difference may be explained either by impact coincidentally within a highly compressional setting and/or beneath an unusually thick cratonic nucleus, where decompression melting at higher pressures yielded comparatively smaller mafic melt volumes. For the plume model to be valid in this case, mafic melt products would generally not have ascended to mid- or upper-crustal levels but ponded at the base of the crust, where they drove extensive crustal anatexis and mixed with silicic crustal melts (Stewart, 1994). East of the Elizabeth Creek Fault Zone, any mafic underplate melt may have been evacuated to form the basaltic volcanism of the Roopena Volcanics and equivalents to the north, which are up to several hundred metres thick in the Olympic IOCG Province (Fig. 5).

The lithospheric detachment model requires shallow asthenospheric upwelling following removal of a gravitationally metastable thickened SCLM root zone originating from a previous orogeny or orogenies (e.g., Houseman *et al.*, 1981; Kay and Kay, 1993; Schott and Schmeling, 1998; Houseman and Molnar, 2001). This model is commonly proposed for post-collisional A-type magmatic provinces and involves far-field collisional triggers to destabilise dense, depleted, overthickened lithosphere. Similar geological consequences may result from slab break-off following continental collision (e.g., Davies and von Blanckenburg, 1995). The lithospheric detachment model could account for the chemistry and timing of magmatism in relation to extension and compression as well as the rapid exhumation of parts of the Olympic IOCG Province (Skirrow, 2009). A possible problem with this scenario is that Hiltaba Suite plutons and Gawler Range Volcanics extend not only over Proterozoic crust, but also over a broad portion of the Archaean craton nucleus, where it is difficult to envisage detachment of a buoyant and thick SCLM root that is typical of Archaean lithosphere. Removal of Proterozoic SCLM to the east of

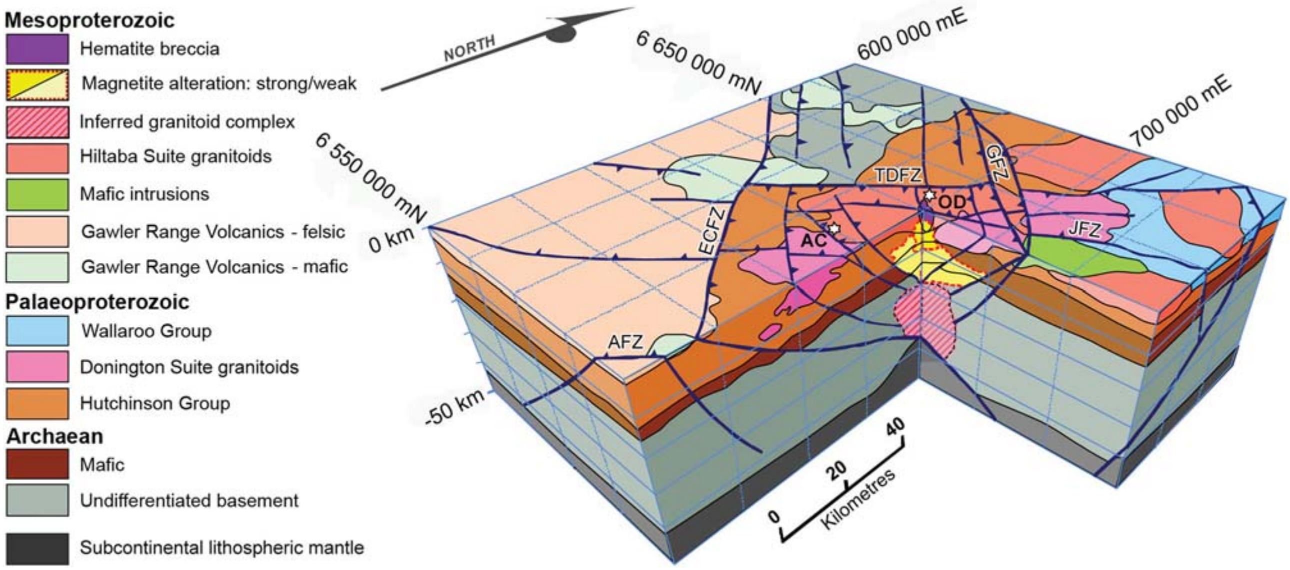


Figure 7: 3D perspective interpreted geology block model of the Olympic Dam district, viewed to the northwest, modified after Hayward (2007). Deposits: OD – Olympic Dam, AC – Acropolis. Wirrda Well is in the cut-out section. Fault Zones: ECFZ – Elizabeth Creek, AFZ – Andamooka, TDFZ – Todd Dam, GFZ – Gregory, JFZ – Jubilee.

the Archaean nucleus, overthickened possibly during the Cornian and/or Kimban orogenies (Skirrow, 2009), may explain the locus of mafic magmatism along the western margin of the Olympic IOCG Province, noted above, but does not readily account for extensive crustal melting within the Archaean nucleus.

The Olympic Dam Breccia Complex and most, if not all, of the associated hydrothermal iron, copper, uranium and gold mineralisation is generally interpreted to have formed at ~1590 Ma, approximately coincident with emplacement of the Gawler Range Volcanics (see above). Timing evidence is discussed further below. It is significant however, that the metallogenic province developed in only a small portions of the broader magmatic province, specifically along the east margin of the Gawler Craton. This spatial restriction attests to the local presence of fertile lithospheric source rocks and hydrothermal brines within the Olympic IOCG Province. The strongest lithological association for IOCG mineralisation in the region is with a combination of oxidised A-type Hiltaba Suite plutons and mafic Gawler Range Volcanics (e.g., Roopena Volcanics and equivalents; Fig. 5). The Gawler Range Volcanics were previously interpreted to have been emplaced during an episode of extension (Flint *et al.*, 1993; Creaser, 1995). However, Hand *et al.* (2007, 2008) and Direen and Lyons (2007) recently argued that northwest-southeast compression continued during emplacement of the Hiltaba Suite and Gawler Range Volcanics. Hand *et al.*(2008) further proposed this magmatism occurred in an orogenic foreland setting. Hand *et al.* (2007) reported dating evidence for widespread metamorphic recrystallisation and dip-slip movement along major east- to northeast-trending shear zones, which could be either compressional or extensional, although the Gawler Range Volcanics were not affected. It remains possible that that while far-field weak compression prevailed, there were intermittent periods of northwest-southeast extension, particularly in the interval around 1595±5 Ma when the Gawler Range Volcanics were emplaced and many of the IOCG deposits including Olympic Dam were formed (Fig. 4). As discussed in the next section, the economically significant IOCG deposits are interpreted here and by Skirrow (2009) to have formed during a brief extensional deformation event.

3D Crustal-scale Architecture of the Super Giant Olympic Dam Ore System

Olympic Dam is one of the best examples in the world where the architecture of a supergiant ore system can be mapped at the scale of the whole crust. Two near-orthogonal deep seismic reflection traverses (NS 03GA-OD1 and EW 03GA-OD2) were conducted by Geoscience Australia in 2003 with the intersection located a short distance east of Olympic Dam (Lyons and Goleby, 2005). A long-period magnetotelluric survey was also collected along the north-south seismic traverse by The University of Adelaide (Heinson *et al.*, 2006). The seismic data show that the Olympic Dam deposit is situated directly above the position where the Elizabeth Creek Fault Zone apparently offsets the base of crust with normal displacement of up to 5 km, creating the shallowest position of the SCLM observed on the seismic sections (Fig. 6).

In the lower crust above the Moho offset, there is a large (>40 km wide), elliptical zone of reduced or transparent seismic reflectivity (Fig. 6). From correlation between the two seismic sections, the seismically transparent zone appears to strike northeast, although there are no constraints on its length beyond the seismic traverses. There is no long wavelength gravity high associated with this feature and no reason to interpret it as a mafic magma chamber (Direen and Lyons, 2007). The body of seismic transparency may relate to a zone of migmatites and altered felsic batholiths derived from unusually intense crustal anatexis. The age of this magmatism is unconstrained. On the basis of its interpreted northeast trend, which parallels the shape of the overlying Burgoyne Batholith, and spatial correlation with large scale magnetite alteration patterns, we assume that it is associated with the Hiltaba Suite. Two-dimensional inversions of the regional magnetotelluric data show that an anomalous zone of low-resistivity (<100 Ω·m) coincides with this zone of seismic transparency and extends upward from the mid-crust towards the Olympic Dam deposit (Heinson *et al.*, 2006). The low resistivity zone was interpreted to arise from upward movement of CO_2-rich mantle-derived fluids and precipitation of conductive graphite upon reduction along grain boundaries (Heinson *et al.*, 2006). However, magnetite may also be conductive if coarse grained and well connected in seams (Hart and Freeman, 2003), and is interpreted to be present within at least the upper portions of the conductive zone (Fig. 6). Similar seismically transparent zones with roughly elliptical shapes have been identified beneath some giant orogenic gold deposits in the Yilgarn craton, such as the Golden Mile and St Ives deposits (Goleby *et al.*, 2006), where they are also interpreted as the signature of mid-crustal felsic batholiths and texturally-destructive CO_2-rich alteration.

Olympic Dam occurs near the intersection of regional northwest- and eastnortheast-trending fault zones. Seismic data show that proximal northwest-trending regional faults predominantly dip eastward to the west of the deposit and predominantly dip westward to the east (Figs. 6 and 7). A second-order northwest-trending fault associated with Olympic Dam can be effectively delineated in high resolution magnetic and gravity data but is not imaged well in the seismic sections, possibly because of its subvertical dip and perhaps also because of attendant alteration. Furthermore, it is not evident in large scale horizontal gradient ("worming") analyses of regional gravity and magnetic data. Mafic dykes are commonly localised along these northwest-trending faults, especially west of the ECFZ where they mostly relate to the 827 Ma Gairdner Dyke Swarm (Wingate *et al.*, 1998). At Olympic Dam, many of the subvertical northwest-trending mafic dykes have an interpreted syn-mineralisation timing and are commonly extensively replaced by hematite or altered to chlorite and sericite (Reeve *et al.*, 1990; Chambefort *et al.*, 2009).

In the upper crust, the Olympic Dam, Wirrda Well and Acropolis IOCG deposits occur within an eastnortheast-trending fault-bound block that partially cuts second-order northnorthwest-trending faults (Fig. 7), and is characterised by broad magnetic anomalism, indicative of widespread magnetite alteration. There is also a cluster of eastnortheast- to northeast-elongated Hiltaba Suite plutons, e.g., the Burgoyne Batholith and Roxby Downs Granite. The Burgoyne Batholith has a lopolith geometry with a base at around 5 km depth above interpreted Hutchison Group metasediments (Lyons and Goleby, 2005). The fault-bound block has a rectilinear geometry bounded by moderately inward-dipping faults, including the Todd Dams Fault, Gregory Fault and Andamooka Fault (Figs. 7, 8), which we interpret to be the expression of an inverted eastnortheast-trending graben that was filled with thick volcaniclastic sediments, remnants of which are preserved at the top of the Olympic Dam Breccia Complex. Eastnortheast-trending faults near the centre of this block have steep to subvertical dips. Olympic Dam is centred on the Jubilee Fault (also Mashers Fault in Olympic Dam Operations terminology), a subvertical eastnortheast-trending structure that cuts across all major northwest-trending faults in the area due to significant post-mineralisation reactivation. The intersection of the major northwest and eastnortheast faults at Olympic Dam thus define a subvertical crustal fault conduit that may have linked with the ECFZ at the base of crust. This structural shortcut pathway to the mantle could have controlled the emplacement of the relatively anomalous volumes of ultramafic and mafic dykes in the deposit.

The Olympic Dam deposit appears to have been located in an area of significant local exhumation, likely related to pop-up inversion of the bounding eastnortheast-trending faults. The host Roxby Downs granite is a massive megacrystic pluton which was likely emplaced at depths of greater than ~4 km at around 1596 Ma (Creaser, 1996). Remarkably, this pluton was subsequently overprinted by dyke complexes and the Olympic Dam Breccia Complex at near surface depths between 1596 to 1592 Ma (Jagodzinski, 2005), since the breccia complex appears to have vented to surface and contains collapse breccia clasts and blocks of volcaniclastic sediments (1594.5±3.3 Ma), and lower Gawler Range Volcanics (1592±3 Ma) within the Roxby Downs Granite (Fanning *et al.*, 1988). Dates from hydrothermal zircons are indistinguishable from those of magmatic zircons, indicating that hydrothermal alteration

Figure 8: (A) Basement structural geology interpretation for the Olympic IOCG Province with IOCG, gold and iron deposits and prospects. Insets show deposit-scale basement structural geology interpretations for Prominent Hill **(B)**, Olympic Dam **(C)**, Wirrda Well **(D)** and Carrapateena **(E)** based on aeromagnetic and gravity imagery. Prominent Hill geology modified after Belperio *et al.* (2007). Olympic Dam geology modified after Widdup *et al.* (2004). Unpatterned areas in insets represent older (pre-Hiltaba) rock units. Deposit labels as per Fig. 5. Fault labels as per Fig. 1, including BFZ – Bulgunnia Fault and FFZ – Fitzgerald Fault.

immediately followed magma emplacement and cooling (Jagodzinski, 2005). Subsequent exhumation was very minor, permitting preservation of much of the Olympic Dam deposit.

Three dimensional joint inversion modelling of regional magnetic and density data by WMC Limited (unpublished data; Hayward, 2007) and Geoscience Australia (Williams *et al.*, 2004; Howe, 2009) show that magnetite alteration extends deep beneath the Burgoyne Batholith under Olympic Dam, possibly down to the top of the postulated lower crustal felsic batholith zone at around 15 km below surface (Fig. 6). Given the limitations of inversion modelling at these depths, 15 km is considered a maximum depth. The deep alteration likely comprises a sodic-calcic alteration assemblage with low to moderate magnetite abundances (ca. 2 to 20%), similar to that exposed on Yorke Peninsula in the southern part of the Olympic IOCG Province (Conor, 2003; Conor *et al.*, this volume). The inversion models show a number of shallow apophyses or chimneys of increasing magnetic susceptibility and density extending upward beneath each of the main deposits in the fault-bound block (Fig. 6). The zone beneath Olympic Dam coincides with the upward extension of the low resistivity zone observed in the magnetotelluric data (Heinson *et al.*, 2006). The geophysical signature may be attributed to upward increasing abundance of hydrothermal iron oxides within the Olympic Dam alteration system, passing from magnetite- to hematite-dominant within the host Roxby Downs Granite at around 3 to 4 km below surface, although no comparable low resistivity zone was mapped below the much smaller Wirrda Well IOCG deposit. Hematite-rich breccias at the top of this alteration system are defined by coincident geophysical anomalies corresponding to high density and low magnetic susceptibility. Based on joint inversion of the potential field data by WMC Resources, it was suggested that the hematite-rich breccias may extend to deeper levels than drilled, possibly as much as 4000 m below surface (Hayward, 2007). To date, the hematite breccias have been drilled to 1900 m below surface (RD 1988) with open-ended copper-gold-uranium mineralisation.

District- to Deposit-scale Structural Controls on Ore Location

All significant IOCG deposits discovered to date in the Olympic IOCG Province occur within 40 to 50 km-wide structural corridors that parallel two regional north- to northwest-trending, domain boundary faults (Figs. 1 and 8). In the northern part of the province, IOCG deposits occur along second-order northwest-trending faults in the hangingwall of the first-order, northeast-dipping ECFZ. In the southern part of the province, they occur within and west of the first-order west-dipping Pine Point Fault Zone (PPFZ). Second-order northnorthwest-trending faults occur with high frequency in the northern half of the province where they can be traced in high resolution aeromagnetic data over strike extents of 100 to 200 km and are commonly spaced 10 to 20 km apart. From our aeromagnetic data interpretations (Fig. 8), the Carrapateena, Oak Dam and Wirrda Well IOCG deposits appear to be associated with one particular northnorthwest fault. The Acropolis and Emmie Bluff IOCG prospects appear to follow another northnorthwest fault located approximately 15 km further to the west, whereas Olympic Dam is located along yet another northnorthwest fault located 15 km to the east. The latter fault may be traced northward to possibly join up with the Fitzgerald Shear Zone adjacent to Prominent Hill. In contrast, the regional eastnortheast- to northeast-trending faults are more widely spaced and can be traced over 200 to >500 km strike extent. All significant IOCG deposits in the Olympic IOCG province show a strong spatial correlation with second-order northeast- to eastnortheast-trending faults, many of which are interpreted to dip moderately to steeply northnorthwest. In many cases, both magnetic anomalies that relate to magnetite-rich alteration and Hiltaba-age plutons are elongated in an eastnortheast direction and distributed along these eastnortheast-trending structural corridors (Figs. 7 and 8). The intersection zones between the regional northwest- and eastnortheast-trending faults are interpreted to have provided steeply-plunging, high-permeability, crustal-scale fluid conduits. The largest IOCG deposits comprise steeply plunging breccia zones located at or adjacent to these fault intersections. In detail however, the deposits may be located along subsidiary faults oriented (sub)parallel and proximal (< 10 km) to the major fault intersections.

The ***Olympic Dam Breccia Complex*** (ODBC) comprises a cluster of upward flaring and coalescing breccia pipes with tabular root zones and overall elongation in a westnorthwest direction. A dextral westnorthwest-trending wrench fault has historically been inferred as the primary syn-mineralisation structural control for breccia development (O'Driscoll, 1985; Reeve *et al.*, 1990; Drexel *et al.*, 1993), although a major westnorthwest-trending fault has not actually been mapped within or beyond the deposit. Mine-scale maps show that individual breccia lenses and fault-bound blocks of volcaniclastic sediments display a rectilinear geometry influenced by two dominant fault sets with northwest and eastnortheast trends (Fig. 8C), similar to the regional fault pattern. Northwest-trending faults are mostly subvertical whereas the eastnortheast-trending faults generally dip steeply northnorthwest. The northern half of the ODBC comprises steeply dipping northnorthwest- and northwest-trending breccia lenses, whereas the southern and northern ends of the ODBC include near orthogonal eastnortheast-trending breccia lenses. The southern boundary of the barren hematite breccia core is relatively planar and may have been influenced by a pre-mineralisation northeast-trending fault, subsequently obliterated by the brecciation process (Fig. 8). Pre- to early syn-mineralisation mafic and felsic dykes mostly strike northwest, parallel to the dominant breccia trend, suggesting that the extension direction during early stage development of the ODBC could have been oriented northeast-southwest, consistent with the interpretation of Hand *et al.* (2007). However, the presence of eastnortheast-trending breccia lenses and a major eastnortheast-trending downfaulted block of Gawler Range Volcanics and volcaniclastic sediments located near the southern end of the ODBC, suggest that eastnortheast-trending faults were also extensional during at least the later stages of development of the ODBC. This syn-mineralisation extensional pattern can be interpreted in two ways. One possibility is that brecciation was initiated during early stage northwest-southeast shortening (with northeast-southwest extension) and continued during later northwest-southeast extension. Alternatively, extension was locally orthorhombic and resulted in dilation of pre-existing basement faults in diverse directions. We favour the second alternative because there is no evidence for significant timing differences in brecciation that can be related to the structural trends. Orthorhombic extension (cf. Miller *et al.*, 2007) may occur in the roof zone of

Table 1: Iron oxide Cu-Au±(U,Ag) deposits and prospects.

Name	Total Resource[1]	Status	Iron Oxide Style	Reference
Olympic Dam[2]	9231 Mt @ 0.86% Cu, 0.33 g/t Au, 0.27 kg/t U_3O_8, 1.5 g/t Ag	Underground production	Hematite breccias	BHP Billiton Ltd Annual Report 2009
Prominent Hill[3]	297.7 Mt @ 0.93% Cu, 0.78 g/t Au, 2.49 g/t Ag	Open pit production	Hematite breccias	Belperio *et al.* (2007) OZ Minerals ASX Resource Statement 23/12/2008
Wirrda Well	*Best intersection: 248 m @ 0.86% Cu, 4.6 g/t Ag (from 419 m in WRD9)*	Prospect delineation	Hematite breccias	WMC Limited unpublished memoranda (1985)
Carrapateena[4]	203 Mt @ 1.31% Cu, 0.56 g/t Au, 0.27 kg/t U, 6 g/t Ag	Resource delineation	Hematite breccias	OZ Minerals Explanatory Notes, April 2011
Oak Dam	(~300 Mt @ 0.2% Cu) *Best intersection: 5 m @ 7.1 kg/t U_3O_8 within 63 m @ 0.7 kg/t U_3O_8, 0.3% Cu (in AD1)*	Sub-economic prospect	Hematite breccias and mantos	Davidson *et al.* (2007)
Moonta-Wallaroo[5]	10.1 Mt @ 3.7% Cu, 0.42 g/t Au	Closed Mines	Magnetite-bearing veins	Conor (2003)
Hillside[6]	170 Mt @ 0.7% Cu, 0.2 g/t Au	Scoping Study	Magnetite-bearing veins	Rex Minerals Ltd., ASX release, December, 2010
Cairn Hill	11.4 Mt @ 0.37% Cu, 0.11 g/t Au	Open Pit development	Magnetite-rich breccias and stratabound replacement	IMX Resources Limited Annual Report 2007
Punt Hill	*Best intersection: 159 m @ 0.47% Cu, 5.3 g/t Ag, 0.12 g/t Au, 0.48% Zn, 0.12% Pb (from 846m, GHDD6)*	Prospect delineation	Hematite breccias and veins	Monax Mining Limited Annual Report 2008

Notes: 1 Total for Measured, Indicated and Inferred Resources, Reserves and Production, or best downhole drill intersection results. 2 Includes the gold-only resource. 3 Total for copper, gold and Western copper resources. 4 Inferred Resource (unclosed). 5 Combined production only. 6 Inferred Resource from partial drill-out.

ballooning mid to upper crustal batholiths and this process is consistent with the 3D architecture described above, where a large felsic batholith is interpreted to occur beneath the Olympic Dam district, and consistent with the unusually rapid exhumation of the Roxby Downs granite just prior to development of the ODBC.

Post-mineralisation movement at Olympic Dam reactivated the eastnortheast-trending faults and resulted in apparent sinistral offsets of the northwest-trending faults, breccias and dykes by 50 to 500 m in mine plans, resulting in the overall westnorthwest elongation direction of the ODBC (Fig. 8C). There was also a component of reverse movement along these eastnortheast-trending faults that elevated the narrow root of the northern half of the deposit relative to the broad southern half. The shallowest level of the deposit is preserved at the southern end of the ODBC which contains thick volcaniclastic sediment beds, extensive phreatomagmatic breccia complexes, and peripheral gold-sericite mineralisation. The timing of this inversion event is unconstrained, but we suggest that it may be correlated with northwest-southeast shortening of the 1570 to 1540 Ma Kararan Orogeny (Hand *et al.*, 2007). At the mine scale, much of the ODBC is overprinted by numerous small-scale planar to anastomosing brittle faults with narrow (<10 cm) cores of gouge, pseudotachylite, breccia, or local barite-flourite±carbonate vein infill (Widdup *et al.*, 2004). The dominant mine-scale fault pattern comprises northwest-trending reverse faults, conjugate northeast-trending dextral and east-trending sinistral strike-slip faults, plus subordinate westnorthwest-trending sinistral-reverse faults (Reeve *et al.*, 1990; Sudgen and Cross, 1991; Widdup *et al.*, 2004). The kinematics of these mine-scale structures are consistent with bulk eastnortheast-westsouthwest horizontal shortening related to the 520-490 Ma Delamerian Orogeny (Sugden and Cross, 1991).

The ***Prominent Hill*** deposit (Fig. 8B) is located close (<10 km) to the intersection of the regional eastnortheast-trending Bulgunnia Fault and the northwest-trending Fitzgerald Shear Zone (Belperio *et al.*, 2007). The deposit-scale structural pattern is dominated by moderately steep (50 to 80º) north-dipping reverse faults, which emplaced older Palaeoproterozoic metasediments over Gawler Range Volcanics, and emplaced a skarn-like magnetite assemblage over shallow-level hematite alteration. As with Olympic Dam, the shallowest level mineralisation and volcaniclastic sediments occur on the south side of the deposit. The southern bounding fault, which also dips steeply northward, juxtaposes stratigraphically higher fine-grained volcaniclastic rocks in the hangingwall against deeper level andesite volcanic rocks in the footwall and appears to retain gross normal displacement. These volcanic units are correlated with the lower Gawler Range Volcanics and interpreted by Belperio *et al.* (2007) to have been deposited within an eastnortheast-trending graben, bounded by active growth faults that are represented by some of the main east-trending structures at the deposit. Subvertical syn- to post-mineralisation andesite dykes also strike eastnortheast within the breccia complex (Belperio *et al.*, 2007), but their age has not been determined. An intrusive dacite porphyry in the hangingwall yielded a U-Pb zircon crystallisation age of 1585±8 Ma (Belperio *et al.*, 2007). These observations support an interpretation of early northnorthwest-southsoutheast extension during emplacement of the host volcaniclastic sequence, intermediate dykes, and hydrothermal hematite breccias between 1595 and 1585 Ma, followed by southsoutheast-directed inversion.

The ***Wirrda Well*** (Fig. 8D) and ***Cairn Hill*** (Betts *et al.*, 2003) deposits similarly comprise eastnortheast-trending hydrothermal breccias and iron oxide replacement systems developed along eastnortheast-trending faults located near intersection zones with second-order northwest-trending faults. At Cairn Hill, the associated eastnortheast-trending fault is parallel to stratigraphy and dips moderately steeply southsoutheast, whereas at Wirrda Well, the principal eastnortheast-trending fault dips steeply northnorthwest. Magnetite alteration at Wirrda Well occurs in an uplifted block along a northwest-trending fault north of the main mineralised zone, which is hematite-dominant. The ***Emmie Bluff*** and ***Oak Dam*** IOCG prospects are similarly located along an eastnortheast-trending fault zone at intersections with second-order northwest-trending faults (Fig. 8A). ***Carrapateena*** is associated with a subcircular gravity anomaly located adjacent to the intersection of an eastnortheast- and a prominent northwest-striking fault zone evident in aeromagnetic data (Fig. 8E; Fairclough, 2005). The ***Moonta-Wallaroo-Alford*** IOCG district is similarly elongate in a northeast-direction, although the structural control is more subtle. Vein deposits at Moonta follow northeast-striking, moderate to steep northwest-dipping arcuate faults (Ruano *et al.*, 2002). The Wallaroo deposit occurs along the same strike trend but comprises vein sets with more variable strike, commonly trending westnorthwest and northnortheast. The ***Hillside*** prospect (Fig. 8A) is located at the intersection of a major northeast-trending fault with the PPFZ.

From these deposit scale observations, we conclude that the primary structural control on IOCG deposit location was proximity to the steeply-plunging intersection zones of regional eastnortheast- and second-order northwest- to northnorthwest-trending faults. At this stage there are no direct observations of kinematic indicators recorded along northwest- and eastnortheast-trending faults that can be directly linked to the ore forming event. Nevertheless, we interpret the IOCG mineralisation to have mostly formed during the late stages of a short lived episode of northnorthwest-southsoutheast extensional strain that coincided with eruption of the Gawler Range Volcanics (ca. 1595 to 1590 Ma) and the development of eastnortheast-trending grabens, including those near the Prominent Hill and Olympic Dam deposits, but was preceded and closely followed by more protracted northwest-southeast to northnorthwest-southsoutheast contraction during the broader episode of Hiltaba Suite pluton emplacement (ca. 1600 to 1575 Ma; Hand *et al.*, 2007). This interpretation does not preclude a role for syn-mineralisation strike-slip deformation along northwest-trending faults as previously suggested (e.g., Reeve *et al.*, 1990; Drexel *et al.*, 1993), but requires it to have been sinistral-transtensional rather than dextral-transpressional.

Iron Oxide Copper-Gold Mineralisation and Alteration

Distribution, Resources and Key Deposits

The distribution of IOCG (copper-gold±silver±uranium) deposits and prospects in the Olympic IOCG Province are shown in Figs. 1 and 8A and resource data are summarised in Table 1. Olympic Dam currently represents the world's fourth largest copper, fifth largest gold and by far the largest uranium resource, all contained within a single deposit covering an area of <25 km² (BHP Billiton Annual Report 2009). The current underground operation produces around 195 000 tonnes per annum (tpa) of Cu cathode, 4 500 tpa U_3O_8, 3.1 tpa (0.1 Moz) Au and 29.5 tpa (0.95 Moz) Ag. A feasibility study is presently underway for a major mine expansion to increase the annual production rates of the operation six-fold, from 12 to 72 Mtpa, yielding around 2.40 Mtpa Cu concentrate containing 750 000 t of Cu, 19 000 tpa U_3O_8, 25 tpa (0.8 Moz) Au and 90 tpa (2.9 Moz) Ag (BHP Billiton Limited Olympic Dam Expansion Draft Environmental Impact Statement 2009). The expansion would require development of one of the largest open pit mines of its kind in the world. The only other currently producing IOCG mine in the Province is the Prominent Hill open pit, which commenced operations in 2009, although historical copper production also came from several small open pits and underground mines in the Moonta-Wallaroo IOCG district on the Yorke Peninsula (Fig. 1). Cairn Hill in the Mt Woods Inlier (Figs. 1 and 8) is in the early stages of pit development, and will be mined for iron with by-product copper. Carrapateena and Wirrda Well (Figs. 1 and 8) are significant deposits buried under relatively deep cover (>450m), for which resource statements have not yet been published.

IOCG deposit styles and mineralogy vary systematically along the Olympic IOCG Province (Skirrow *et al.*, 2002). Deposits in the central-northern part of the Province (Prominent Hill, Olympic Dam, Carrapateena) mostly comprise hematite-rich breccias with disseminated hypogene chalcopyrite-bornite±chalcocite mineralisation formed at shallow crustal levels. Deposits in the southern one-third of the Province (Moonta-Wallaroo, Hillside) and far north (Mt Woods Inlier) mostly comprise magnetite-bearing alteration systems with hypogene chalcopyrite mineralisation that is interpreted to have formed at deeper crustal levels (Skirrow *et al.*, 2002; Skirrow, 2009). These variations are considered to reflect different levels of post-mineralisation exhumation and syn-mineralisation fluid redox conditions. In detail, hematite-rich alteration overprints earlier magnetite-rich assemblages (see below), with both magnetite- and hematite-rich deposit styles occurring in close proximity within some districts. Furthermore, the range of secondary elements (gold, silver, uranium, REE) is highly variable between deposits and shows little district scale zonation, with the possible exception of uranium which appears most enriched in IOCG systems in the central part of the Province (Olympic Dam, Oak Dam).

The ***Olympic Dam*** deposit is hosted by the Olympic Dam Breccia Complex (ODBC) within the Roxby Downs granite, a member of the Hiltaba Suite. Aspects of the geology of the ODBC are summarised on Fig. 8C and are described in detail elsewhere (Reeve *et al.*, 1990; Oreskes and Einaudi, 1992; Cross *et al.*, 1993; Haynes *et al.*, 1995; Reynolds, 2000). In brief, the zoned funnel-shaped ODBC comprises multi-phase heterolithic breccias ranging from granite- to hematite-rich. The core zone of hematite-quartz breccias lacks major copper mineralisation but has elevated concentrations of REE, barium and locally uranium. The core zone also contains ultramafic to felsic igneous dykes and diffuse zones of fragmented intrusive rocks interpreted as phreatomagmatic diatreme breccias (Reeve *et al.*, 1990; Cross *et al.*, 1993). Large blocks of altered volcaniclastic rocks are present within the inferred maar craters. The margins of the core zone contain native gold and copper mineralisation with low temperature illite and local silicification, and grade outwards and downwards into hematite-granite breccias hosting the bulk of the copper-uranium-gold mineralisation. The distribution of individual hematitic breccia bodies partly controls copper grades. However, grades are also controlled by an

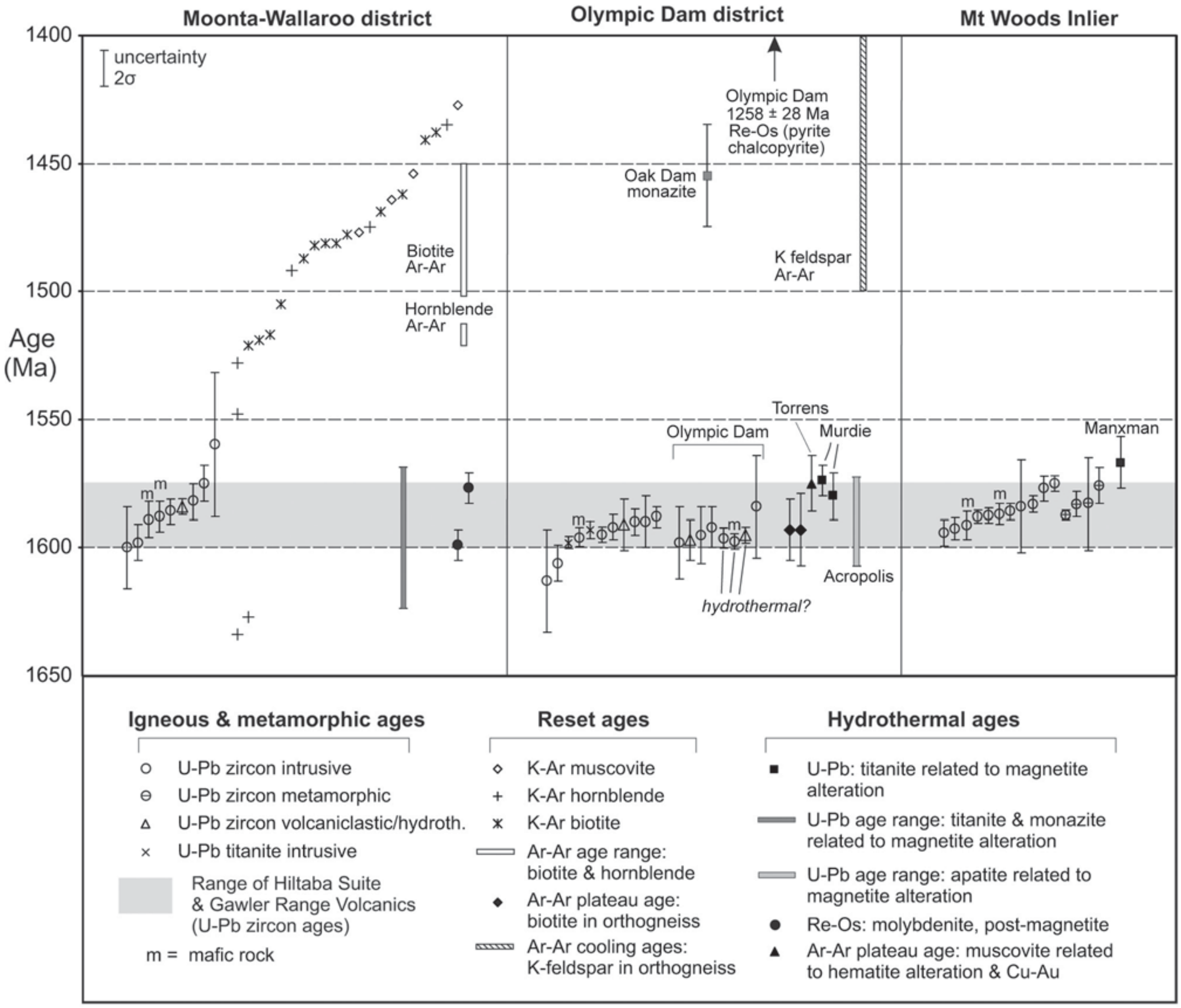


Figure 9: Time-space diagram of the Olympic IOCG Province for the late Palaeoproterozoic to Mesoproterozoic, subdivided by IOCG district (modified from Skirrow *et al.*, 2007). Most U-Pb ages are from ion probe analysis. Interpreted reset ages include K-Ar and ^{40}Ar-^{39}Ar ages for biotite, hornblende and K feldspar. Sources of published data are: Creaser and Cooper (1993), Webb *et al.* (1986), Mortimer *et al.* (1988), Johnson (1993), Fanning in Conor (1995), Johnson and Cross (1995), Daly *et al.* (1998), Raymond *et al.* (2002), Jagodzinski (2005), Holm (2005), Zang *et al.* (2007), Davidson *et al.* (2007), Skirrow *et al.* (2007, filled black symbols), McInnes *et al.* (2008), Raymond *et al.* (this volume), and G. Fraser and R. Skirrow (unpublished data, K-feldspar ^{40}Ar-^{39}Ar cooling ages).

important deposit-wide sharp interface between bornite and chalcopyrite that is broadly funnel shaped and in detail highly convoluted. Bornite-chalcocite mineralisation above the interface commonly attains grades of 4 to 6% Cu, whereas chalcopyrite mineralisation below the interface rarely exceeds 3% Cu (Reeve *et al.*, 1990). The deeper and peripheral zones of the ODBC contain greater proportions of magnetite and chlorite relative to hematite and sericite, and siderite is locally abundant. Uranium mineralisation is present throughout the hematite-rich breccias, broadly in association with copper, although higher grade zones occur at the upper margin of the bornite-chalcocite zone. Uraninite (as pitchblende) is the dominant uranium mineral, whereas minor coffinite and brannerite occur in upper/shallower and deeper/peripheral zones, respectively (Reynolds, 2000).

The ***Prominent Hill*** Cu-Au deposit is situated on the southern flank of the Palaeo- to Mesoproterozoic Mt Woods Inlier, concealed beneath ~100 m of Mesozoic sediments and regolith (Figs. 1 and 8). Few descriptions have been published, and the following summary is based on that of Belperio *et al.* (2007). The major hosts to mineralisation at Prominent Hill are hematitic breccias, which are themselves hosted by a sequence of andesitic volcanic rocks and sedimentary strata including sandstone, greywacke, argillite and carbonate rock. This sequence is intruded by a variety of dykes including dolerite, (andesite), diorite, granite and felsic porphyry. Hematitic breccias were emplaced within, and replaced, the sedimentary and volcanic strata as a series of steeply north-dipping tabular zones. Drilling and gravity data indicate the hematite-rich rocks extend for at least 2 km east-west and are up to ~400 m wide. This zone contrasts with a strongly magnetic domain immediately to the north of the hematitic breccias, characterised by the presence of magnetite, actinolite, chlorite, phlogopite, serpentine, talc, antigorite, carbonate, pyrite and minor chalcopyrite. The highest grade copper-gold mineralisation occurs within the hematitic breccias to the south of the magnetic domain. The breccias are multi-stage and heterolithic with sedimentary and/or volcanic clasts and hematite-rich matrix. They were ascribed by Belperio *et al.* (2007) to hydrothermal brecciation and explosive volcanism. In places, the breccias are almost entirely hematite and cryptocrystalline silica; gold-only mineralisation occurs in this type of breccia, typically on the margins of the copper zone. Chalcopyrite, chalcocite and bornite are the principal copper minerals. Chalcocite-bornite breccia zones have higher copper grades (average 2.5% Cu, 0.5 g/t Au) than chalcopyrite-uranium breccia zones (average 1.4% Cu, 0.6 g/t Au), although the latter are volumetrically dominant. As at Olympic Dam, chalcocite and chalcopyrite are not observed together, although zoning at Prominent Hill has not been reported for the deposit as a whole. Uranium grades are higher in the chalcopyrite zone than in the chalcocite zone, and locally exceed 5000 ppm. Uranium occurs as coffinite and uraninite. Elevated REE (mainly Ce, La) concentrations are widespread in the hematitic breccias and average ~3000 ppm (Belperio *et al.*, 2007). In addition to hematite, the principal hydrothermal alteration minerals associated with copper-gold-uranium mineralisation are sericite, chlorite, silica, fluorite and barite.

The ***Carrapateena*** deposit was discovered in 2005 by RMG Services with joint funding from PIRSA, and is currently under a joint venture with Teck Australia Ltd. Copper-gold mineralisation is hosted by heterolithic hematite-rich breccias corresponding to a gravity anomaly in an area where depths to basement are ≥470 m (Fairclough, 2005). A weak magnetic anomaly to the north may correspond to mafic volcanic rocks intersected in drillhole CAR001. There is both vertical and lateral zonation of sulphide minerals, with chalcocite-bornite zones developed at the top and central portions of the deposit, flanked by chalcopyrite mineralisation. Breccia clasts are predominantly of medium grained, gneissic diorite, variably altered to chlorite, sericite and hematite, as well as hematite-dominated clasts of earlier breccia phases. Sulphides occur mainly in the breccia matrix with hematite. Some parts of the breccia are noticeably vuggy and there is no evidence in CAR001 of a tectonic fabric within the hematitic breccias. Available geochemical data indicate elevated concentrations of LREE, F, Ba and U in addition to Cu and Au.

Mineralisation and Alteration Assemblages and Timing

Descriptions of IOCG mineralisation and alteration in the Gawler craton were focussed up to the mid 1990s on individual deposits and prospects (e.g., Olympic Dam: Reeve *et al.*, 1990, Oreskes and Einaudi, 1992, Johnson and Cross, 1995; Emmie Bluff: Gow *et al.*, 1994a; Moonta: Both *et al.*, 1993). Conor (1995) documented for the first time in detail the district- to regional-scale IOCG hydrothermal alteration (Moonta-Wallaroo district), and compared this with similar alteration elsewhere within the context of the newly defined IOCG deposit class (Hitzman *et al.*, 1992). The IOCG-related alteration and mineralisation assemblages occur in a wide range of rock types, including metasiltstones and calcareous protoliths of the Wallaroo Group, granitoids of the Donington Suite and Hiltaba Suite, and the Gawler Range Volcanics. The temporal sequence of assemblages and their spatial distribution is as follows (Skirrow *et al.*, 2002, 2007; Bastrakov *et al.*, 2007; Davidson *et al.*, 2007; Skirrow, 2009). Geochronological data are summarised in Fig. 9, and are discussed further below.

1. *Albite-calcsilicate±magnetite alteration*, representing Na-Ca-Fe metasomatism, is well developed in the Mt Woods Inlier and Moonta-Wallaroo districts as kilometre-scale regional alteration zones. Albitic alteration is rare in the Olympic Dam district, but it may be present at deeper levels where large scale magnetite-alteration is interpreted from geophysical modelling. Actinolite, clinopyroxene (generally diopside or salite) and minor titanite and scapolite occur in places in assemblage 1. This alteration appears to be paragenetically the earliest of the IOCG assemblages, and is similar to the Na-Ca alteration observed in the Cloncurry district (Williams *et al.*, 2005), Olary Domain in the Curnamona Province to the east of the Gawler craton, and other IOCG provinces globally (Hitzman *et al.*, 1992; Williams *et al.*, 2005). The only available isotopic age for the albite-actinolite±magnetite assemblage in the Gawler craton is from the Mt Woods Inlier where titanite yielded a U-Pb ion probe age of 1567±10 Ma (Fig. 9; Skirrow *et al.*, 2007). However, this is considered a minimum age and may represent resetting during local or regional metamorphism, as recorded in leucogabbro-hosted zircon overgrowths at 1576±7 Ma (Jagodzinski, 2005).
2. *Biotite-magnetite alteration*, representing Fe^{2+}-K (rather than simply 'potassic') metasomatism, has been observed in the Mt Woods Inlier and Moonta-Wallaroo districts where it shows mutually cross-cutting relationships with Hiltaba Suite granitoids (Conor, 1995; Hampton, 1997). Biotite-magnetite alteration zones may be very extensive and are clearly imaged in regional aeromagnetic data (Raymond, 2003). Albite appears to be a stable phase during this Fe-K metasomatism, and minor quantities of pyrite, chalcopyrite, pyrrhotite, monazite and titanite were deposited at this stage in some areas. Copper±gold mineralisation is generally low grade (<0.5% Cu), but at the Wallaroo deposit small higher grade zones have been mined. Biotite-magnetite altered rocks typically contain a cleavage that developed during alteration, particularly in the Moonta-Wallaroo district (Conor, 1995; Skirrow, 2009). Ion probe U-Pb dating of titanite and monazite in biotite-magnetite alteration in the Moonta-Wallaroo district has revealed a range of ages from ~1620 to ~1570 Ma (Conor *et al.*, this volume), and a Re-Os age of 1575±6 Ma for molybdenite cross-cutting the biotite-magnetite alteration provides a minimum age constraint (Fig. 9; Skirrow *et al.*, 2007).
3. *Magnetite-Kfeldspar±actinolite±carbonate alteration*, also representing Fe^{2+}-K metasomatism, is an important alteration assemblage in the Olympic Dam district but on current knowledge is not present in other parts of the Olympic IOCG province. Minor pyrite, quartz, carbonate, chalcopyrite, apatite and titanite are present in places. The very large magnetite-rich alteration systems at the Acropolis, Wirrda Well and Murdie Murdie prospects are representatives of this assemblage, and relicts of it are observed in many of the IOCG systems (e.g., Davidson *et al.*, 2007). In most of this alteration copper±uranium±gold mineralisation is generally low grade (<0.5% Cu), although long intervals of such mineralisation may be present. At the Olympic Dam deposit, we suggest that the hydrothermal magnetite with siderite observed in peripheral and deeper parts of the deposit (Reeve *et al.*, 1990; Haynes *et al.*, 1995) may have affinities with the magnetite-K feldspar±actinolite±carbonate alteration assemblage seen regionally. Inversion modelling of gravity and magnetic data indicate that magnetite alteration could extend beneath the Olympic Dam deposit to depths of at least 10 km (Fig. 6; see also Williams *et al.*, 2005). Isotopic ages for minerals in this

assemblage are presently limited to an apatite U-Pb TIMS age of 1604±7 Ma for the Acropolis prospect (Mortimer *et al.*, 1988) and two titanite U-Pb ion probe ages from the Murdie Murdie prospect yielding a pooled age of 1576±5 Ma (Fig. 9; Skirrow *et al.*, 2007).

4. *Hematite-sericite-chlorite-carbonate alteration*, a form of H_2O-CO_2 metasomatism involving oxidation of Fe^{2+} to Fe^{3+}, is the critical assemblage associated with higher grade copper-gold-uranium mineralisation. Chalcopyrite, pyrite, bornite, chalcocite, gold and uranium-bearing minerals are characteristically deposited with hematite, sericite, chlorite and carbonate, although only rarely are all of these minerals present in any given sample. Other phases present locally are: barite, fluorite, native copper, and REE phosphate minerals (Reeve *et al.*, 1990; Gow *et al.*, 1994a; Bastrakov *et al.*, 2007; Belperio *et al.*, 2007; Davidson *et al.*, 2007). This assemblage is most extensively developed in the Olympic Dam district and at the Prominent Hill deposit immediately south of the Mt Woods Inlier, although it occurs sporadically in the Moonta-Wallaroo district (e.g., Hillside prospect) and Mt Woods Inlier. Hematite of assemblage 4 replaces magnetite, or is developed separately from magnetite (e.g., Prominent Hill, Belperio *et al.*, 2007). Sericite replaces igneous, metamorphic or earlier hydrothermal, K-bearing phases such as K feldspar, whereas chlorite replaces Fe-Mg silicates such as actinolite and biotite. However, in many cases no precursor minerals are evident, and in these cases hematite, sericite, chlorite and carbonate grew in veins and breccia matrix. This hematite-sericite-chlorite-carbonate assemblage is similar to the 'hydrolytic' alteration described in IOCG districts elsewhere (Hitzman *et al.*, 1992; Williams *et al.*, 2005) but we prefer the use of the more descriptive mineralogical terminology. The absolute (radiometric) age of hematite-sericite-chlorite-carbonate alteration has been established in only a few localities in the Olympic IOCG Province. Sericite alteration associated with weak copper-gold mineralisation in the Torrens prospect yielded an ^{40}Ar-^{39}Ar age of 1575±11 Ma (Skirrow *et al.*, 2007). In the Moonta-Wallaroo district, molybdenite in chalcopyrite-bearing veins with chloritic alteration aureoles, possibly related to the hematite-sericite-chlorite-carbonate event, gave Re-Os ages of 1574±6 and 1577±6 Ma (Fig. 9). The geochronological constraints on the timing of IOCG mineralisation at Olympic Dam are discussed in detail below.

Age of Olympic Dam Mineralisation and Alteration

The timing of IOCG (U) mineralisation at the Olympic Dam deposit has been the subject of debate since its discovery. In essence, two scenarios have been proposed: (1) approximately coeval timing of brecciation, iron oxide development and copper-uranium-gold mineralisation during or immediately following deposition of the Gawler Range Volcanics (GRV) between 1595 and 1585 Ma (Reeve *et al.*, 1990; Haynes *et al.*, 1995; Johnson and Cross, 1995; Jagodzinski, 2005; Skirrow *et al.*, 2007), and (2) later introduction of copper-uranium-gold mineralisation post-dating brecciation, iron oxide development and the GRV by up to 160 m.y. (Oreskes and Einaudi, 1992; Meffre *et al.*, 2010; McPhie *et al.*, 2010). Ion probe U-Pb dating of zircons in felsic dykes cross-cutting the copper-uranium-gold mineralised breccias led both Johnson and Cross (1995) and Jagodzinski (2005) to deduce minimum ages of brecciation, iron oxide alteration and copper-uranium-gold mineralisation of ~1595 to 1590 Ma. This timing is supported by the ~1597 to 1595 Ma ages of zircons of probable hydrothermal origin, which contain inclusions of chalcopyrite and hematite and very high REE contents (Jagodzinski, 2005). Maximum ages were provided by host rock igneous ages of ~1595 to 1590 Ma (Johnson and Cross, 1995; Jagodzinski, 2005), which are within uncertainty of the minimum ages, constraining copper-uranium-gold mineralisation to ~1595 to 1590 Ma.

Table 2: Temporally and spatially related non-IOCG deposits and prospects of the Gawler Craton

Name	Resource	Status	Style	Reference
Tarcoola	1.61 Mt @ 3.21 g/t Au	Closed mines	Quartz-sulphide veins; disseminated sulphides	Budd and Skirrow (2007)
Tunkillia	14.3 Mt @ 1.78 g/t Au, 3.42 g/t Ag	Feasibility	Quartz-sulphide veins; disseminated sulphides	Helix Resources Ltd Annual Report, 2008
Nuckulla Hill	*Drilled 24m @ 1.0 g/t Au*	Subeconomic prospect	Quartz-sulphide veins; disseminated sulphides	Fraser *et al.* (2007)
Barns	*Drilled 2m @ 67.6 g/t Au; 36m @ 1.8 g/t Au*	Subeconomic prospect	Quartz-sulphide veins; disseminated sulphides	Fraser *et al.* (2007)
Weednanna	*Drilled 16m @ 1.93 g/t Au, 3m @ 16.8 g/t Au*	Subeconomic prospect	Quartz-sulphide-Bi-Pb veins; disseminated sulphides	Fraser *et al.* (2007)
Cairn Hill	15.2 Mt @ 48.5% Fe	Open pit development	Magnetite-rich breccias and stratabound replacement	IMX Resources Limited Annual Report 2007
Iron Magnet	92 Mt @ 59.5% Fe	Open pit production	Magnetite-rich stratabound replacement in BIF	Faulkner *et al.* (2007)
Peculiar Knob	19.0 Mt @ 63.7% Fe	Development	Massive specular (micaceous) hematite	Western Plains Resources Limited Annual Report 2009
Oak Dam	(~560 Mt @ 41-56% Fe)	Undeveloped	Magnetite-rich breccias and stratabound replacement	Davidson *et al.* (2007)
Wilcherry Hill	60 Mt @ 31% Fe	Feasibility study	Enriched magnetite replacement zones in iron formation	Ironclad Mining Limited Investor Presentation February 2010 (www.ironcladmining.com)

There is uncertainty regarding the significance of the ~1595 to 1590 Ma ages for zircons in the volcaniclastic sediment units: they either represent depositional ages if derived from tuffaceous material (Johnson and Cross (1995) and Jagodzinski (2005), or maximum ages if detrital (McPhie *et al.*, 2010). Furthermore, several post-1590 Ma dates have been reported for the Olympic Dam deposit. These include a Re-Os isotopic date of ~1258±28 Ma for chalcopyrite and pyrite (McInnes *et al.*, 2008), and most recently Meffre *et al.* (2010) reported LA-ICPMS Pb/Pb ages for galena of 1400 to 1200 Ma, plus Nd-Sm data consistent with a Palaeozoic age for a late-stage fluorite-barite vein. There is evidence for a number of regional thermal events that have affected the metallogenic province post-GRV. In the Olympic Dam district, $^{40}Ar/^{39}Ar$ data from K feldspars yield evidence for low-temperature (<150°C) event(s) during the period ~1500 to 1400 Ma (G. Fraser and R. Skirrow, unpublished data). Similarly, $^{40}Ar/^{39}Ar$ and K-Ar ages of hydrothermal biotite and hornblende in the Moonta-Wallaroo district were evidently reset during the period ~1520 to 1450 Ma (Fig. 9; Webb *et al.*, 1986; Conor *et al.*, this volume), suggesting temperatures at that time were significantly higher than in the Olympic Dam district. High-temperature thermal events occurred during ~1586 to 1540 Ma in the northern Gawler craton (Hand *et al.*, 2007), and thermal events at ~1450 Ma are recorded in shear zones in the western and northern parts of the craton (Fraser and Lyons, 2006).

The available geochronological and geological data are most consistent, in our view, with IOCG (U) mineralisation and alteration at Olympic Dam, and elsewhere in the Olympic IOCG Province, developing between ~1595 and ~1585 Ma, during the late stages of the Hiltaba-GRV magmatic event, when dyke emplacement, intense hydrothermal brecciation, and iron oxide development also formed. The IOCG deposits have been disrupted by post-mineralisation reverse fault movements along east- to eastnortheast-trending faults, which we attribute to the distal effects of the 1570 to 1540 Ma Kararan orogeny. Disturbance of some isotopic systems is apparent during younger thermal events, along with minor hydrothermal remobilisation of base metal sulphides, and may account for some of the 'young' ages reported for Olympic Dam and other deposits in the region.

Related Mineralisation

The Gawler craton hosts other styles of non-IOCG mineralisation that are believed to be spatially and temporally related to the same regional events that produced the IOCG deposits (Table 2). The most important of these are a group of gold deposits in the central Gawler craton, and several iron ore deposits in the eastern and central parts of the craton. It is likely that copper sulphide-rich (iron oxide-poor) deposits will also be discovered, similar to those commonly found in or near other IOCG provinces (e.g., Mt Isa copper in Queensland, Kansanshi copper-gold in Zambia, and El Soldado copper-silver in Chile), although exploration search methods under cover in the province have to date been focussed on iron oxide-rich mineralisation.

Gold Deposits

The Central Gawler Gold Province (Fig. 1) encompasses the historic gold mines at Tarcoola and several undeveloped deposits and prospects to the south, including Tunkillia, Nuckulla Hill, Barns and Weednanna (Table 2). Hydrothermal sericite and muscovite associated with gold yields $^{40}Ar/^{39}Ar$ plateau ages between ~1590 and ~1570 Ma (Budd and Fraser, 2004; Fraser *et al.*, 2007). These ages are within error of the ages of both the Hiltaba Suite and IOCG alteration and mineralisation in the eastern Gawler craton, indicating genesis during the same metallogenic episode.

Gold occurs as disseminated and veinlet-hosted mineralisation within brittle to brittle-ductile fault zones in a variety of Palaeoproterozoic meta-granitoid and metasedimenary host rocks. Hydrothermal alteration is locally zoned from sericite-pyrite proximal to quartz-rich vein systems, to a distal chlorite±epidote±hematite assemblage. Pyrite is widespread, and minor galena, sphalerite and chalcopyrite are present in many of the gold mineralised zones. Iron oxides are generally volumetrically minor and hematite is dominant over magnetite within gold-related alteration. However, the Weednanna gold deposit differs in the abundance of paragenetically-early magnetite and related high-temperature skarn-like minerals (Fraser *et al.*, 2007). The magnetite-bearing assemblages at Weednanna are overprinted by Au-Bi (±Pb) mineralisation and sericite-chlorite-carbonate-quartz alteration that closely resemble the hydrothermal assemblages in other gold deposits of the Central Gawler Gold Province. Multiple hydrothermal fluid types have been recorded in some of the studied gold deposits, although one type appears to be common to all: a low- to moderate-salinity (up to ~10 wt.% $NaCl_{equiv.}$) fluid with inclusion homogenisation temperatures of ~300 to 150°C, commonly containing CO_2. Depths of ore formation of 2 to 10 km were estimated by Budd and Skirrow (2007) based on fluid inclusion data.

The genesis and classification of gold mineralisation in the central Gawler craton remains unclear, as there may be affinities with both intrusion-related and orogenic gold deposit types. In any case, there is evidence from timing relationships and Nd isotope data for involvement of syn-mineralisation intermediate (high-K dioritic) dykes that are associated with the Hiltaba Suite (Budd and Skirrow, 2007). Whereas the lithological setting of the central Gawler craton appears to have differed from that in the eastern IOCG province, it is notable that mafic/intermediate igneous intrusive activity is temporally and spatially associated with both the gold and IOCG systems. The Au-only metallogeny is likely a consequence of involvement of low to moderate salinity CO_2-bearing fluids that had less capacity than the hypersaline fluids in IOCG systems to leach and transport iron and other base metals. Furthermore, the lack of basaltic volcanic units in the lower Gawler Range Volcanics in the central Gawler craton may have contributed to the contrasting metal inventories between the gold and IOCG provinces.

Iron Oxide Deposits

There are at least three end-member styles of iron oxide mineralisation present in the central and eastern Gawler craton: (1) low grade, metamorphosed banded iron formation, typically magnetite-rich and averaging 20 to 35% Fe, (2) hydrothermal magnetite and/or hematite replacement bodies ranging from 20 to 65% Fe (Table 2), and (3) supergene-enriched martite and/or goethite replacement bodies, commonly with 40 to 68% Fe. Historical Fe ore production was mostly derived from the third group in open pit mines to a depth of 90 m within the

Palaeoproterozoic Middleback Iron Formations (Spencer Domain). Only the second group of iron oxide deposit styles may be related to events that formed the Olympic IOCG Province. These hydrothermal iron deposits mostly comprise structurally-discordant, medium- to coarse-grained, magnetite-rich breccias and skarn-like mantos with subsidiary amphibole, apatite, biotite and carbonate, or at shallower levels they comprise fine-grained, hematite-rich (±sericite, carbonate, quartz) breccias and stratabound mantos. The hydrothermal iron deposits can be very large (>1 billion tonnes) but commonly have only low to medium iron grades with high phosphorous and LREE contents which, combined with significant cover depths and rock hardness, makes the majority of these bodies uneconomic. Centrex Metals (2008) geologists suggested that some of the stratabound, BIF-hosted iron-deposits (e.g. Iron Knob) in the Middleback Ranges were pre-enriched by hydrothermal iron metasomatism, although there have been no detailed studies published on the alteration paragenesis and ore controls in these deposits.

IOCG Ore Genesis

Studies of Cu-Au-U ore genesis are relatively limited in the Olympic IOCG Province, despite the enormous economic value of this metallogenic province. Major new datasets and interpretations for Olympic Dam were published by Reeve *et al.* (1990), Oreskes and Einaudi (1992), Johnson and Cross (1995), Johnson and McCulloch (1995) and Haynes *et al.* (1995). The sub-economic Emmie Bluff deposit was studied by Gow *et al.* (1994a), whereas small deposits of the Moonta-Wallaroo district have received some attention (Both *et al.*, 1993; Conor, 1995; Ruano *et al.*, 2002). More recently Geoscience Australia undertook a range of studies of the regional setting of IOCG mineralisation, including seismic reflection surveys (Lyons and Goleby, 2005; Drummond *et al.*, 2006; Direen and Lyons, 2007) and studies of IOCG alteration and mineralisation (Bastrakov *et al.*, 2007; Skirrow *et al.*, 2002, 2007). Complimentary work on regional geology and geochronology by PIRSA and The University of Adelaide (e.g., Hand *et al.*, 2007) has led to substantially improved datasets for the Olympic IOCG Province, which now permit a more informed debate on IOCG ore genesis models. Whereas many studies have focussed on fluid sources, few have specifically addressed metal sources. Constraints on the temperature, chemical environments and sources of fluids, sulphur and metals, and models of IOCG genesis in the eastern Gawler craton, are discussed below.

Constraints on Magnetite-bearing Alteration and Fluids

Fluid inclusion data and oxygen isotope geothermometry for the magnetite-bearing assemblages in the Olympic Dam district indicate that fluid temperatures reached ~420 to 540ºC (Oreskes and Einaudi, 1992; Bastrakov *et al.*, 2007; Davidson *et al.*, 2007). No pressure estimates are available for magnetite in this district. However, from the presence of brittle-ductile deformation textures in early magnetite-bearing alteration at Emmie Bluff, the Moonta-Wallaroo district and Mt Woods Inlier, and from 3D geophysical inversion models (Fig. 6), we infer that syn-deformational hydrothermal magnetite deposition spanned depths of several kilometres. Based on fluid inclusion microthermometry and proton ion probe analysis, fluids responsible for high-temperature magnetite alteration in the Olympic Dam district were hypersaline brines (30 to 50 wt.% $NaCl_{equiv.}$) with very high concentrations of Fe, Na, Ca, up to 0.5% Zn and 1.5% Pb, and at least 300 to 600 ppm Cu (Bastrakov *et al.*, 2007). The lack of significant copper mineralisation associated with this alteration assemblage is attributed to undersaturation with respect to copper minerals at the prevailing high temperature and unusually high Cl/S conditions, and/or lack of available sulphur. Hypersaline brine inclusions coexist with vapour-rich fluid inclusions, suggesting phase separation, but the vapour-rich inclusions in the IOCG systems studied by Bastrakov *et al.* (2007) and Davidson *et al.* (2007) comprised only water vapour with no detectable CO_2. In contrast, fluid inclusions associated with some melt inclusions in the Gawler Range Volcanics contain significant CO_2 (Chambefort *et al.*, 2009).

Reconnaissance data for Br/Cl ratios of the brines lie at and above the upper limit for magmatic and mantle fluids, suggesting a contribution from bittern brines or evaporated seawater, but do not rule out magmatic input (Bastrakov *et al.*, 2007). Oxygen isotope data for magnetite, quartz and actinolite yield calculated values of $\delta^{18}O_{water}$ of ~8 to 13‰, the higher values of which are incompatible with purely magmatic-hydrothermal fluids that have values of 5.5 to 9‰ (Taylor and Sheppard, 1986; Bastrakov *et al.*, 2007). Extensive oxygen isotopic exchange with heavier ^{18}O-rich reservoirs, such as metasedimentary rocks, appears to be necessary to explain the results from the Olympic Dam district. The sulphur isotope compositions of pyrite, chalcopyrite and pyrrhotite associated with magnetite alteration in the Olympic IOCG Province range from ca. -6 to +2‰ (Knutson *et al.*, 1992; Eldridge and Dante, 1994; Bastrakov *et al.*, 2007; Davidson *et al.*, 2007). Whereas the lowest of these values includes a pyrrhotite sample and cannot be of direct igneous or magmatic-hydrothermal origin, most magnetite-related sulphide values can be explained by sulphide mineral deposition from a slightly reduced magnetite-pyrite stable fluid ($H_2S>SO_4^{2-}$) with a bulk $\delta^{34}S$ value of ~2‰. Hence, sulphur in the generally minor sulphides associated with most magnetite-bearing alteration was arguably of magmatic-hydrothermal or leached-igneous rock origin (Bastrakov *et al.*, 2007).

Constraints on Hematite-bearing Alteration and Cu-Au-U Mineralising Fluids

For all fluids related to hematite alteration, fluid inclusion homogenisation temperatures are mostly between 150 and 300ºC and salinities range from ~1 to ~23% $NaCl_{equiv.}$ (Knutson *et al.*, 1992; Oreskes and Einaudi, 1992; Bastrakov *et al.*, 2007). This is consistent with textural studies indicating a shallower and/or cooler crustal setting where brittle deformation was dominant (Skirrow, 2009). The few chemical analyses of fluid inclusions associated with hematite alteration, obtained by proton ion probe, revealed very low copper concentrations at the Emmie Bluff prospect (below detection limits; Bastrakov *et al.*, 2007). Calculated oxygen isotope compositions of fluids associated with hematite-bearing alteration in the Olympic IOCG Province range widely from ~0 to ~11‰ (Oreskes and Einaudi, 1992; Gow, 1996; Morales *et al.*, 2002; Bastrakov *et al.*, 2007). These results may be explained either by (1) involvement of an isotopically light fluid, such as meteoric water in the formation of hematitic alteration (Oreskes and Einaudi, 1992; Gow *et al.*, 1994a); and/or by (2) down-temperature re-equilibration of isotopically heavier fluids with felsic igneous host rocks towards lighter compositions (Bastrakov *et al.*, 2007; see below for further discussion of genetic models).

Sulphides associated with hematitic alteration in the Olympic IOCG Province have a wider range of values than for magnetite-associated sulphides. The most negative values are at Olympic Dam (ranging from $\delta^{34}S_{pyrite}$ = -6‰ to $\delta^{34}S_{chalcocite}$ = -10‰, average values reported by Eldridge and Danti, 1994) and at Oak Dam ($\delta^{34}S_{chalcopyrite}$ = -8 to -14‰, Davidson *et al.*, 2007; Bastrakov *et al.*, 2007). The highest values reported are for Emmie Bluff with $\delta^{34}S_{chalcopyrite}$ of up to +12.5‰ and pyrite in barren hematitic alteration in drill hole ES21 (~ +12‰, Knutson *et al.*, 1992). The interpretation of sulphur sources for the hematite-sulphide assemblages is problematic without further constraints, such as the sulphur isotopic composition of coexisting sulphate and sulphide minerals over a range of temperatures. Nevertheless, two possible scenarios could explain the negative sulphur isotope values (Bastrakov *et al.*, 2007): (1) a fluid with bulk $\delta^{34}S_{fluid}$ of approximately +2‰ and intermediate redox ($H_2S \approx SO_4^{2-}$), and (2) a highly oxidised fluid with bulk $\delta^{34}S_{fluid}$ of approximately +13‰ and $H_2S << SO_4^{2-}$. The former is consistent with a magmatic-hydrothermal or leached igneous rock source of sulphur, but cannot easily explain the presence of chalcocite which is stable only at highly oxidised conditions, whereas the latter scenario would correspond to a sulphate-rich surface-derived and highly oxidised fluid such as lake water.

Models of IOCG Deposit Formation

Three groups of models have been proposed for the formation of the Olympic Dam deposit and other copper-gold-uranium deposits in the Olympic IOCG Province: (1) progressive fluid mixing models involving at least one non-magmatic fluid (Reeve *et al.*, 1990; Haynes *et al.*, 1995; Davidson *et al.*, 2007), (2) sequential (two-stage) models involving two or more fluids (Oreskes and Einaudi, 1992; Gow *et al.*, 1994a; Johnson and McCulloch, 1995; Gow, 1996), and (3) single-fluid magmatic-hydrothermal models (Reynolds, 2000; Morales *et al.*, 2002). All of these models acknowledge the importance of a relatively high-temperature hypersaline fluid in equilibrium with paragenetically early magnetite, and the importance of oxidised conditions during overprinting copper-gold(±uranium) mineralisation with hematitic alteration. The major divergences between models are in interpretation of the origin of the fluids and metals involved; with proposals for either magmatic and/or non-magmatic sources mirroring the same debate on IOCG systems globally (e.g., Williams *et al.*, 2005).

The timings of hydrothermal brecciation, iron oxide deposition and most alteration in the Olympic IOCG province, as well as gold mineralisation and alteration in the Central Gawler Gold Province, are constrained radiometrically to between ~1595 and ~1575 Ma, overlapping the duration of Hiltaba Suite granitoids, coeval mafic intrusions, and Gawler Range Volcanics (Fig. 9; Johnson and Cross, 1995; Skirrow *et al.*, 2007). Syn-mineralisation dyke emplacement has been inferred at Olympic Dam (Johnson and Cross, 1995; Jagodzinski, 2005; Chambefort *et al.*, 2009), in the Moonta-Wallaroo district (Conor, 1995; Skirrow, 2009), in some gold deposits in the central Gawler Craton (Budd and Skirrow, 2007), and possibly also at Prominent Hill (Belperio *et al.*, 2007). Geochemical and isotopic constraints on magnetite-bearing alteration and related fluids noted above suggest contributions from both deeply circulated bittern brines and subordinate magmatic brines that partially equilibrated isotopically with country rocks. Given the abundance of syn-mineralisation A-type plutons, which typically contain 1 to 2.5, and rarely up to 4 wt.% H_2O (e.g., Dall'Agnol and Oliveira, 2007), some involvement of magmatic fluids is very likely. Furthermore, explosive degassing of magmatic H_2O-, CO_2- and possibly F-rich fluids is the most likely mechanism for development of steeply-plunging, highly fluidised mill breccia pipes and lenses at the Olympic Dam, Wirrda Well, Carrapateena and Prominent Hill deposits. Diatreme and hydrothermal mill breccias similar to these are commonly developed in other orthomagmatic copper-gold and gold deposit settings (e.g., Sillitoe, 1997) and in some magmatic iron deposits (e.g., Von der Flaas, 1990). Explosive degassing is commonly attributed to injection of more mafic melt batches into silicic magma chambers (Vigneresse, 2007), and there is widespread evidence for co-mingling and mixing of tholeiitic mafic and A-type felsic magmas amongst the Hiltaba Suite (Stewart, 1994).

High-temperature, hypersaline brines have the capacity to leach and transport high concentrations of iron (as $FeCl_2$), ore-forming metals and REE, regardless of whether derived from magmatic or bittern fluid sources. Iron depletion is generally associated with large-scale albitic alteration zones in country rocks (e.g. Barton and Johnson, 1996). Magnetite-series A-type granitoid and gabbroic intrusions within the Olympic IOCG Province may also have been a significant iron source, potentially via deuteric leaching of magnetite upon magmatic brine exsolution or external brine infiltration. Evidence for late stage magmatic iron enrichment in the Hiltaba A-type intrusions, which may be triggered by mingling with mafic melts (e.g., Clark and Kontak, 2004), has not been reported.

The involvement of a second fluid during formation of copper-gold-uranium mineralisation, which was distinctly cooler, less saline and more oxidised, is strongly supported by the hematitic alteration mineral parageneses, fluid inclusion and isotopic compositions summarised above. Collectively, these data indicate non-magmatic sources of oxygen, hydrogen and sulphur and implicate meteoric or lake water. Whether this second fluid was coeval and mixed with the magnetite-forming fluid, or overprinted the magnetite-bearing alteration in a two-stage process, appears to vary from system to system in the IOCG province. At the Olympic Dam deposit, Reeve *et al.* (1990) and Haynes *et al.* (1995) proposed fluid mixing to account for a continuum in fluid homogenisation, isotopes and salinities between the two end-member fluid types. A schematic representation of a two-fluid model is presented in Fig. 10, based largely on the Olympic Dam deposit. The deep-sourced fluid, labelled 'A', resulted in regionally extensive magnetite-bearing alteration zones that are barren or contain low grade copper-gold mineralisation (e.g., <0.1% Cu, Stage 1), even though the hypersaline fluid A in places carried hundreds of ppm Cu (see above). In this model, fluid A evolved to a hematite-stable fluid at shallower crustal levels as pressure-temperature conditions decreased along upflow paths. In some cases, the 'primary' relatively heavy oxygen isotopic composition of these fluids was preserved in hematite alteration (e.g., ~ +11‰ Emmie Bluff, Bastrakov *et al.*, 2007; cf. Gow, 1996). The magnetite-bearing alteration systems are inferred to have been rapidly exhumed during Stage 2, placing these high-temperature hydrothermal systems at shallow crustal levels (middle and right panels, Fig. 10). In such settings, oxidised surface-derived waters circulated in shallow geothermal systems, driven by very high geothermal gradients associated with regional magmatism of the Hiltaba Suite and Gawler Range Volcanics.

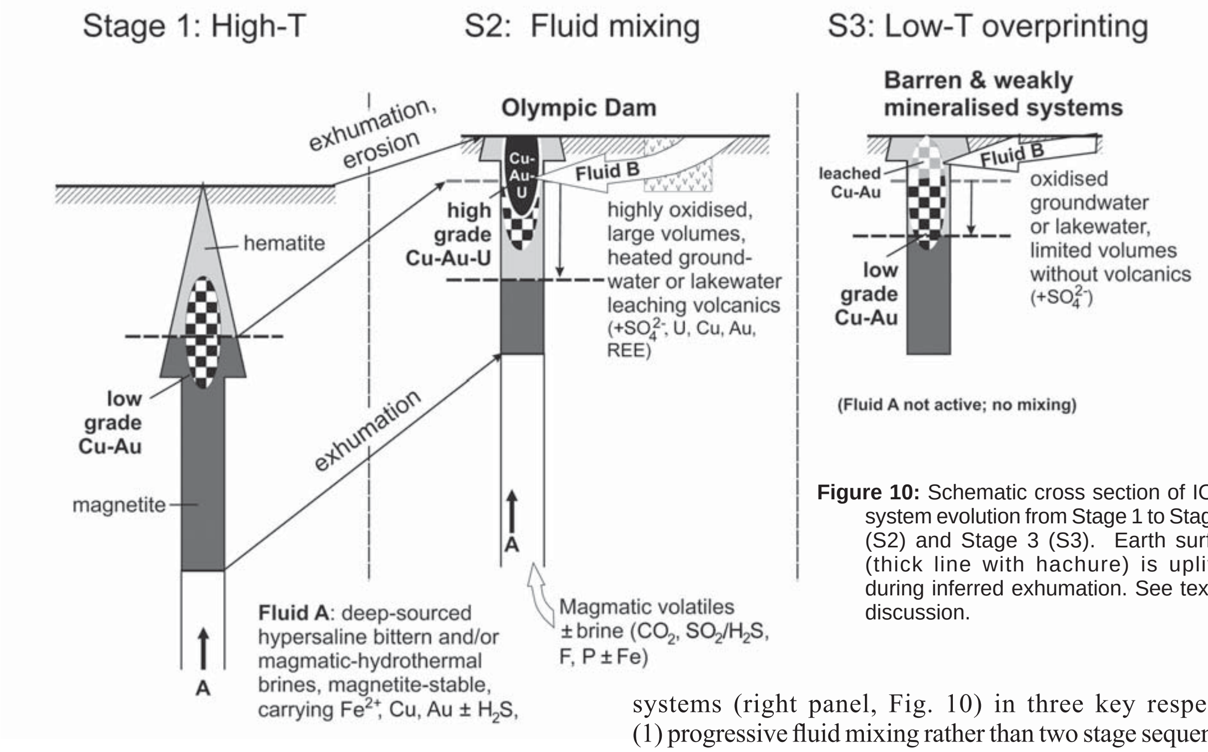


Figure 10: Schematic cross section of IOCG system evolution from Stage 1 to Stage 2 (S2) and Stage 3 (S3). Earth surface (thick line with hachure) is uplifted during inferred exhumation. See text for discussion.

The co-spatial relationship between the Olympic IOCG Province and mafic volcanic units in the lower Gawler Range Volcanics noted above supports models that invoke leaching of copper and gold from basalt sources (e.g., Knutson *et al.*, 1992; Haynes *et al.*, 1995). The >450 m thick Roopena Volcanics show widespread intense hematite-chlorite-carbonate alteration with significant copper depletion, commonly reduced from average background levels around 127, to <20 ppm Cu (Creaser, 1989; Knutson *et al.*, 1992). The fluids associated with this alteration were oxidised, moderate-temperature (150 to 250°C), NaCl-CO_2-rich brines, interpreted to be of either bittern brine (Haynes *et al.*, 1995), or evolved magmatic origin (Knutson *et al.*, 1992). Both the S and Nd isotopic signatures of ore sulphides indicate igneous sources, which can be explained by leaching of basalts. By contrast, the unusually high concentrations of U_3O_8 at Olympic Dam and Oak Dam are interpreted to arise from leaching of strongly radiogenic felsic components of Gawler Range Volcanics and Hiltaba Suite plutons exposed at surface prior to mineralisation (Hitzman and Valenta, 2005).

As shown in Fig. 10, we can conceptually expect four modes of formation of hematitic iron oxides and this has significant ramifications for exploration. Mineralised hematite-facies rocks can result from either (1) cooled evolved fluid A, or (2) moderately deeply circulated fluid B, providing both encountered sufficient fertile source rocks en-route. Barren hematite-facies rocks can result from either (3) moderately deeply circulated fluid B that failed to encounter sufficient fertile source rocks, or (4) shallow fluid B that leached metals from previously mineralised magnetite (or even mineralised hematite) bodies. In support of the latter point, we suggest that hypogene metal leaching and redistribution could account for the presence of barren hematite breccia zones at Prominent Hill and Olympic Dam which are flanked by a downward and outward zonation pattern from native gold, then chalcocite then bornite then chalcopyrite. This process can lead to mineralisation upgrading (Bastrakov *et al.* 2007).

The richest IOCG deposits (middle panel, Fig. 10) may differ from barren and weakly mineralised IOCG systems (right panel, Fig. 10) in three key respects: (1) progressive fluid mixing rather than two stage sequential alteration; (2) greater fluid interaction with mafic volcanic units, leading to more primitive εNd signatures (Skirrow *et al.*, 2007); and (3) interaction with more oxidised and sulphate-rich meteoric fluids at higher fluid/rock ratios, resulting in lower δ^{34}S and δ^{18}O isotope compositions of hydrothermal minerals. Dissolved sulphate carried by fluid B is viewed as critical in generating the gigantic mass of sulphide mineralisation in an otherwise relatively low-sulphur iron oxide-dominated hydrothermal system. The largest IOCG ore deposits in the province also show the most extreme hydrothermal brecciation and most extensive hematite replacement of magnetite assemblages. Our proposed model of the IOCG hydrothermal system in the Olympic Dam region is shown in Fig. 11, which is an attempt to integrate the key aspects of ore genesis discussed above. This schematic cross section illustrates the immense scale of the hydrothermal system, and the involvement of multiple fluid and metal sources as well as the zonation of IOCG alteration at the regional to deposit scales.

Exploration Guidelines

The observations and ore genesis model presented above allow refinements to be made to exploration models for the discovery of economic IOCG deposits in the Olympic IOCG Province, with possible application in other IOCG provinces. The emphasis is on hematite- and potentially uranium-rich styles similar to Olympic Dam, and builds on the criteria outlined by Skirrow (2009). Area selection guidelines are considered here at three decreasing scales: (1) subprovince- to district-scales (~300x300 km), (2) project or local scale (~30x30 km), and (3) vectors to ore within an alteration system (~3x3 km).

Subprovince Area Selection

The distribution and relative rank of IOCG-prospective subprovinces and districts in the Gawler Craton can be defined by the spatial coincidence of five principal criteria, listed in approximate order of decreasing importance:

1. Regional scale magnetite- and hematite-rich hydrothermal alteration systems,

2. Continental tholeiitic to calc-alkaline basalts in the upper crust prior to exhumation,
3. Hangingwall of first-order north- to northnorthwest-trending trans-lithospheric shear zones, particularly those marking the boundary between Archaean and Proterozoic terranes,
4. Preserved subvolcanic depth intervals (preferably <5 km),
5. Upper crustal sequence lacking thick reduced packages.

Considerations of other non-geological criteria, such as cover sequence depth and infrastructure proximity, are also important for area selection at this scale, but these factors commonly vary for each explorer according to their strategic requirements. Proximity to oxidised Hiltaba Suite plutons is not included here because they have a broader distribution than iron oxide rich alteration systems in the Gawler Craton and may occur more than 2 km deeper than mineralisation, rendering them a less effective parameter than the first criterion. The distributions of high-amplitude magnetic anomalies that correspond to hydrothermal magnetite alteration are mapped by various techniques using proprietary and public aeromagnetic data. Magnetic integral images, for example, are effective at highlighting broad districts of mid-crustal alteration, whereas total magnetic intensity and derivatives such as analytical signal and first vertical derivative images are useful for providing higher resolution maps of upper crustal magnetite-rich bodies (e.g., Gow *et al.*, 1994b; Vella and Cawood, 2006). It is important to recognise that some IOCG deposits such as Prominent Hill and Carrapateena are located peripheral to, rather than above, large-scale magnetite alteration systems and their attendant aeromagnetic anomalies.

Both the presence of shallow level continental basalts and andesites and preservation and exposure of subvolcanic depth intervals are best developed in the northern half of the province, specifically within the Olympic geological domain and immediately south of the Mt Woods Inlier in the Prominent Hill area (e.g., Skirrow *et al.*, 2006). Roopena Volcanics appear most abundant near the ECFZ, although the distribution was probably much greater before partial exhumation then burial under Neoproterozic sedimentary cover. It is also possible that the thickest part of the basalt pile developed proximal to feeder faults associated with translithospheric shear zones, such as the ECFZ (Fig. 5). Altered basalts hundreds of metres thick were intersected in the Snake Gully area to the northeast of the Olympic Dam deposit (e.g., WMC drill hole SGD 7; Haynes *et al.*, 1995). Conceptually, the requirement to sustain high fluid fO_2 and metal transport capacity (ore genesis model above) requires little interaction with rock reductants along the fluid recharge paths, although reduced sequences are acceptable at fluid discharge sites.

Local Area Selection

Area selection and ranking criteria for blind discovery opportunities at the scale of typical exploration licences include the following:

1. Kilometre-scale hydrothermal alteration zones of intense Fe-K metasomatism, particularly magnetite-K feldspar or magnetite-biotite alteration juxtaposed laterally or vertically with hematite-sericite-chlorite-carbonate alteration zones,
2. Intersection zones of two or more favourable syn-mineralisation faults,
3. Thick competent host units that are chemically reactive in the presence of oxidised and acidic fluids (e.g., Fe^{2+}-rich, S-bearing or K feldspar-rich rocks),
4. Peripheral base metal (Cu, Pb, Zn, Mo) and/or Au sulphide mineralisation.

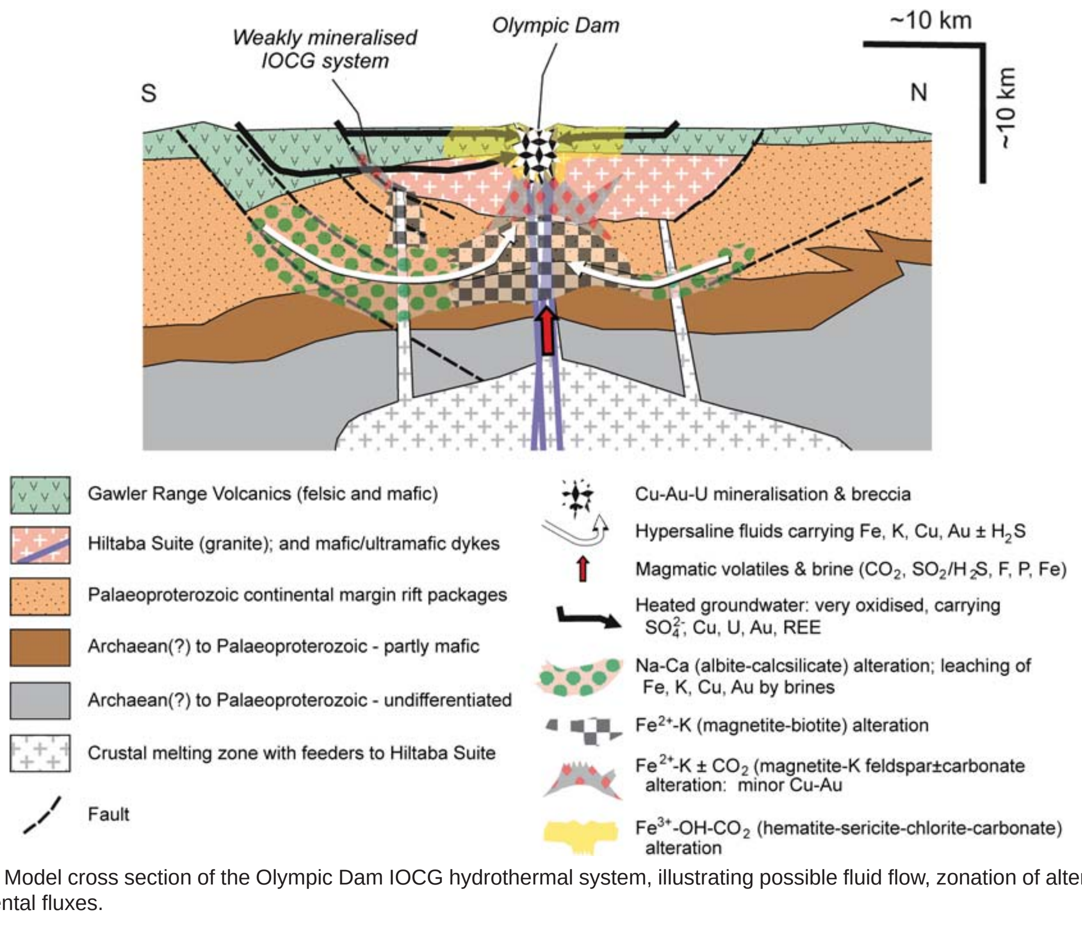


Figure 11: Model cross section of the Olympic Dam IOCG hydrothermal system, illustrating possible fluid flow, zonation of alteration, and elemental fluxes.

The presence of sodic-calcic alteration assemblages is generally not useful at the local scale given their widespread distribution. Delineation of high-amplitude residual gravity anomalies is the most effective method for identification of hydrothermal iron oxide bodies. By contrast, magnetic signatures of iron oxide bodies are highly variable, depending on the iron oxide mineralogy (magnetite versus hematite), magnetic remanence, and source unit geometry and latitude with respect to earth's magnetic field. The application of very high amplitude thresholds for anomaly selection helps filter out false positive responses associated with, for example, magnetite-bearing gabbros (e.g., Hanneson, 2003), but may exclude some relatively deep and smaller alteration systems such as at the Carrapateena deposit. It is important to ensure that data resolution is adequate to capture the majority of anomalies with size exceeding target deposit thresholds. Discordant, structurally-controlled magnetic anomalies are generally more favourable than those that are simply stratabound.

Favourable structural controls noted above include the intersection of second-order north- to northwest- and eastnortheast-trending faults, especially where both are steeply dipping. Few major IOCG deposits occur directly within first-order faults. The presence of favourable second-order fault intersections can help prioritise the most prospective geophysical targets: they increase the chances of prolonged fluid focus and introduction of (sub)alkaline mafic mantle melts and volatiles. No particular host rock is required, but there is a common association with thick, feldspar-rich, volcanic or intrusive host units that facilitate extensive brittle fracturing, brecciation, and wallrock alteration (e.g., fluid pH increase). Host units containing reductants such as organic carbon (e.g., carbonaceous shale) or ferrous iron (e.g., magnetite skarn, banded iron formation) also may be favourable chemical environments for deposition of copper, gold and uranium.

Peripheral sulphide mineralisation may be detected from electrical geophysical methods, such as EM, IP and MT, but within iron oxide-rich alteration zones it is commonly difficult to distinguish a sulphide- from an iron oxide-response. For example, coarse grained magnetite is conductive and specular hematite is chargeable (e.g., Hart and Freeman, 2003). Any geochemical method which can effectively test for anomalous concentrations of one or more of the suite of elements including Cu, Au, S, U, Ag, LREE, Mo, Zn (also Ba, F) under cover will be useful.

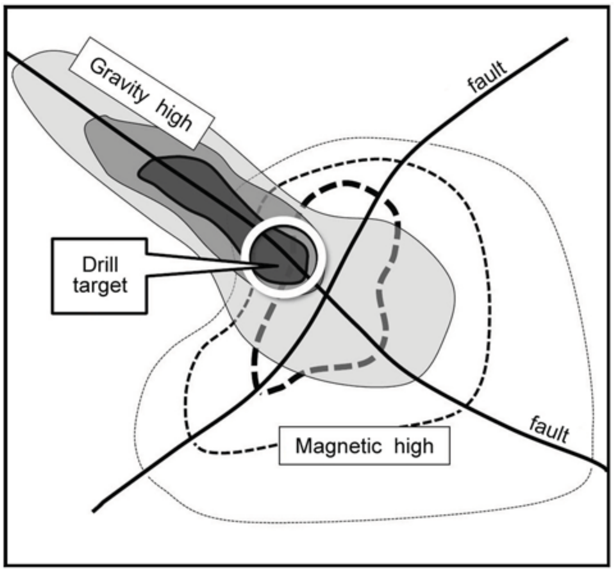


Figure 12: Schematic map (at 1x1 km to 10x10 km scale) of integrated geophysical anomalism for an IOCG alteration system with optimal first-pass drill target located at the Fe^{2+}/Fe^{3+} redox boundary between strong magnetic anomalism (Magnetics in dashed outlines with thicker lines for higher susceptibility, representing magnetite alteration zones) and high density – low magnetic susceptibility anomalism (Gravity in grey shading with darker shades for higher density, representing hematite-rich alteration zones).

Vectors to Ore

It is commonly challenging to effectively vector towards IOCG mineralisation within large hydrothermal iron oxide-rich alteration systems, and to distinguish between mineralised and unmineralised systems in the early stages of target testing under cover. There are typically many more poorly mineralised and uneconomic iron oxide±apatite deposits than IOCG deposits in any given IOCG province. Even within a single IOCG deposit or district, it is common for IOCG mineralisation to be located adjacent to barren iron oxide bodies, such as the barren hematite cores of the Olympic Dam and Prominent Hill deposits, and barren magnetite zones at Prominent Hill and Wirrda Well. In these cases, one or two drill holes testing the centre of the strongest coincident gravity and/or magnetic anomaly may miss mineralisation. The following criteria help vector towards the most prospective parts of IOCG-related alteration systems:

1. Hematite-bearing alteration close to the chemical (redox) gradient between magnetite- and hematite-bearing (Fe^{2+} to Fe^{3+}) alteration,
2. Proximal feeder fault conduits linked to eastnortheast-/northeast-fault intersections,
3. Most intense (high frequency, polyphase) veining and brecciation,
4. Sericite, chlorite and/or carbonate alteration associated with abundant hematite.

As mineralisation is precipitated in response to steep temperature and redox gradients, it is necessary to vector towards the transition zones between cooler, more oxidised, alteration facies and the high-T magnetite zones, rather than on the end-member alteration zones themselves. Constrained and unconstrained 3D joint inversions of both magnetic and gravity data (e.g., Williams *et al.*, 2005; Howe, 2009) are particularly useful for mapping spatially-distributed redox boundaries, especially the transition from deeper magnetite-rich alteration (corresponding to a high amplitude magnetic anomaly with medium- to high amplitude density anomaly) to dense hematite-rich breccia bodies (corresponding to a low amplitude magnetic anomaly with high amplitude density anomaly), as shown in Fig. 12. However, some transitions may be temporal with little spatial separation (compare with Candelaria deposit: Marschik and Fontboté, 2001). The three largest IOCG deposits in the province are distinguished by mineralisation-related polymict breccias, whereas subeconomic and smaller systems are typically restricted to stratabound replacement mantos associated with stockwork fractures or sheeted to *en-echelon* vein arrays.

Other criteria can help identify the potential for high grade ore within mineralised zones. Zoning of native copper to chalcocite to bornite to chalcopyrite to pyrite is typical of higher grade systems, although the highest tenor copper minerals need not correspond to the highest grade copper mineralisation. Additionally, relatively high (juvenile) εNd isotope compositions of copper-gold mineralised rocks may help differentiate major versus minor IOCG systems (Skirrow *et al.*, 2007).

Concluding Remarks

What makes the Olympic IOCG Province so well endowed? In comparison with other parts of the Gawler and Curnamona cratons, it is distinguished by an abundance of mafic volcanics in the lower Gawler Range Volcanics, more oxidised A-type plutons, greater juvenile magmatic input manifest in mafic-ultramafic intrusions and basalts, more extensively reworked lithosphere with older metasomatised SCLM, a lack of thick reduced crustal units, and a higher frequency of translithospheric shear zones. Several of these factors combine to produce the most fertile metal source units. We regard the distribution of mafic volcanics to be more critical than the distribution of Hiltaba plutons as the critical metal source. Compared to other IOCG provinces, the Olympic IOCG Province is also notable for the intensity of the associated Mesoproterozoic felsic volcanism, which defines an unusually large and rapidly emplaced Felsic Large Igneous Province. Comparisons may be drawn with the Siberian Traps, one of the world's largest Mafic Large Igneous Provinces (e.g., Li *et al.*, 2009), which hosts the supergiant Norils'k-Talnakh Ni-Cu-PGM deposits. Both the Olympic Dam and Norils'k-Talnakh deposits are the largest and most shallowly-formed deposits of their class, reflecting extraordinary high energy systems.

Despite more than 30 years of IOCG exploration, we regard the residual discovery potential of the Olympic IOCG Province as high, given its large extent and extensive post-mineralisation cover. This conclusion is supported by the recent resurgence in the discovery rate over the last eight years which has seen the addition of two major deposits and three significant prospects (Table 1; e.g., Prominent Hill in 2001; Carrapateena in 2005; Hillside in 2008). The challenges for economic discoveries include finding sufficient high quality and bulk mineable resources to support development under thick overburden, and in reducing the false-positive rate for buried geophysical targets. Many of the highest amplitude coincident gravity and magnetic anomalies within 500 m of the surface have received at least first pass drill testing. Future discoveries require testing of geophysical anomalies that are deeper, inadequately tested, more remote, or non-conventional. In the latter case, the potential for related sulphide-rich (iron oxide-poor) copper and/or gold deposits remains largely untested within the Gawler craton. Delineation of deeper drill targets will require more sophisticated 3D joint inversion models of multiple geophysical data types to help reduce the potential for high false-positive anomaly rates that accompanies the lowering of anomaly thresholds.

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