Geology of the Olympic Dam Cu–U–Au–Ag–REE deposit

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Introduction

The giant Olympic Dam iron-oxide-associated Cu–U–Au–Ag–REE deposit is 520 km north-northwest of Adelaide in central SA (Fig. 1). The discovery history of the deposit in 1975 is well documented in Laylor (1984, 1986), O'Driscoll (1985), Reeve (1990a,b), Reeve et al. (1990), and Rutter and Esdale (1985).

The deposit contains ore reserves in excess of 600 Mt averaging 1.8% Cu, 0.5 kg/t U_3O_8, 0.5 g/t Au and 3.6 g/t Ag. This is included within an enormous resource of >2300 Mt containing ~30 Mt of Cu, 930 000 t of U_3O_8, 1200 t of Au and 6700 t of Ag. The deposit also contains ~10 Mt of REE (principally La and Ce) that are presently uneconomic to recover. Average iron grade of the resource is ~26% Fe.

Aerial view east of the Olympic Dam process plant and mine infrastructure. (Photo 48168)

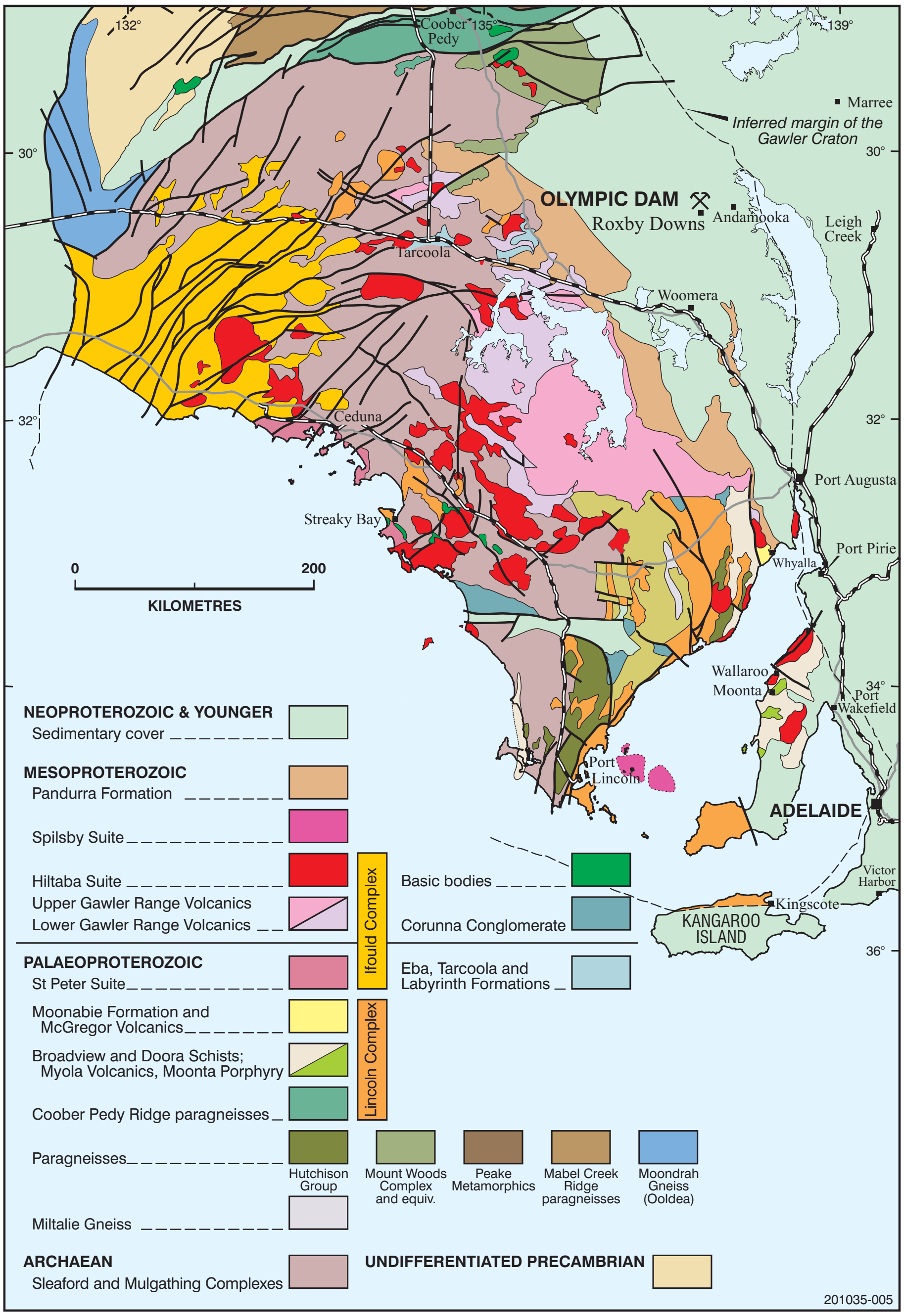


Fig. 1 *Interpreted subsurface geology of the Gawler Craton (after Daly et al., 1998).*

Regional geological setting

The Olympic Dam deposit is on the eastern margin of the Gawler Craton, unconformably overlain by ~300 m of Neoproterozoic to Cambrian age, flat-lying sedimentary rocks of the Stuart Shelf (Fig. 1). The oldest basement rocks in the province are metasedimentary rocks and deformed granites correlated with the Palaeoproterozoic Hutchison Group and Lincoln Complex granitoids, respectively (Parker, 1990). These rocks are intruded by Mesoproterozoic Hiltaba Suite granitoids and locally overlain by similar aged bimodal volcanic units correlated with the Gawler Range Volcanics (Flint, 1993).

The deposit is hosted within a large body of hydrothermal breccias, named the Olympic Dam Breccia Complex (ODBC) by Reeve et al. (1990), which occur entirely within the Roxby Downs Granite (Fig. 2). The Roxby Downs Granite is a pink to red-coloured, undeformed, unmetamorphosed, coarse to medium-grained, quartz-poor syenogranite with A-type affinities (Creaser, 1989). Petrological and petrochemical characteristics of the granite (Creaser, 1989) indicate that it is

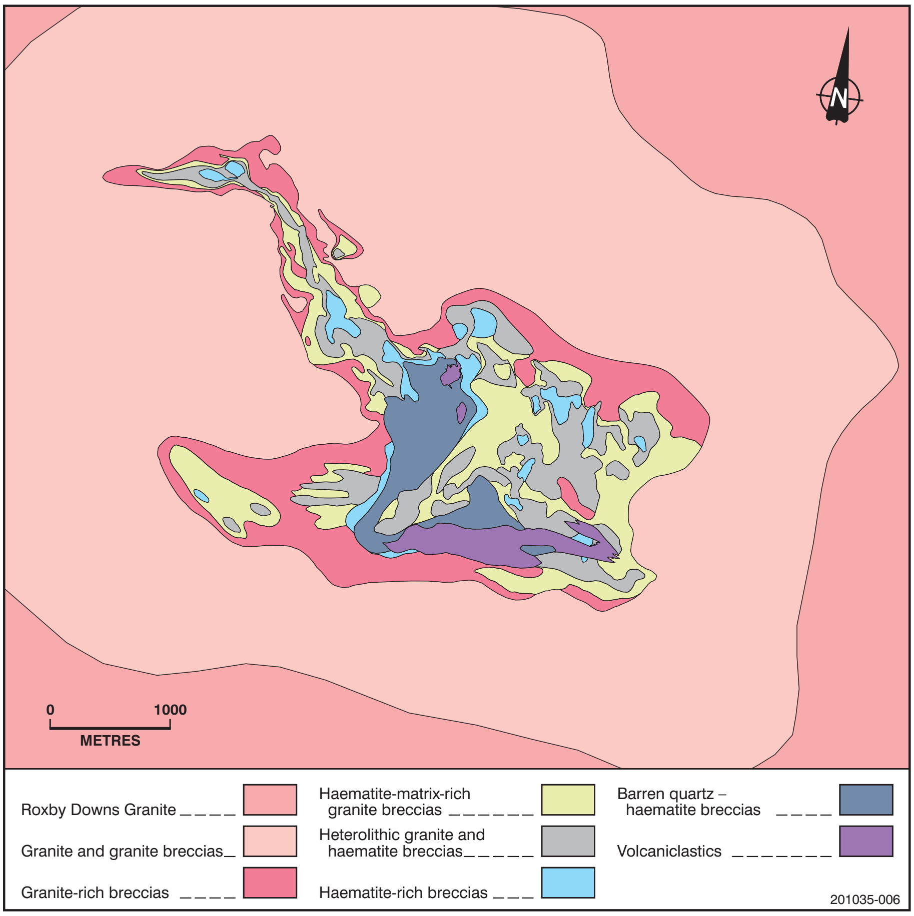
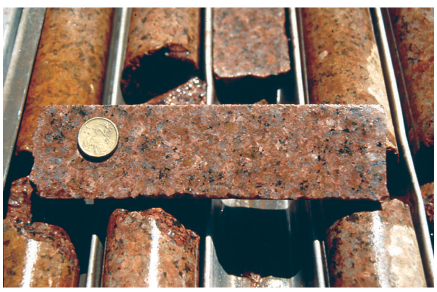


Fig. 2 Simplified geological plan of the ODBC showing the general distribution of major breccia types. Note the broad zonation from the host granite at the margins of the complex to progressively more haematite-rich lithologies at the centre.

similar to granitoid rocks of the Hiltaba Suite, which are widespread in the Gawler Craton (Flint, 1993).

The sedimentary rock units of the cover sequence are shown schematically on Figure 3 and are described by Roberts and Hudson (1983) and Preiss (1987).

The Olympic Dam deposit lies at the intersection of the major north-northwest-trending G2 and west-northwest-trending G9C gravity lineaments identified by O'Driscoll (1985). Regional geophysical data sets indicate that Olympic Dam is one of numerous coincident magnetic–gravity anomalies on the Stuart Shelf. Diamond drilling has revealed that many of these anomalies are caused by hydrothermal iron-oxide alteration in the basement, spatially associated with Hiltaba Suite granitoids (Gow et al., 1993).



Weakly altered Roxby Downs Granite. (Photo 48169)

Deposit host rocks

Olympic Dam Breccia Complex

Detailed descriptions of the ODBC have been documented by Oreskes and Einaudi (1990) and Reeve et al. (1990). The ODBC primarily consists of a funnel-shaped, barren, haematite–quartz breccia 'core' surrounded by an irregular array of variably mineralised and broadly zoned haematite–granite breccia bodies (Figs 2, 3). These breccia bodies have a range of lithologies, from granite-dominated on the periphery of the system to intensely haematised equivalents within the complex which show textural evidence for polycyclic alteration and brecciation events.

In plan view, the ODBC is irregular in shape (Fig. 2), with haematite–granite breccia bodies arranged around the central haematite–quartz breccia core,

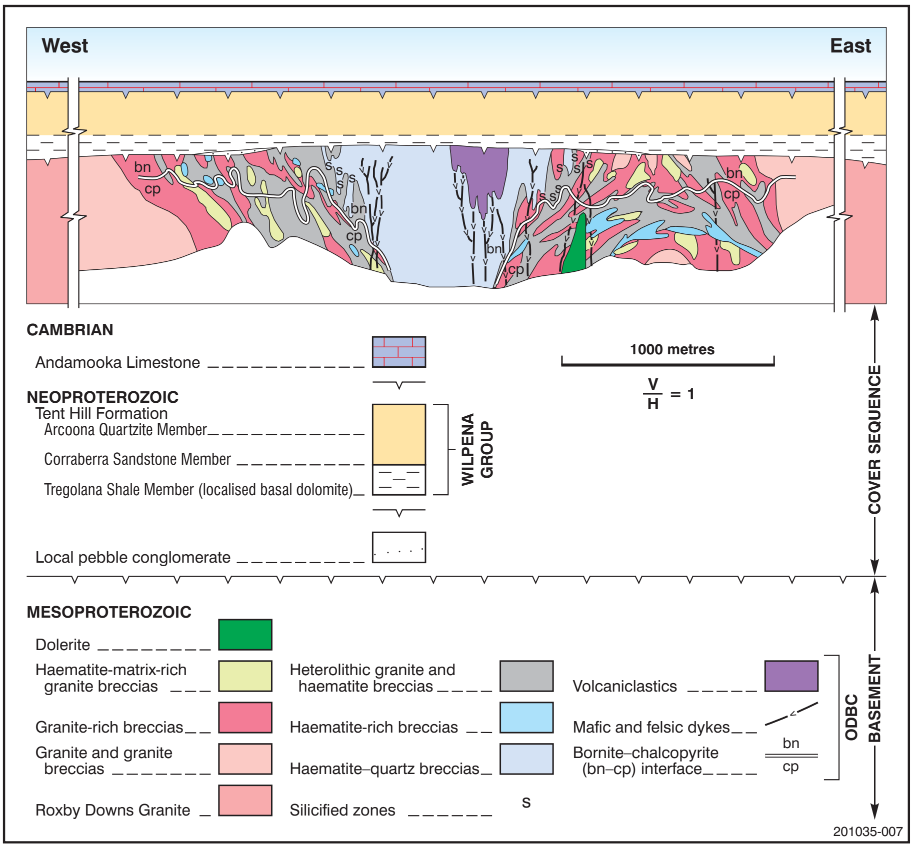


Fig. 3 Schematic east–west cross-section through the ODBC (after Reeve et al., 1990).

and a relatively long and narrow extension to the northwest. A halo of weakly altered and brecciated granite extends out 5–7 km from the core in all directions to an indistinct and gradational margin with the host granite. The strike length of the more haematite-altered breccias within the complex is >5 km in a northwest– southeast direction, and it is up to 3 km across. The ODBC locally extends to depths of >1.4 km, beyond the limits of current drilling.

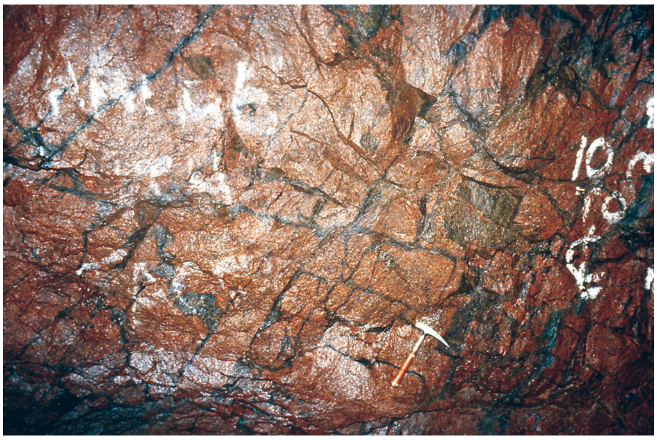
Haematite–granite breccias

Haematitic breccia bodies in the ODBC are irregularly shaped and sized, though typically elongate and steeply dipping to subvertical. Breccia zones can taper or thicken with depth and may pinch and swell over short distances. The individual bodies are variably mineralised and, while locally interconnected, are highly variable in composition, depending on the degree of brecciation and alteration they have undergone. Breccias are interpreted by Reeve et al. (1990) to have formed through a combination of five main processes: hydraulic fracturing, tectonic faulting, chemical corrosion, phreatomagmatism and gravity collapse.

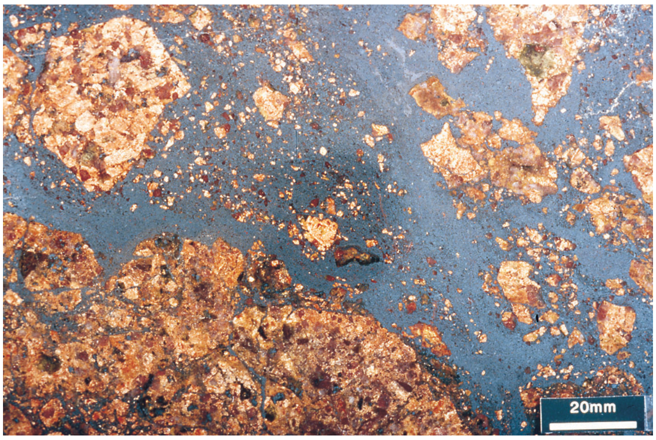
Granite-rich breccias are characterised by fracturing and veining and/or clast-supported breccias, with crackle and jig-saw textures locally preserved. Haematite-rich breccias are more commonly matrix supported, poorly sorted and contain angular clasts generally <0.2 m in size, although isolated clasts metres or tens of metres across are locally recognised. The breccia matrix is generally haematite with a component of fine-grained, intensely altered fragments derived from the granite host rock.

Repetitive lithification and rebrecciation has resulted in the mixing of granite clasts with clasts of haematite to produce heterolithic breccias and, in more extreme examples, haematite breccias where both the clasts and matrix are dominated by haematite. Heterolithic breccias are the most common haematite-rich breccia type and can contain a wide variety and proportion of different haematite clasts and altered granite clasts (Reeve et al., 1990). Other lithologies occurring as minor clast types include porphyritic volcanics correlated with the Gawler Range Volcanics; highly altered ultramafic to felsic intrusives; vein fragments of copper sulphides, fluorite, barite or siderite; highly altered fragments of unknown primary lithology; and laminated fine-grained to arkosic sediments.

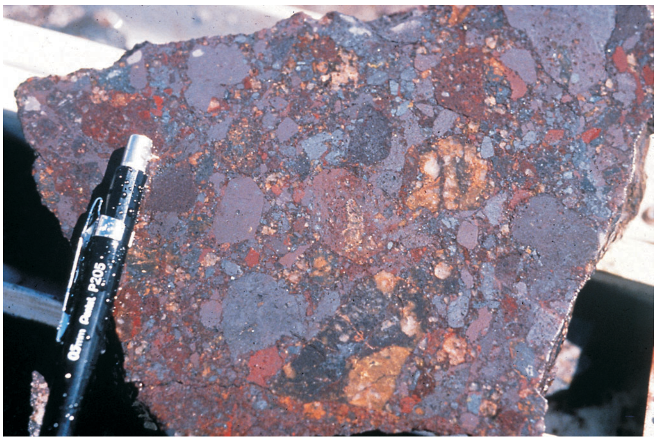
Haematite–quartz breccias occurring in the core of the deposit are considered an endmember product of repeated brecciation and haematite alteration of the host granite. These rocks typically only contain clasts of haematite and quartz within a matrix composed of haematite, barite and quartz grains (Reeve et al., 1990). They are differentiated from other completely haematised breccias within the ODBC by a distinct lack of sulphide mineralisation.



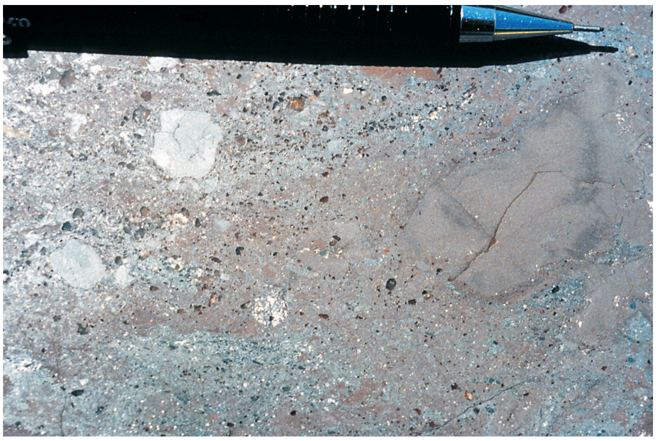
Weakly brecciated Roxby Downs Granite. The breccia matrix primarily consists of sericite and haematite, and occupies steep dilated joints and crosscutting fractures. (Photo 48170)



Typical granite-rich breccia with haematite-rich matrix. Note the partial disaggregation of the larger granite clasts. (Photo 48171)



Heterolithic haematite breccia containing a variety of haematite-rich, granitic and transitional clast types. (Photo 48172)



Haematite-quartz breccia containing haematite as clasts and matrix. Minor white disseminations are barite. (Photo 48173)

Clasts of rock types interpreted to have formed in a near-surface subaqueous or subaerial depositional environments (Reeve et al., 1990) are minor but widespread components of heterolithic breccias. Most abundant are clasts and blocks of fine-grained and finely laminated haematite–quartz± sericite siltstone and sandstone showing graded bedding and soft-sediment deformation features, interpreted by Reeve et al. (1990) to be fragments of epiclastic rocks derived from the major hydrothermal breccia types.

Surficial volcaniclastic rocks such as lapilli tuffs and laminated ash-fall tuffs showing semi-pervasive or highly selective haematite replacement are preserved in the upper parts of phreatomagmatic diatreme structures in the central part of the ODBC (Reeve et al., 1990).

Some porphyritic felsic volcanic clasts within the ODBC may be derived from coherent extrusive lava flows correlated with the Gawler Range Volcanics. These rocks were either overlying the Roxby Downs Granite and subsequently incorporated into the breccia complex as the hydrothermal system developed or, alternatively, may have been epiclastic in origin (Reeve et al., 1990).

Veins

Narrow (generally <10 mm thick) mono- or polymineralic veins, veinlets and vein fragments occur throughout the ODBC and in the surrounding granite. Vein assemblages typically consist of minerals which are also the dominant alteration and mineralisation phases within the breccia complex (Reeve et al., 1990) and consist of haematite, sericite, chlorite, siderite, barite, fluorite, quartz, sulphides or pitchblende in a variety of combinations.

Dykes

The ODBC is intruded by a variety of ultramafic, mafic and felsic dykes and their intrusive pyroclastic equivalents. In the upper part of the ODBC, dykes typically occur as narrow (<1 m), coherent bodies with irregular, tentacular or wispy morphologies (Reeve et al., 1990). The general distribution of dykes within the ODBC and their importance to brecciation and mineralisation is poorly understood.

The more mafic dykes have undergone intense texturally destructive sericite and haematite alteration, and their intrusive origins are generally interpreted from morphology, geometry and lithogeochemistry. Felsic dykes commonly have preserved porphyritic textures and are petrologically similar to the Gawler Range Volcanics. Alteration and local mineralisation of dykes, quench-fragmentation textures, reworked equivalents within breccia zones, juvenile fragments, and preservation of dykes within the root zones of diatreme structures indicate that intrusive activity was probably contemporaneous with hydrothermal activity.

Alteration

The characteristic hydrothermal alteration mineralogy at Olympic Dam is sericite–haematite, with less abundant chlorite, silica, carbonate (siderite) and magnetite. In detail, alteration assemblages are highly variable and show complex mineral distribution patterns. Despite this, systematic patterns of alteration are recognised across the overall deposit and at the scale of individual breccia zones (Fig. 4). In general, the degree of alteration intensity is directly associated with the amount of brecciation.

Highly contorted ash fall tuffs consisting of intensely sericitised layers (pale) and partially haematised layers (dark). Width of view is ~4 m across. (Photo 48174)

Intensely sericitised mafic dyke (yellowish brown) within a haematite-rich breccia. View is ~2 m high. (Photo 48175)

Iron oxide association

Magnetite cores within haematite grains suggest that the earliest phase of iron oxide alteration within the breccia complex was magnetite. Magnetite has subsequently been overprinted by widespread haematite alteration and is now only preserved at depth and within apparently less evolved breccia systems on peripheries of the ODBC. Magnetite contents in excess of 20% have been recorded within some strongly iron oxide altered breccia zones.

Haematite alteration is generally more abundant and intense towards the centre of the deposit, locally forming >95% of the rock. Haematite mainly replaces pre-existing minerals, including primary granitic components, dykes and secondary hydrothermal or vein minerals (Reeve et al., 1990). Haematite has also precipitated from solution in veins and vugs.

Iron oxides, predominantly haematite, are intimately associated with copper mineralisation at all scales. A number of studies suggest that Cu, U and REE were introduced contemporaneously with Fe (Oreskes and Einaudi, 1990; Johnson, 1993; Johnson and McCulloch, 1995; Roberts and Hudson, 1983; Reeve et al., 1990). Textural relations in mineralised breccias have been interpreted by Reeve et al. (1990) to suggest that sulphides either post-date or are coeval with closely associated or intergrown haematite.

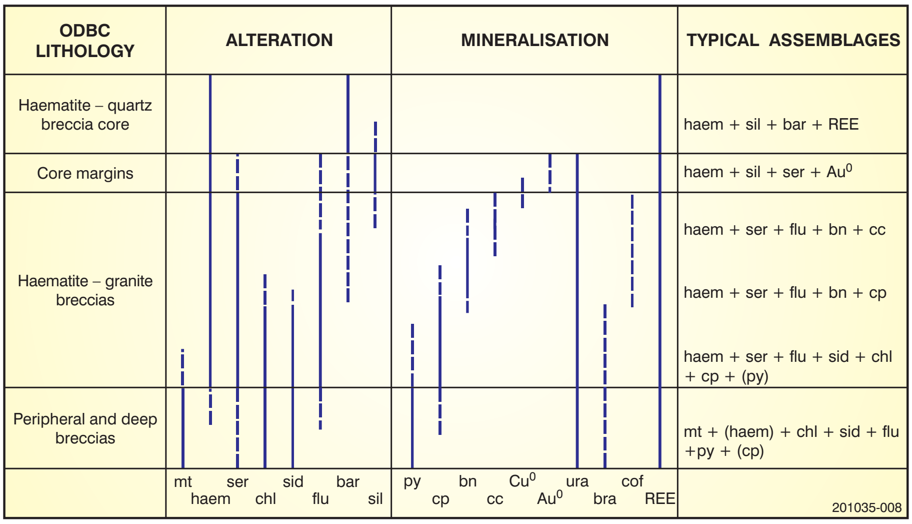


Fig. 4 *Generalised alteration and mineralisation patterns within the ODBC with some typical mineral assemblages. More common components of the ODBC shown in solid lines; neither absolute nor relative abundances are implied. mt=magnetite, haem=haematite, ser=sericite, chl=chlorite, sid=siderite, flu=fluorite, bar=barite, sil=silicification, py=pyrite, cp=chalcopyrite, bn=bornite, cc=chalcocite, Cu^{o}=native copper, Au^{o}=free gold, ura=uraninite, bra=brannerite, cof=coffinite, REE=lanthanum and cerium.*

Silicate alteration

Sericite is the dominant product of hydrothermal alteration of feldspar within the Roxby Downs Granite and is widespread within all breccias, except the haematite–quartz core. Locally very intense, texturally destructive sericitic alteration in particular results in zones or clasts of 'alteration lithologies' (Reeve et al., 1990).

Pseudomorphic chlorite alteration of feldspar within the Roxby Downs Granite is patchy but widespread within the breccia complex, and generally of low to moderate intensity. Carbonate alteration is dominated by siderite and is generally weak within mineralised breccias. Chlorite and siderite alteration is more abundant at depth and on the periphery of the breccia zones, and is commonly associated with more magnetite-dominated alteration and chalcopyrite mineralisation.

Minor quartz alteration is present throughout the breccia complex. However, more intense silicification occurs in discrete, irregular zones, mainly around the margins of the central core of haematite–quartz breccias. These silicified zones are prospective for higher grade gold mineralisation.

Mineralisation

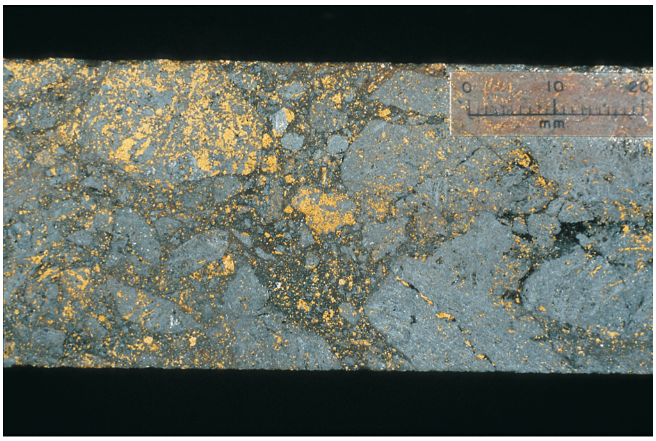
Ore minerals

The principal copper-bearing minerals in the deposit are chalcopyrite, bornite, chalcocite (djurleite–digenite) which, on the basis of Nd isotopic data and textural and geochemical features, appear to have precipitated cogenetically (Johnson and McCulloch, 1995). A minor amount of native copper and other copper-bearing minerals are locally present. The main uranium mineral is uraninite (pitchblende), with lesser coffinite and brannerite. Minor gold and silver are intimately associated with the copper sulphides. The main REE-bearing mineral is bastnaesite (Oreskes and Einaudi, 1990).

Copper ore minerals occur as disseminated grains, veinlets and fragments within the breccia zones (Reeve et al., 1990). Massive ore is rare. Mineralisation primarily occurs within the matrix of the breccias, though repeated lithification and rebrecciation has also resulted in mineralised clasts. Gold typically occurs as extremely fine particles within and associated with the copper sulphide grains. Silver largely occurs in solid solution with the sulphide minerals. Pitchblende generally occurs as fine-grained disseminations within haematitic breccias, intergrown with sulphides and haematite (Oreskes and Einaudi, 1990).

Fluorite or barite mineralisation characteristically occurs together with sulphide mineralisation. Fluorite is locally abundant within mineralised breccias, occurring at levels of up to 1–2% as disseminations, clasts and veinlets (Reeve et al., 1990). Barite is present at low levels within most of the haematite–granite breccias, occurring as disseminations and crackle veins. Higher concentrations (typically 2–5% Ba) occur in the central haematite–quartz breccia core of the deposit.

High-grade bornite–chalcocite mineralisation hosted by haematite–granite breccia. (Photo 48176)



High-grade disseminated chalcopyrite mineralisation hosted within both clasts and matrix of a haematite-rich breccia. (Photo 48177)

Ore zones

Ore zones in the ODBC account for only a small fraction of total volume of breccia but weak Cu, U, Au, Ag and REE mineralisation is widespread within the ODBC at background levels of up to 0.5% Cu, 0.2 kg/t U_3O_8, 0.5 g/t Au and 1 g/t Ag (Reeve et al., 1990). There is a general correlation between higher grade Cu–U mineralisation and more haematite-altered rocks. However, the central haematite–quartz breccia zone is essentially barren of Cu–U mineralisation.

Copper grade within the ore zones averages 1–6%, and is generally higher within bornite–chalcocite ore due mainly to the increased copper tenor of the sulphides (Reeve et al., 1990). Bornite–chalcocite mineralisation comprises ~35% of the ore, while the remainder is dominated by chalcopyrite. Average gold grades of 0.6 g/t and uranium grades of 0.6 kg/t are found throughout the ore zones, though higher grades show a weak correlation with bornite–chalcocite mineralisation, and both show local enrichment associated with favourable host lithologies. Silver grades average ~3 g/t but are also generally higher for bornite–chalcocite mineralisation. Variable REE mineralisation averaging 3000–5000 ppm combined La and Ce occurs throughout the breccia zones, including the central haematite–quartz core, where concentrations are generally higher.

The geometries of the ore zones are highly complex as a result of the sulphide zonation pattern (see below) and the distribution of more favourable haematite-rich lithologies within the breccia complex (Fig. 5).

Mineralisation zonation patterns

Sulphide mineralisation within the deposit shows a broad, lateral and vertical zonation pattern (Reeve et al., 1990; Oreskes and Einaudi, 1990) from pyrite–chalcopyrite at depth and on the periphery of the deposit, grading into bornite, then chalcocite (Fig. 4). Higher grade gold zones occur in narrow, complex zones within and around the silicified margins of the haematite–quartz core.

The interface between chalcopyrite and bornite is generally sharp and readily mappable (Reeve et al., 1990). On a broad scale, this boundary is flat lying, becoming steeply dipping around the margins of the central haematite–quartz core. In detail, the bornite–chalcopyrite interface and other observed mineralogical boundaries are highly irregular and locally convoluted.

Reeve et al. (1990) argued that the overall sulphide pattern is hypogene in origin, suggesting multi-stage introduction of hydrothermal fluids and a variety of ore precipitation mechanisms to explain the principal sulphide paragenetic series and complex relationships observed in mineralisation and alteration assemblages (Eldridge and Danti, 1994).

Structure

Structural studies of the Olympic Dam deposit are summarised by Sugden and Cross (1991). They observed that the individual breccia bodies within the ODBC generally have a northwest to north-northwest trend, and are aligned along an overall west-northwest axis. Breccia zones also trend in east–west and northeast–southwest directions in particular parts of the complex. The pattern of breccia bodies within the ODBC suggests an *en echelon* fault network, possibly within a dextral dilational jog zone.

At the mine scale, the ODBC is transected by an array of irregular and discontinuous brittle faults, with multiple and episodic movement histories. Most of these structures appear to postdate the major breccia formation events and many have exploited pre-existing anisotropies such as the lithological or intrusive contacts (Sugden and Cross, 1991).

Dominant structural trends documented by Sugden and Cross (1991) within the ODBC are subdivided into:

- syn-hydrothermal structures
- early strike-slip faults
- reverse faults
- late-stage vein arrays.

Syn-hydrothermal structures inferred to have been active during development of the ODBC are only preserved as isolated, discontinuous fragments. Early strike-slip faults which overprint the syn-hydrothermal structures are typically subvertical, discontinuous and occur throughout the mine as a conjugate set trending in west-northwest and north-northwest. A prominent east-northeast-trending structure in the southeastern part of the deposit is also correlated with this phase of faulting.

Geochronology

The age of the Roxby Downs Granite and maximum age of the brecciation and mineralisation at Olympic Dam is constrained by a U–Pb zircon date of 1588±4 Ma (Creaser, 1989; Creaser and Cooper, 1993). SHRIMP U–Pb zircon data obtained from three felsic dykes within the ODBC by Johnson and Cross (1995) indicated an age of ~1590 Ma. On the basis of textural relationships between sulphides and Fe-rich breccias,

Disseminated mineralisation in drill core showing the chalcopyrite–bornite sulphide transition, almost in the centre of the image and marked by a faint brown line. (Photo 48178)

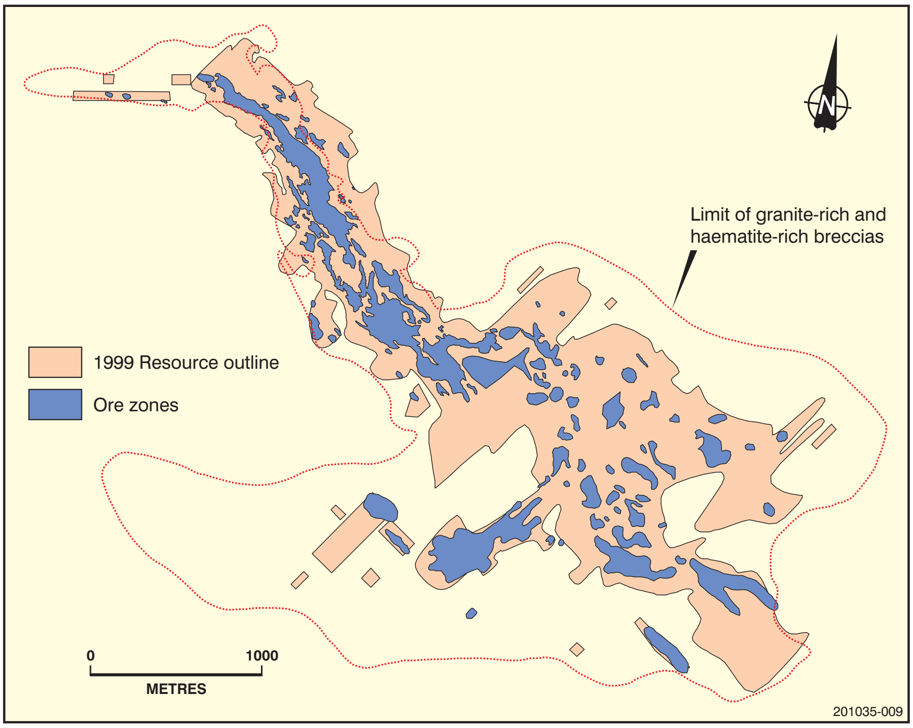


Fig. 5 *Olympic Dam resource outline at the 41 Level±100 m, showing distribution of ore zones.*

and the crosscutting relationship of the igneous units to the mineralised breccias, Johnson and Cross (1995) argued that brecciation, mineralisation and intrusive activity at Olympic Dam were contemporaneous at ~1590 Ma.

Deposit model

Formation environment and geological evolution

The ODBC predominantly formed in a high-level volcanic environment (Oreskes and Einaudi, 1990, 1992; Reeve et al., 1990). Surficial lithologies within the complex suggest that the hydrothermal system breached the palaeosurface, and it has been proposed by Reeve et al. (1990) that the deposit may have formed a phreatomagmatic volcanic edifice similar to a maar complex.

Hydrothermal brecciation initiated at structurally controlled sites within the Roxby Downs Granite evolved contemporaneously with alteration, veining, dyke intrusion, phreato-magmatic activity and mineralisation in a highly energetic, dynamic and complex system. Multiple overprinting brecciation events and the incorporation of subvolcanic, volcaniclastic and epiclastic lithologies into the breccias contributed to the highly variable nature of the deposit host rocks. Brittle structures developed as the hydrothermal system waned and breccias became more lithified (Reeve et al., 1990).

The Roxby Downs Granite and an estimated 500 m of the upper parts of the ODBC were eroded during the Meso- to Neoproterozoic, possibly during Marinoan glaciation (Reeve et al., 1990). The overlying sedimentary rock sequence was subsequently deposited. With the exception of large, late-stage barite–fluorite veins which overprint mineralisation and intrusion of mafic dykes possibly correlated with the Gairdner Dyke Swarm, there has otherwise been only minor geological modification of the deposit since burial; there is no significant sulphide recrystallisation (Reeve et al., 1990).

Genetic models

As underground development of the deposit has advanced, it was recognised that mineralisation was contained within a granite-hosted breccia complex, and a near-surface hydrothermal origin was proposed to account for the observed geological features and mineralisation distribution (Oreskes and Einaudi, 1990; Reeve et al., 1990). However, the source or sources of the hydrothermal fluids and metals which formed the deposit remains a contentious issue.

Haynes et al. (1995) proposed that metal deposition was controlled by coupled redox reactions resulting from the mixing of an ascending, hot, reduced Fe-rich water, with cooler, oxidised and saline meteoric and/or lacustrine water in the upper part of the breccia complex. These workers argued on the basis of mineral composition, ore texture and thermodynamic modelling that the oxidised groundwaters primarily contributed ore components to the system and invoke polycyclic mixing events to explain the observed mineralisation and alteration zonation patterns. On the basis of this work, Barton and Johnson (1996) have included Olympic Dam in their evaporitic-source model for Fe-oxide–(REE–Cu–Au–U) mineralisation.

Oreskes and Einaudi (1992) proposed a two-stage genesis of the iron oxide assemblage at Olympic Dam, involving at least two temporally distinct hydrothermal fluid types. In their model, magnetite formation is associated with an earlier high-temperature fluid, possibly of magmatic origin. A significantly later, lower temperature fluid which destructively overprints the primary magnetite with haematite alteration and associated ore mineralisation possibly has some component of surficial origin. A similar model has been proposed for other iron oxide associated deposits on the Stuart Shelf such as Emmie Bluff (Gow et al., 1994).

A magmatic origin for mineralising fluids is also a possibility proposed by Johnson and McCulloch (1995) who analysed the Sm–Nd isotopic signature of the ore. Results indicate at least two mineralising fluid compositions: one in isotopic equilibrium with the Roxby Downs Granite and a magnetite alteration assemblage; the other strongly influenced by a mafic–ultramafic, mantle-derived magma associated with haematite alteration and ore mineralisation. Mafic and felsic dykes within the ODBC may indicate a direct magmatic association for these hydrothermal fluid sources (Johnson and McCulloch, 1995; Hitzman et al., 1992).

Current consensus among geologists at Olympic Dam is that the deposit is the product of an evolving hydrothermal system in which the hydrothermal fluids and associated metals were both primarily derived from a magmatic source. WMC sulphur isotope data support this interpretation (Eldridge and Danti, 1994). Overall geological relationships within the ODBC indicate that hydrothermal activity, breccia formation and dykes were probably associated with high-level mafic–felsic Hiltaba Suite plutons and coeval Gawler Range Volcanics extrusive equivalents (Reeve et al., 1990; Johnson and Cross, 1995).

Acknowledgements

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References

Barton, M.D. and Johnson, D.A., 1996. Evaporitic-source model for igneous related Fe oxide–(REE–Cu–Au–U) mineralisation. *Geology,* 24(3):259-262.

Creaser, R.A., 1989. The geology and petrology of Middle Proterozoic felsic magmatism of the Stuart Shelf, South Australia. *La Trobe University, Melbourne. Ph.D. thesis* (unpublished).

Creaser, R.A. and Cooper, J.A., 1993. U–Pb geochronology of Middle Proterozoic felsic magmatism surrounding the Olympic Dam Cu–U–Au–Ag and Moonta Cu–Au–Ag deposits, South Australia. *Economic Geology,* 88:186-197.

Daly, S.J., Fanning, C.M. and Fairclough, M.C., 1998. Tectonic evolution and exploration potential of the Gawler Craton, South Australia. *AGSO Journal of Australian Geology and Geophysics,* 17(3):145-168.

Eldridge, C.S. and Danti, K., 1994. Low sulfur isotope ratios; high gold values — a closer look at the Olympic Dam Deposit via SHRIMP. *Geological Society of America. Abstracts with Programs,* 26(7):A489-A490.

Flint, R.B. (Compiler), 1993. Mesoproterozoic. *In:* Drexel, J.F., Preiss, W.V. and Parker, A.J. (Eds), The geology of South Australia. Vol. 1, The Precambrian. *South Australia. Geological Survey. Bulletin,* 54:106-169.

Gow, P.A., Wall, V.J. and Valenta, R.K., 1993. The regional geophysical response of the Stuart Shelf, South Australia. *Exploration Geophysics,* 24:513-520.

Gow, P.A., Wall, V.J., Oliver, N.H.S. and Valenta, R.K., 1994. Proterozoic iron oxide (Cu–U–Au–REE) deposits: further evidence of hydrothermal origins. *Geology,* 22:633-636.

Haynes, D.W., Cross, K.C., Bills, R.T. and Reed, M.H., 1995. Olympic Dam ore genesis: a fluid mixing model. *Economic Geology,* 90:63-74.

Hitzman, M.W., Oreskes, N. and Einaudi, M.T., 1992. Geological characteristics and tectonic setting of Proterozoic iron oxide (Cu–U–Au–REE) deposits. *Precambrian Research,* 58:241-287.

Johnson, J.P., 1993. The geochronology and radiogenic isotope systematics of the Olympic Dam copper–uranium–gold–silver deposit, South Australia. *Australian National University, Canberra. Ph.D. thesis* (unpublished).

Johnson, J.P. and Cross, K.C., 1995. U–Pb geochronological constraints on the genesis of the Olympic Dam Cu–U–Au–Ag deposit, South Australia. *Economic Geology,* 90:1046-1063.

Johnson, J.P. and McCulloch, M.T., 1995. Sources of mineralising fluids for the Olympic Dam deposit (South Australia): Sm–Nd isotopic constraints. *Chemical Geology,* 121:177-199.

Laylor, J.H., 1984. Olympic Dam South Australia — the discovery history. *Geological Society of Australia. Abstracts,* 12:321-322.

Laylor, J.H., 1986. Olympic Dam copper–uranium–gold deposit, South Australia. *AAPG Bulletin*, 70:926.

O'Driscoll, E.S.T., 1985. The application of lineament tectonics in the discovery of the Olympic Dam Cu–U–Au deposit at Roxby Downs, South Australia. *Global Tectonics and Metallogeny,* 3(1):43-57.

Oreskes, N. and Einaudi, M.T., 1990. Origin of rare earth element-enriched haematite breccias at the Olympic Dam Cu–U–Au–Ag deposit, Roxby Downs, South Australia. *Economic Geology,* 85:1-28.

Oreskes, N. and Einaudi, M.T., 1992. Origin of hydrothermal fluids at Olympic Dam: preliminary results from fluid inclusions and stable isotopes. *Economic Geology,* 87:64-90.

Parker, A.J., 1990. Gawler Craton and Stuart Shelf — regional geology and mineralisation. *In:* Hughes, F.E. (Ed.), Geology of the mineral deposits of Australia and Papua New Guinea. *Australasian Institute of Mining and Metallurgy. Monograph Series,* 14:999-1008.

Preiss, W.V. (Compiler), 1987. The Adelaide Geosyncline: Late Proterozoic stratigraphy, sedimentation, palaeontology and tectonics. *South Australia. Geological Survey. Bulletin,* 53.

Reeve, J.S., 1990a. The discovery and evaluation of the Olympic Dam deposit. *In:* Glasson, K.R., Blaikie, A.H. and Woodcock, J.T. (Eds), *Geological aspects of the discovery of important minerals in Australia.* Australasian Institute of Mining and Metallurgy, Melbourne, pp.125-133.

Reeve, J.S., 1990b. The discovery and evaluation of gold mineralisation within the Olympic Dam deposit. *In:* Glasson, K.R., Blaikie, A.H. and Woodcock, J.T. (Eds), *Geological aspects of the discovery of important minerals in Australia.* Australasian Institute of Mining and Metallurgy, Melbourne, pp.57-58.

Reeve, J.S., Cross, K.C., Smith, R.N. and Oreskes, N., 1990. Olympic Dam copper–uranium–gold–silver deposit. *In:* Hughes, F.E. (Ed.), Geology of the mineral deposits of Australia and Papua New Guinea. *Australasian Institute of Mining and Metallurgy. Monograph Series,* 14:1009-1035.

Reynolds, L.J., 2000. Geology of the Olympic Dam Cu–U–Au–Ag–REE deposit. *In:* Porter, T.M. (Ed.), *Hydrothermal iron oxide copper–gold and related deposits: a global perspective.* Australian Mineral Foundation, Adelaide.

Roberts, D.E. and Hudson, G.R.T., 1983. The Olympic Dam copper–uranium–gold–silver deposit, Roxby Downs, South Australia. *Economic Geology,* 78:799-822.

Rutter, H. and Esdale, D.J., 1985. The geophysics of the Olympic Dam discovery. *Exploration Geophysics,* 16(2-3):273-276.

Sugden, T.J. and Cross, K.C., 1991. Significance of overprinting fault systems in the Olympic Dam Breccia Complex. *In:* Structural geology in mining and exploration. *University of Western Australia. Geology Department and University Extension. Publication,* 25:93-98.