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# GEOLOGY OF THE OLYMPIC DAM Cu-U-Au-Ag-REE DEPOSIT

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**Abstract -** The ~1590 Ma Olympic Dam Cu-U-Au-Ag-REE deposit is located in the Stuart Shelf geological province of South Australia, on the eastern margin of the Gawler Craton. The deposit is hosted by the Olympic Dam Breccia Complex, a large hydrothermal breccia system wholly contained within the Roxby Downs Granite, a Proterozoic age granitoid interpreted to be part of the Hiltaba Suite. Initial hydrothermal activity within the Olympic Dam Breccia Complex was probably localised by structures in a dextral fault jog environment. Subsequent development of the complex involved repetitive and overprinting physical, chemical and volcanic brecciation mechanisms, resulting in a highly variable array of irregularly shaped and distributed breccia zones with widely differing and gradational lithologies. A complex pattern of hydrothermal alteration dominated by hematite and sericite, with lesser chlorite, siderite and quartz is associated with the breccia zones. Mineralisation within the deposit is intimately associated with iron-oxide alteration of the granitoid, which dominantly occurs as hematite, with lesser magnetite at depth and on the periphery of the breccia complex. The principal copper minerals within the deposit show a broad lateral and vertical, hypogene zonation pattern grading from chalcopyrite on the margins to bornite, then chalcocite adjacent to a central barren core. Gold and silver are mainly associated with the copper sulphides, while uranium dominantly occurs in pitchblende disseminated throughout the hematitic breccia zones. Overall, mineralisation grade generally correlates with the degree of hematite alteration and is largely dependent on copper sulphide tenor. Minor brittle faulting post-dates breccia development and appears to have exploited existing anisotropies within the complex. Late-stage fault movements are associated with barite-fluorite vein arrays which overprint the orebody. The deposit formed in a high level volcanic environment, venting to the surface and possibly forming a composite phreatomagmatic eruption crater, which has subsequently been completely eroded. Mafic and felsic dykes intruded the breccia complex, locally producing diatreme structures. Tectonism, hydrothermal activity, dyke intrusion, brecciation, alteration and mineralisation within the system were broadly concurrent and interdependent. Hydrothermal fluids and metals have a dominantly magmatic source, probably associated with the Middle Proterozoic volcano-plutonic event correlated with the Gawler Range Volcanics and Hiltaba Suite intrusives.

## Introduction

The giant Olympic Dam iron oxide associated copper-uranium-gold-silver-REE deposit is located in South Australia, approximately 520 km NNW of Adelaide (Fig. 1). The discovery of the deposit in 1975 by Western Mining Corporation (WMC) was the result of a multi-disciplinary exploration effort for sediment-hosted copper deposits integrating geology, geophysics and tectonic analysis. Discussion of various aspects of the discovery are detailed in Laylor (1984 and 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 (see Table 1). This is included within an enormous resource containing approximately 30 Mt of Cu, 930 Kt of $U_3O_8$, 1,200 t of Au and 6,700 t of Ag. The deposit also contains approximately 10 Mt of rare earth elements (principally La and Ce), however recovery of these metals is uneconomic with current technology. Average iron grade of the resource is approximately 26% Fe.

The orebody is exploited by a mechanised underground mining operation and on-site processing facilities comprising an autogenous mill, concentrator, hydrometallurgical plant, smelter, and refinery. Recent expansion of the mine and process plant has raised the annual production capacity of the operation to around 9 million tonnes of ore to recover approximately 200,000 t of refined copper, 4,300 t of $U_3O_8$, 80,000 oz Au and 800,000 oz Ag. Details of the development history of the deposit are documented by Roberts and Hudson (1983), Reeve (1990a,b) and Reeve *et al.* (1990).

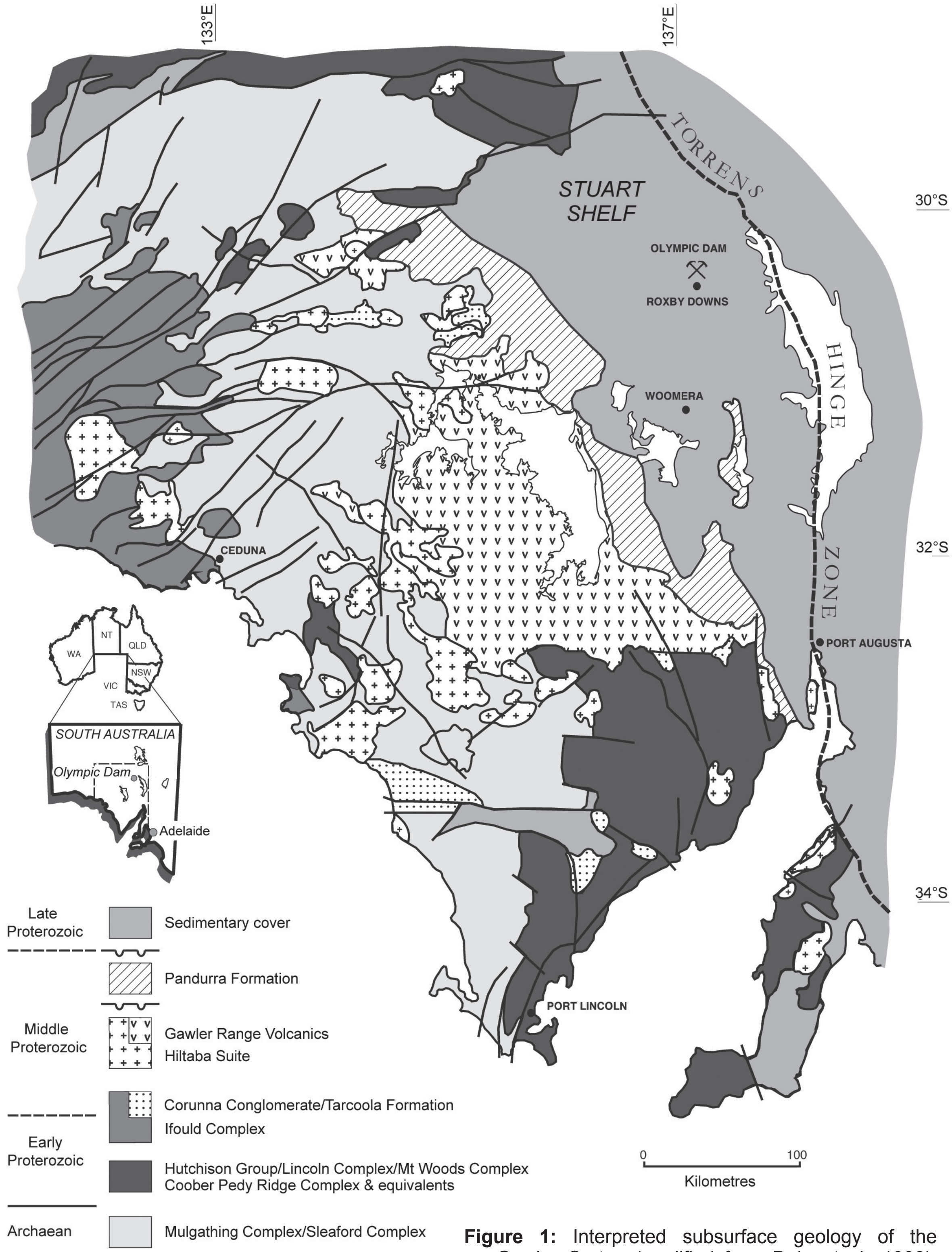


**Figure 1:** Interpreted subsurface geology of the Gawler Craton (modified from Daly *et al.*, 1998).

## Regional Geological Setting

The Olympic Dam deposit is located on the eastern margin of the Gawler Craton, unconformably overlain by approximately 300 m of Late Proterozoic to Cambrian age, flat-lying sedimentary rocks of the Stuart Shelf geological province (Fig. 1). The oldest basement rocks in the province are metasedimentary rocks and deformed granites correlated with the Early Proterozoic Hutchison Group and the Lincoln Complex granitoids, respectively (Parker, 1990). These rocks are intruded by Middle Proterozoic Hiltaba Suite granitoids and locally overlain by similar aged bimodal volcanic units correlated with the Gawler Range Volcanics (Flint, 1993). The edge of the craton, and the divide between the undeformed sediments on the Stuart Shelf and their thicker, deformed equivalents within the Adelaide Fold Belt, lies approximately 75 km east of the deposit, where it is defined by the NNW trending Torrens Hinge Zone.

The deposit is hosted within a large body of hydrothermal breccias, called the Olympic Dam Breccia Complex (ODBC) by Reeve *et al.* (1990), which occur entirely within the Roxby Downs Granite. 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 detailed by Creaser (1989), indicate that the Roxby Downs Granite is similar to granitoids of the Hiltaba Suite, which are widespread in the Gawler Craton (Flint, 1993).

The ODBC and the surrounding areas of Roxby Downs Granite form a local basement high on a broader regional basement uplift. The basement unconformity has a gently undulating palaeotopographic relief of about 70 m (Reeve *et al*, 1990) and the overlying cover sequence has a minimum thickness of 260 m. The sedimentary rock units of the cover sequence are shown schematically on Fig. 3 and are described by Roberts and Hudson (1983) and Preiss (1987).

The Olympic Dam deposit lies at the intersection of the major NNW trending G2 and WNW 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).

# Deposit Host Rocks

## *Olympic Dam Breccia Complex*

Detailed descriptions of the Olympic Dam Breccia Complex (ODBC) have been documented by Oreskes and Einaudi (1990) and Reeve *et al.* (1990). The ODBC primarily consists of a funnel-shaped, barren, hematite-quartz breccia "core" surrounded by an irregular array of variably mineralised and broadly zoned hematite-granite breccia bodies (Figs. 2 and 3). These breccia bodies have a range of lithologies from granite-dominated on the periphery of the system, to intensely hematised equivalents within the complex which show textural evidence for polycyclic alteration and brecciation events. There is a complete gradation from granite breccias to hematite-rich breccias and the subdivisions of the rock types within the breccia complex are largely artificial (Reeve *et al.*, 1990). Development of the ODBC can be considered as having formed by the progressive hydrothermal brecciation and iron metasomatism of the host granite (Oreskes and Einaudi, 1990).

In plan the ODBC is irregular in shape (Fig. 2), with hematite-granite breccia bodies arranged around the central hematite-quartz breccia core, and a relatively long and narrow extension to the NW. An apparently less significant extension occurs in the SE of the deposit, and recently a new area of breccias has been identified in the SW of the deposit. A halo of weakly altered and brecciated granite extends out approximately 5 to 7 km from the core in all directions, to an indistinct and gradational margin with the host granite. The strike length of more hematite altered breccias within the complex is greater than 5 km in a NW-SE direction, and it is up to 3 km across. The ODBC is generally poorly explored below 800 m depth but locally extends to depths of greater than 1.4 km, beyond the limits of current drilling.

## *Hematite-Granite Breccias*

The hematitic breccia bodies within the ODBC are irregularly shaped and sized, though typically elongate and steeply dipping to sub-vertical. 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, they 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. The complex and repeated interplay of these processes contributes to the variable nature of the breccia compositions. Owing to the highly dynamic nature of breccia formation, correlation of the brecciation and alteration histories between different breccia zones is generally impossible.

In detail, breccia zones can mimic the general deposit trends, grading outward from hematite-rich breccias through "heterolithic" granite-hematite breccias, to granite breccias with hematite matrices, then to hematite altered

**Table 1:** Olympic Dam Resources and Reserves 1999 (from WMC Limited Annual Report, 1999). Note that Resources listed include Reserves.

| | Million Tonnes | Cu (%) | $U_3O_8$ (kg/t) | Au (g/t) | Ag (g/t) |
|---|---|---|---|---|---|
| **Reserves** | | | | | |
| Proved | 121 | 2.4 | 0.6 | 0.6 | 4.2 |
| Probable | 485 | 1.6 | 0.5 | 0.5 | 3.4 |
| **Total** | **605** | **1.8** | **0.5** | **0.5** | **3.6** |
| **Resources** | | | | | |
| Measured | 500 | 1.8 | 0.5 | 0.5 | 3.6 |
| Indicated | 1,150 | 1.3 | 0.4 | 0.5 | 2.9 |
| Inferred | 670 | 1.1 | 0.4 | 0.4 | 2.4 |
| **Total** | **2,320** | **1.3** | **0.4** | **0.5** | **2.9** |

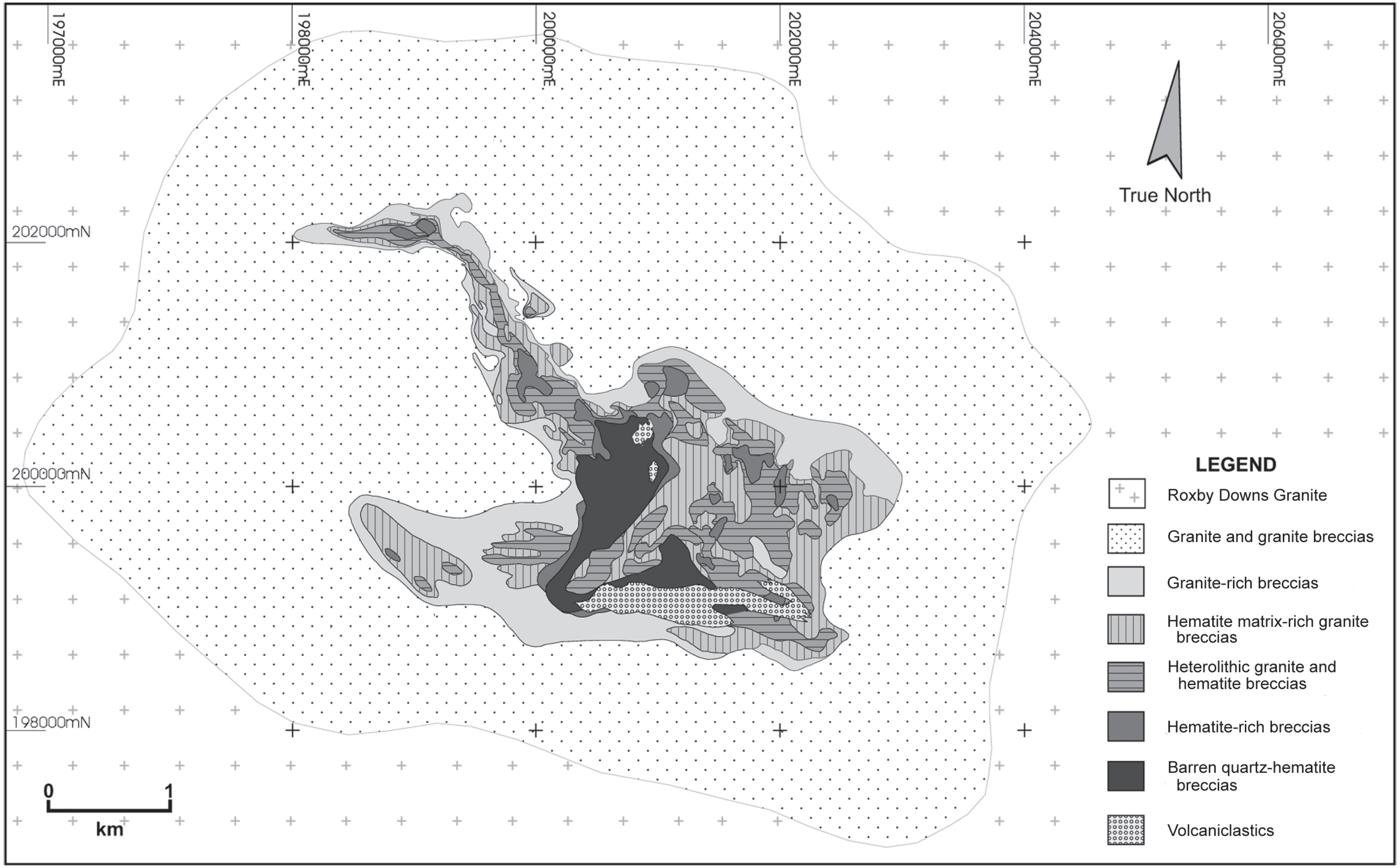


**Figure 2:** Simplified geological plan of the Olympic Dam Breccia Complex showing the general distribution of the major breccia types. Note the broad zonation from the host granite at the margins of the breccia complex to progressively more hematite rich lithologies in the centre.

granite or hematite veined granite, and finally into weakly sericitised and fractured granite. Gradational boundaries like these are observed on a scale of metres to tens or hundreds of metres. In contrast, breccia zone margins can also be abrupt, juxtaposing hematite-rich breccias with relatively weakly altered granite.

Textural variation of the breccias as a result of variable brecciation processes and intensity has been documented in detail by Reeve *et al.* (1990). Granite-rich breccias are characterised by fracturing and veining and/or clast supported breccias, with crackle and jig-saw textures locally preserved. Hematite-rich breccias are more commonly matrix supported, poorly sorted and contain angular clasts generally <20 cm in size, although isolated clasts metres or tens of metres across are locally recognised. The breccia matrix is generally hematite with a component of fine-grained, intensely altered fragments derived from the granite host rock. Layering and discontinuous streaming textures are locally developed within the matrix.

Repetitive lithification and rebrecciation results in the mixing of granite clasts with clasts of hematite producing heterolithic breccias and, in more extreme examples, hematite breccias where both the clasts and matrix are dominated by hematite. Heterolithic breccias are the most common hematite-rich breccia type and can contain a wide variety and proportion of different hematite 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.

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

## *Incorporated Surficial Lithologies*

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 hematite-quartz±sericite siltstones and sandstones 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. Some may also represent exhalative sediments (Oreskes and Einaudi, 1990). A large, apparently down faulted block of these lithologies occurs in the southern part of the ODBC juxtaposed against hematite-quartz breccias and mineralised hematitic breccias (Fig. 2).

Surficial volcaniclastic rocks such as lapilli tuffs and laminated ash-fall tuffs showing semi-pervasive or highly selective hematite 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 alternately may have been epiclastic in origin (Reeve *et al.*, 1990).

## *Veins*

Narrow (generally <1cm thick) mono- or poly-mineralic 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 hematite, sericite, chlorite, siderite, barite, fluorite, quartz, sulphides or pitchblende in a variety of combinations. Rarer tourmaline and dolomitic veins also occur. Similar to the breccia zones which host the veining, the paragenesis of vein development is complex and multi-stage (Reeve *et al.*, 1990), and impossible to correlate across the deposit.

A late-stage conjugate array of laminated barite-fluorite-siderite-sulphide veins up to several metres thick overprints the ODBC and locally extends into the sedimentary cover sequence. These veins are not considered to be associated with the development of the ODBC, despite the similarity of their vein mineral assemblages.

## *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 (<1m), coherent bodies with irregular, tentacular or wispy morphologies (Reeve *et al.*, 1990). Extensional drilling suggests that dykes are more abundant at depth within the deposit and are less disrupted by brecciation processes. However, 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 hematite 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.

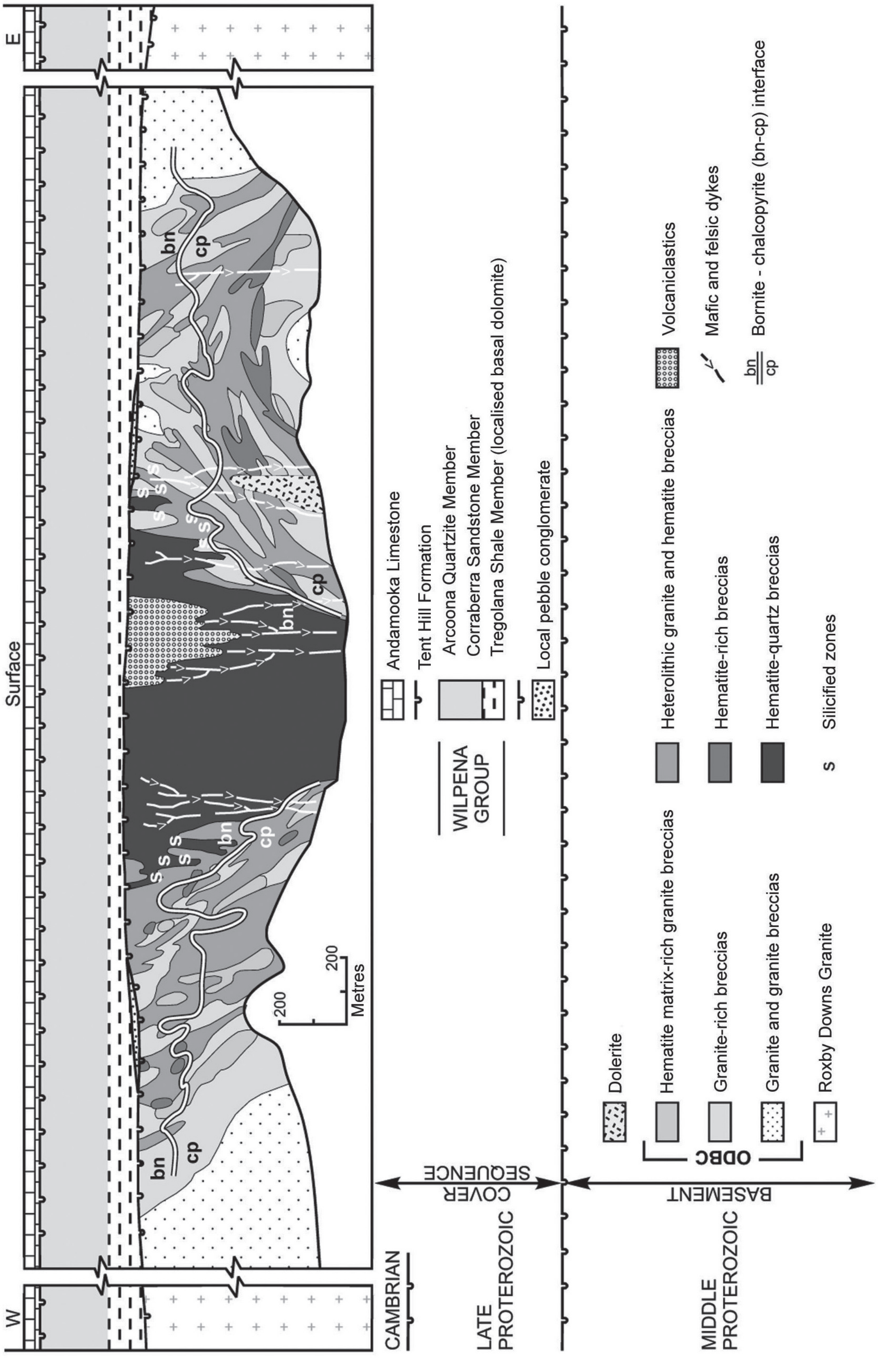


**Figure 3:** Schematic E-W cross section through the Olympic Dam Breccia Complex (modified from Reeve *et al.*, 1990).

A post-mineralisation, medium grained dolerite dyke, possibly associated with the regional Gairdner Dyke Swarm intrudes the breccia complex in the SE part of the deposit (Fig. 3).

# Alteration

The characteristic hydrothermal alteration mineralogy at Olympic Dam is sericite-hematite, with less abundant chlorite, silica, carbonate (siderite) and magnetite. The orebody is not associated with any sodic metasomatism (K. Ehrig, *pers. comm.*). In detail, alteration assemblages are highly variable and show complex mineral distribution patterns due to the polycyclic nature of the hydrothermal activity. Despite this, there are systematic patterns of alteration that 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. The strongest alteration is therefore localised within, and on the margins of, the hematite-granite breccia bodies which host the ore deposit. The halo of weakly brecciated granite which surrounds the main breccia bodies is characterised by only weak and highly variable sericite-hematite-chlorite-carbonate alteration.

## *Iron Oxide Association*

Magnetite cores within hematite grains suggest that the earliest phase of iron oxide alteration within the breccia complex was magnetite. Magnetite has subsequently been overprinted by widespread hematite 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.

Hematite alteration is generally more abundant and intense towards the centre of the deposit, locally forming greater than 95% of the rock. Hematite mainly replaces pre-existing minerals, including primary granitic components, dykes and secondary hydrothermal or vein minerals (Reeve *et al.*, 1990). Hematite has also precipitated from solution in veins and vugs. This variety of origins results in visually distinct hematite types defined by differences in crystallinity, grain size and colour.

Iron oxides, predominantly hematite, 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; and Reeve *et al.*, 1990). Textural relations in mineralised breccias have been interpreted by Reeve *et al.* (1990) to suggests that sulphides either post-date or are coeval with closely associated or intergrown hematite.

## *Silicate Alteration*

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

Psuedomorphic chlorite alteration of feldspars within the Roxby Downs Granite is patchy but widespread within the breccia complex, and generally low to moderate intensity. Carbonate alteration is dominated by siderite and is generally weak within mineralised breccias. In the NE and SW parts of the ODBC, siderite veins, vein fragments and locally pervasive alteration are more abundant. 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 hematite-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, 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 also locally observed. The main uranium mineral is uraninite (pitchblende), with lesser coffinite and brannerite. Minor gold and silver is 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. Sulphides precipitated from the hydrothermal fluids, rather than replacing pre-existing mineral grains (K. Cross, pers. comm.), and consequently mineralisation primarily occurs within the matrix of the breccias, though repeated lithification and rebrecciation also results 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 hematitic breccias, intergrown with sulphides and hematite (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 hematite-granite breccias, occurring as disseminations and crackle veins. Higher concentrations (typically 2-5% Ba) occur within the central hematite-quartz breccia core of the deposit.

## *Ore Zones*

Ore zones within 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 copper-uranium mineralisation and more hematite altered rocks. However, the central hematite-quartz breccia zone is essentially barren of copper-uranium mineralisation.

Copper grade within the ore zones averages between 1% and 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 approximately 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 similar 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 around 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 hematite-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 hematite-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). Similar trends are observed at the scale of individual breccia zones (Oreskes and Einaudi, 1990). Higher-grade gold zones occur in narrow, complex zones within and around the silicified margins of the hematite-quartz core. Patchy but locally high-grade native copper and chalcocite mineralisation occurs in granite-rich breccia zones, both within and on the margins of the breccia complex (Reeve *et al.*, 1990).

The interface between chalcopyrite and bornite, in particular, 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 hematite-quartz core. In detail, the bornite-chalcopyrite interface and other observed mineralogical boundaries are highly irregular and locally convoluted.

Reeve *et al.* (1990) argue 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. The patterns can be considered to represent sulphide stability fields, primarily controlled by temperature, shifting Fe/Cu ratios, oxidation or depletion of reduced sulphur availability (Eldridge and Danti, 1994). These patterns probably evolved and changed over time with the development of the breccia zones.

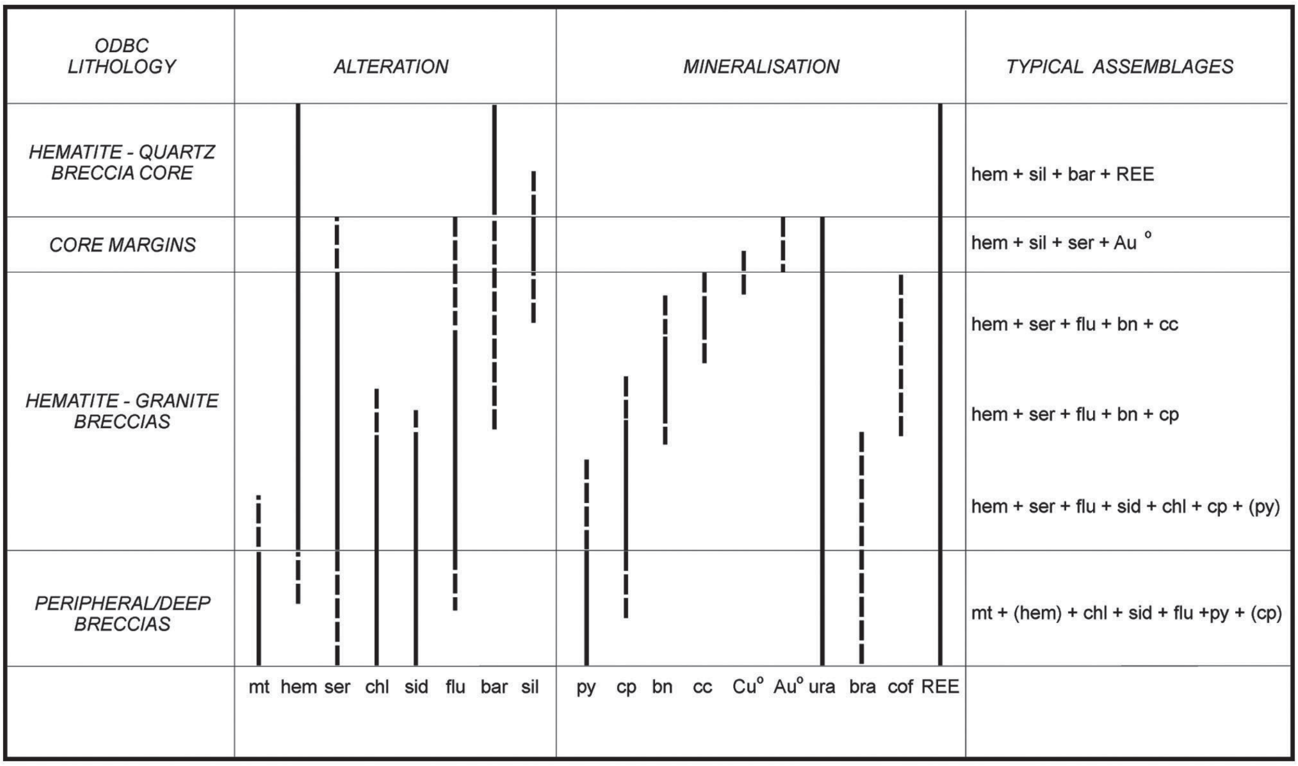


**Figure 4:** Generalised alteration and mineralisation patterns within the ODBC with some typical mineral assemblages. More common components of the ODBC shown in solid lines; neither absolute nor relative abundances are implied. mt=magnetite, hem=hematite, ser=sericite, chl=chlorite, sid=siderite,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

There is apparently only minor local modification to the mineralisation pattern by supergene weathering processes (Reeve *et al.*, 1990).

## Structure

Structural studies of the Olympic Dam deposit are summarised by Sugden and Cross (1991). They observe that the individual breccia bodies within the ODBC generally have a NW to NNW trend, and are aligned along an overall WNW axis. Breccia zones also trend in E-W and NE-SW directions in particular parts of the complex. Early controls on the formation of the ODBC have probably been obliterated during the on-going processes of brecciation and alteration (Reeve *et al.*, 1990; Sugden and Cross, 1991). However, the pattern of breccia bodies within the ODBC suggests an en-echelon fault network, possibly within a dextral dilational jog zone. The major bounding faults for such a jog have not been identified but it is possible that the photolineaments identified by O'Driscoll (1985) are the surficial expression of regional basement structures which have undergone minor post-Adelaidean reactivation.

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 post-date the major breccia formation events and many have exploited pre-existing anisotropies such as the lithological or intrusive contacts (Sugden and Cross, 1991). Individual faults are generally minor structures with small displacements (<10m) and short strike lengths which are only traceable in detailed mine development. A few structures are more prominent, with strike continuity of up to 2 km, inferred displacements of around 100m and locally containing cataclastic zones up to 1m wide. Few structures are observed to offset the ODBC-Adelaidean unconformity surface.

Dominant structural trends documented by Sugden and Cross (1991) within the ODBC are subdivided into 1) syn-hydrothermal structures, 2) early strike-slip faults, 3) reverse faults and, 4) late stage vein arrays. Syn-hydrothermal structures inferred to have been active during the 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 WNW and NNW orientations. A prominent ENE trending structure in the SE part of the deposit is also correlated with this phase of faulting. Reverse faults which post-date the strike-slip faults are prominent in the NW of the deposit where they occur either as NW trending structures with a moderate (30 to 50$^{o}$) dip to the SW, or as steeply E dipping faults (60 to 80$^{o}$) with a N-S strike orientation. Late stage conjugate NW and E-W trending strike-slip fault zones are associated with barite-fluorite$\underline{+}$carbonate vein arrays which transect the ODBC. Where observed, fracture trends in the cover sequence are similar to the late-stage vein arrays in the ODBC and these are interpreted by Sugden and Cross (1991) to have formed contemporaneously during the *ca* 500 Ma Delamarian Orogeny.

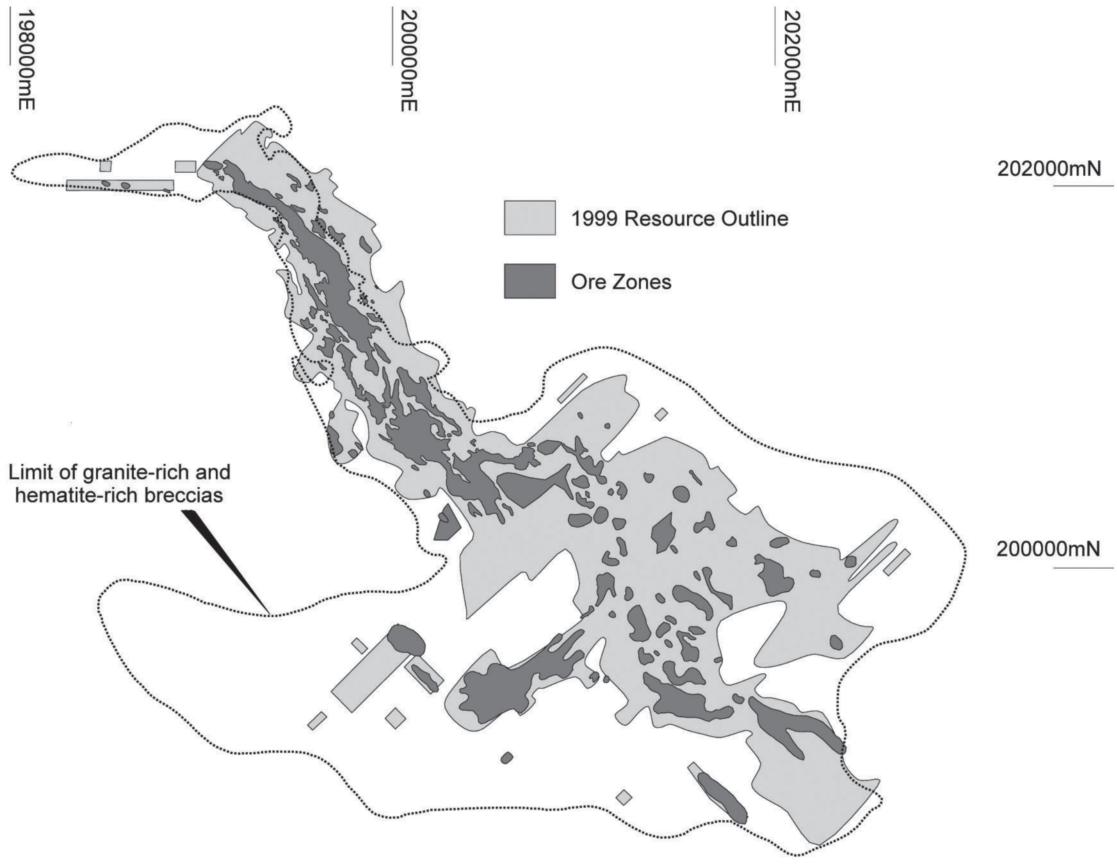


**Figure 5:** Olympic Dam resource outline at the 41 Level + 100m, showing distribution of ore zones.

## 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$\pm$4 Ma (Creaser, 1989, Creaser and Cooper, 1993). SHRIMP U-Pb zircon data collected from three felsic dykes within the Olympic Dam Breccia Complex by Johnson and Cross (1995) indicate an age of approximately 1590 Ma. On the basis of textural relationships between sulphides and Fe-rich breccias, and the cross-cutting relationship of the igneous units to the mineralised breccias, Johnson and Cross (1995) argue that brecciation, mineralisation and intrusive activity at Olympic Dam were contemporaneous at ~1590 Ma.

These data imply that brecciation at Olympic Dam must have closely followed emplacement and cooling of the Roxby Downs Granite (Johnson and Cross, 1995). The apparently short time lag between granite crystallisation and hydrothermal activity in a subvolcanic environment suggests that the granite was emplaced at a high level within the crust, an interpretation supported by field observations that some Hiltaba Suite granitoids intrude units of the Gawler Range Volcanics (Flint, 1993).

## Deposit Model

### *Formation Environment And Geological Evolution*

The Olympic Dam Breccia Complex predominantly formed in a high-level volcanic environment (Oreskes and Einaudi, 1990, 1992; Reeve *et al.* 1990). Surficial lithologies within the breccia 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. It is unlikely that the ODBC was a significant eruptive centre of coherent lavas or ignimbrites associated with the Gawler Range Volcanics.

Hydrothermal brecciation initiated at structurally controlled sites within the Roxby Downs Granite evolved contemporaneously with alteration, veining, dyke intrusion, phreatomagmatic 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 (K. Cross, pers. comm.) were eroded during the Middle to Late Proterozoic, 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 and no significant sulphide recrystallisation (Reeve *et al.*, 1990).

### *Genetic Models*

During delineation drilling of the deposit, Roberts and Hudson (1983) described Olympic Dam as a stratabound sediment-hosted ore deposit, inferring that ore minerals were introduced by hydrothermal fluids associated with local volcanism. As underground development of the deposit 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 in the deposit 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 waters in the upper part of the breccia complex. Haynes *et al.* (1995) argue on the basis of mineral composition, ore texture and thermodynamic modelling that the oxidised ground waters 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 hematite 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 hematite 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 (Eldridge and Danti, 1994) and unpublished fluid inclusion data support this interpretation (K. Ehrig, pers. comm.). 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).

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