BHP

Olympic Dam and regional prospects - controls and key aspects of the geology

Kathy Ehrig (Superintendent Geometallurgy) and Jesse Clark (Senior Geologist)

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Disclaimer: The opinions expressed here are solely those of the presenters

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ARC Linkage LP130100438- The supergiant Olympic Dam uranium-copper-gold rare earth element ore deposit: towards a new genetic model

ARC Linkage LP160101497- Reverse engineering Nature: metal extraction through mineral replacement
As an industry, we exploit minerals

Minerals, minerals, minerals
• elements occur in mineral deposits as minerals
• minerals are mined
• metallurgy extracts elements from minerals.

Elements are proxies for minerals
• historically, assaying at the deposit scale was the only option.
• mineral abundances can now be measured and/or estimated at the deposit scale.
• no longer necessary to rely on assaying alone to characterise a mineral deposit.

Geologists
• quantify qualitative mineralogical observations across the entire mining value chain
• EVERY MINERAL HAS A STORY !*

* Nigel Cook, personal communication
Today’s presentation

Olympic Dam and regional prospects: controls and key aspects of the geology

• Olympic Dam geology – very brief summary
• Controls on mineralisation at Olympic Dam
• geochemistry and mineralogy – defining the spectrum at OD
• Wirrda Well and Acropolis – geochemistry and mineralogy
• Conclusions

Later today, Liam and Max
• The micro- to nano-scale characterisation of zircons and Fe-oxides.

(Ken Cross personal communication,

… adapted from a source long forgotten…

however, on deep reflection:
Olympic Cu-Au Province—Summary

Why is the Olympic Province so well endowed?

Hayward and Skirrow (2010)
• “…extensively reworked lithosphere with older [prior to ~1590 Ma] metasomatised SCLM…”
• “…high frequency of translithospheric shear zones…”
• “…oxidised A-type plutons…”
• “…juvenile magmatic input manifest in mafic-ultramafic intrusions and basalts…”
• “…abundance of mafic volcanics in the lower Gawler Range Volcanics”

Reid and Fabris (2015)
• “…preservation of [Fe-rich sediments] rocks at low metamorphic grade containing formation waters and porosity provided a fertile geochemical environment into which high-temperature, felsic and mafic magmas, and their associated hydrothermal cells were emplaced and developed…”

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Olympic Domain – Geology and Falcon Gravity

- OD - Olympic Dam
- WW - Wirrda Well
- AC - Acropolis
- SG - Snake Gully
- BL - Bill’s Lookout
- ID - Island Dam
- TD - Todd Dam

Fe-oxides (IOA-IOCG)

- banded iron formation
- mafic GRV (~1590 Ma)
- felsic GRV (~1590 Ma)
- Hiltaba Intrusive Suite (1575-1595 Ma)
- Curramulka gabbronorth (~1565 Ma)
- Moonta-Wallaroo Fm. (1740-1790 Ma)
- Mt Woods Complex (1736-1750 Ma)
- Donington Intrusive Suite (~1850 Ma)
- Mulgathing Metamorphic Complex

Fault: AFZ/TDF
Olympic Dam Cu-U-Au-Ag Deposit
A world class ore deposit, by any definition

Key Points

- no surface expression of the deposit
- concealed by ~350m of unaltered ‘cover sequence’
- tectonic-magmatic-hydrothermal breccia-hosted Fe-oxide Cu-U-Au-Ag deposit (IOCG-U type)
- Olympic Dam Breccia Complex (ODBC) footprint ~50 km²
- hosted within the ~1593 Ma Roxby Downs Granite (RDG)
- deposit footprint ~6 km x 3 km x 800 m (deepest ~2.3km)
- unequivocal spatial correlation between Fe, Cu, U₃O₈, Au, and Ag across the deposit due to the co-precipitation of these elements

Deposit-wide Mineralogical Zonation

- progressive increase in Fe from edge to centre
- Fe-oxide alteration (Fe⁺² → Fe⁺³).
- magnetite + apatite + chlorite → hematite + sericite
  siderite → fluorite → barite
- py → cp-py → cp → cp-bn → bn → bn-cc → cc
- polymetallic Zn-Pb-Ag and granite-related Mo-Sn-W
- uraninite - coffinite – brannerite
- three styles of gold mineralisation
Controls on Mineralisation

Well understood - one major and three minor controls on mineralisation

Geological Controls on Copper Mineralisation

Pre to syn-mineral Structural Framework

Alteration

Lithology / Protolith

Hypogene sulfide species
Iron oxide abundance
HEMQ contact
c. 1590 Ma (ultra-‐)mafic dykes

c. 1590 Ma KASH contact

Major

Minor

Preserved Volume and Geometry

Post-mineral Structural Dismemberment

Uplift and exhumation/ denudation
Hydrothermal disruption

Major
Progressive brecciation and alteration of RDG

Predictability – the granite to HEMQ continuum

Olympic Dam Breccia Complex

Fe (<5 wt%) gr-rich bx
Fe (5-25 wt%) gr- to hem-rich bx
Fe (>25 wt%) hem-rich bx

Modified after Ehrig et al. (2012)

HEMQ
hematite + quartz bx

BCF: VBX
feldspar-phyric volc-clast bx

BCF: KHEMQ
interbedded res ss – mds
c

BCF: KASH
interbedded green ss – mds
c

BCF: VASH
thinly-bedded tuffaceous mds
c

BCF: KFMU
Polymictic felsic-mafic volc cg

~1590 Ma MDY
Ultramafic-mafic undiff. dykes

~825 Ma DOL
Gairdner Dolerite Dyke Swarm

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~3 wt% Fe

~60 wt% Fe
Insights into post-mineral structural disruption

Burial & orebody dislocation is the most fundamental control to present-day geometry

Geology long-section (NW-SE): relative depth of ore increases from north to south

Andamooka Lmst.
Arcoona Qtz.

NW

cover sequence
unconformity

Au > 4 ppm

Cu > 1 wt%

Olympic Dam Breccia Complex

Turnbull Fault
Jubilee Fault
( locally Mashers Fault)

Woodall Fault Jr
Woodall Fault

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Roxby Downs Granite (RDG)

“... fresh but NOT pristine ...” (Kontak, SGA Conference Quebec 2017)

Magmatic → post-magmatic → hydrothermal alteration

RDG Mineralogy

• ~50% alkali feldspar
• ~20-25% quartz
• ~20-25% sodic plagioclase
• <10% magnetite, biotite, amphibole
• trace abundances of titanite, apatite, zircon, rutile, allanite, fluorite, ankerite, synchysite, uranothorite, galena, sphalerite, pyrite, chalcopyrite

“Fresh” RDG criteria (Ehrig et al. 2012)

• whole rock chemistry: $\frac{K_2O}{Na_2O} = \frac{5.5}{3.5} = \sim 1.6$
• magnetic susceptibility $\sim 25-50 \times 10^{-3}$ SI units
• presence of magmatic biotite
• ~300 diamond drill holes in unbrecciated RDG, none of which are entirely “fresh”

refer to Kontonikas-Charos et al., Krneta et al., and Mauger et al. (2016)
Felsic Gawler Range Volcanics (~1590 Ma)

RU56-10548: 195.5m : qtz-feldspar phyric felsic dyke
Olivine-phyric dykes and lava/sills (~1590 Ma)

Johnson and Cross (1995) and Huang et al. (2016, 2017)
Olivine± pyrox± plag± phlog± qtz dykes (~1590 Ma)

Johnson and Cross (1995) and Huang et al. (2016, 2017)
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Sericite-altered, vfg mafic-ultramafic dykes

Alkaline

Sericite-altered ‘waxy’ (ultra-)mafic dykes

• anomalous Al (>9 wt%), Zr (>400 ppm), Ti (>0.3 wt%), Mg (13 wt%) and other HFSE e.g. REE, Hf, U, Th, Ta, Nb + K.

• micron size sericite and crystals of zircon, rutile, and REE minerals

• ‘waxy’ sericite texture accompanied with elevated Ti and Mg suggests mafic-ultramafic

• intense hematite-sericite alteration is common

• high grade sulphide concentrations are often associated with the margins of these dykes

• ‘feeder-style’ dykes to most mineralization in the NW arm of the deposit
Bedded Clastic Facies (BCF)

McPhie et al. (2011, 2016), Cherry et al. (2017, 2018), Clark and Ehrig (2019)

Contains ~1590 Ma zircons

Interbedded Sandstones and Mudstones

KHEMQ

RD2919B 682-690m

VASH

RD2765 448-451m

KASH

RD3449 458-466m

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Conglomerate: polymictic volcanic clasts (KFMU)

RD3449 398-406m

Contains ~1590 Ma zircons

Brecciated, quartz-rich sandstone (KGRN)

RD2751 860-868m

Contains ~1590 Ma and OLDER zircons.

Pandurra Formation (~1424 Ma)

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Gairdner Dyke Swarm (dolerites-basalts) ~820 Ma

Huang et al. (2015)

Residual Total Magnetic Intensity showing the Gairdner Dyke Swarm (modified from Direen and Lyons, 2007).

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Mafic dyke lithology: minor local-scale ore control
but, likely provided significant energy into brecciation and fluid circulation

Definition
- Two major mafic-ultramafic intrusive events:
  i. 1600–1590 Ma Gawler Range Volcanics (felsic to) mafic dyke and extrusive equivalents
  ii. ~820 Ma Gairdner Dyke Swarm
- Composition ranges from basalt, picrite and lamprophyre

Mineralisation Control
- Highly chemically reactive protolith resulting in:
  i. Intensely altered by predominantly a chlorite-sericite mixture, and hematite at varying proportions — barren in Cu mineralisation (<0.3 wt% Cu) but margins can be enriched
  ii. Penecontemporaneous mafic dykes can be hematite altered with high-grade Cu mineralisation
Epithermal-style quartz veins, … barren now …
Hypogene sulfide zonation (distal, deep → central, shallow)

\[ \text{py} \rightarrow \text{py-cp} \rightarrow \text{cp} \rightarrow \text{cp-bn} \rightarrow \text{bn} \rightarrow \text{bn-cc} \rightarrow \text{cc} \rightarrow \text{Au}^0 \]
Sulfide veins in altered granites and granite-breccias

Sulfides do occur not associated with Fe-oxides, how would you discover this?

Sulfide veins also occur in the breccias
Deep mineralisation (RD2773)

Apukhtina et al. (2017) and Verdugo-Ihl et al. (2019)

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[Diagram showing geological layers and mineralisation zones.

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Unconformity

- Tregolana Shale
- Pebble conglomerate

- Mag+albite+chl alteration
- Gairdner Dyke Swarm-
dolerite/basalt
- Anhydrite
- RDG, minor brecciation: ser and chl alteration
- RDG + qtz-phyric felsic unit
- Qtz-phyric felsic unit, intense ser alteration

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RDG clasts

Min + Anh

Cal vein

OD815, 2012.2 m

OD818, 2036.7 m

OD827, 2182.4 m

OD830A, L 2236.4 m

OD830A 2, 2258.4 m
Mineralisation and Alteration Footprints - Olympic Dam

Dmitrijeva et al. (2019) – Ore Geology Reviews

Unmineralised rock  IOCG signature

Group 1  Group 2  Group 3  Group 4

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Acropolis prospect

~1590 Ma alteration mineralisation hosted in felsic GRV

Intensely altered Donington granites

mt-apatite veins

intensely altered GRV rhyolites/dacites

phlogopite

apatite

ksp

mt

apatite

py-cb-mt veins
Mineralisation and Alteration Footprints - Acropolis

Wirrda Well prospect

~1590 Ma mineralisation hosted in Donington Suite Granites and pre-1590 Ma mafic dykes

Donington Suite
~1850 Ma
dykes, up to 5000 ppm Cr

Mineralisation initiates along mafic dyke margins then propagates into the Donington granites

py-cp (<0.5% Cu)
mt-ap → hem-sid-chl

py-cp (>0.5% Cu)
(mt-ap) → hem-sid-chl

bn-cc breccias up to 1% Cu
Mineralisation and Alteration Footprints - Wirrda Well

Dmitrijeva et al. (2019) – to be submitted before end of Dec 2019
Whole-rock chemistry does tell the story

Ehrig et al. (2017)
Conclusions
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Repeated lithogeochemical similarities between mineral occurrences on the Stuart Shelf

- No matter which lithogeochemical classification scheme is used (Ehrig and Clark or Dmitrijeva et al. or Corriveau et al., etc), schematic trends are observable and have been successfully used to vector towards mineralisation.
- Host rock is likely not the primary source of metals or ligands.
- Stuart Shelf IOA → IOCG deposit spectrum mineral system and alteration zonation patterns are very well understood
- The most prospective part of an IOCG deposit forms at the shallowest crustal levels of the ore forming system (<0.5 – 1km)
- At Olympic Dam, the present orebody geometry does not reflect the pre- or syn-mineralisation structural architecture – rather remnants
- Multiple regional- and local-scale deformation events spanning over the billion years (1.59-0.5 Ga) have dismembered the deposit
- Deposit preservation is critical; post Mesoproterozoic sediments on the Stuart Shelf and thick GRV lavas on the central Gawler Craton