Neutralising Cobar type: an evolving skarn model for the Hera-Nymagee orebodies

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Cobar Basin in a slide

- Ordovician basement
- Intruded by Silurian granite
  - Exhumed prior to...
- Siluro-Devonian Basin
  - Deepwater sedimentary basin
  - Volcanogenic troughs
  - Western shelf
  - Eastern shelf
    - Shelf/volcanic belt
    - Early Devonian intrusions (420-415 Ma)
- Overlain by middle-late Devonian
- Major fault systems active in
  - Basement
  - Basin opening
  - Inversion
- Cobar-type mineralisation

Northern Cobar mineral field
  e.g. CSA mine

Southern Cobar mineral field
What is a Cobar-type?

- **Described in the NE**
  - CSA, Peak, Great Cobar, Chesney

- **Geometry e.g. CSA**
  - Multiple pipe like lenses
  - Short strike length
  - Large vertical extent

- **Deposit-scale**
  - Metal zoning/variability
    - Within and between deposits
  - Massive sulfide and vein-hosted
    - Multiple overprinting veins sets
  - Broadly stratabound, but cross-cut bedding at **deposit-scale**

- **Genesis**
  - Syn-deformation - developed during basin inversion c. 380 Ma
  - Mixing of basin Pb-Zn and basement Cu-Au-rich fluids
  - Remain enigmatic. Variously attributed in the past
    - VMS, epithermal, subhalative-exhalative…

If structural/metamorphic model then...
Need to understand metamorphism in the basin

Lawrie&Hinman (1998)
GSNSW HyLogger

- Ultraviolet
- Infrared
- Microwave

Wavelength (nm):
- TIR: 10^16
- MWIR: 10^14
- SWIR: 10^12
- NIR: 10^10

Wavelength (μm):
- TIR: 0.75
- MWIR: 1.1
- SWIR: 2.5
- NIR: 6
Digging up heat in the Cobar Basin

How a washed up metamorphic petrologist ended up in Cobar
Burial metamorphism

<table>
<thead>
<tr>
<th>Facies zone</th>
<th>Metapelitic zone (depth, km)</th>
<th>Temperature (°C)</th>
<th>illite crystallinity</th>
<th>Vitrinite reflectance R₀, %</th>
<th>Conodont Alteration Index (CAI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Early diagenetic zone</td>
<td>3.5–4</td>
<td>100</td>
<td>1.0</td>
<td>0.5</td>
<td>1 yellow</td>
</tr>
<tr>
<td>Late diagenetic zone</td>
<td>6.0–8</td>
<td>200</td>
<td>~0.42</td>
<td>2.00</td>
<td>2 light brown</td>
</tr>
<tr>
<td>Low anchizone</td>
<td>~0.60</td>
<td>2.50</td>
<td>4 dark brown</td>
<td></td>
<td></td>
</tr>
<tr>
<td>High anchizone</td>
<td>~0.3</td>
<td>3.00</td>
<td>5 black</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Epizone</td>
<td>10–12</td>
<td>300</td>
<td>~0.25</td>
<td>4.00</td>
<td>5.5</td>
</tr>
<tr>
<td>Biotite zone</td>
<td>10–12</td>
<td>300</td>
<td>~0.25</td>
<td>4.00</td>
<td>5.5</td>
</tr>
<tr>
<td>Amphibolite facies/pyroxene hornfels</td>
<td>&gt;400°C</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Diagenetic: 0-200°C
Anchizone: 200-300°C
Epizone: 300-350°C
Biotite zone: 350-400°C
Amphibolite facies/pyroxene hornfels >400°C

Number of methods to determine burial metamorphic grade in very low grade pelitic rocks.

- Illite crystallinity (Kübler index)
- Vitrinite reflectance
- CAI (Conodont Alteration Index)
Mapping heat in the Cobar Basin

- **CAI**
- Unaltered conodonts exhibit a pale yellow colour and a smooth surface with silky brightness (CAI 1). Exposure to increasing temperatures results in carbonization of conodont matter that produces a progressive colour sequence of light to dark brown (CAI 1.5–4) to black (CAI 5), then grey (CAI 6) and white (CAI 7).

1) Virgin Hills (0-100°C)
2) The Rookery (100-150°C)
3) Manuka (150-200°C)
5) Beloura Tank (250-300°C)
Unexplained high to the southeast
Mapping heat in the Cobar Basin

Distal to mineralisation

- Illite crystallinity ($\Delta^\circ 2\theta$ Cu-K$\alpha$) values
  - Kyne (2014) – CSA mine (0.24–0.27)
  - Brill (1988) – Endeavor mine (0.24–0.27)
- Fluid inclusions
  - Seccombe (1990) – Endeavor mine (170-225°C)
  - Giles (1993) – Manuka mine (~150°C)
- Chlorite thermometry
  - Bush (1980) – Mineral Hill mine (~150°C)
- Vitrinite reflectance
  - Robertson and Taylor (1987) – CSA mine (3.3–3.4)

Proximal to mineralisation

- Illite crystallinity ($\Delta^\circ 2\theta$ Cu-K$\alpha$) values
  - Brill (1988) - CSA mine (0.25-0.21), Chesney mine (0.26-0.18)
  - Queen Bee mine (0.21-0.19), The Peak mine (0.29-0.21)
- Fluid inclusions
  - Sun & Secombe (2000) – Endeavor mine (286-374°C)
  - Forster & Secombe (2000) – Mackinnons mine (270-340°C)
- Chlorite thermometry
  - Page (2011) – Hera mine (270-365°C), Nymagee (292-394°C)
  - Bush (1980) – Mineral Hill mine (~300°C)

Temperatures of 150-250°C distal to mineralisation.

Localised nature of heat

Temperatures of 300-380°C proximal to mineralisation.

Within 100’s of meters.
Mapping heat

• Basement
  – Lower greenschist east of Gilmore
  – Sub-greenschist west of Gilmore

• Western Shelf
  – Diagenetic zone

• Deep water basin
  – Sedimentary – anchizone
  – Contact metamorphism

• Eastern shelf
  – Anchizone-middle greenschist

• Hydrothermal metamorphism
  – Close to major faults
  – Northeast – greenschist (biotite)
  – South – pyroxene hornfels facies

Important!
Hydrothermal heat is very localised
100’s of meters around orebodies
Not a regional field gradient

Anchizone
detrital biotite/muscovite-rich sandstone

Garnet-actinolite flooded sandstone
Tour mineralisation in Hydrothermal ‘Hot Zone’

Nymagee orebody

Norma Vale prospect

Hera orebody
Hera orebody

- Au-Ag-Zn-Pb
  - Steeply west-dipping
  - Short strike length
  - Sulfide vein/breccia zones
  - Similar to other Cobar type deposits

- Mineralisation hosted within intensely silicified siliciclastic turbidite

- Gold associated with sulfide zones, but not always within the sulfides

High-T minerals have been described
Hera Orebody

- Orebody interpreted as a single horizon
- Orebody enveloped by steeply west-dipping foliation
- Late (post-foliation) steeply east dipping thrust repartition
  - Titanite 380 Ma

Massive sulfide core

Late-stage titanite vein

Foliated orebody margin
Hera orebody

- Nymagee Hylogger study.. Downes et al (2016)

- Drill holes from south of the main orebody

- Chlorite–phengitic muscovite dominant alteration.

- Chlorite becomes Mg-rich

- Sniff of K-feldspar

- Hylogger failed to pick up biotite

- But no signs of anything abnormal
Hera Orebody

- A drill hole through Main North and the top of Far West
- K-feldspar-biotite-actinolite
- Strongly overprinted by chlorite-albite.
- Suggestion of high-T potassic, calc-potassic alteration
Hera Orebody

- Into the skarn
  - Far West/North Pod

- Remnant high-T skarn and carbonate clasts
  - South to north zonation
  - Garnet-rich
  - Pyroxene-rich
  - Anorthite-scapolite (remnant carbonate)

- Siliciclastic-hosted skarn alteration and veins
  - South to north zonation
    - Garnet (±scheelite)
    - Biotite (±scheelite)
Hera Orebody

Hydrous retrogression & mineralisation

Rare to find high-T skarn due to pervasive retrogression and mineralisation

Sulfide-tremolite hydrous rind

Textural preservation

Complete tremolite replacement

Near complete sulfide replacement
Corbett and Leach

MAGMATIC SOFTARAS (BILIRAN, WHITE ISLAND, SURIMEAT)

LITHOLOGICAL CONTROL

MARAGORIK
PEAK HILL
NANSATSU
WAFI (zone A)
DOBROYDE
MIWAH
WAFI
PORPHYRY
MT McKenzie

500 m
(approximate vertical scale)

major
crustal
structure

permeable
horizon

STRUCTURAL
CONTROL

MARAGORIK
MT. KASI
PEAK HILL
LEPANTO
NENA

Dilational structures

Exsolution of volatiles and metals from high level cooling melt

Exsolution of volatiles and metals from parent melt at depth

PORPHYRY SHOULDERS

BATU HIJAU
LOOKOUT ROCKS
HORSE IVAAAL
CABANG KIRI

FSE
Nymagee Orebody

• Cu-Zn-Pb-Ag mineralisation in steeply west-dipping sulfide vein/breccia zones similar to other Cobar-type deposits

• Foliation envelopes orebody
  – Preliminary evidence of same bulky white quartz cross veins terminating ore lenses

• Metals zoned between lenses
  – Western zone is Zn-Pb-rich
  – Eastern zone is Cu-rich

• Initial magnetite-rich mineralisation overprinted by sulfides

• Muscovite-illite-chlorite-rich alteration
Nymagee Orebody - Digging deeper
Nymagee Orebody

- Garnet-anorthite-zoisite-tremolite skarn
  - Coincident with mineralisation

- Pervasive retrograde evolution
  - Initial tremolite-sulfide
  - Pervasive chlorite-talc-muscovite-sulfide
    - Particularly Cu lodes

- Ferrotschermakite-annite-magnetite-rich skarn
  - Fe-pelite-hosted

- Complete retrogression
  (Sulfide-replaced garnet-tremolite)

- Complete retrogression
  (Chlorite-white-mica)

- Ferrotschermakite-annite alteration

- Pyrrhotite-replaced magnetite

- Stilpnomelane-rich outer zone
Hera-Nymagee Orebodies
Silicate mineral chemistry

- Garnet = sub-calcic
  - Siliciclastic = spessartine
  - Carbonate = grossular

- Initial carbonate → zoisite-rich

Mo-poor scheelite locally abundant
The black arts Isotopes

- **Pb\textsuperscript{20}** this over **Pb\textsuperscript{20}** that Hera and Nymagee:
  - Crustal lead isotopic signature with a lead model age of (Downes et al 2016)
    - \(\sim 420\) Ma and 420-428 Ma respectively
    - I think latest is 400 odd Ma?, but seems to be a lot of recent change?
  - Consistent with age of basin deposition and igneous activity, Maybe younger?

- S Hera and Nymagee
  - \(\delta^{34}\text{S}(\‰)\) multiple sulfides range of 3-10
    - Downes (2016)
    - paragenetically unconstrained
  - Sulfides constrained from single lens hydrous skarn only Hera orebody
    - \(\delta^{34}\text{S}(\‰)\) ranges from 3-5

Low numbers consistent with magmatic S input, possibly mixed with formational
One off?

Garnet-veins in dolomite

Canbelego magnetite skarn

Happy Jacks, garnet-rich vein/zone

Hebe quartz-garnet-scheelite veins
Norma Vale

Actually two pyroxene-hornblende Quartz diorite to monzonite and even Leuco syenogranite

Norma Vale pyroxene skarn

Large allochthonous limestone
Norma Vale

Silicate mineral chemistry

• Garnet = sub-calcic
  – Siliciclastic = spessartine
  – Carbonate = grossular

• Carbonate-rich skarn

• Pyroxene = Hedenbergite

• Sulfides phase
  – Fe-rich stilpnomelane
  – Fe-rich epidote
  – Amphibole = actinolite
What is a southern Cobar-type?

- **Secret herbs and spices**
  - **Never deeply buried**
    - Anchizone basin (250°C) with very local zones of thermal perturbation up to ?500°C
  - **Carbonate-bearing stratigraphy**
    - Allochthonous horizon
  - No direct link to intrusive rocks
    - But, high heat flow, skarn development and…
  - **Hera Zn(W)-Au skarn**
    - Consistent with strongly reduced, low CO₂ Zn-skarn
      - Low-Mo scheelite, sub-calcic garnet
      - Zoisite-anorthite-rich skarn
      - Mn-enriched calc-silicate mineralogy
  - **Nymagee Fe-Cu and Pb-Zn-(Cu) skarn**
    - Early Fe-Oxide evolving to pyrrhotite-chalcopyrite
      - Usual ferrotschermakite hydrous skarn
    - Zn-Pb lodes consistent with low CO₂ Zn-Skarn
      - Zoisite-anorthite-rich
      - Mn-enriched calc-silicate mineralogy
c. 420 Ma I-type magmatism - a link?

Tollingo magnetic high

Fountaindale magnetic high

Fault-bound magnetic high

Calc-potassic alerted granodiorite

K-feldspar-actinolite-epidote-chlorite

Field of Cu, Zn and W skarns (Meinert)
Norma Vale, mafic link…
• Southern skarn formation

380Ma (titanite) E-dipping thrust

?400-380 Ma Basin inversion

Hera orebody

Reactive horizon

Ift to sag

Reef-shelf early rift

Volcanics

Conglomerate/arkose/lithic sandstone

Limestone

Devonian intrusion

Basement

Silurian granite

Ordovician turbidite

Ordovician black shale
Cobar described in terms of east to west

But… South to north

Higher Intrusion level in the south. Intrusion proximal mineralisation
Northern sister deposits

Twins?
Sister deposits, twins?

- Northern Cobar-type
- Similar stratigraphic level as south
- \( \delta^{34}S \) of 4.0–10.0 (Seccombe and Brill, 1989)
- Lower-T alteration
  - Chlorite-muscovite dominant
  - Distal?
  - Some telltale signs!
  - Calcareous sands distal (shelly)
  - Carbonate replacement style Pb-Zn horizons
  - Early magnetite-rich lodes to some massive Cu-zones
  - Biotite-stilpnomelate-rich alteration with magnetite
- Zn-Pb carbonate replacement calcrete sandsstone (shelly)
- Pyrrhotite-chalcopyrite replaced magnetite
- Detrital carbonate fragments
- Acicular/bladed magnetite (Mushketovite)
Conclusions

Importance of...

- Syn-rift faults
- Reactive horizons (carbonate)
  - Proximal = skarn
  - Distal = Lower-T lithological control?
- Devonian intrusions?
  - High thermal contrast
  - Fluid/metals
- Inversion, remobilisation or continued mineralisation?

Implications...

- Potential for metal trapping at several stratigraphic levels in the basin
- Skarn? in drowned, early-rift carbonate sequences
- Look through deformation and Cobar-type could be anywhere in the basin...

But... age of intrusive rocks?
Is intrusion diachronous?
Are there younger intrusive rocks?
Age of mafic intrusive rocks?
What’s next? Everything but…

- **Northern Deposits**
  - **Great Cobar**
    - H-O isotopes on early oxide phase
    - Titanite dating
  - **Perseverance**
    - H-O isotopes on early potassic alteration
    - Titanite dating
  - **CSA**
    - H-O isotopes on early oxide phase
    - Systematic S-isotope studies
    - Titanite dating
  - **Nymagee-Hera**
    - Scheelite REE-studies
    - Apatite dating
    - Titanite dating
    - VR-C-isotopes
    - Whole rock O
  - **Norma Vale**
    - 3x SHRIMP dates on I-type intrusives
Thanks