Base metal and tungsten mineralisation in the Jervois mineral field and the Bonya Hills: Characterisation, potential genetic models and exploration implications

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Outline

• Characterising the Jervois-Bonya mineralisation

• In the context of local and regional sedimentation, magmatism, metamorphism and deformation

• New genetic model and some exploration implications
Mineralisation styles

- Metamorphosed polymetallic Cu-Ag-Au-Pb-Zn-Fe (± W, Mo) massive sulfide deposits/prospects
  - Found near/in the ‘J-Fold’

- Cu ± W ± Mo prospects/occurrences
  - Spatially associated with mafic and calc-silicate rocks
  - Some overprint earlier sulfide mineralisation
Genetic models previously suggested....

- sediment-hosted Cu
- mafic intrusion-related
- IOCG
- SEDEX
- volcanogenic
- carbonate-replacement
- skarn
- Broken Hill-type
- felsic intrusion-related
Plotted in mineral systems space…

- sediment-hosted Cu
- mafic intrusion-related
- IOCG
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Host rocks: Bonya Metamorphics

- Hosts all known regional mineralisation
- Muscovite-garnet schist
- Subordinate quartzite, marble, marlstone, calc-silicate, tourmalinite
- Deposition ca 1824-1781 Ma
- Schist consists of clastic and chemical sediments

Plotted based on diagram of Spry (2000)
Bimodal magmatism at ca 1785 Ma

- Emplaced into the Bonya Metamorphics
- Gabbros (1786 Ma) and various felsic intrusions (1970-1770 Ma)

Unnamed gabbro sill, 400m E of Reward

Denara Orthogneiss
Bimodal magmatism at ca 1785 Ma

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Unnamed gabbro sill, 400m E of Reward

Denara Orthogneiss

- Ambiguous metamorphosed quartz-sericite schists at Jervois...

Peters et al 1985
Further regional magmatism

- Local fractionated pegmatites at Jervois
- Some overprint mineralisation, most deformed, metamorphosed, metasomatised
- U-Pb apatite $1756 \pm 17$ Ma
- Probably related to ca $1770$ Ma felsic magmatic event

- Jinka Granite event at $1710$ Ma
- Relatively undeformed tourmaline pegmatites and quartz-tourmaline veins
Host rock deformation

- foliation parallel to bedding: $S_{0/1}$

- horizontally folded with axial planar $S_2$ (main foliation in the ‘J’)

boudinage in $S_2$ plane
Jervois Event 1: Early Mineralisation

- Stratabound and stratiform
- Gn, cpy, py, sph ± garnet, magnetite, hematite, chlorite
- Significant Fe oxide content and unusual skarnoid mineralogy
- Cu, Pb, Zn, Fe, Mn hosted in chemical sediments

Reward deposit

Bellbird deposit
Jervois Event 2: Metamorphosed mineralisation

- Evidence for pre-existing sulphides before metamorphism…

- Sulphides within metaminerals (eg garnet, cordierite)
- Zn-rich gahnite, staurolite
  (eg Teale, 1982; Peters 1985, this study)

- Cpy-py concentrated in porphyroblast pressure shadows and $S_2$ main foliation
Jervois Event 3 / Late metasomatic regional event:

- Late mineralised Cu, W, Mo veins follow or cross-cut main $S_2$ foliation

cpy-quartz veins following $S_2$ foliation
Reward deposit

molybdenite-cpy overprinting $S_2$
Reward deposit
Late metasomatic event: Bonya and Jericho mines

- Late Cu-only and Cu+W+Mo mineralisation
- eg Bonya Cu Mine in quartz-hematite veins
- Over 70 occurrences…no Pb-Zn, relatively undeformed
- W±Cu occurrences eg Jericho: associated with quartz-turm and pegs

Bonya mine (Photo courtesy of Rox Resources Ltd)

Pegmatite at Jericho Scheelinite mine
New $\delta^{34}S$ sulfide data from various paragenetic stages

- Early (deformed)
- Remobilised
- Metasomatic
- Molybdenite
- Late
- Pegmatites

- Most Jervois $\delta^{34}S$ values ~ 0 \%
- None above 0.5 \%
New $\delta^{34}$S sulfide data from various paragenetic stages

- Most Jervois $\delta^{34}$S values $\sim 0\ \%$
- Bonya system forms later, but similar $\sim 0\ \%$ values
New $\delta^{34}S$ sulfide data from various paragenetic stages

- early (deformed)
- remobilised
- metasomatic
- molybdenite
- late
- pegmatites

Bonya Mine
Attutra metagabbro / Kings Legend Amphibolite

- gabbro
- granitic rocks

$\delta^{34}S$ values:

- mantle sulfur $0 \pm 3$‰
- Most Jervois $\delta^{34}S$ values ~ 0‰
- Bonya system forms later, but similar ~ 0‰ values
- Data most consistent with magmatic sulfur
- i.e. sulphide from magmatic-hydrothermal fluids or leached magmatic rocks
- Data consistent with sulfides within local mafics
New $\delta^{34}$S sulfide data from various paragenetic stages

- $\delta^{34}$S data not consistent with bacterial sulfate reduction eg SEDEX deposits
- More spread/variable values would be expected
- Data is homogenous and more consistent with VMS and mantle-like S
- Mixing of S sources possible
- However $\delta^{34}$S data is most consistent with a magmatic HS$^-$ source
New Pb-Pb galena and Re-Os molybdenite dating...
in a regional context

- 1785 Ma
  - Jervois mineralisation
  - Sedimentation
  - Bimodal magmatism
  - Contact/regional metamorphism and deformation

Timeline:
- 1820
- 1800
- 1780
- 1760
- 1740
- 1720
- 1700

- Galena primary sulphides?
- Galena pegmatite-related?
- Galena remobilised? metamorphic? magmatic?
- Molybdenite reward 1706 ± 7 Ma
New Pb-Pb galena and Re-Os molybdenite dating... in a regional context

ca 1770-1760 Ma
Minor mineralisation
Local intrusions and pegmatites
Contact metamorphism
New Pb-Pb galena and Re-Os molybdenite dating… in a regional context

ca 1755 Ma
‘High-pressure’ regional metamorphism
Deformation and remobilisation at Jervois
New Pb-Pb galena and Re-Os molybdenite dating… in a regional context

- ca 1720-1705 Ma
- Late Jervois mineralisation
- Regional Cu-W-Mo
- Hydrothermal/deformation event
- Felsic magmatism
Palaeoenvironment and sulfur implications

- Oxidised basin rift setting at ca 1785 Ma
- No ore zone sulfate
- Possible very minor evaporites in calc-silicate/carbonate host rocks
- **But** many evaporites at 1.8 Ga halide not sulfate-rich
- Lack of sulfate may indicate S-poor water column
- Marine or inland basin?
- Global sulfur sources at 1.78 Ga?
Palaeoenvironment and sulfur implications

- Lack of sulfate may indicate S-poor water column
- So how do you form sulfides?

Roberts, 2012

- $\delta^{34}S$‰ = sulphides
- $\gamma^{34}S$‰ = Sulphate
- $\mu^{34}S$‰ = Seawater sulfate evolution

First oxygenation event

1.7 Ga

CLASTIC-DOMINATED DEPOSITS

VOLCANIC-DOMINATED DEPOSITS

Northern Territory Government

AGES2015
How do you form Cu-Pb-Zn sulfides?

e.g. traditional oxidised saline basin system
Regional 1705 Ma event also has saline fluids, easily mobilise Cu
How do you form Cu-Pb-Zn sulfides?

eg traditional oxidised saline basin system
Regional 1705 Ma event also has saline fluids, easily mobilise Cu

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\text{Sulfide mineralisation} \quad \text{HS}^- + \quad \text{Cu}^+ + \text{Pb}^{2+} + \text{Zn}^{2+} + \text{Cl}^- \rightarrow \text{CuCl}_2^- + \text{PbCl}_2^- + \text{ZnCl}_2^- \]
What about Jervois?

- In clastic basins (ie Jervois 1785 Ma) suggested that reduced, high temperature fluids transport $\text{HS}^-$ into an oxidised basin.

- $\delta^{34}\text{S}$ data & unusual high Cu-Fe with Pb-Zn indicate higher temperature, reduced, S-rich fluids

Where does the $\text{HS}^-$ come from?
- Bacterial or thermochemical sulfate reduction?
- S-rich minerals leached from basin rocks?
- or derived from magmatism?

Why can’t metals and $\text{HS}^-$ be transported together in fluids?

- This is thought to limit fluid metal transport, whilst it is considered difficult to mobilise Pb, Zn, Cu and Au together…
  
  *eg Large et al 1996, Wilkinson, 2014*
New Cu-Pb-Zn solubility-speciation models

- Model incorporates the latest thermodynamic data...
- Suggest that at temperatures >300°C, base metals preferentially transported as $\text{HS}^-$ rather than $\text{Cl}^-$ complexes in S-rich fluids...... regardless of fluid salinity!

Zhong and Brugger, 2015

Cu in reduced, high (or low) salinity fluid

Pb in reduced, high (or low) salinity fluid
Not surprising that a range of genetic models were previously suggested.
Models can be poorly defined with contradictory characteristics.
Eg VMS mineralisation can be hosted in sediments or contain exhalites. SEDEX need not be exhalative.
Classification

Jervois deposits (ca 1785 Ma)

• Metamorphosed sediment-hosted, volcanic-associated massive sulfide mineralisation
• Atypical S source, unusual polymetallic base metal and gangue assemblage, unusual palaeoenvironment
Classification

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**Regional Cu-W-Mo prospects and occurrences (ca 1705 Ma)**

- Syn/post regional metamorphic sulfide mineralisation
- No Pb-Zn, relatively undeformed
- Some occurrences overprint earlier sulfide mineralisation
How did the J-Fold form?

TMI + aerial photography overlay, J-Fold gross-structure

general trend of main foliation
trend of various fold axial planes
How did the J-Fold form?

1787 ± 6 Ma  
Deposition of Bonya Metamorphics
- D1/M: extensional, during bimodal magmatism, porphyroblast growth
- progressive D2/M: compressional
  F, S1: isoclinal folding, boudinage, local main foliation

1786 ± 4 Ma  
- Deposition of Bonya Metamorphics
- Early bimodal magmatism in back arc environment?
- D1/M: extensional, during bimodal magmatism, porphyroblast growth
- progressive D2/M: compressional
  F, S1: isoclinal folding, boudinage, local main foliation

1756 ± 6 Ma  
Peak-pressure regional metamorphic and deformation event produces main S2 foliation
How did the J-Fold form?

- Deposition of Bonya Metamorphics
- D1/M: extensional, during bimodal magmatism, porphyroblast growth
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1756 ± 6 Ma Peak-pressure regional metamorphic and deformation event produces main S2 foliation
How did the J-Fold form?

progressive deformation after 1756 ± 6 Ma:

folding of transposed, boudinaged sulphide bodies with the J-Fold

shearing along Jervois Fault
Exploration implications...
Local Exploration Implications: the ‘big’ J

- Increasing tonnage of known local resources?
- Local structures / isoclinal folding / repetition
- Geophysical targets: Sulphide/magnetite and gabbros

TMI + aerial photography overlay, J-Fold gross-structure
Regional Exploration Implications

- Using unusual mineralogy/alteration eg gahnite, staurolite, cordierite, garnet as vectors to similar mineralisation
- Minerals indicate chemical sediments, hydrothermal alteration and metamorphosed sulphides
- Implications for outcrop/creek sampling; ASTER/HyMap imagery

Peters et al 1985

Zn-rich staurolite

Fe/Mn garnet

Zn-rich gahnite

eg Teale, 1982
Peters et al 1985
District Exploration Implications

- Fertile bimodal magmatism emplaced into basins regionally at 1.8 to 1.76 Ga
- **VMS-SEDEX District** associated actively/passively with magmatism in E Arunta
- Most other Australian Proterozoic metallogenic belts >120 my younger

![Map](image-url)
Thank you

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