Integrating insights from geophysics, geochemistry and structural geology in 3D to understand mineral systems

Examples from Eastern Succession, Mt Isa Inlier

Jim Austin + Ben Patterson, Michael Gazley, John Walshe Belinda Godel, Steph Hawkins, Matt Sisson

www.csiro.au
Exploration Undercover
Batting Order

- Why are we (still) confounded about Cloncurry
- What new techniques are we using
- An example of the outputs from Ernest Henry
- What are the relationships between:
  - Structural Controls and Mineralisation?
  - Different generation Structures and different alteration styles?
  - Alteration, Redox and Magnetic signatures?
- How can we use these insights to explore under cover??
Cloncurry Mineral Systems

- Pb-Zn-Ag BHT deposit (Cannington)
- Mt-rich IOCG Breccia Pipes (e.g., Ernest Henry)
- Au-rich, Mt-poor, Po-rich Breccias (Eloise)
- Mt-rich Stratiform Iron with Cu-Au (Osborne, Starra)
- Mt+Po Stratiform Iron with Cu-Au (Monakoff)
- Po-rich linear horizons with Au and Cu (Cormorant)
- Mt-rich Stratiform Iron with Pb-Zn-Ag (Pegmont)
- Non-Magnetic Po-rich systems with Cu, Zn (Artemis)
- Carbonate-rich (non-magnetic) Cu (Great Australia)
- Skarn-like deposits (Near Mary K)
- REE-rich deposits (Merlin and Milo)

- Large variation in deposit style, but......
- Many different alteration styles
- All deposits have strong structural controls
Mineral System Ingredients (Isan Orogeny)

**Stratiform Magnetite±Hematite**
- Reactant for reduced and oxidized fluids in IOCG systems. Occurs in QF sequences. Predates Cu-Au.

**Mafic Rocks**
- Source of heat, sulfur and some metals.

**Granitic Intrusion**
- Source of heat and fluids, source of some metals.

**Evaporites & Carbonates**
- Reactant for reduced and oxidized fluids, source of metal carrying brines. (Carbonate is Gangue in many deposits)

**Structural Controls**
- Shear, Fault, Intersection, Jog, Contact, Breccia, etc.

**Magma Mingling**
AMS (Anisotropy of Magnetic Susceptibility)

- Anisotropy of magnetic susceptibility (AMS)
  - physical property of rock
  - Caused by preferred orientation of anisotropic magnetic minerals.
  - It is essentially a magnetic fabric
  - Can be used to define strain distribution prior to mineralisation
**Key to AMS data**

- **K1**: Lineation (Long Axis)
- **K2**: Intermediate
- **K3**: Short Axis (typically azimuth of shortening)

Great circle joining K1 and K2 defines the foliation.
TIMA
(Tescan Integrated Mineral Analyser)

• 10 μm resolution
• spectra-matched to international & in-house standards,
• Allows us to:
  • Observe textures
  • Quantify (consistently) mineralogy
  • Infer different styles of alteration.
  • & Different styles of mineralisation

Molybdenite Matrix Breccia – Merlin
Calcite-Pyrrhotite Matrix Breccia – Canteen

Magnetite-Pyrite-Apatite – Osborne
Leucophoenicite, Mn-calcite-Bixbyite-Garnet-Rhodochrosite – Maran
Ernest Henry Cu-Au
(Hematite-Magnetite)

Actual Geology
Interpreted Geology
Magnetics
Reassessment of Geophysical evidence

- Yes there are NE- fabrics
- But N-S and NNW fabrics control magnetite.
- The N-S structure passes straight through ore-body
- Mineralisation sits on intersection lineation

*Magnetics 1st Vertical derivative of RTP*
Matching AMS and Structural Controls

Hanging Wall AMS

Breccia AMS

Foot Wall AMS

K1 With Structure

Deformation Model for Ernest Henry Consistent with D4/D5 (≤1530 Ma)

Shortening Direction (Sigma 1, ≠ K3)

Plane within which K1 & K2 both lie

Dominant Lineation Main Shear Vector (K1)

Shortening Direction (Sigma 1, ≠ K3)

Equal-area projection

N=22

N=13

N=7
Integrating Mag + Geochem modelling

The ore “pipe” picks up multiple fabrics in different orientations, all along an intersection with a sub-vertical, N-S fault.
1. Hangingwall

2. Albite-Calcite Proto-breccia

3. Qtz-Calcite Py-Cp breccia

4. K-feld-Qtz-Mt breccia

4. K-feld-Ca-feld Sheared breccia

5. Qtz-Ca-feld Ca-feld sheared breccia

6. Foot wall

Ernest Henry DDH691

Mineral Count

Titanite
Ilmenite

Distal alteration
Relatively oxidized albite-titanate ± Fe-oxides
Reduced neutral
Highly oxidized alkaline
Distal alteration
Relatively reduced Ca-silicates -ilmenite ± po
Alteration Type as a function of petrophysics and mineralisation

### Alteration Type

<table>
<thead>
<tr>
<th>Alteration</th>
<th>Chalcopyrite</th>
<th>Chamosite</th>
<th>Pyrite</th>
<th>Albite</th>
<th>Microcline</th>
<th>Quartz</th>
</tr>
</thead>
<tbody>
<tr>
<td>And-Alb+Potassic+Calcic</td>
<td>0.00</td>
<td>0.82</td>
<td>0.27</td>
<td>7.41</td>
<td>23.54</td>
<td>10.56</td>
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<tr>
<td>Magnetite-Apatite*</td>
<td>3.80</td>
<td>1.84</td>
<td>1.09</td>
<td>1.09</td>
<td>1.09</td>
<td>1.09</td>
</tr>
<tr>
<td>Potassic (Bt)</td>
<td>0.00</td>
<td>0.29</td>
<td>0.07</td>
<td>58.79</td>
<td>2.80</td>
<td>8.48</td>
</tr>
<tr>
<td>Potassic (Kf)</td>
<td>0.25</td>
<td>2.27</td>
<td>3.38</td>
<td>2.52</td>
<td>45.91</td>
<td>8.22</td>
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<tr>
<td>Potassic+ Cal-Qtz-Py</td>
<td>2.00</td>
<td>1.19</td>
<td>4.03</td>
<td>0.96</td>
<td>31.62</td>
<td>15.88</td>
</tr>
<tr>
<td>Qtz-Cal-Chl-Py±Cpp±Hem</td>
<td>2.88</td>
<td>10.26</td>
<td>13.96</td>
<td>0.16</td>
<td>2.70</td>
<td>33.56</td>
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<tr>
<td>Sodic (Ab-Mt-Ti)</td>
<td>0.00</td>
<td>0.31</td>
<td>0.31</td>
<td>54.96</td>
<td>3.73</td>
<td>2.38</td>
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<tr>
<td>Sodic + Potassic (Bt)</td>
<td>0.05</td>
<td>1.12</td>
<td>0.27</td>
<td>20.11</td>
<td>20.00</td>
<td>10.03</td>
</tr>
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</table>

For Ernest Henry

### Density (g/cm³)

<table>
<thead>
<tr>
<th>Alteration</th>
<th>Density (g/cm³)</th>
<th>Mag Sus K (SI)</th>
<th>Koenigsberger Ratio (Q)</th>
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<tbody>
<tr>
<td>And-Alb+Potassic+Calcic</td>
<td>2.85</td>
<td>0.19</td>
<td>0.52</td>
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<tr>
<td>Potassic (Bt)</td>
<td>2.78</td>
<td>0.13</td>
<td>0.36</td>
</tr>
<tr>
<td>Potassic (Kf)</td>
<td>3.02</td>
<td>0.52</td>
<td>0.83</td>
</tr>
<tr>
<td>Potassic+ Cal-Qtz-Py</td>
<td>3.10</td>
<td>0.41</td>
<td>0.70</td>
</tr>
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<td>3.27</td>
<td>0.34</td>
<td>0.47</td>
</tr>
<tr>
<td>Sodic (Ab-Mt-Ti)</td>
<td>3.14</td>
<td>0.76</td>
<td>0.62</td>
</tr>
<tr>
<td>Sodic + Potassic (Bt)</td>
<td>2.98</td>
<td>0.52</td>
<td>3.31</td>
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### Magnetic Susceptibility (SI)

- **Magnetite-Apatite**: * indicates a potential indicator of magnetic anomalies in mineralisation.

### Density (g/cm³)

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</tr>
</tbody>
</table>

For Ernest Henry
Mineralisation

Geographic coordinate system

Equal-area projection N=5

Quartz
Cincohlore
Hematite Magnetite
[Unclassified]
Chalcopyrite
Calcite
Chamosite
Pyrite
Apotie
Siderite
Rubite
Calcite Fe
Zusmmatite
Calciocyanite
Pyrrhotite
Barite
Molybdenite

Chalcopyrite
Calcite
Pyrite
Hematite Magnetite
Chamosite
Clinochlore
Quartz
Ilmenite

Ernest Henry DDH691
K-alteration + Cu mineralization
Hangingwall Na-alteration
Footwall Ca-alteration

Pyrite > 10 vol %
Chalcopyrite > 2.5 vol %
Ilmenite > 0.5 vol %
Arsenopyrite
Magnetic Modelling

- Shearzones are highly magnetic
  - Sodic alt+Magnetite (reduced)
- Breccia is moderately magnetic
  - Mt-Destructive
- Orezone is weakly magnetic
  - Hematite-Pyrite (Oxidised)
- Inverse Bullseye mag target

<table>
<thead>
<tr>
<th>Alteration</th>
<th>Density (g/cm³)</th>
<th>Mag Sus K (SI)</th>
<th>Koenigsberger Ratio (Ω)</th>
</tr>
</thead>
<tbody>
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<td>And-Alb+Potassic+Calcic</td>
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<td>Potassic (BT)</td>
<td>2.78</td>
<td>0.13</td>
<td>0.36</td>
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<td>Potassic (KF)</td>
<td>3.02</td>
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<td>0.83</td>
</tr>
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<td>Potassic+Cal-Qtz-Py</td>
<td>3.10</td>
<td>0.41</td>
<td>0.70</td>
</tr>
<tr>
<td>Qtz-Cal-Chl-PytCpsHem</td>
<td>3.27</td>
<td>0.34</td>
<td>0.47</td>
</tr>
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Geophysical expression of mineralisation: Redox or Overprinting Metasomatic events??
A simple view of Deposit geophysics (IOCG)

Ultra reduced (magnetic Pyrrhotite) — Reduced — Oxidised

Ultra reduced (non-magnetic Pyrrhotite)

Reduced-type (magnetite + Pyrrhotite)

Intermediate-type (magnetite + pyrite)

Oxidised-type (Hematite-magnetite-pyrite)

Most known Cloncurry Types

Big Question: Are mineral gradients controlled by redox or overprinting relationships or both????
Petrophysics Overview

Uncover Cloncurry AMS19 | Mt-rich

Po-rich
- Maronan Po
- Cormorant-Po
- Can_Po
- Canteen_All
- Monakoff Hem-BIF
- Cormorant-Py

Py-rich
- Maronan Mt
- E1-Mt

Py, Po, Hem, Sph, Gal

Weak-Min
- Ernest Henry
- Gr. Aust (Mt-Cp)
- Can_Mt
- Kalam-Hem
- Monakoff-Ore
- Cormorant-Py

Mt-rich
- Gr. Aust (Py-Cp)
- E1-Hem
- SWAN
- Osborne
- Can_Po
- Can_Mt
- Monakoff Hem-BIF
- Cormorant-Py

Density (g/cc)

Magnetic Susceptibility (SI)

Avg Koenigsberger

Avg Susceptibility
Petrophysics Overview

Mag + Grav High

Intermediate

Reduced

Oxidised

Grav High

Density (g/cc)

Magnetic Susceptibility (Sl)

Avg Koenigsberger

Avg Susceptibility

Uncover Cloncurry AMS
Magnetic Susceptibility
Sulfur and Copper
Mag vs Min - Maronan

Mag Sus (Magnetite)

Lead

Zinc

Silver

Distal Magnetite-Apatite (Intermediate)

Core: Pyrrhotite-Galena (Reduced)
ca 1650 Ma (CS$_3$) Sedex/ BHT mineralisation

Fault zones are associated with:
- Potassic Alteration
- Mt-destructive (oxidising)
- Associated with Copper

<table>
<thead>
<tr>
<th>Maronan</th>
<th>Density (g/cm$^3$)</th>
<th>Mag Sus K (SI)</th>
<th>Koenigsberger Ratio (Q)</th>
</tr>
</thead>
<tbody>
<tr>
<td>host rock</td>
<td>2.91</td>
<td>0.01</td>
<td>11.37</td>
</tr>
<tr>
<td>Po skarn</td>
<td>3.27</td>
<td>0.01</td>
<td>62.17</td>
</tr>
<tr>
<td>Potassic Alt</td>
<td>2.91</td>
<td>0.37</td>
<td>0.99</td>
</tr>
<tr>
<td>sedex</td>
<td>3.71</td>
<td>0.62</td>
<td>5.32</td>
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</tbody>
</table>
Redox zonation
Petrophysical Zonation

![Map of Petrophysical Zonation](image)

<table>
<thead>
<tr>
<th>Rock type</th>
<th>Density (g/cm³)</th>
<th>Mag Sus K (SI)</th>
<th>Koenigsberger Ratio (Q)</th>
<th>Anisotropy (P)</th>
<th>Fabric Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intact laminated siltstone</td>
<td>2.81</td>
<td>0.0014</td>
<td>-</td>
<td>1.05</td>
<td>Isotropic</td>
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<tr>
<td>Altered Toole Ck Volcanics</td>
<td>2.81</td>
<td>0.072</td>
<td>0.2</td>
<td>1.07</td>
<td>Isotropic</td>
</tr>
<tr>
<td>Mt + Chl Altered Metasedimentary</td>
<td>2.96</td>
<td>0.25</td>
<td>0.15</td>
<td>1.35</td>
<td>Foliation/Lineation</td>
</tr>
<tr>
<td>BIF West (Qtz-Hem)</td>
<td>3.19</td>
<td>0.03</td>
<td>12.27</td>
<td>1.02</td>
<td>Isotropic</td>
</tr>
<tr>
<td>BIF East (Qtz-Mt-Hem)</td>
<td>4.19</td>
<td>0.32</td>
<td>1.54</td>
<td>1.02</td>
<td>Isotropic</td>
</tr>
<tr>
<td>Magnetite BIF + Mt Alteration</td>
<td>3.36</td>
<td>0.51</td>
<td>0.08</td>
<td>1.48</td>
<td>Lineation/Foliation</td>
</tr>
<tr>
<td>Ore Zone (Mt-Cp-Py)</td>
<td>3.99</td>
<td>0.48</td>
<td>0.16</td>
<td>1.58</td>
<td>Lineation/Foliation</td>
</tr>
</tbody>
</table>

![Graph showing Correlation between K (SI) and Density](image)

**S₀/₁**  
**AMS**  
**“D₁” Shear**

Uncover Cloncurry AMS
Principal Component Analysis (PCA)

Comparing samples, or bits of systems, to allow us to see what may be related.

- 57 samples
- 30 elements
- <LOD substituted 50% LOD
- CLR for closure issues
- 61.03% summarised by PC5
- Bayesian mixture-modelling cluster
How can we use it??
- Future Research directions
Structural Framework

- Mapped strain in 16 deposits across the Inlier
- Well clustered results
- N-S “D2” fabrics dominant
- Major deposits also have a D4, NE-SW- fabric
- Some deposits have late D5 fabrics (reactivation)
Tectonothermal-metasomato-magma-metallogenic Summary

- Temporally Relates:
  - Thermal History
  - Tectonic Fabrics
  - Depositional Events
  - Alterations Styles
  - Magmatic Events
  - Mineralisation Styles
Exploring Undercover

• Don’t limit it to “undercover”
• There’s geophysically subtle targets left on the inlier too
• But possibly at deeper levels
• If drilling deep holes you need to get as much info as you can
• CSIRO has new technology to garner a lot of information from limited sampling
• We can build on these insights
• We hope to continue this work
Uncover Report – Summary Docs

• Integrated structural, metasomatic and metallogenic history of Cloncurry District.

• Geophysical Expressions of Cloncurry Mineral System.

• Chemical gradients in Cloncurry Mineral System: Vectors to grade?

• Multivariate analyses of geochemical data from Cloncurry deposits.

• Exploring for value: A geometallurgical perspective.

• Summary of methods.

QDEX Link: http://bit.ly/2jESB74
Deposit Reports

- Altia Pb-Zn deposit.
- Artemis Zn-Cu deposit.
- Cameron River Cu prospect.
- Canteen Cu-Au prospect.
- Cormorant Cu-Au Prospect.
- E1 Cu-Au deposit.
- Ernest Henry Cu-Au deposit.
- Kalman Mo-Re-Cu-Au deposit.
- Maronan Pb-Ag deposit.
- Merlin Mo-Re deposit.
- Monakoff Cu-Au-U deposit.
- Mount Colin Au-Cu deposit.
- Osborne Cu-Au deposit.
- Starra Cu-Au deposits.
- SWAN Cu-Au prospect.
- Trekelano Cu-Au Deposit