Geophysical Exploration for Gold: Regional to Mine Scale Targeting

B. Bourne, Principal Consultant @ Terra Resources
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(E) b.bourne@terraresources.com.au | (M) +61 409 493 485
(W) www.terraresources.com.au
Outline

- Challenges
- Gold Model Types
  - Carlin
  - Greenstone
  - Porphyry
  - HS Epithermal
- Challenges
- Summary
- Long life, high margin, high throughput deposits
- 20% biggest deposits = 80% production or resources
- Those are rare!
- Gold: 55 deposits >20 Moz after 125 years of exploration
  - ~45 producing or mined out
  - ~10 in the pipeline

Legend
- ≥ 20Moz Au
- ≥ 5Moz Au

(Barrick, 2010)
Preferred target types:
- High deposit abundance
- Highest % of population >10 Moz deposits
- Good economics and mineability

(After Robert et. al., 2007)
Regional Targeting Implications

- Second and third order processes influence nature of mineralization and detailed spatial distribution but not relevant to regional targeting.

- Regional targeting needs to focus on the three fundamental elements of the unified model:
  - Fertile Upper Mantle Zone
  - Favourable Lithospheric Architecture
  - Favourable Extraction Event

(Hronsky and Groves, 2009)
Greenstones

- **Geology**
  - Greenstone stratigraphy (includes seds)
  - Sediment hosted sulphide-rich end member
  - Near volcanic sequence or porphyry
  - *Au associated with sulphides*

- **Petrophysics**
  - Resistivity contrasts
    - Disseminated sulphides
    - More resistive host
  - Density, magnetic contrasts (in strat.)

- **Airborne EM**
  - Acquisition:
    - High resolution (50/100m line spaced)
    - Target late time conductive responses
  - Processing:
    - Channel amplitude maps
    - 1D transforms and inversions routine

(Robert et. al., 2007)
Yilgarn Granites: Nd Isotope Map/Gravity

Narryer  
Ida Fault

EGP Inverted Back-Arc Basin (an Accretionary Orogen)

NWB Pericontinental Basin

Model ages (Ga): All
- 2.7 - 2.8 Ga
- 2.6 - 2.85
- 2.85 - 2.9
- 2.9 - 3.0
- 2.99 - 3.0
- 3.0 - 3.05
- 3.05 - 3.1
- 3.1 - 3.2
- 3.2 - 3.3
- 3.3 - 3.4
- 3.4 - 3.5

- Layered Intrusions
- Zn-Ni sample locations

- model ages 200-300 Myr
- emplacement ages
- central/western Yilgarn - protocraton
- complex eastern Yilgarn

Gravity 1VD

(Data Source GSWA)
Regional Gravity – Yilgarn and Abitibi

Gold Deposits by Total Moz Au

- >10 Moz Au (5)
- 5 to 10 (13)
- 1 to 5 (77)

(Robert et. al., 2007)
Greenstone – Airborne EM Example

- Helicopter time domain VTEM surveys
- Late time channel data (8.9 ms) shown
- Draped over greyscale magnetics (RTP 1VD)
- Tusker 4.54 Moz @ 1.5 g/t Au (2009) – Sulphidised BIF
- Killimani anomaly identified as another sulphide response

(Pittard and Bourne, 2009)
Airborne EM (Greenstone)

- Major advances in acquisition technology (Time Domain)
  - Eg. VTEM and XCITE

- Best of both worlds
  - Good early time resolution
  - Plenty of moment for depth

- Ease of interpretation

- Moving toward full 3D inversion

- Jomu – Partial pyrrhotite replacement of magnetite in BIF (mineralised)

(Robert et. al., 2007)
Porphyry – Various Methods

- Geology
  - Porphyries form in various settings
  - Usually at convergent plate margins
  - Commonly hosted in volcanics or sediments
  - *Au in centre of porphyry system*

- Petrophysics
  - Magnetic, electrical & potassium contrasts
    - Alteration zonation
    - Response varies depending on host
    - Disseminated sulphides

- Various geophysical methods
  - Acquisition:
    - 1) Regional airborne mag & radiometrics
    - 2) Follow-up airborne EM
    - 3) IP/resistivity methods (100-200m dipoles)
  - Processing:
    - Channel amplitude maps
    - 1D/2D/3D transforms and inversions

Volcanic arc (island/continental) porphyry Cu-Au
- Diorite-granodiorite (tonalite)
- Preserved (?) lithocap +/- gold mineralization
- Post-mineral diatreme breccia

AEROTEM IV system
Regional Magnetics/Gravity

TMI Magnetics (after Holliday and Cooke, 2007)

Lachlan Fold Belt

Reko Diq Region

Isostatic Corrected Gravity
Porphyry – Geological Cross Section

Potassium Anomaly

Chargeable Anomaly 1km

Resistivity Anomaly

Magnetic Anomaly

(Howe and Kroll, 2010)
Porphyry – Integrated Example

- K-silicate core
  - magnetic
  - resistive

- Phyllitic alteration
  - resistive
  - chargeable

- Propylitic alteration
  - chargeable
  - magnetic

- Outer propylitic alteration
  - Potassium anomaly

(Howe and Kroll, 2010)
Mineralized Porphyries in the Reko Diq Cluster

- Porphyry with resource
- Mineralized Porphyry with drilling

(Fletcher et al., 2009)
Statistical Summary

- 29 Pre-existing prospects
  - 21 Recognised
  - 8 failed to meet user defined criteria (size, contrast, not circular)
- 35 Centres located
  - 30 Boundaries
  - 9 Additional targets

(Hope et. al., 2010)
Epithermal (HS) – CSAMT

- **Geology**
  - Diatreme dome complexes with associated volcanics
  - Pre, syn and post mineral diatremes
  - Pre-mineral domes can be unaltered and overlying
  - Large advanced argillic alteration zones (100’s km²)
  - Topographic highs of silicic alteration
  - *Au in vuggy silica core*

- **Petrophysics**
  - Resistive, massive vuggy silica core
  - Magnetite depletion
  - Chargeable alteration halo

- ** Resistivity methods**
  - Acquisition:
    - IP/res (100-200m dipoles)
    - CSAMT
  - Processing:
    - Amplitude maps, depth slices
    - 1D/2D inversions
Epithermal (HS) – CSAMT Example

- Veladero: ~ 12.0 Moz Au proven and probable (2009)
- Image of CSAMT resistivity
  - 100m depth slice, with alteration outline
- 400m line spacing
- Cross section through anomaly

(Bourne, 2010)
Epithermal (HS) – CSAMT Example

(Bourne, 2010)
- +250 Moz in Carlin deposits in area 200 x 400 km
- ~5% of world Au production
- Distributed along “Trends”

<table>
<thead>
<tr>
<th>Top 5</th>
<th>Moz Au</th>
<th>g/t</th>
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<tbody>
<tr>
<td>Goldstrike</td>
<td>55</td>
<td>8.6</td>
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<tr>
<td>Getchell-TR</td>
<td>26</td>
<td>7.1</td>
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<td>Gold Quarry</td>
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<td>1.2</td>
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<td>Twin Creeks</td>
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<td>2</td>
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<tr>
<td>Goldrush</td>
<td>14</td>
<td>4.2</td>
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</table>

(After Townsend et. al., 2010)
Basement Structures Gravity/Magnetics

Isostatic Corrected gravity 20-50km

Regional Magnetics 20-50km

(Data Source USGS)
Carlin - Deposit Characteristics

Seal

Conduit structure (plumbing)

Favorable rocks (sink for gold)

After Robert 2010 – Scale 5km across
Airborne Magnetics - Goldstrike

- Remains the most effective reconnaissance mapping tool
  - Despite limited developments in acquisition technology
  - Lower cost, better processing tools, better geologic integration

- Stippled high-low volcanic signature
  - Magnetite in primary composition
  - Variable remnant and normally magnetized Basalt flows

- Intrusive stock high
  - Magnetite in primary composition
  - Remnant and normally magnetized

Also consider
- high from Monoclinic Pyrrhotite in magnetic skarn surrounding intrusion

(After Townsend et al, 2010)
- No geophysical “silver bullet” for Carlin-style gold mineralization

- Petrophysical **GENERALIZATIONS** of typical Great Basin rocks:

<table>
<thead>
<tr>
<th>Rock type</th>
<th>Physical Property</th>
<th>Magnetization</th>
<th>Density</th>
<th>Conductivity</th>
<th>Chargeability</th>
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<tbody>
<tr>
<td>Paleozoic Lower Plate Carbonates</td>
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<td>M-H</td>
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<td>Pen-Perm overlap sediments</td>
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<tr>
<td>Mesozoic Intrusive stocks</td>
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<td>M - H</td>
<td>M</td>
<td>M</td>
<td>L</td>
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<tr>
<td>Tertiary/Quaternary Alluvium/Colluvium</td>
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<td>L</td>
<td>L</td>
<td>H</td>
<td>L</td>
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<tr>
<td>Tertiary/Quaternary Volcanics</td>
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<td>H</td>
<td>M</td>
<td>M</td>
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</tr>
</tbody>
</table>

- Overprinting structural, alteration and metamorphic events inherently causes **highly variable** petrophysical properties

(After Townsend et. al., 2010)
Residual gravity highlights density contrasts in upper 500m

- Defines bedrock horst beneath alluvial pediment
  - 1500ft wide, 3 miles long

- 2D gravity modeling to quantify geometry and offset
  - Simple 2-layer earth model
    - Bedrock (2.4 g/cc)
    - Alluvium (2.0 g/cc)
Simple two-layer* 2D gravity model (Encom ModelVision)

*Tertiary Basalt layers of unknown thickness are not accounted for in modeling

(Townsend et. al., 2010)
Geology
- Carbonate stratigraphy
- Low-angle architecture
- Thrusting and stacking
- **Au in antiform structure**

Petrophysics
- Density & velocity contrast between
  - lithologies
  - deposition facies
  - structure

Hardrock Seismic
- Acquisition:
  - High resolution & frequency
  - 10m receiver, 20m shot
  - At least 120 fold
  - 3D acquisition in 2011, 2012
- Processing:
  - Statics corrections for topography
  - Huge velocity contrasts in near-surface
- Location of Gold Acres seismic line

(Townsend et. al., 2010)
Blue = drillholes

- Good reflectors in Lower Plate
- Incoherent reflectors in intrusion
- First good reflector is coincident with the base of intrusion from drilling
- Interpret laccolithic shape to intrusion

(Townsend et. al., 2010)
Challenges for Exploration Geophysics

- Near-mine success for deep discoveries
- Need to extend success to all our frontiers
  - At depth, under cover, in remote areas

Carlin discoveries in Nevada (near-mine)
Challenges - Targeting

- Understand fundamental controls on mineral systems, deposit formation and distribution through time.

- Collaborative research to improve understanding of mega-scale terrains and giant mineral systems footprints combined with Government precompetitive raw data.

- Direct Targeting is company responsibility not broad collaborative research – Company competitive advantage.
Conclusions

- **Carlin: Hardrock Seismic**
  - Seismic suits the carbonate stratigraphy, having low-angle structural control on architecture and good acoustic impedance contrasts between lithologies and deposition facies
  - Hardrock seismic requires high spatial resolution (10m receiver, 20m shot) and frequency and higher fold (120+)

- **Greenstone: Airborne EM**
  - Sediment hosted sulphide-rich end member is better suited to electromagnetic (EM) techniques
  - Conductive near-surface response usually identifies centre of the system
Conclusions (cont)

- **Porphyry Cu-Au: Integrated Methods**
  - Magnetics/ radiometrics to map potassic alteration is well known
  - Potassic core can be either conductive in sulphide-rich systems, or resistive in sulphide-poor systems, depending on host
  - Outer phyllic/ propylitic alteration is chargeable, magnetite destructive and is often resistive

- **High Sulphidation Epithermal: CSAMT**
  - Resistivity data can effectively map the typical alteration of advanced argillic with vuggy silica (resistive), advanced argillic with quartz alunite (moderate resistor), to argillic with intense clay (conductive, chargeable)
  - Magnetite depletion and chargeable alteration also system indicators
Summary

- Demand for resources will increase
- Maturity in shallow search space, forcing us deeper
- Discovery success rates expected to remain low
- Risk – increasingly important in choice of where to explore, technical risk will eventually increase
- Tools need further development and in some cases step change to improve exploration success rates
- Integrated exploration will be the key in the next round of discoveries – geophysics will be key
- Geoscientists – remember fundamental geology and boots on the ground
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