Vision for Future Exploration: Geophysics and Gold

B. Bourne, ASEG-PESA Melbourne, 13th August, 2013
Outline

- Gold Trends
- Challenges
- Gold Model Types
  - Carlin
  - Greenstone
  - Porphyry
  - HS Epithermal
- Research
- Future
- Summary
Gold Discoveries since 1995

- Looking at +2Moz deposits:
  - 52 discoveries for 580 Moz (6 are >20 M oz)
  - 26 grassroots, 26 near-mine

- Only 10 in production
  - 4 grassroots, 6 brownfields

- We discover but
  - Few get to production
  - Takes longer

Barrick 2010
Discovery trends

- Discovery rates down
- Discovery cost up
- Effectiveness down

Increasing maturity
- Shrinking of search space

From McKeith 2009

Decreasing exploration effectiveness
World class discoveries required

- Long life, high margin, high throughput deposits
- 20% biggest deposits = 80% production or resources

Those are rare!
- Gold: 55 deposits >20 Moz
  - ~45 producing or mined
  - ~10 in the pipeline
Exploration Challenge Maturity

Outcrop Shallow basement
Basement depth <500m
Basement depth 500m to 1000m
Basement depth > 1000m

Source: Geoscience Australia Intierra
Targeting the Best Models

- **Preferred target types:**
  - High deposit abundance
  - Highest % of population >10 Moz deposits
  - Good economics and mineability

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![Graph showing preferred target types](image)

**Greenstone**
- >10 Moz: 28%
- >3 Moz: 36%
- Hollinger, Homestake

**Porphyry Cu-Au**
- >10 Moz: 30%
- >3 Moz: 45%
- Yanacocha, Rosia Montana

**HS Epithermal**
- >10 Moz: 30%
- >3 Moz: 45%
- Round Mountain, Porgera

**Epithermal LS**
- >10 Moz: 4%
- >3 Moz: 10%
- Muruntau

**CSH**
- >10 Moz: 29%
- >3 Moz: 45%
- Goldstrike

**Carlin**
- >10 Moz: 45%
- >3 Moz: 10%
- La Ronde

**Au-VMS**
- >10 Moz: 10%
- >3 Moz: 0%
- La Ronde

- 468 deposits >3 Moz
Nevada Hot Spot

- +250 Moz in Carlin deposits in area 200 x 400km
- ~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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<td>Getchell-TR</td>
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<td>7.1</td>
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<td>1.2</td>
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<td>Twin Creeks</td>
<td>17</td>
<td>2</td>
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<td>Goldrush</td>
<td>14</td>
<td>4.2</td>
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Carlin deposits
- > 10 Moz
- 5-10 Moz
- 1-5 Moz
- <1 Moz

Scale: 100 km
Mineralization characteristics

- Au with fine disseminated pyrite
  - Au-As in rims (*main ore stage*)
  - Later realgar, orpiment, stibnite (*late ore stage*)
  - Au-As-Tl-Sb-Hg association

- Forms as wallrock replacement or breccia matrix

Silicified silty micrite, Cortez Hills; 25 g/t Au

Photo courtesy of Jean Cline
Deposit characteristics

- Favorable rocks (sink for gold)
- Conduit structure (plumbing)
- Seal

Legend:
- Jasperoid
- Silicification
- Decalcification
- Breccia
- Ore
- 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>L</td>
<td>M-H</td>
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<td>Paleozoic Upper Plate Siliciclastics</td>
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<tr>
<td>Pen-Perm overlap sediments</td>
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<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>
<td></td>
<td>H</td>
<td>M</td>
<td>M</td>
<td>L</td>
</tr>
</tbody>
</table>

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

- Geophysical applications in the Great Basin require:
  - Specific **petrophysical studies**
  - understanding of **geologic controls on mineralization**

- Recent Great Basin examples:
  - Gravity: Project A ★
  - Hardrock Seismic: Cortez ★
  - IP/Resistivity: Bald Mountain ★

*Image from M. Jackson, 2010*
Detailed Gravity

- Gravity for Great Basin exploration
  - Map **denser** Lower Plate vs Upper Plate
  - Map **alteration and metamorphism**
    - Decalcification=low, Hornfelsing=high
  - Map bedrock structure **beneath cover**

- Project A example
  - Immediately north of mine
  - Ore is structurally controlled on high-angle (75° W) fault
  - Use gravity to map extension of mineralised structure

- Pediment cover greater than 150m
  - 300m gravity station spacing

Google Earth image over Project A
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)
Detailed Gravity – Project A

- Simple two-layer* 2D gravity model (Encom ModelVision)

*Tertiary Basalt layers of unknown thickness are not accounted for in modeling
Carlin – Hardrock Seismic

- **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
Terra Resources

**Hardrock Seismic - Cortez**

- **Upper Plate siliciclastics**
- **Metamorphic halo**
- **Lower Plate carbonates**
- **Intrusive**

**TARGET**

- 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

Depth conversion from downhole velocity work

Blue = drillholes
Induced Polarization

- Pyrite and Arsenopyrite will have an IP response
- ....BUT so does geological ‘noise’:
  - Diagenetic pyrite that is not associated with mineralization
  - Graphitic ‘black’ shales
  - Remobilized carbon outbound of contact metamorphic aureole

- Use of IP in the Great Basin is limited and applied on case by case basis depending on geologic setting

- Innovative applications of traditional IP techniques
  - Distributed array systems
  - 3D inversion
  - Downhole IP experiments
  - AMIRA P1058 Spectral Induced Polarization for 3D Mineral Discrimination
IP - Bald Mt example

- RBM dipole-dipole IP Survey
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

*VTEM system*
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
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

**Thompson (2004)**

**AEROTEM IV system**
Porphyry – Geological Cross Section

Potassium Anomaly

Chargeable Anomaly

Resistivity Anomaly

Magnetic Anomaly

1km

- Outer Propylitic
- Propylitic

Unaltered post-mineral feldspar porphyry dykes

TPD-001

C & Cu in soil ~ 400 – 1060 ppm

increasing fracturing & alt intensity

Unaltered
Porphyry – Integrated Example

- **K-silicate core**
  - magnetic
  - resistive

- **Phyllic alteration**
  - resistive
  - chargeable

- **Propylitic alteration**
  - chargeable
  - magnetic

- **Outer propylitic alteration**
  - Potassium anomaly
Mineralized Porphyries in the Reko Diq Cluster

- Porphyry with resource
- Mineralized Porphyry with drilling

Western Porphyries

H36
H9
H2
H13
H8
H27
H7-H58
H35
H14
H15
H79

Bulet
Pashir

2 km

NE Kohi Dalil
Kahi Dalil
Parra Koh
Ground EM on Tanjeel (H4)
Channel 15 (990 usec)

144m @ 0.49%Cu
24m @ 0.4%Cu
15m @ 0.66%Cu
15m @ 1.08%Cu
27m @ 0.88%Cu

1km
Ground EM on Tanjeel (H4) Channel 15 with Cu Grade

144m @ 0.49%Cu
24m @ 0.4%Cu
15m @ 0.66%Cu
15m @ 1.08%Cu
27m @ 0.88%Cu
Porphyry Filter

- Automatically detect and quantify porphyry magnetic signatures via user defined application of porphyry target model
- Research agreement between UWA-CET and Barrick signed in 2008 to sole-fund “Porphyry Texture Filter”
- Cu-Au rich porphyry focus
- Magnetic coverage available over most projects – capitalise on investment
- Rapid objective analysis of large datasets
- Discrimination within highly magnetic terrains and under cover
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
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
Epithermal (HS) – CSAMT Example

Vuggy Silica
Quartz Alunite
Argillic - Clays

Au 1g/t contour
Au 5g/t contour
- 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)
Where to Look - 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.
Vision for Exploration - Geophysics

- Petrophysical analysis performed on all drill core or routinely determined down hole.

- All deep exploration boreholes with strategic value preserved (cased) and exploited using off hole geophysical techniques (e.g., VSP, gravity, magnetics).

- Routine use of high resolution 3D seismic for mineral exploration - basement mapping.

- Routine use of multi-component sensor technology for airborne acquisition (e.g., EM, magnetics, gravity).

- “Array” style acquisition for ground geophysical surveys. Multiple sensors deployed and acquire data simultaneously.

- Routine 3D inversion of all geophysical data with joint inversion (geology or other geophysical data) common practice.
Advances: Acquisition

- Distributed array electrical methods
  - Multiple source-receiver combinations
  - Reduce non-uniqueness in inversions
  - Higher interpretability, more accurate

- 3D Hardrock Seismic
  - 3D seismic best for complex 3D geology
  - A lot more affordable in past decade
  - Wireless receivers + built-in GPS receivers for formidable terrain

- Airborne gravity
  - Noise levels down
  - Acquire data in rugged areas...or over competitor ground ;)
  - Helicopter platform now available
Advances: Processing and Inversion

- Able to use office PC’s, instead of blades/cluster.
  - Processing with 64-bit machines, +++Gb RAM

- Forward modeling for 3D survey planning
  - 3D seismic / 3D MT station planning to best ‘illuminate’ target

- 3D inversion
  - Faster algorithms, continuous updates through research
  - More complex meshing for topography etc

- Example: Round Mt, NV
- 3D survey acquisition
- Gold Hill 3D IP inversion
- 3D replicated 2D results
Advances: 3D Interpretation

- Integration of geophysical, geochemical and geologic data
- Common earth models populated with multidisciplinary data

3D model for Dee property

From J. Katseanes (Barrick)
Conclusions

- **Barrick Gold**
  - Leading gold producer, with largest reserves
  - Support Universities, professional affiliate groups and research
  - Preferred model type greenstone, epithermal, Carlin and porphyry Cu-Au

- **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
Vision for Future Exploration: Geophysics and Gold

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