Mapping Mineral Systems – New Perspectives and Challenges for Exploration Geophysics

Geophysical Exploration for Gold: Regional to Mine Scale Targeting

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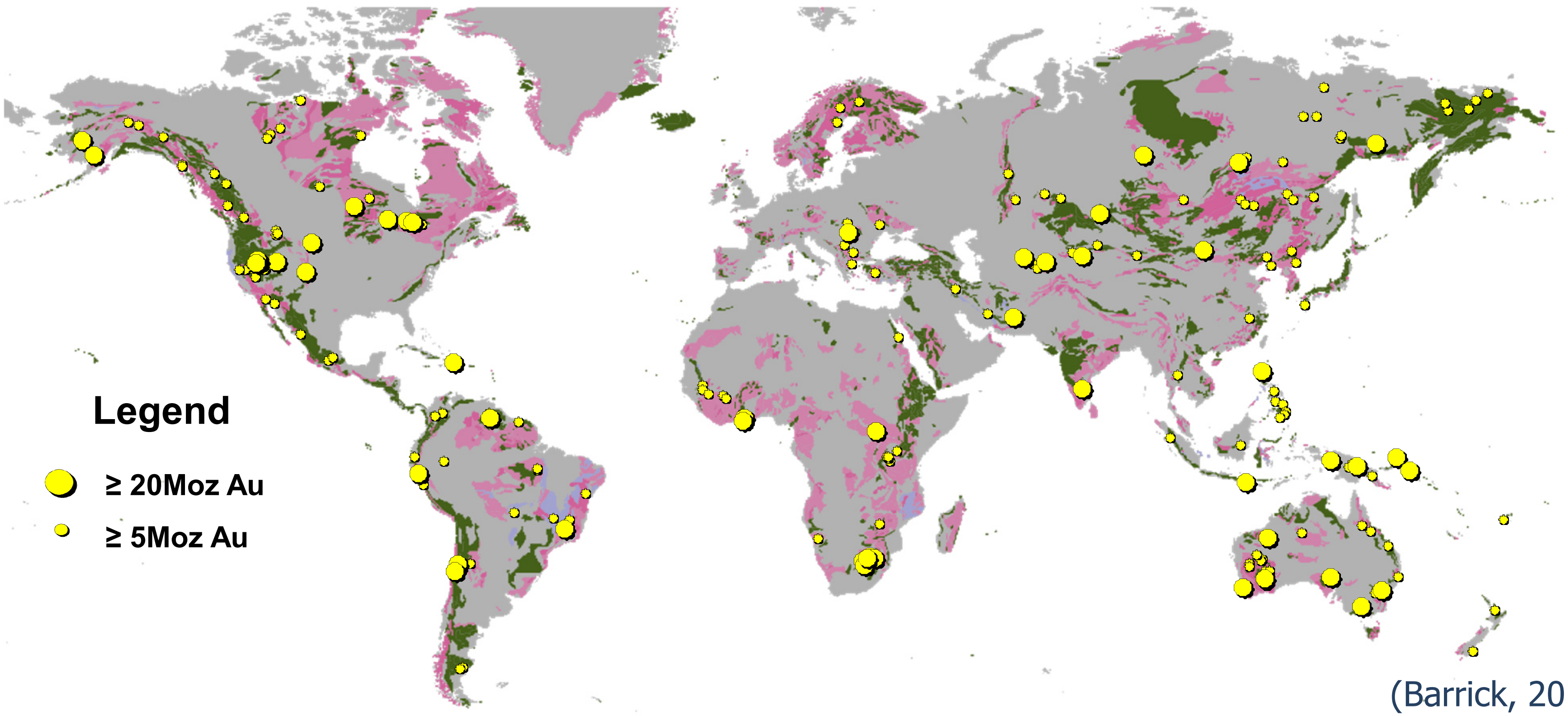
Outline

- Challenges
- Gold Model Types
  - Carlin
  - Greenstone
  - Porphyry
  - HS Epithermal
- Challenges
- Summary

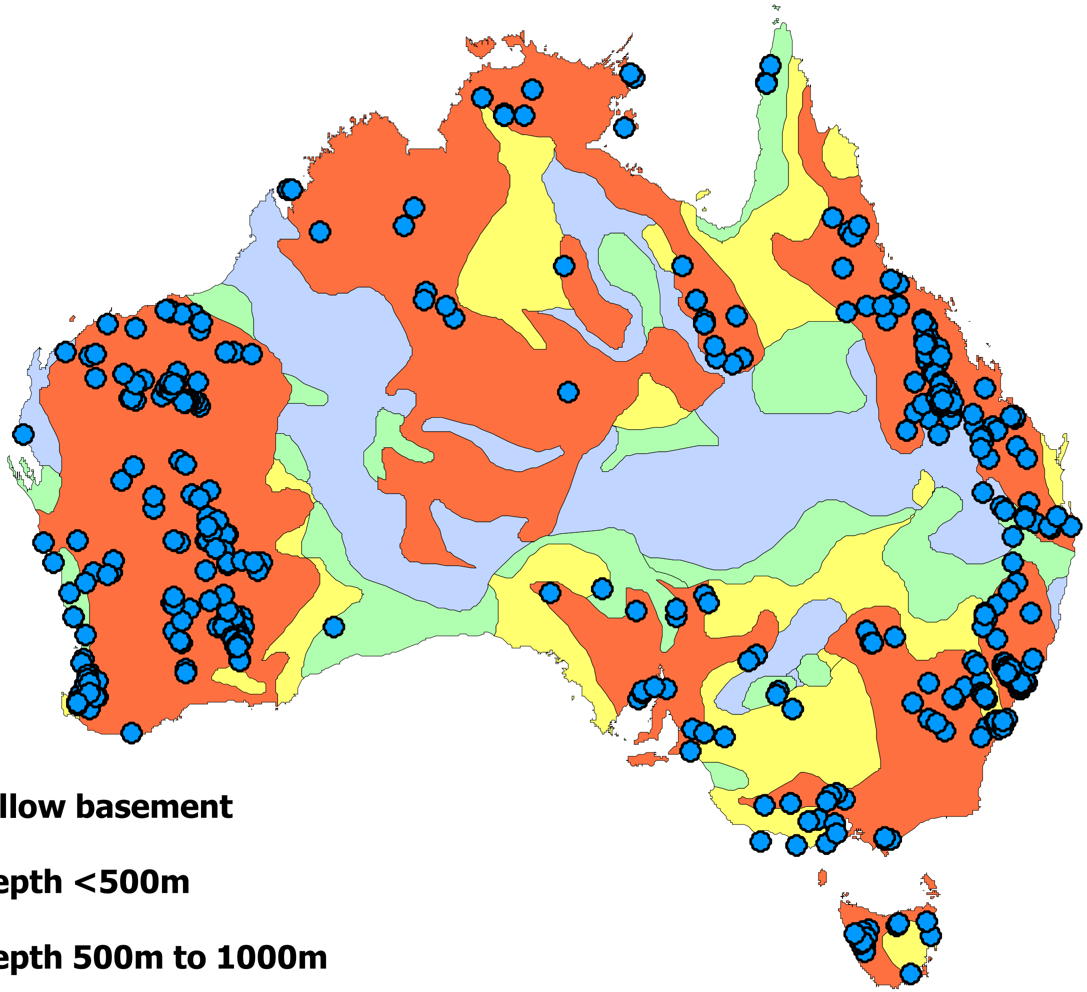
World Class Discoveries Required

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



(Barrick, 2010)

Exploration Challenge Maturity



Outcrop Shallow basement

Basement depth <500m

Basement depth 500m to 1000m

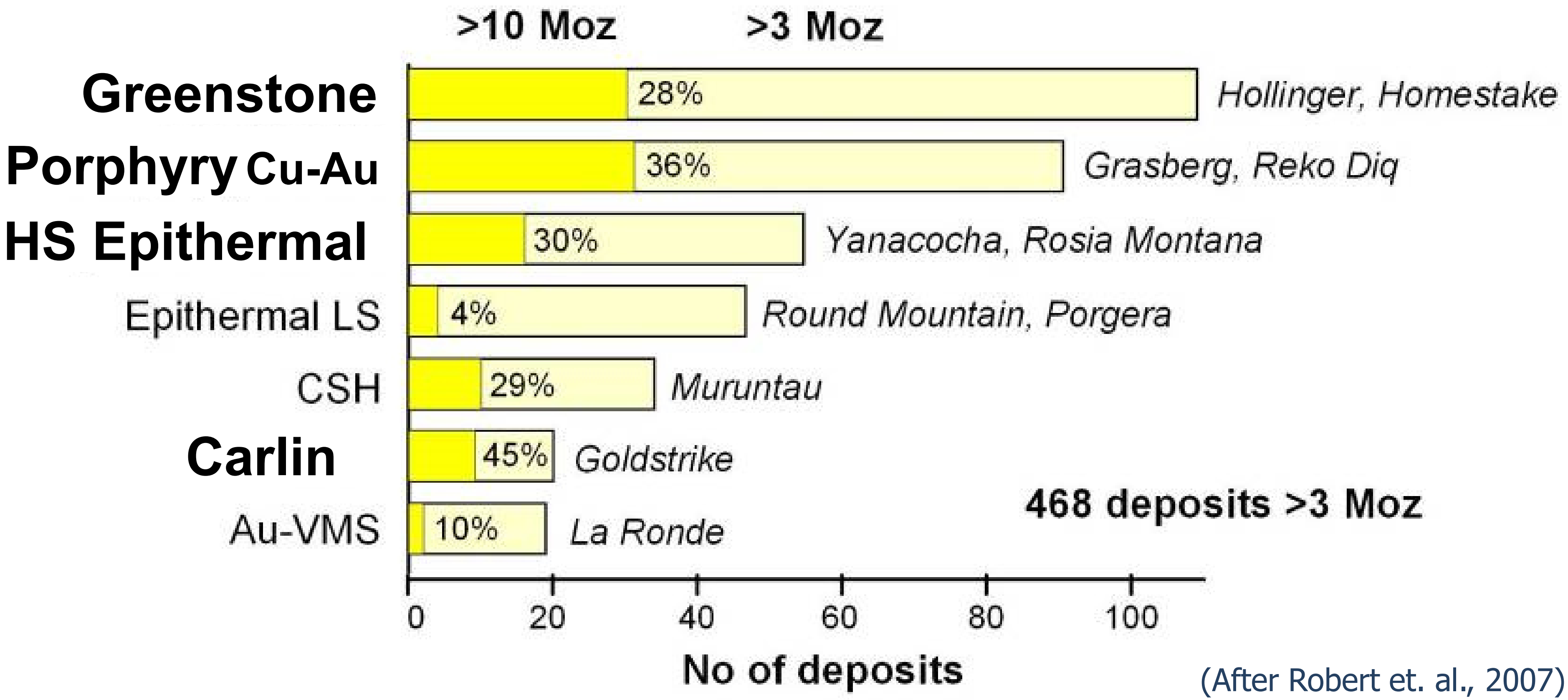
Basement depth > 1000m

Mineral Deposits

Source: Geoscience Australia Intierra

Targeting the Best Models

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



(After Robert et. al., 2007)

Mineral Systems Framework

WESTERN MINING SERVICES LLC

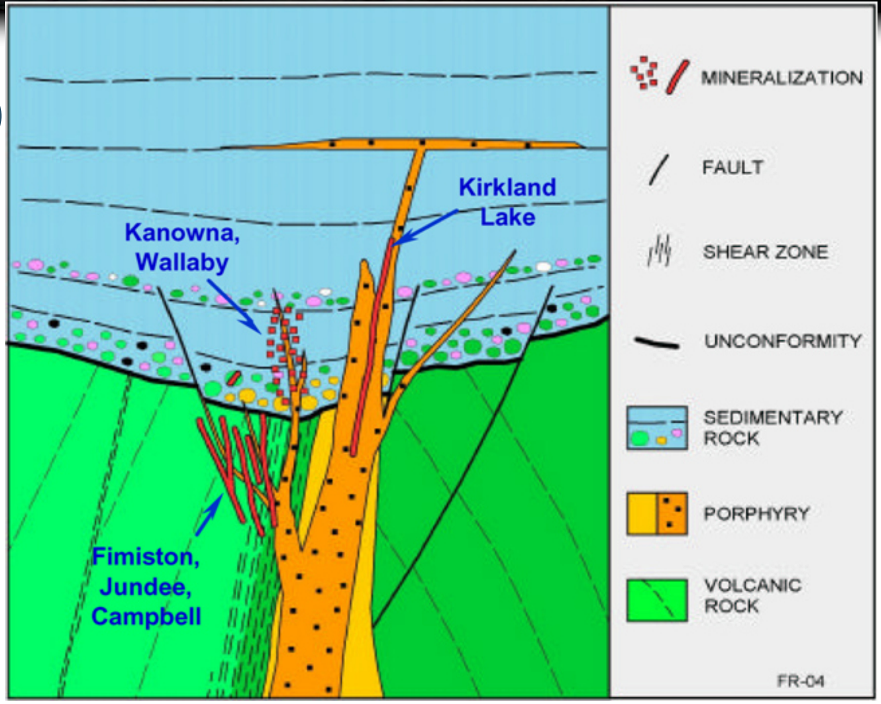
Regional Targeting Implications

- 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

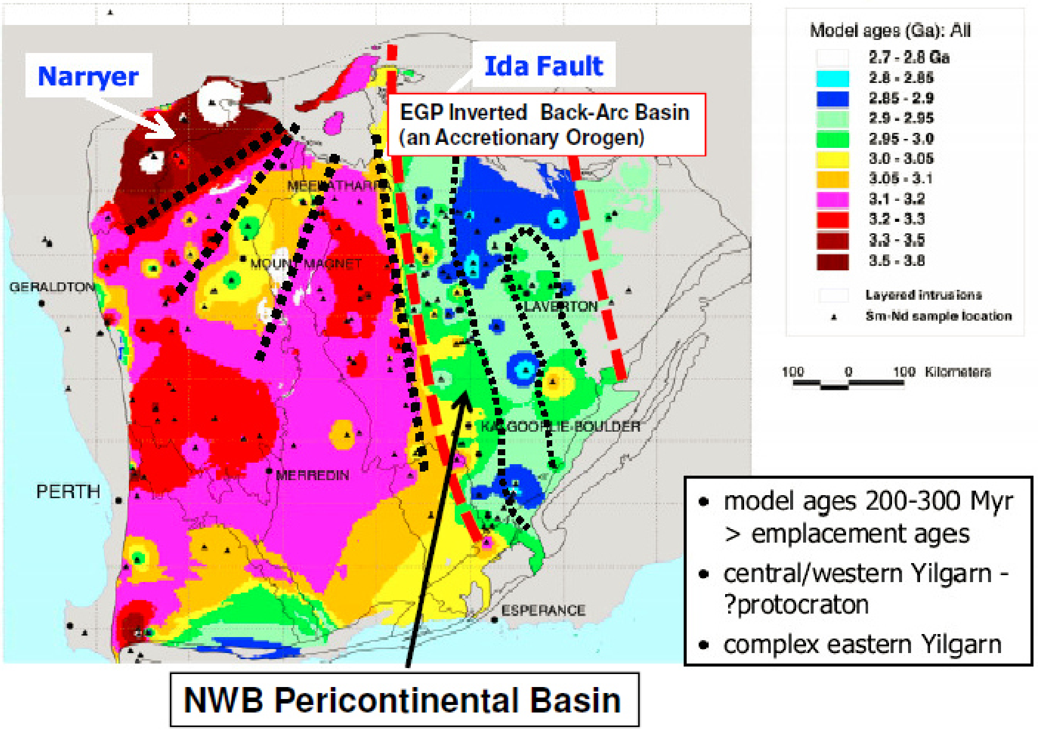
- Geology
  - Greenstone stratigraphy (includes seds)
  - Sediment hosted sulphide-rich end member
  - Near volcanic sequence or porphyry
  - ***Au associated with sulphides***
- Petrophysics
  - Resistivity contrasts
    - Disseminated sulphides
    - More resistive host
  - Density, magnetic contrasts (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)

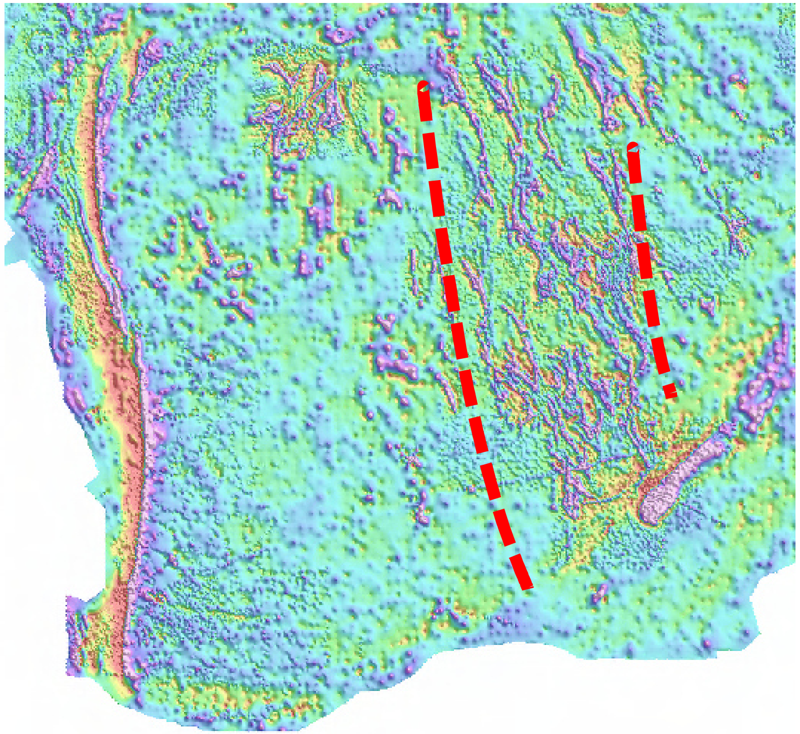
AEM system

Yilgarn Granites: Nd Isotope Map/Gravity



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

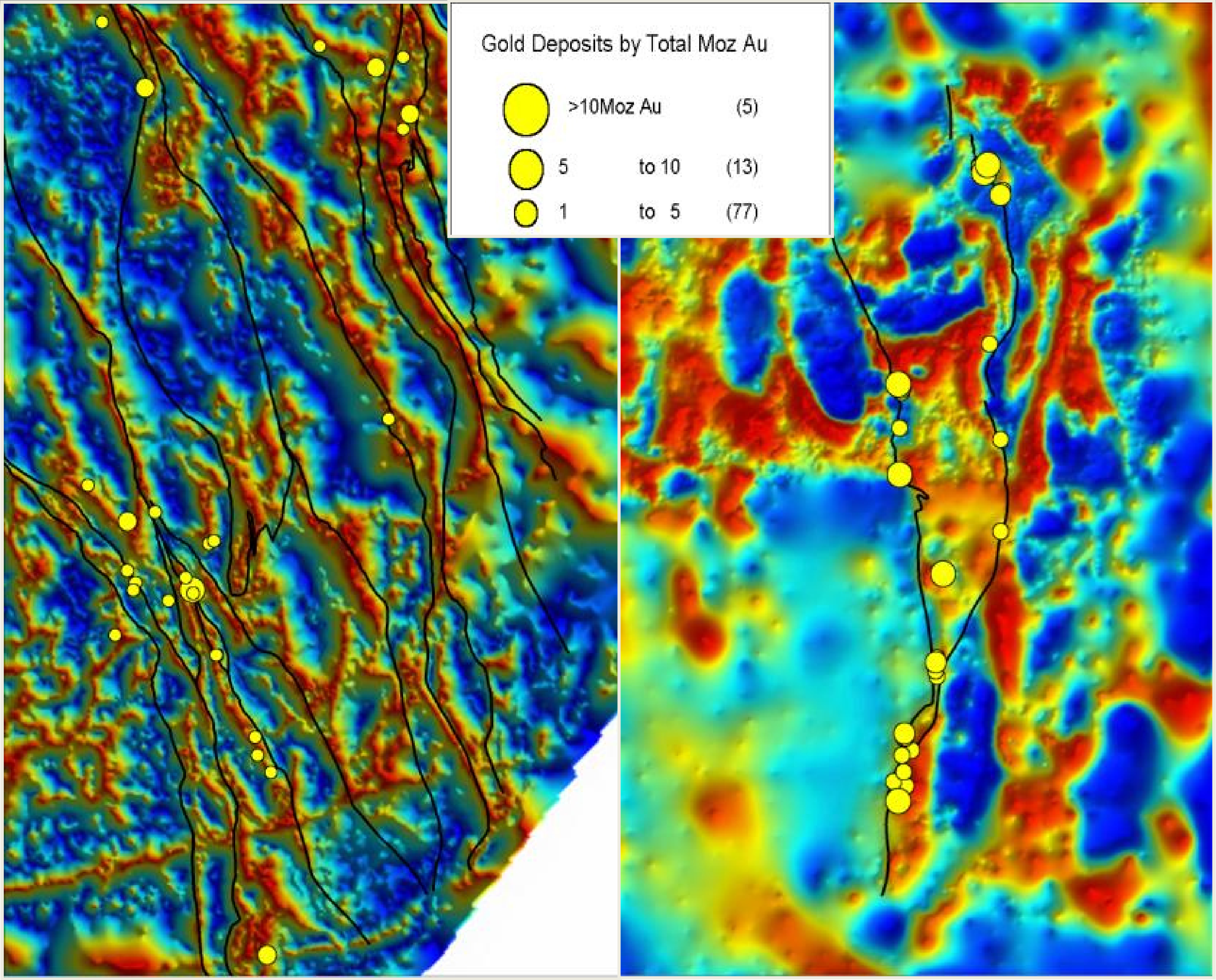
Cassidy & Champion (2004)



Gravity 1VD

(Data Source GSWA)

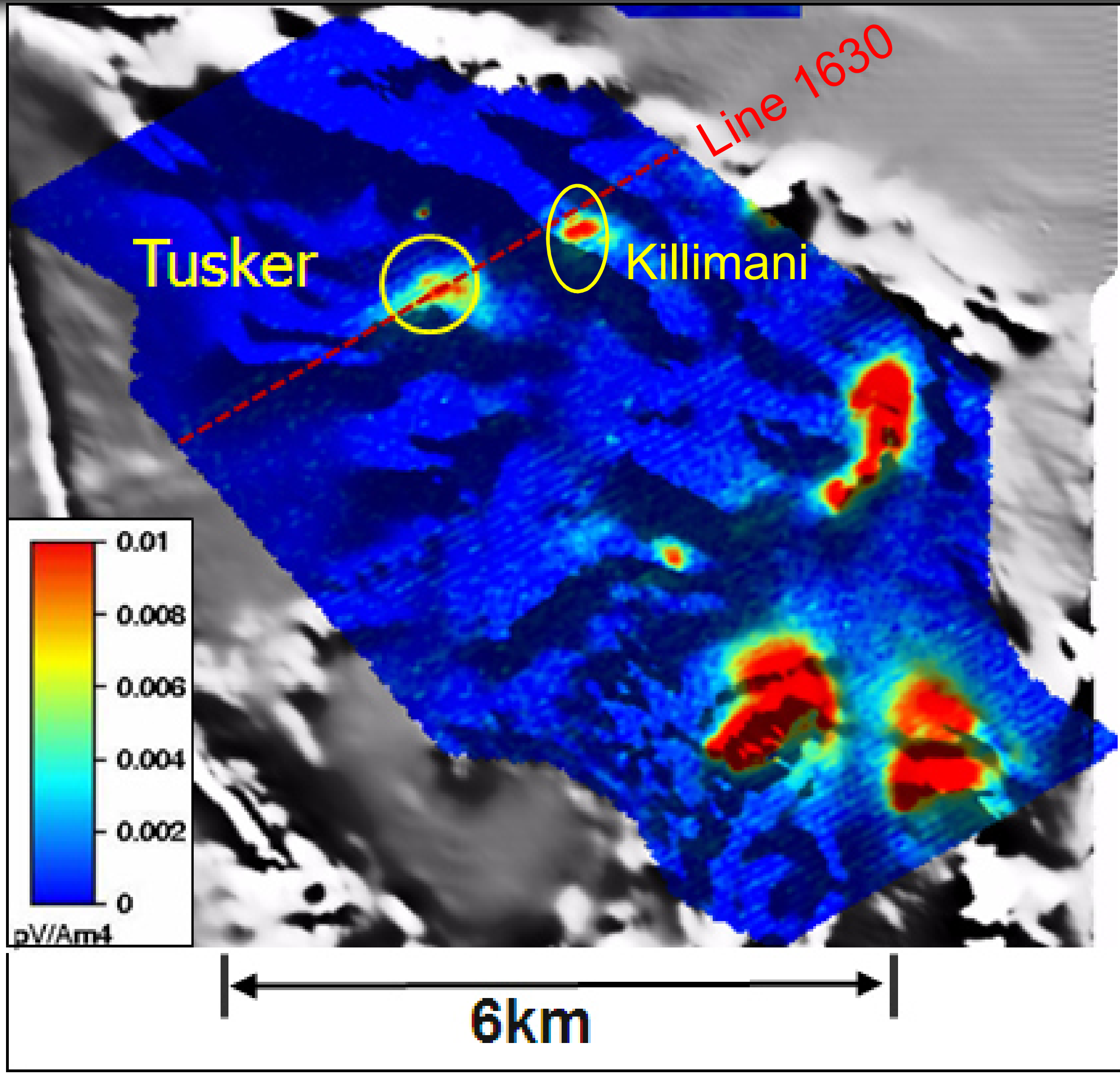
Regional Gravity – Yilgarn and Abitibi



(Robert et. al., 2007)

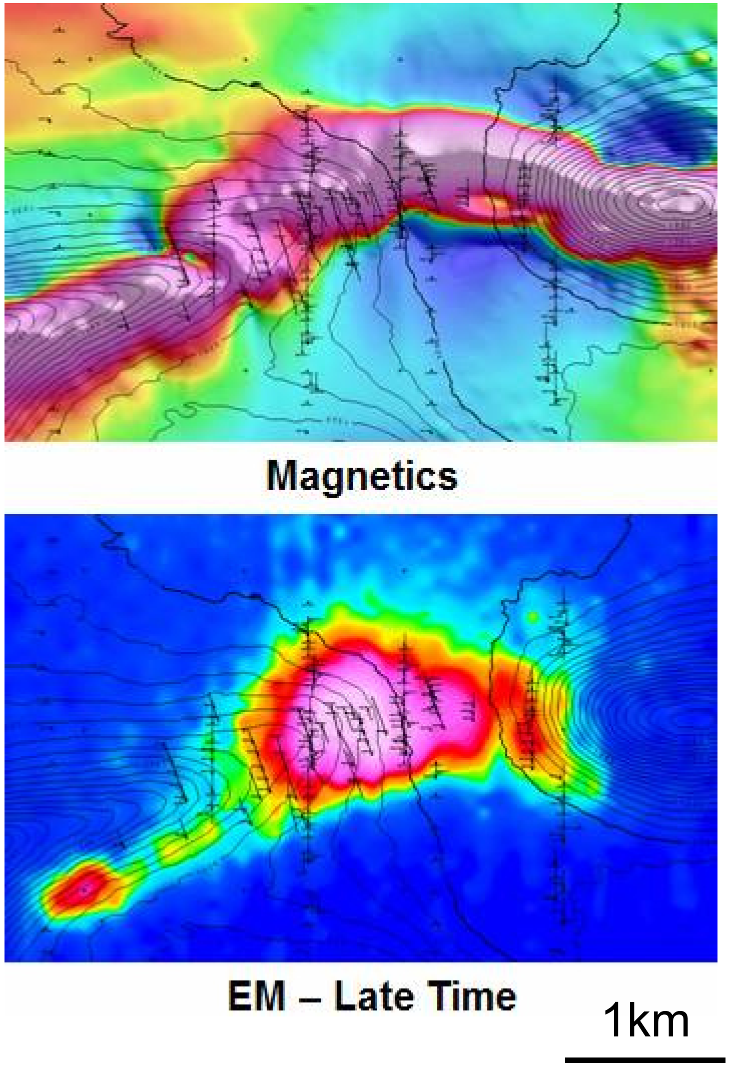
Greenstone – Airborne EM Example

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



(Pittard and Bourne, 2009)

Airborne EM (Greenstone)

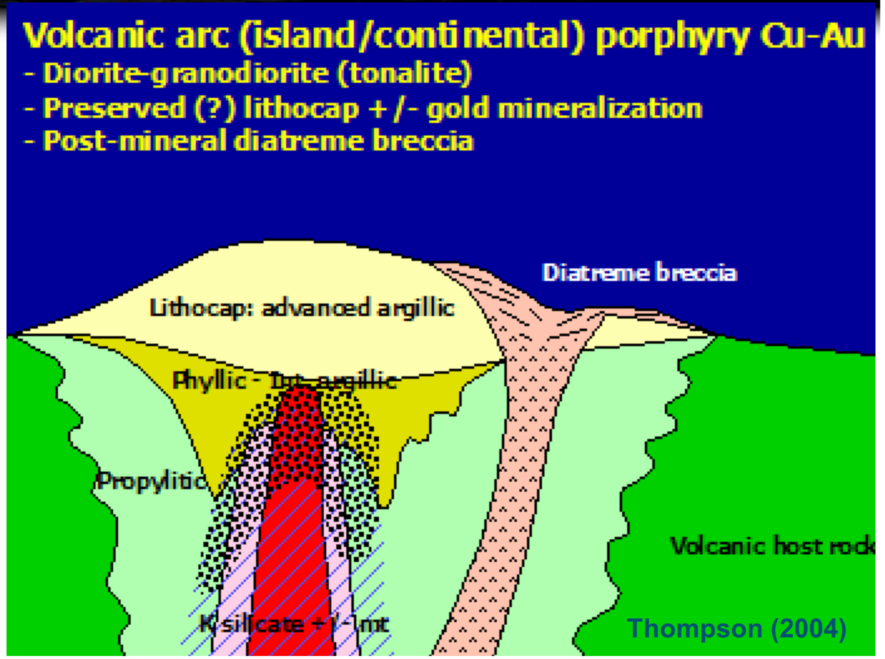


(Robert et. al., 2007)

- 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)

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***

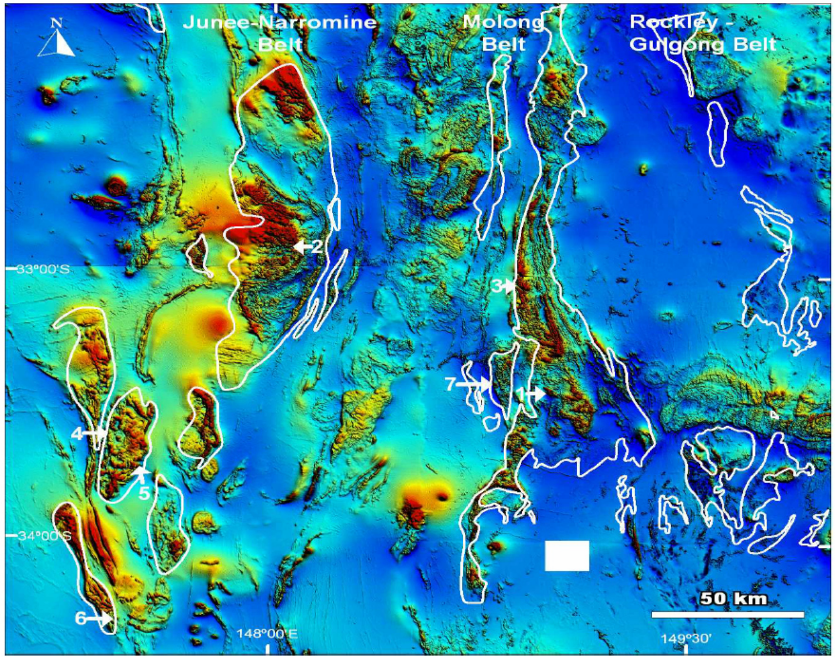


- Petrophysics
  - Magnetic, electrical & potassium contrasts
    - Alteration zonation
    - Response varies depending on host
    - Disseminated sulphides

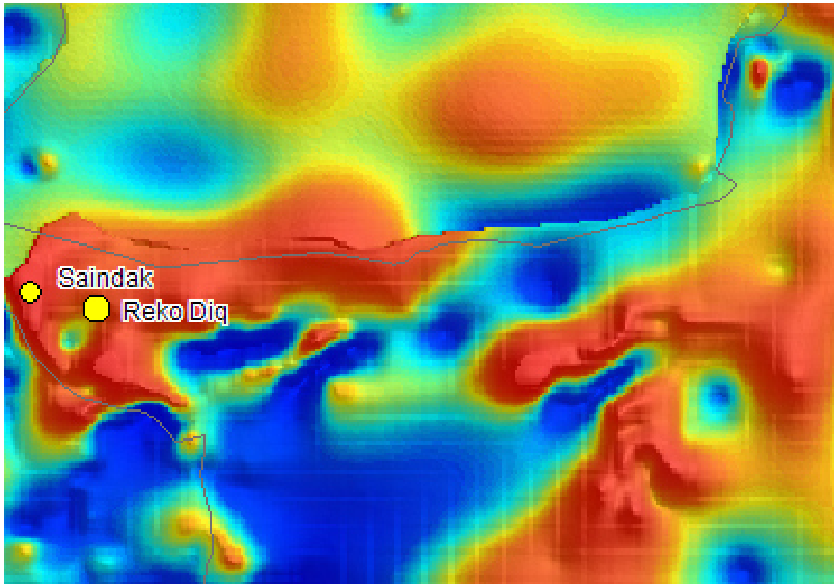
- Various geophysical methods
  - Acquisition:
    - 1) Regional airborne mag & radiometrics
    - 2) Follow-up airborne EM
    - 3) IP/resistivity methods (100-200m dipoles)
  - Processing:
    - Channel amplitude maps
    - 1D/2D/3D transforms and inversions

AEROTEM IV system

Regional Magnetics/ Gravity



TMI Magnetics (after Holliday and Cooke, 2007)



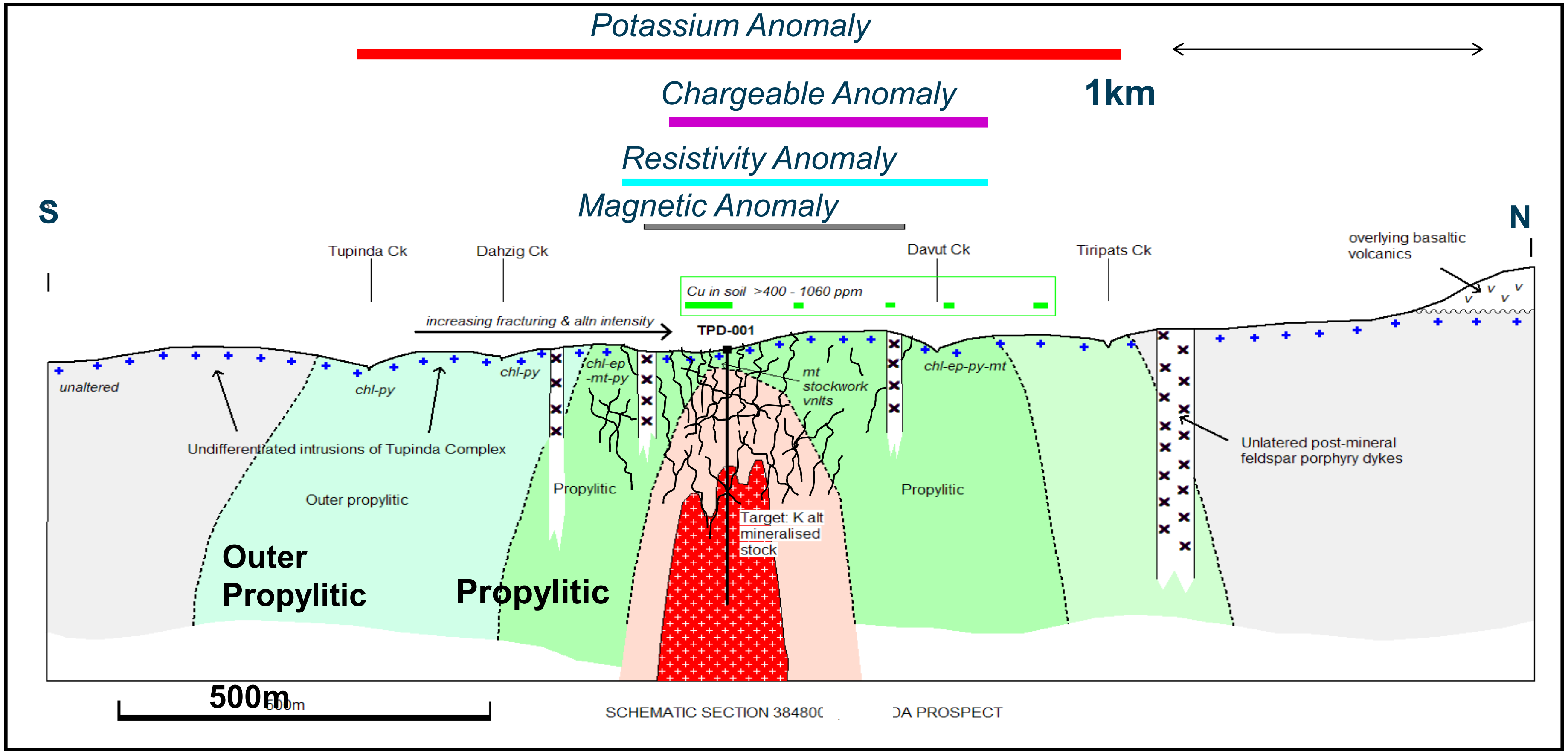
50km

Isostatic Corrected Gravity

Lachlan Fold Belt

Reko Diq Region

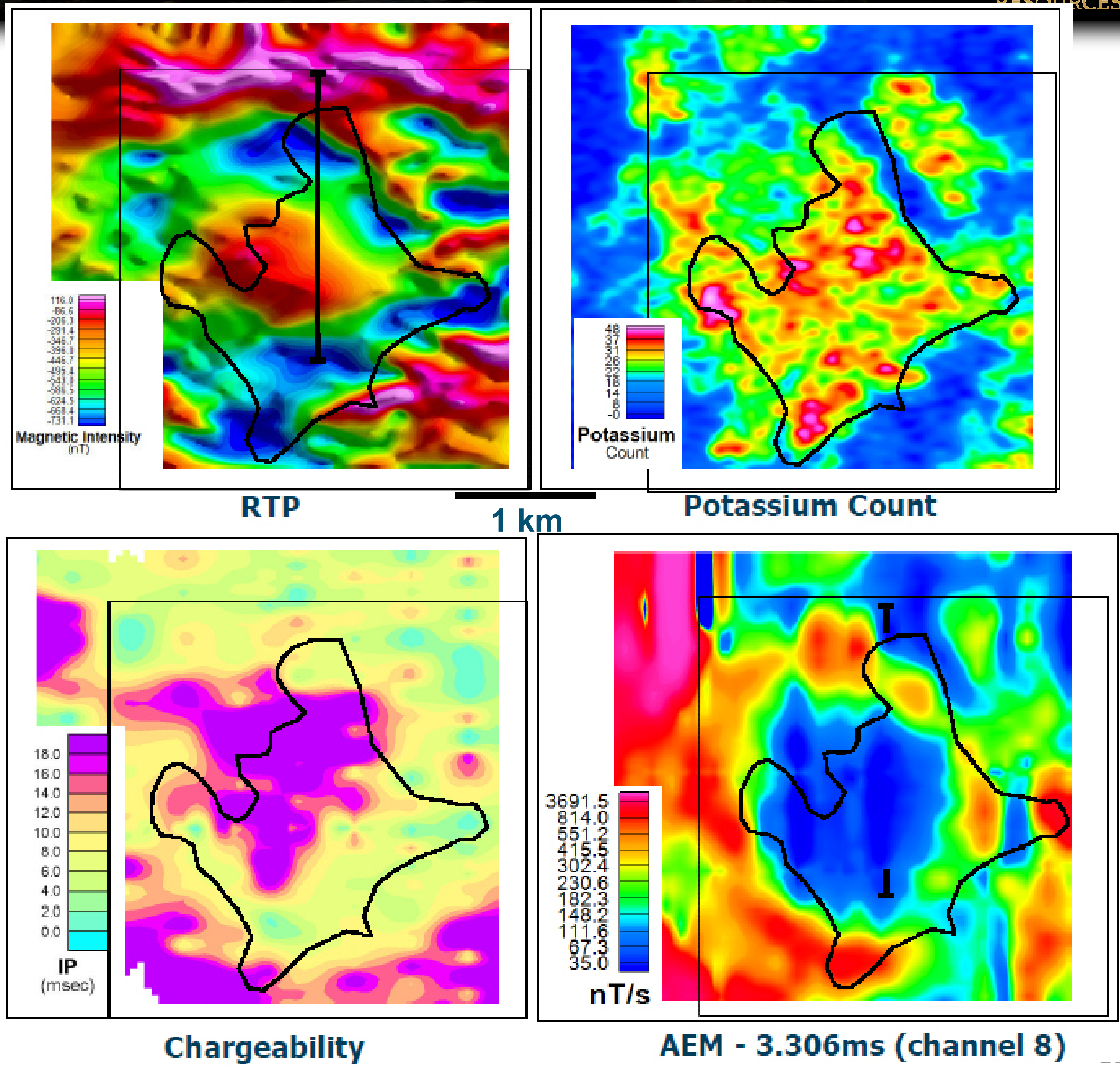
Porphyry – Geological Cross Section



(Howe and Kroll, 2010)

Porphyry – Integrated Example

- K-silicate core
  - magnetic
  - resistive
- Phyllic alteration
  - resistive
  - chargeable
- Propylitic alteration
  - chargeable
  - magnetic
- Outer propylitic alteration
  - Potassium anomaly



(Howe and Kroll, 2010)

Reko Diq Project : Porphyry Centre's

ANTOFAGASTA PLC

TETHYAN COPPER COMPANY LIMITED

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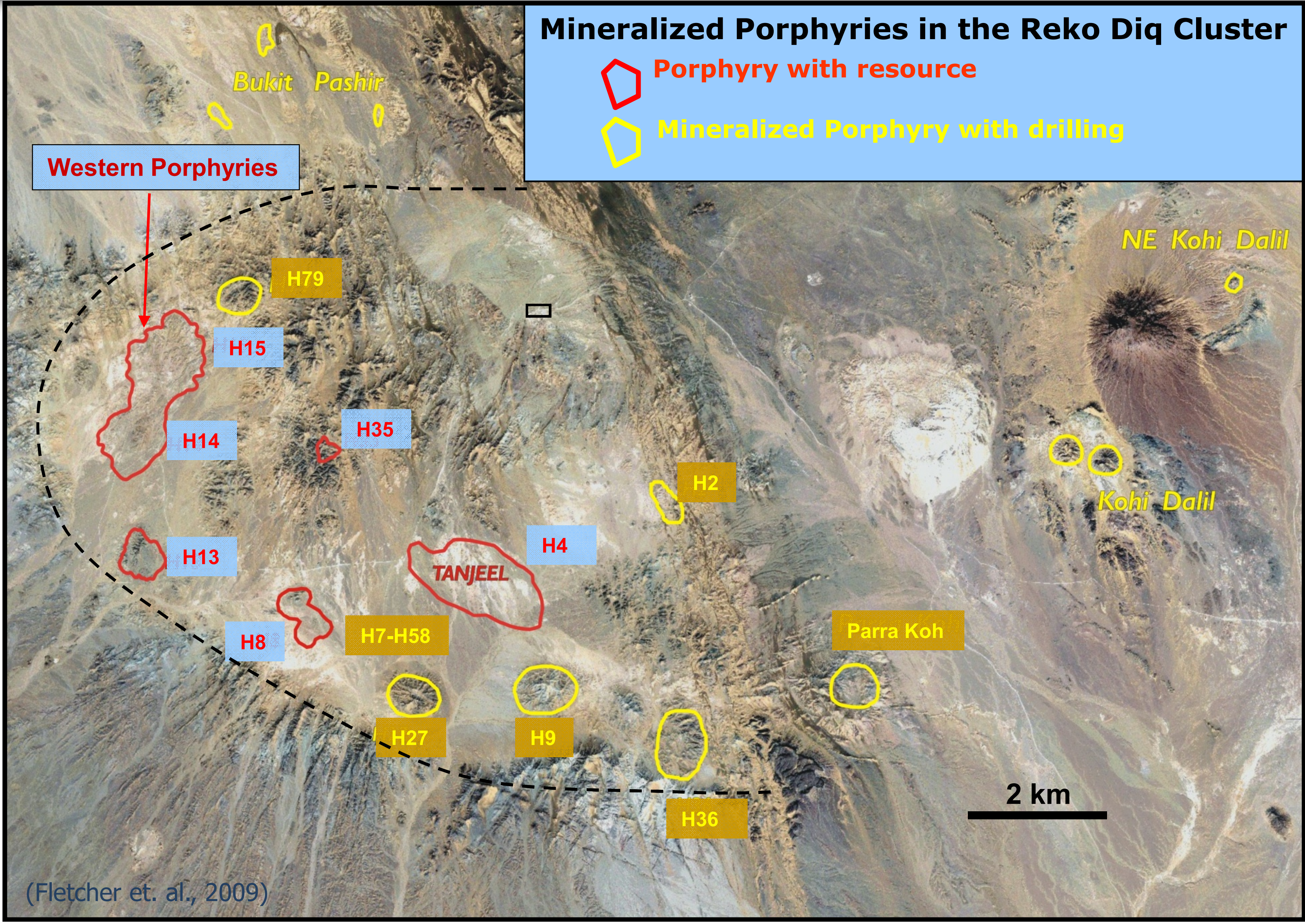
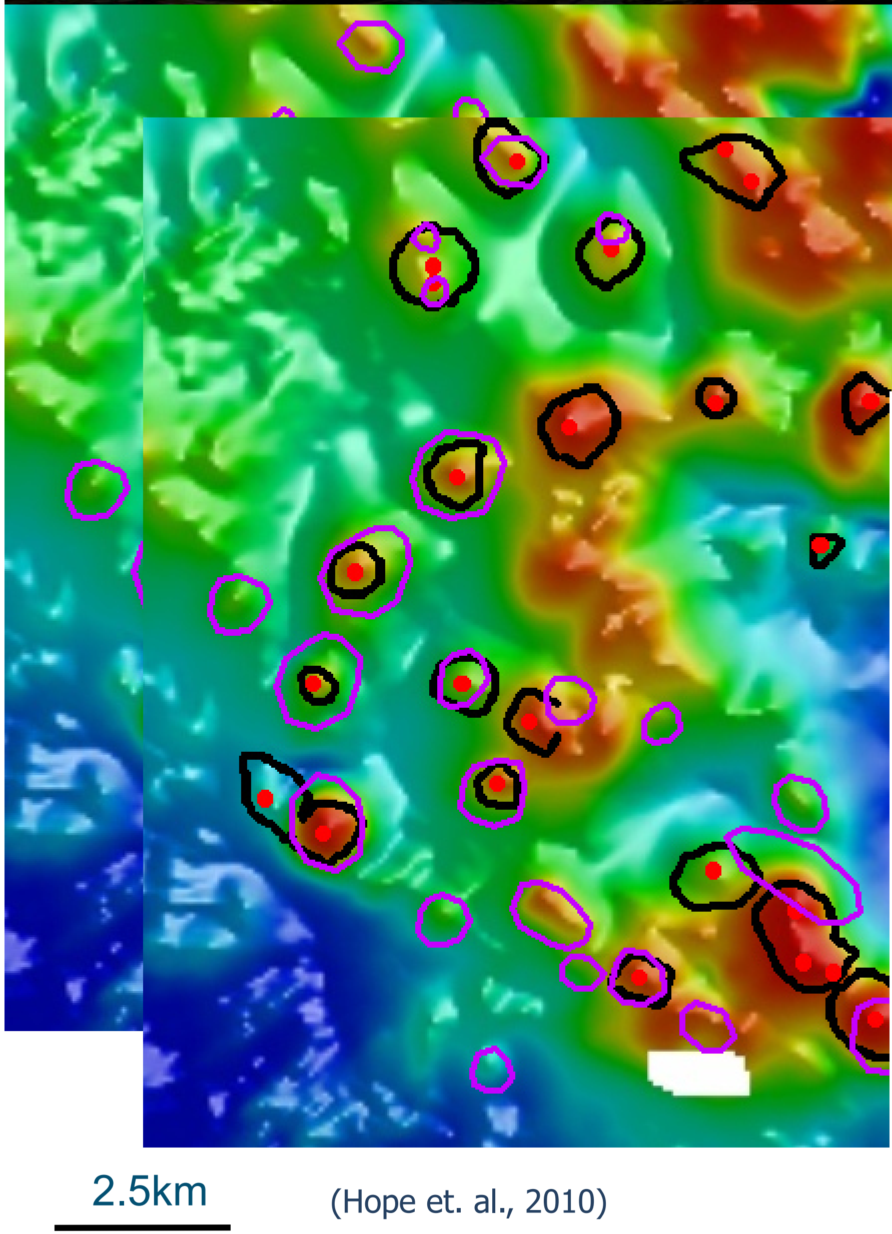
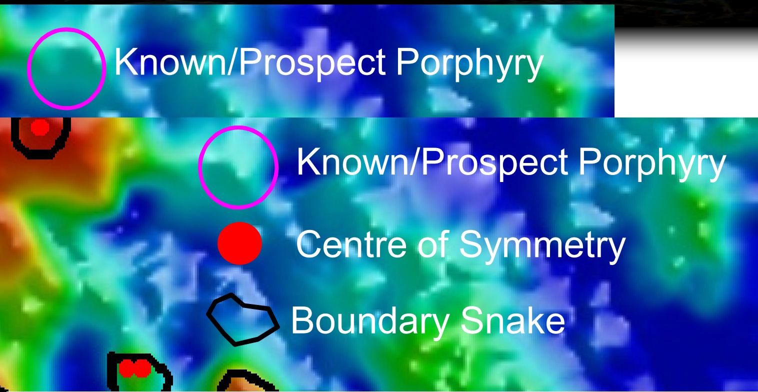


Image Processing Example (CET Porphyry Filter)

(Hope et. al., 2010)

Statistical Summary

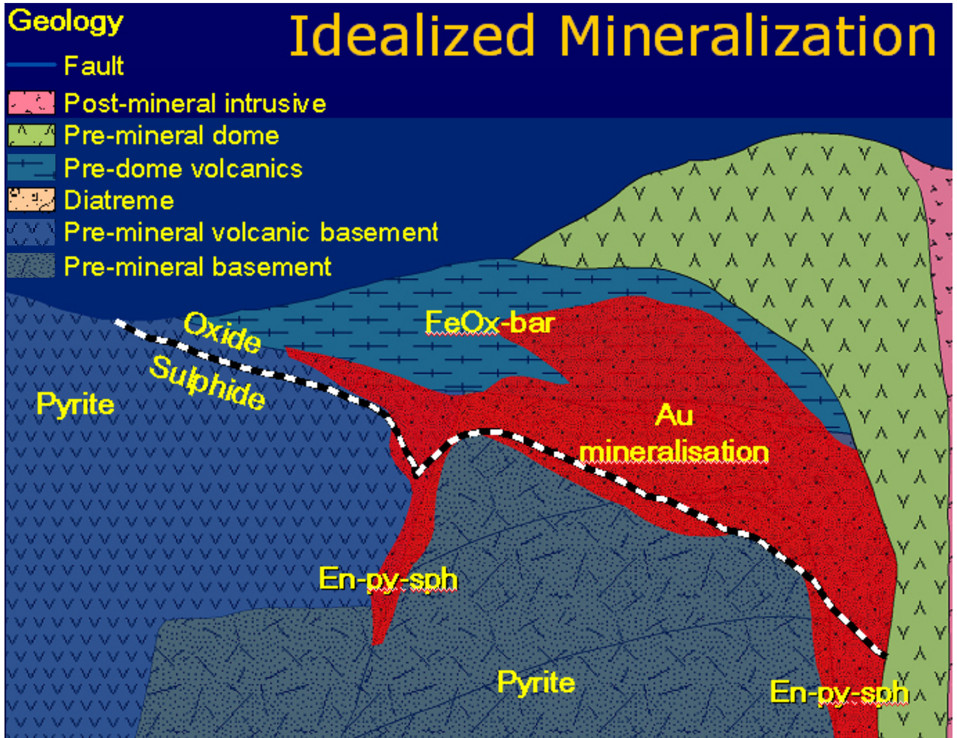
- 29 Pre-existing prospects
  - 21 Recognised
  - 8 failed to meet user defined criteria (size, contrast, not circular
- 35 Centres located
  - 30 Boundaries
  - **9 Additional targets**

Epithermal (HS) – CSAMT

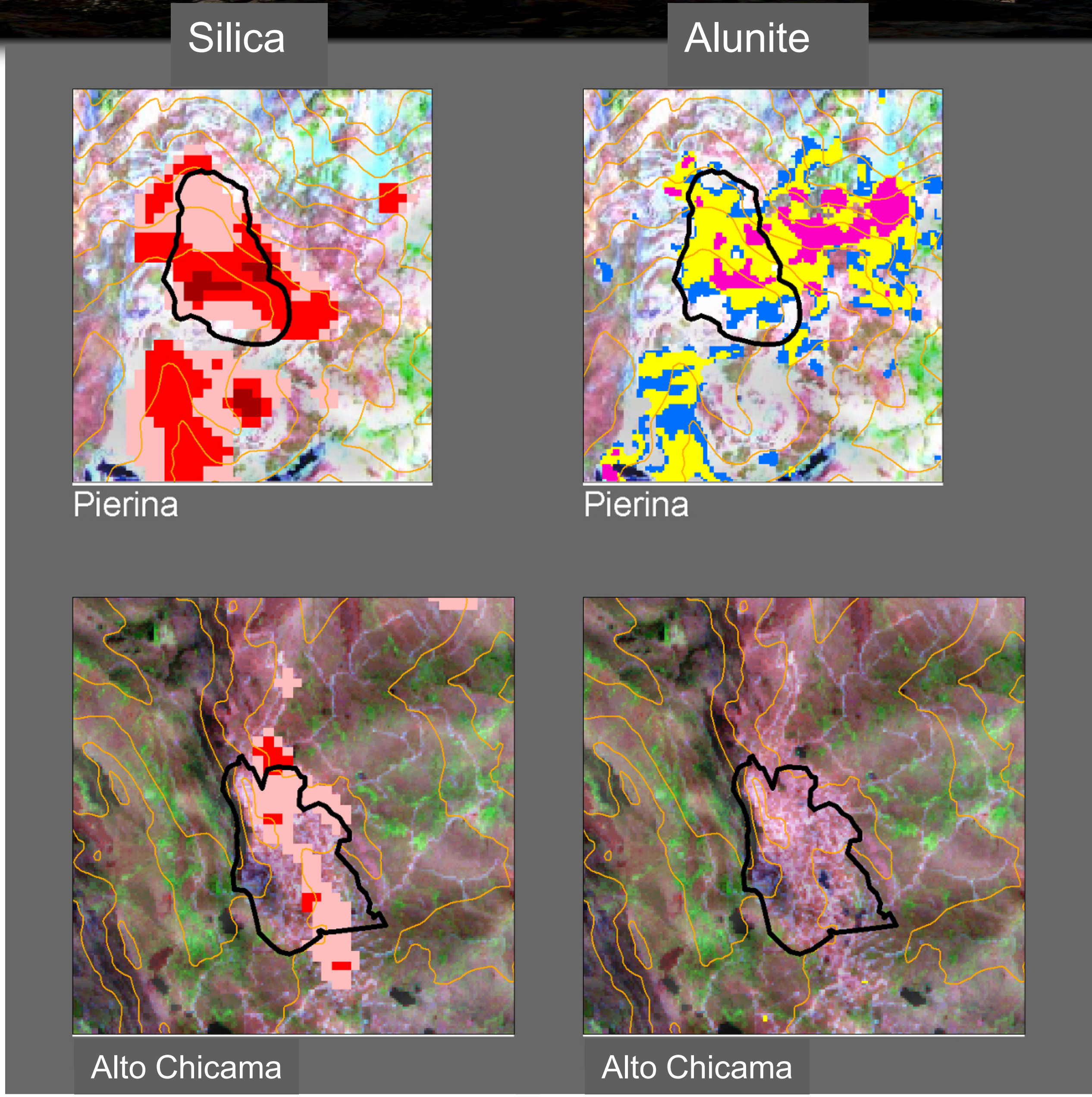
- Geology
  - Diatreme dome complexes with associated volcanics
  - Pre, syn and post mineral diatremes
  - Pre-mineral domes can be unaltered and overlying
  - Large advanced argillic alteration zones (100's km^2)
  - Topographic highs of silicic alteration
  - ***Au in vuggy silica core***

Vuggy silica

- 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



Remote Sensing -Aster



LEGEND

ASTER Mineral Mapping

ALUNITE

- Weak
- Moderate
- Strong

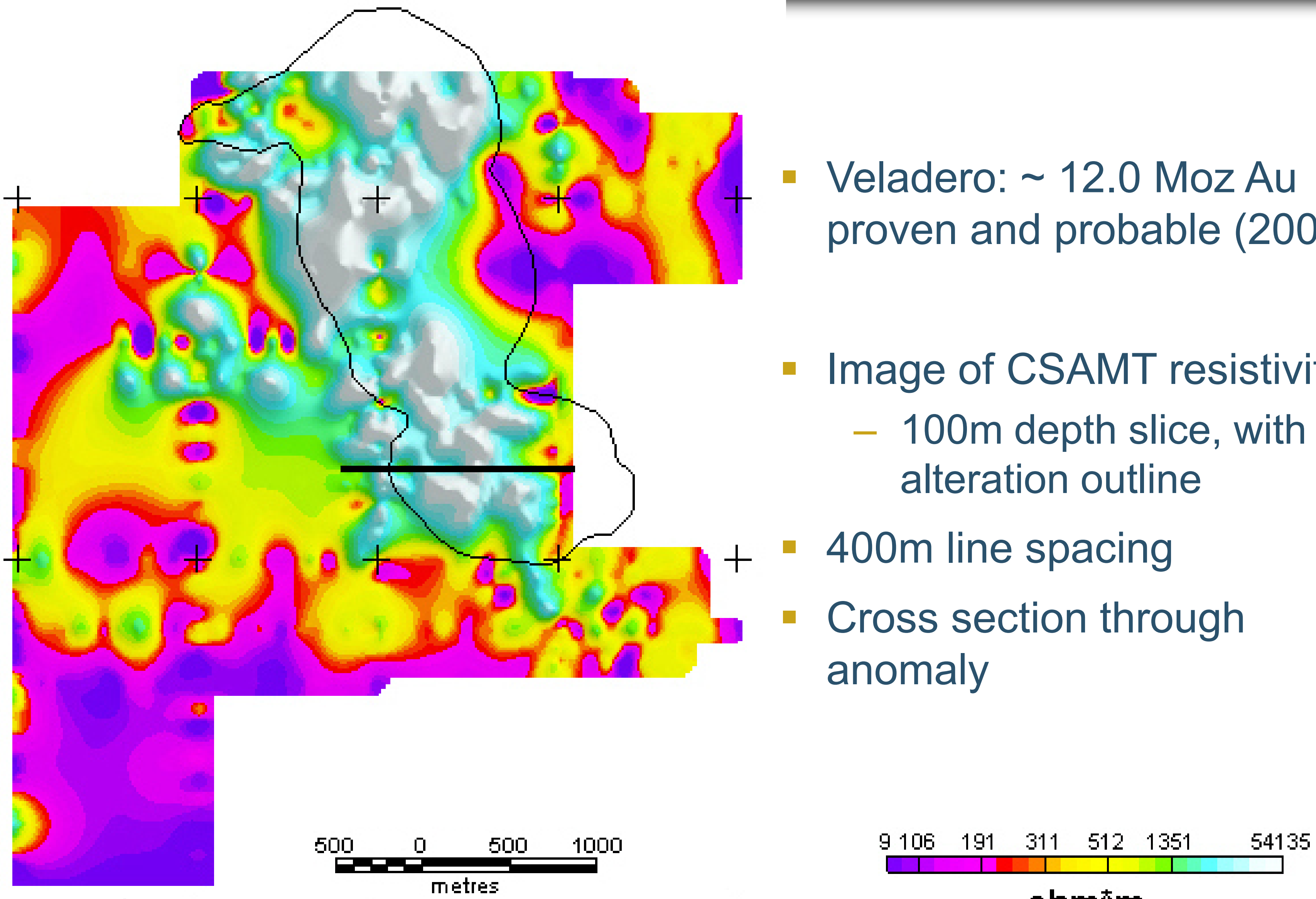
SILICA

- Weak
- Moderate
- Strong

3 Km

(Cerpa et. al., 2013)

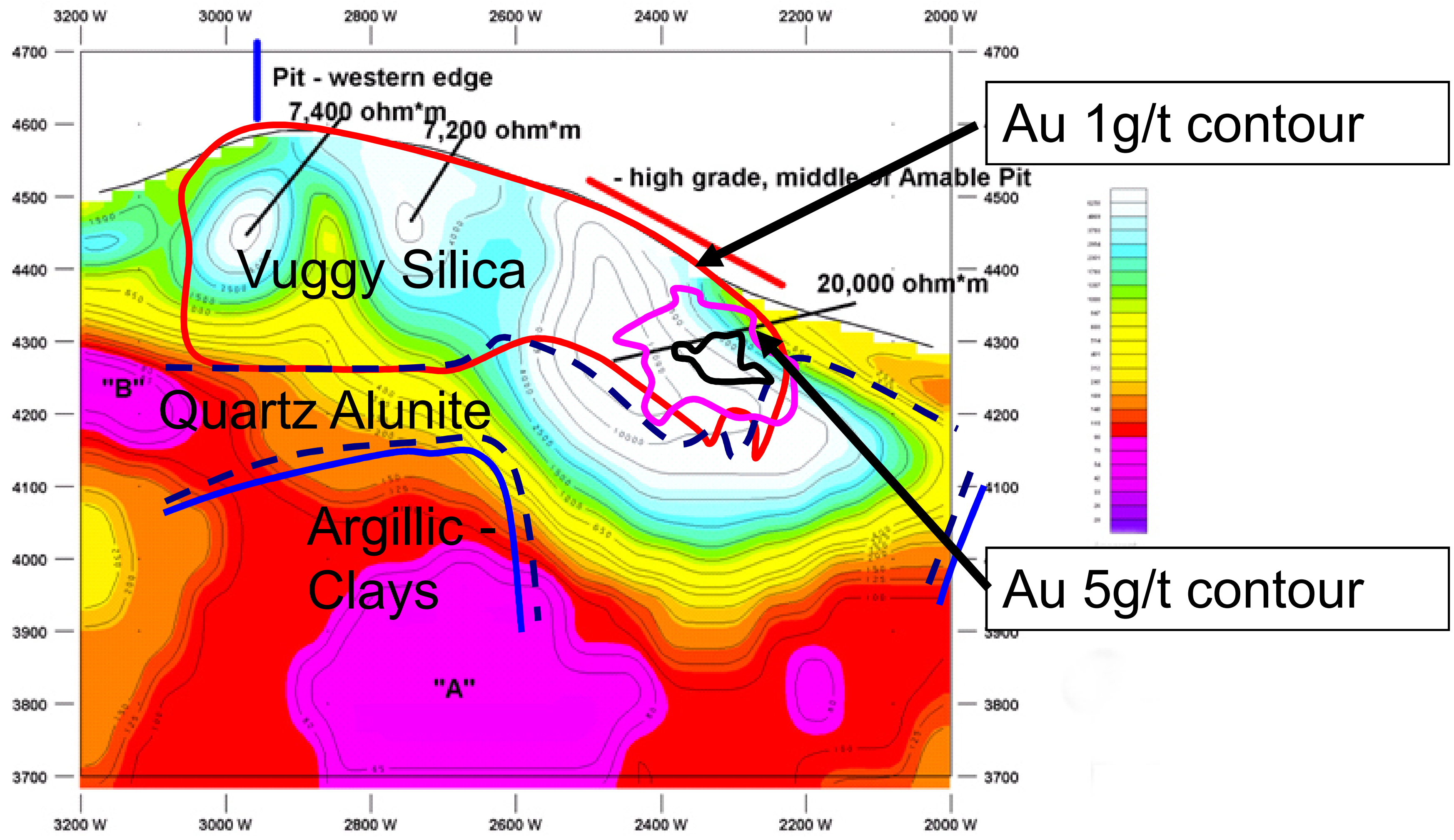
Epithermal (HS) – CSAMT Example



(Bourne, 2010)

- 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



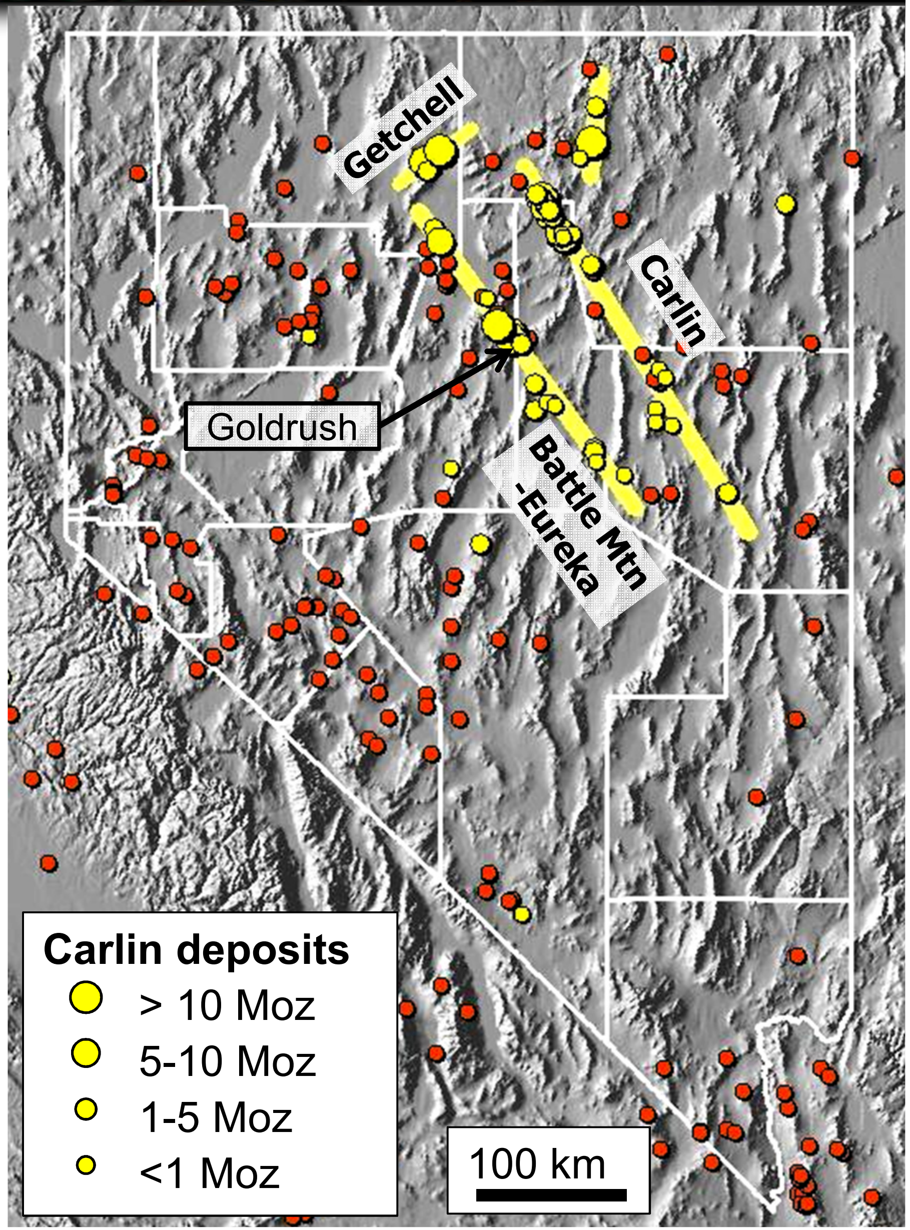
(Bourne, 2010)

Carlin - Nevada Hot Spot

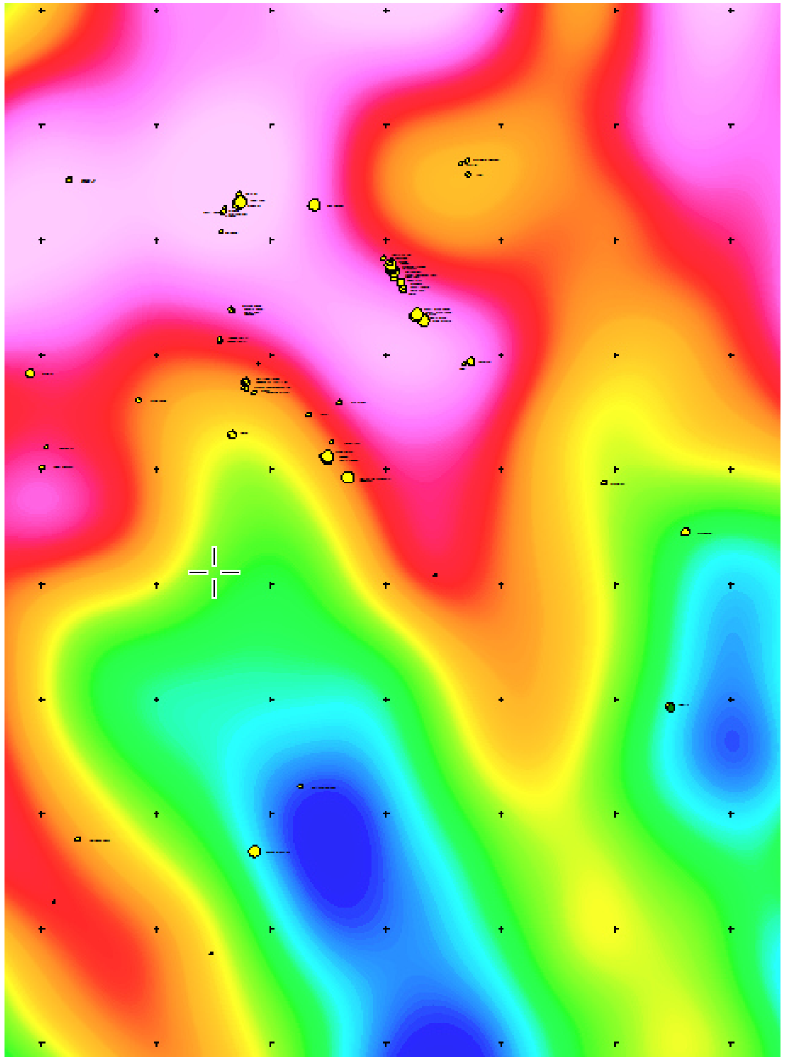
- +250 Moz in Carlin deposits in area 200 x 400km
- ~5% of world Au production
- Distributed along "Trends"

Top 5	Moz Au	g/t
Goldstrike	**55**	**8.6**
Getchell-TR	**26**	**7.1**
Gold Quarry	24	1.2
Twin Creeks	17	2
Goldrush	**14**	**4.2**

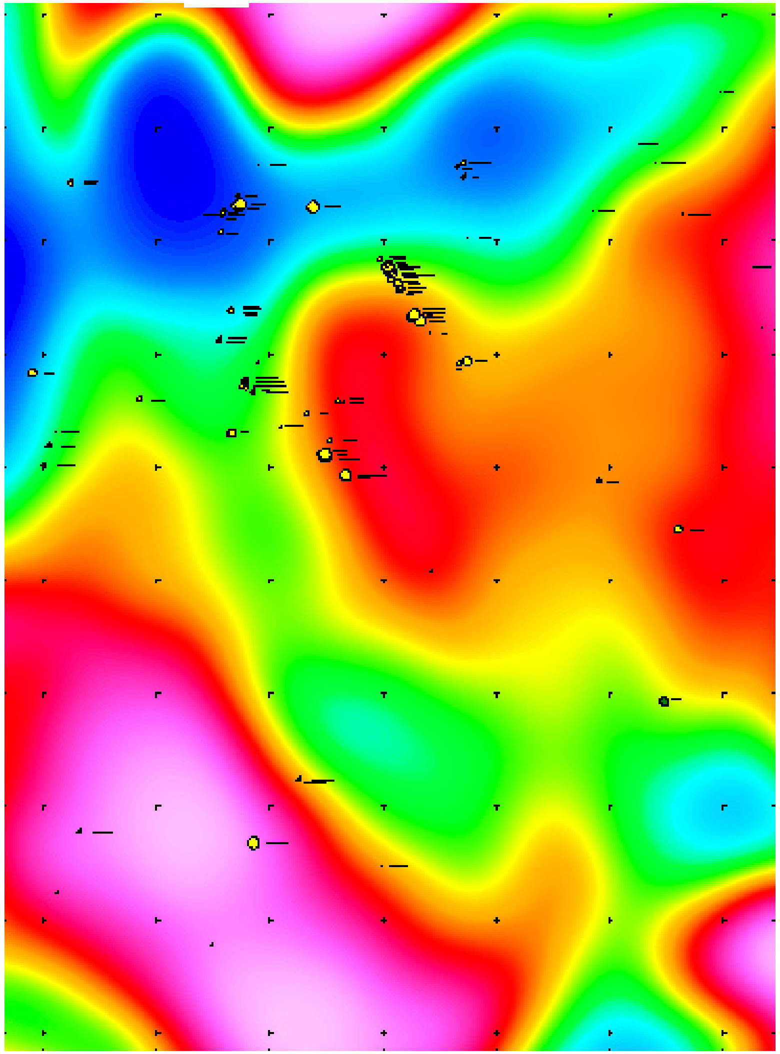
(After Townsend et. al., 2010)



Basement Structures Gravity/Magnetics



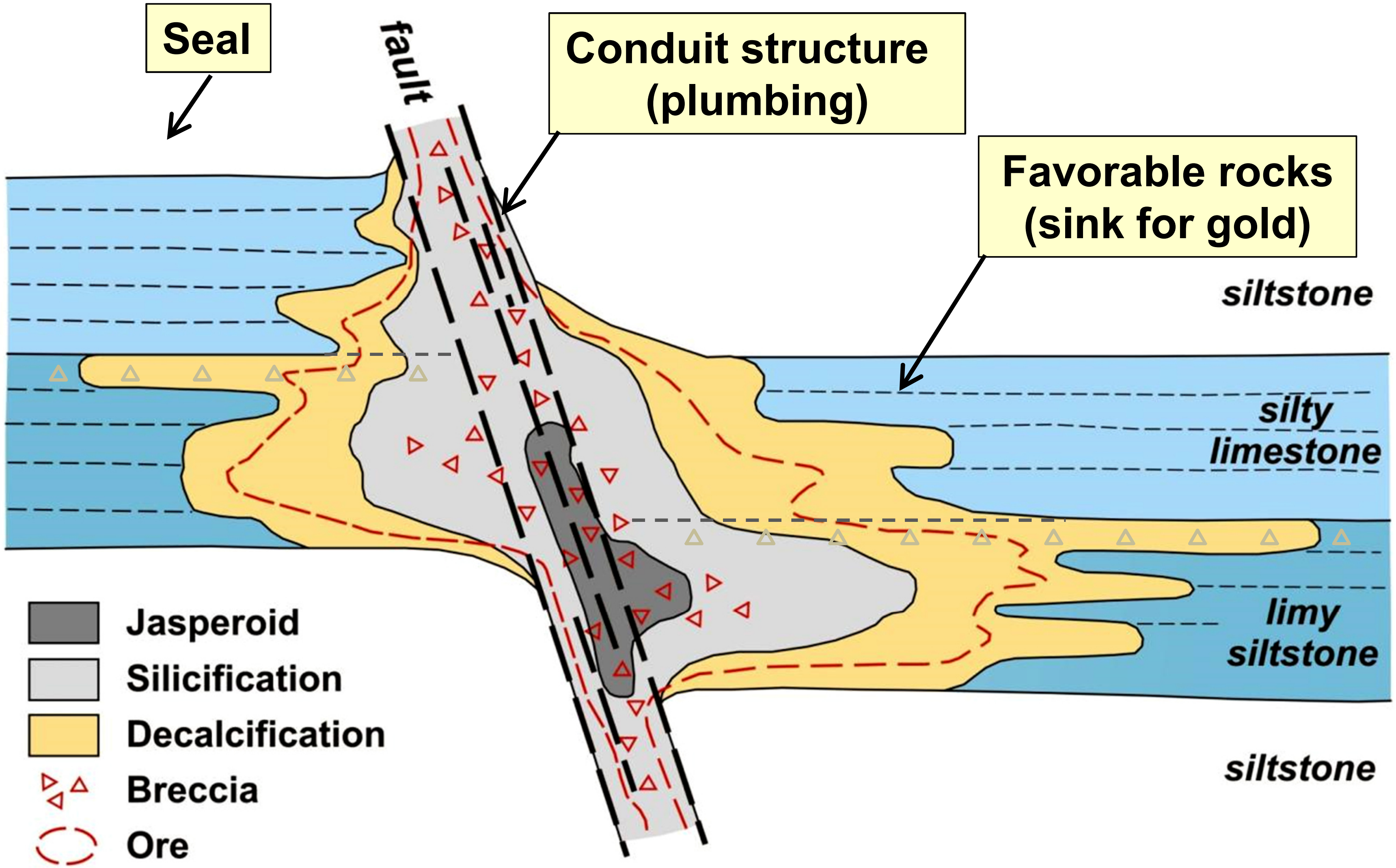
Isostatic Corrected gravity 20-50km



Regional Magnetics 20-50km

(Data Source USGS)

Carlin - Deposit Characteristics



After Robert 2010 – Scale 5km across

Airborne Magnetics - Goldstrike

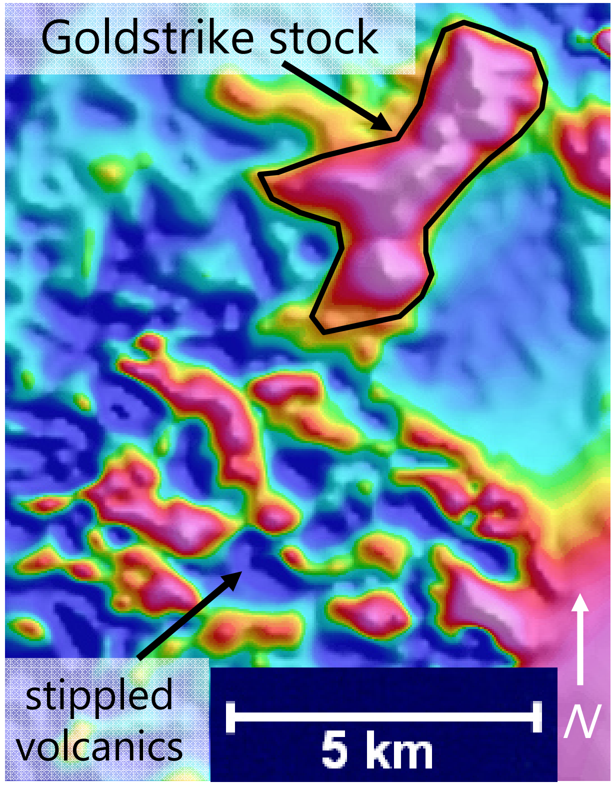
- Remains the most effective reconnaissance mapping tool
  - Despite **limited developments** in acquisition technology
  - Lower cost, better processing tools, better geologic integration

- 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



Goldstrike area RTP

(After Townsend et al, 2010)

Carlin - Petrophysics

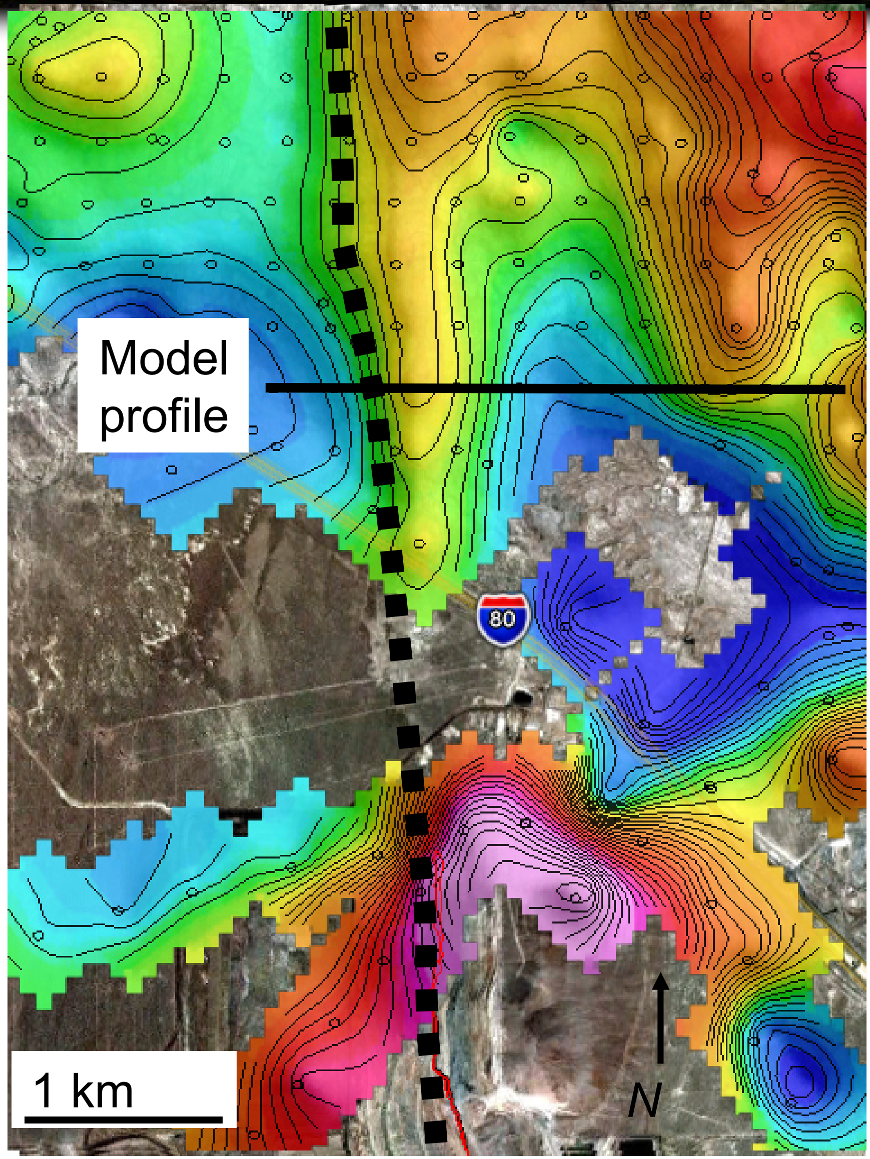
- No geophysical “silver bullet” for Carlin-style gold mineralization
- Petrophysical **GENERALIZATIONS** of typical Great Basin rocks:

Rock type / Physical Property	Magnetization	Density	Conductivity	Chargeability
Paleozoic Lower Plate Carbonates	L	M-H	M	M
Paleozoic Upper Plate Siliciclastics	L	M	M	L
Pen-Perm overlap sediments	L	M	M	L
Mesozoic Intrusive stocks	M - H	M	M	L
Tertiary/Quaternary Alluvium/Colluvium	L	L	H	L
Tertiary/Quaternary Volcanics	H	M	M	L

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

(After Townsend et. al., 2010)

Detailed Gravity



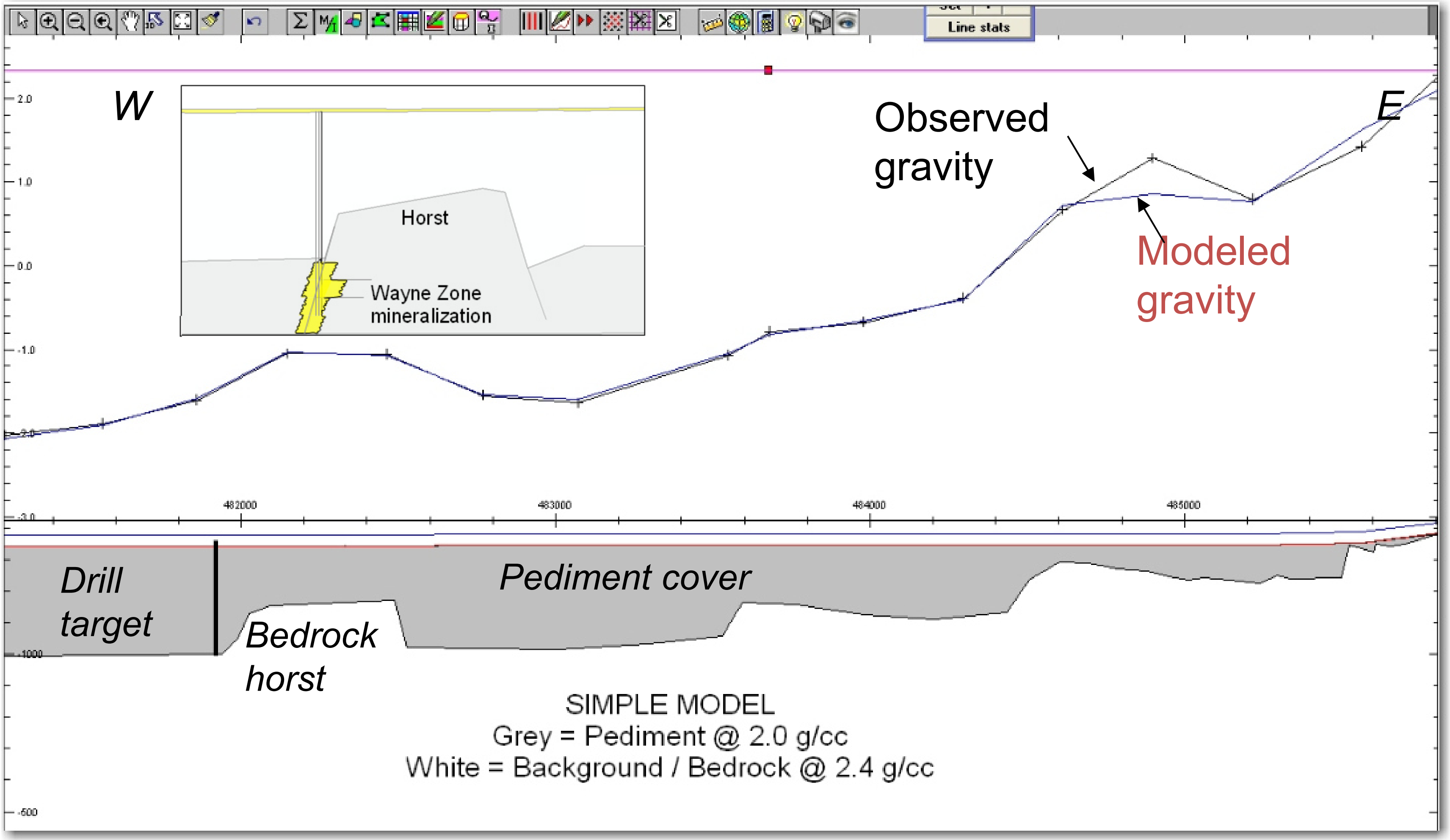
Residual gravity data over Project A

- 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)

(Townsend et. al., 2010)

Detailed Gravity – Project A

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



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

(Townsend et. al., 2010)

Carlin – Hardrock Seismic

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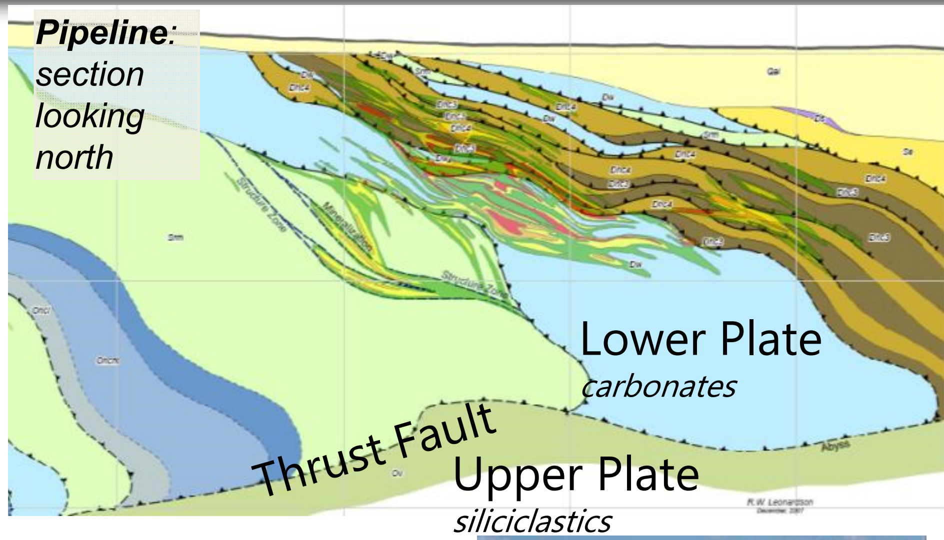
- Geology
  - Carbonate stratigraphy
  - Low-angle architecture
  - Thrusting and stacking
  - ***Au in antiform structure***

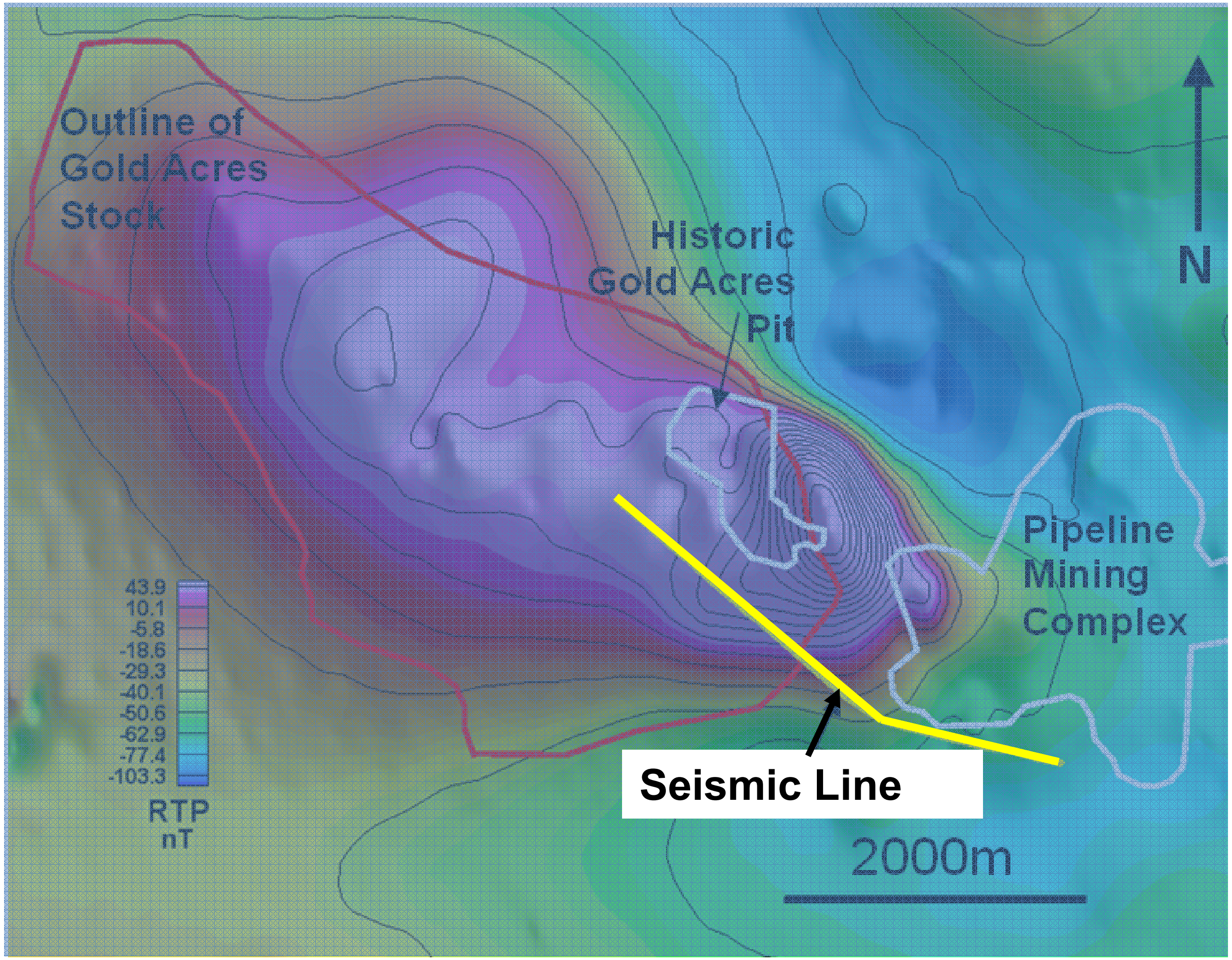


- Petrophysics
  - Density & velocity contrast between
    - lithologies
    - deposition facies
    - structure

- 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

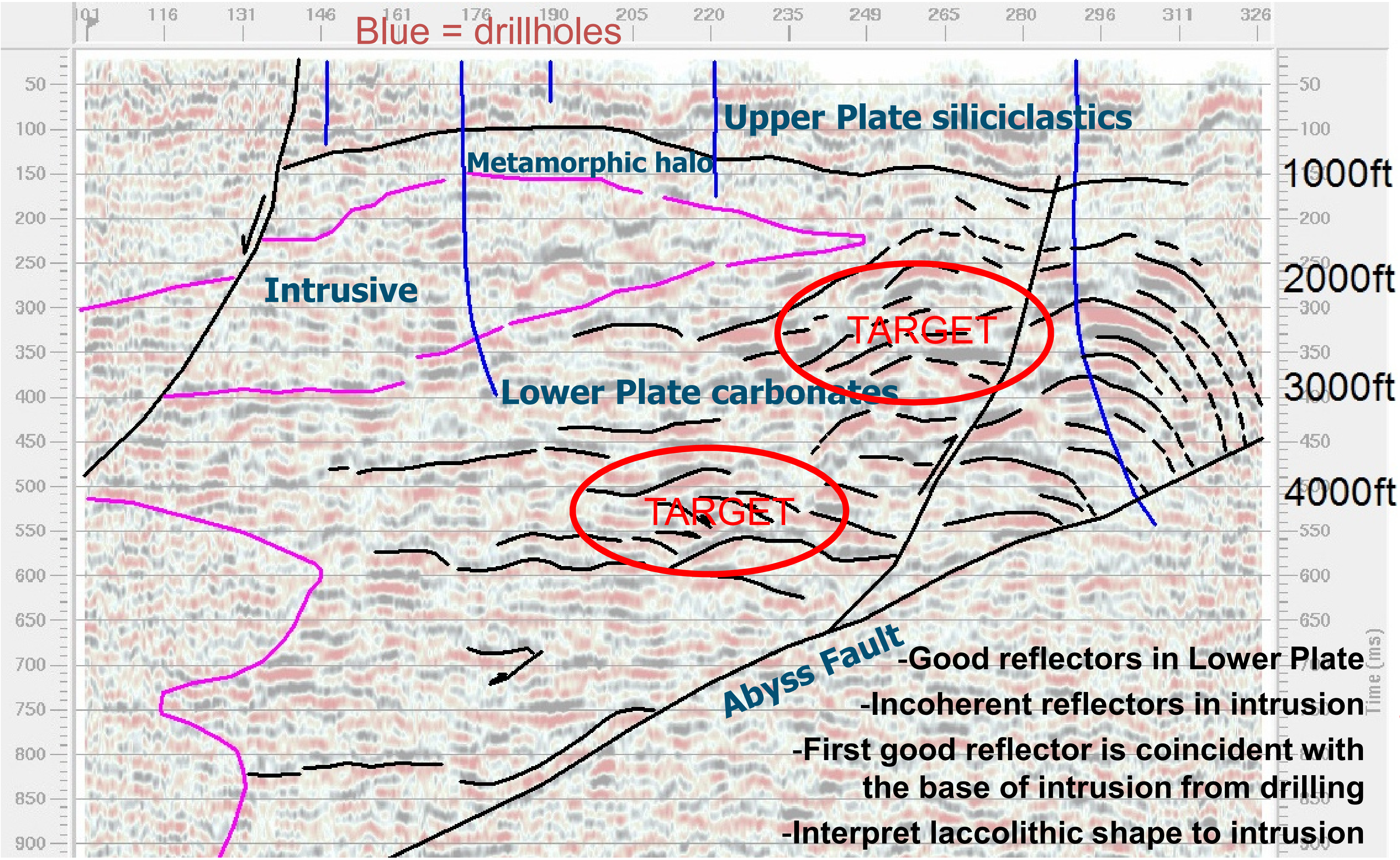
Hardrock Seismic - Cortez

- Location of Gold Acres seismic line



(Townsend et. al., 2010)

Hardrock Seismic - Cortez



-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

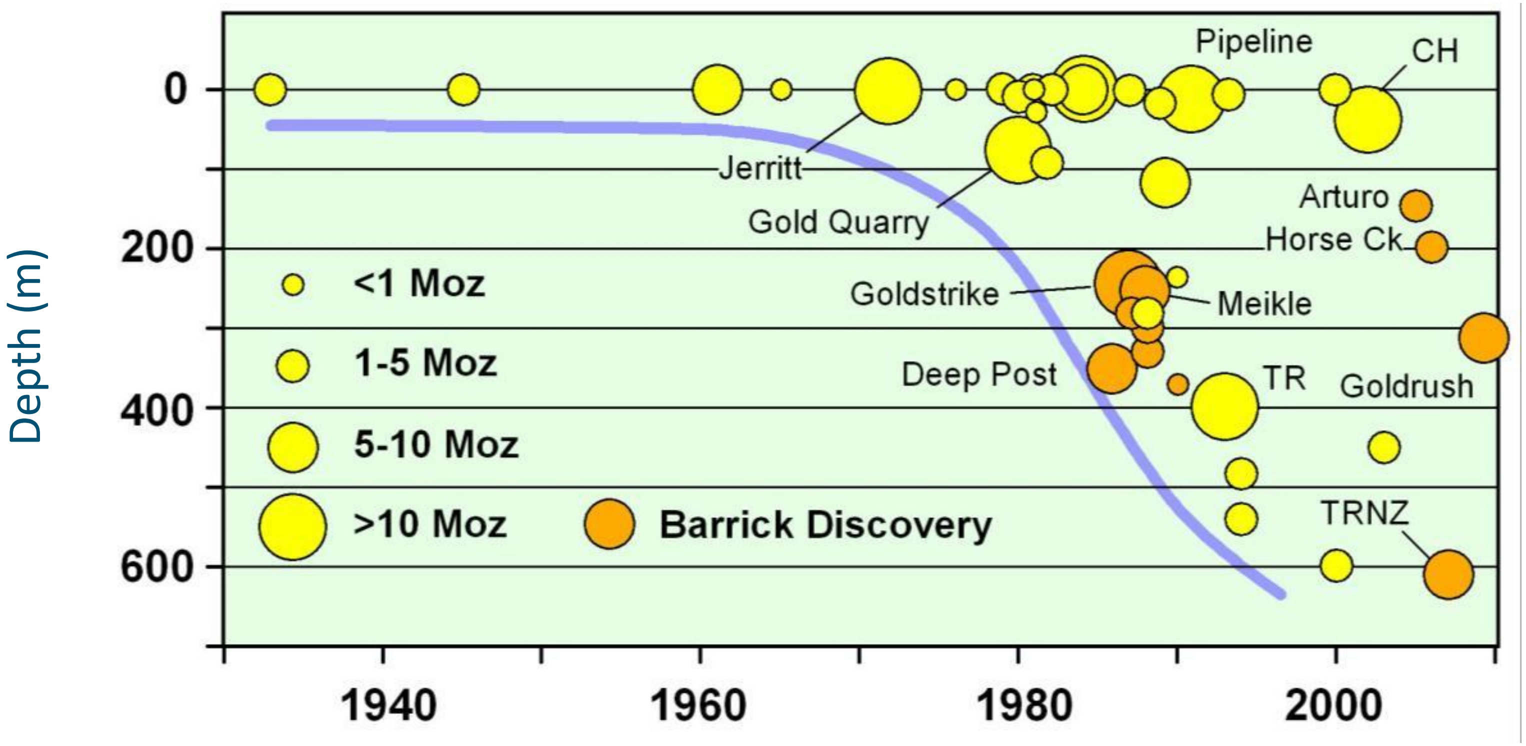
Depth conversion from downhole velocity work

(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)



(Barrick 2012)

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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