DMEC workshop series:
The value of regional data in terrane scale assessments

Wednesday, March 8, 2017
2:00pm to 6:00pm
DMEC workshop series:  
The value of regional data in terrane scale assessments  
Agenda  
Wednesday March 8, 2017  
2:00pm to 6:00pm

2:00-2:05  Introduction; Vicki Tschirhart
2:05-2:15  A Seminar in Honor Professor David Boyd; Ken Witherly
2:15-2:30  The Importance of Regional Geophysical Data in getting to the "Right Place"; Ken Witherly
2:30-3:05  Geosciences across scales: Mineral exploration from the lithospheric mantle to cover; Stephan Thiel/Steve Hill
3:05-3:40  Integrating Public Geoscience and Industry Data for Building Structural Frameworks for Mineral Exploration; Matias Sanchez
3:40-3:55  BREAK
3:55-4:30  Regional geophysical datasets for effective geological interpretations of remote terranes: examples from northern Canada; Vicki Tschirhart
4:30-5:05  Looking at Geophysical data with geological eyes: Using "Structural geophysics" to understand mineral systems; Pete Betts
5:05-5:40  Beyond the Alteration Halo: District-scale Controls and Geophysical Signatures of Porphyry Copper and Related Deposit Types – Insights from Regional Geophysical Data; Jon Woodhead
5:40-6:00  DISCUSSION/WRAP UP
Biographies

Pete Betts  
Monash University, Melbourne, Victoria, Australia

Pete Betts is a structural geophysicist with a diverse research portfolio that includes, structural geophysical analysis and modelling, structural geology, Precambrian tectonics, subduction and accretion geodynamics, intraplate volcanics fields, and Red Sea tectonics. In all of his research interests he integrates geology and geophysical analysis. Pete obtained a BSc and PhD in Geosciences at Monash University. Following a series of post-doctoral and contract teaching positions he gained continuing appointment in 2005. He teaches, field geology, Applied Geophysics, Tectonics and Geodynamics, and an industry short course "Geology from Geophysics". In 2014 Pete became Associate Dean Graduate Research in the Faculty of Science, where he has Academic, Strategic and administrative responsibilities for the faculty's PhD cohort. Pete also is a director of a niche consulting company, PGN Geoscience. Pete was the 2015 recipient of the Bruce Hobbs medal for excellence in Structural Geology and Tectonics.

Matias Sanchez  
Fault Rocks Vancouver, BC

Matías is a structural geology consultant with over 14 years of experience in the mining exploration sector and applied research projects in Chile, Argentina, Turkey, Greece and western Canada. Matías completed an MSc and PhD at the Fault Dynamics Research Group of Royal Holloway University of London and a post-doctoral fellowship at UBC's Mineral Deposit Research Unit. Over the past four years, Matias has been involved in several research and consulting projects that lead to new geophysical and structural interpretations along the Canadian Cordillera, including MDRU's Yukon Gold Project and Geoscience BC's QUEST map area. Since 2014, Matias is Director at Fault Rocks Inc. where he integrates field-based structural geology with geophysical and geological datasets for the understanding of structural controls of epithermal and porphyry style deposits.

Stephan Thiel  
Geological Survey of South Australia, Adelaide, SA, Australia

Stephan Thiel is a Senior Geophysicist at the Geological Survey of South Australia and an Affiliate Lecturer at the University of Adelaide. He obtained his PhD from the University of Adelaide in 2008 and was a Postdoctoral Fellow there until 2014. His research focusses mainly on magnetotellurics applied to lithospheric-scale imaging and geothermal studies. He has applied his research from Archaean/Proterozoic terranes in Australia to younger tectonic areas in Oman and Ethiopia. Throughout his Post-doc, his research focused on monitoring fluid fracking of enhanced geothermal systems in Australia. Together with the relevant co-workers, the research was recognized through the Australian Innovation Award for the Minerals and Energy category. Stephan currently works on mapping the lithospheric architecture of the Gawler Craton through the AusLAMP SA array program to unravel the tectonic history of the Australian continent and develop paradigm shifts in mineral exploration in cratonic areas.

Vicki Tschirhart  
NRC-GSC-Ottawa, ON

Vicki Tschirhart received a B.Sc. (2009) in Earth and Environmental Sciences and her PhD (2014) in Applied Geophysics from McMaster University. In 2014 she joined the Geological Survey of Canada where she is a Research Scientist in the Airborne Geophysics group. Her research interests include integrated interpretations of potential field and geological datasets to solve 3D problems of crustal structure and mineral potential.
Ken Witherly  Condor Consulting Denver, CO, USA

Ken Witherly graduated from UBC (Vancouver Canada) with a BSc in geophysics and physics in 1971. He then spent 27 years with the Utah/BHP Minerals company during which time as Chief Geophysicist, he championed BHP’s programs in airborne geophysics which resulted in the development of the MegaTEM and Falcon technologies. In 1999, Ken helped form a technology-focused service company that specializes in the application of innovative processing and data analysis to help drive the discovery of new mineral deposits.

Jon Woodhead  Consultant Denver, CO, USA

Jon received undergraduate degrees in Botany and Geology at the University of the Witwatersrand and the University of Cape Town, and later, a Masters degree in Mining Engineering, before finally deciding on a career in minerals exploration.

After an initial stint as an underground gold mine geologist, Jon spent a decade in various parts of southern and central Africa, ultimately leading to a sustained association and deep interest in the central African Copperbelt. Following a fortuitous mid-career downturn in the industry, and a chance encounter with Professor Murray Hitzman in the African bush, Jon was easily persuaded to relocate to Golden in order to complete a PhD program at the Colorado School of Mines. In this he took the long route, enjoying a mid-program sojourn and mini-career in Australia and Southeast Asia before returning to complete the PhD program some years later. The title of his thesis was: The Neoproterozoic Roan Group in the Zambian Copperbelt; Sequence Stratigraphy, Alteration and Mineralization.

Prior to working as a consultant, Jon’s last “real job” in the industry was with BHP Billiton in a global generative role, based in Singapore. This position provided him with opportunities to examine the regional distribution and geological controls on a variety of deposits styles using large-scale and multifaceted geological and geophysical datasets. Jon’s association with Condor Consulting in Denver has allowed this interest to grow and to continue in his pursuit to blur the lines between geology and geophysics.
The value of regional data in terrane scale assessments

DMEC Annual Workshop
PDAC 2017 Annual Convention
K. Witherly and V. Tschirhart
Toronto, 8 March 2017

What does DMEC mean?
Decennial Mineral Exploration Conferences

DMEC’s vision statement-2008
The successful use of technology will most likely occur when technology is meaningfully integrated into programs and that this in turn, will most likely occur when the geoscientists involved are working in a collaborative fashion.

Exploration07
http://www.dmec.ca/ex07/ex07.html
Conference held in Toronto, on September 89 to 12, 2007.
This conference was accompanied by a 2-volume Proceedings that was published concurrently with the conference.
DMEC’s activities post-2007

PDAC workshop series- Driving exploration success in deep exploration through multidisciplinary collaboration and data integration

PDAC 2011 - Focus on Abitibi VMS Exploration-Quebec/Ontario
PDAC 2012 - Focus on Quest Undercover Porphyry Cu-Au, British Columbia
PDAC 2013 - Exploring undercover in a world-class copper belt in Chile
PDAC 2014 - Risk in exploration: Measuring it and how to avoid ruin
PDAC 2015 – Developing the tools and techniques to explore undercover: a global initiative
PDAC 2016 – Making technology work; the importance of time and patience

Presentations

• 2:00-2:05-Vicki Tschirhart: Introduction
• 2:05-2:15-Ken Witherly: Prof. Boyd
• 2:15-2:30-Ken Witherly: The Importance of Regional Geophysical Data in getting to the "Right Place"
• 2:30-3:05-Stephan Thiel/Steve Hill: Geosciences across scales: Mineral exploration from the lithospheric mantle to cover
• 3:05-3:40-Matias Sanchez: Integrating Public Geoscience and Industry Data for Building Structural Frameworks for Mineral Exploration
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• 5:05-5:40-Jon Woodhead: Beyond the Alteration Halo: District-scale Controls and Geophysical Signatures of Porphyry Copper and Related Deposit Types – Insights from Regional Geophysical Data
• 5:40-6:00: DISCUSSION/WRAP UP
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Seminar to Honor Professor David Boyd
1926-2016

Career Highlights

• Entered Glasgow University-1943
• Graduated 1946 Double Honors Natural Philosophy and Geology
• Spent 9 years as a Lecturer and conducting field work in Europe and Africa
• Joined Hunting Geology and Geophysics in 1956
• Worked on using aeromagnetics for petroleum and minerals exploration worldwide
• In 1969, joined department of Economic Geology, University of Adelaide
• Major focus was nurturing honors graduates who would be sought after by the mining
  • Industry
• Helped establish the Australian Mineral Foundation course, “Geophysics for Geologists”; over 600
  attended over three decades.
• Retired 1992 but continued to supervise students until 1998.
• Awarded ASEG Honorary Membership 1997
• Awarded ASEG Gold Medal 2016
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1967
The contribution of airborne magnetic surveys to geological mapping
Professor David Boyd

The contribution of airborne magnetic surveys to geological mapping
(David Boyd, Hunting Surveys Ltd. Bareham Wood, Herrs, England)

- Geological mapping and magnetic survey mapping
- Special advantages of airborne magnetic surveys
- Some limitations of airborne surveys
- Interpretation
- Practical interpretation
- Mathematical models
- Standard of data
- Interpretation proper
  - Major intrusions
  - Conformable magnetic horizons
  - Charnockites
- Structures
- Testing the interpretation
- Further interpretation
- Variations on the mineral style survey
- Weakly magnetic areas
- Oil type surveys
- Regional surveys
- Planning an airborne survey
- Conclusion

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Professor David Boyd

University of Adelaide 1969-1992
Supervised Thesis

1972 TUCKER, D. Magnetic and gravity interpretations of an area of Precambrian sediments in Australia.

1975 PECANEK, H.T. Interpretation of geophysical data from the Broken Hill area.

1978 KHAN, D.M. Radiostratic studies in the lower Proterozoic Willyama Complex, Broken Hill district, New South Wales.

1982 GILLILAND, JR. Geod Studies in South Australia.


1985 UKAIGWE, F. Interpretation of aeromagnetic data of the Olary Province, South Australia and the development of interpretation methods.

1988 WHITING, T. A study of the lithology and structure of the eastern Arunta Inlier based on aeromagnetic interpretation.

1990 RAJAGOPALAN, S. Aeromagnetic interpretation of the Kanmantoo Group, South Australia.

1991 LEWIS, A.M. Interpretation of airborne geophysical data over the Petermann Ranges area, southwestern Northern Territory.


1994 SHI, Z. The interpretation of regional aeromagnetic and gravity data from surveys carried out over Eyre Peninsula, South Australia.

1996 KIVOR, I. Geophysical studies of the Palkia Trough.


Professor David Boyd

Students 1969-1993


1978 J Irlande.

1979 M.S. Flis, S.J Grope, R. Klost, P.R. Mora, P. Stephenson.


1982 A. Guthrie, S.W. Jones, R.S. Smith, A.J Sutherland.

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Professor David Boyd

Geological interpretation of Airborne Magnetic Surveys - 40 Years On (with D. Isles-PhD 1983)

2007

Figure 3. Scale 1:2,400,000 approx. Airborne magnetic survey flown at 1,500 feet above southern Scotland, lines spaced 2 km. 1 = Ores. 2 = Major fault (Drumilston Fault). 3 = Major magnetic feature lying below Palaeozoic and Mesozoic rocks. 4 = Caledonian front. 5 = Basement boundaries. Reproduced by permission of the Controller, H.M. Stationery Office.
Norm Paterson was another pioneer in the application of aeromagnetics data to geological interpretation. Norm also worked with Hunting in 1960s and learned his craft from Walter Faessler & John Ratcliffe whom he worked with at Dominion Gulf in the period 1955-1960.

Documented his early experiences -

*Geological mapping by magnetometer surveys.*
*Proceedings of the Benedum Earth Magnetism Symposium* - 1962

Norm was inducted into the Canadian Mining Hall of Fame in 1999.
The Importance of Regional Geophysical Data in getting to the "Right Place"

Fig 2: Ground magnetic traverse Coronation Dam-Olympic Dam relative values.

The Right Place-Olympic Dam Mine-circa 2011
Establishing the ‘right place’ to explore for new deposits is likely the most important decision an explorer/exploration group can make.

Historically, great emphasis was placed on prior knowledge of existing deposits or some key geological feature deemed to be important i.e. ‘Follow the West Fissure’...

We can assume Native Americans who hunted buffalo centuries ago would return to those places where buffalo had been found before or follow valleys or other natural passage ways that the buffalo would likely choose for their migration. This worked up to the point when there were no more buffalo.

**Scale Dependent Targeting**

Mineral system signatures…still early days but holds promise...

Where do we focus the more systematic, detailed and expensive detection technologies?

McCuaig et al. (2010)
The Janus ‘curse’ of the explorer means having a **high expectation of success** also means a **low expectation of failure** and once a program begins in earnest, it came become very hard to ‘turn it off’.
Now in many jurisdictions, high quality pre-competitive regional data is available but it is often poorly understood in terms of ore deposit models or even basic geological mapping. Part of this can be attributed to difficulties in reconciling traditional geological mapping and the derived regional understanding with what can be inferred/interpreted from regional data. A new paradigm is required to take advantage of this regional information. The days of hunting the buffalo are over.
“...back to the future” seems in order

3D susceptibility

Cheng et al., 2009
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The Right Place

We Need Non-Traditional Datasets to See Large Footprints

Magnetotelluric Section through Olympic Dam
Modified after Hayward, 2004; Magnetotelluric section provided R. Gill, Univ. Adel; “better” colours are more conductive

GSC aeromag 1962
ISCU discovery 1967
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- Red Island skarn
- Quartz sericite porphyry in creek
- Cu geochem anomaly
- mag high

they all seem excited so I'll hang in!
Definition of the ‘perfect’ explorer...

Optimistic skeptic with an insatiable curiosity
Geosciences across scales: Mineral exploration from the lithospheric mantle to cover
Stephan Thiel¹,², Graham Heinson², Anthony Reid¹,², Kate Robertson², Steve Hill¹
¹Geological Survey of South Australia
²The University of Adelaide, Adelaide SA, Australia

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8th March 2017
www.statedevelopment.sa.gov.au

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- Geoscience Australia (co-funding for Maralinga AusLAMP Project, $240k) for logistical support, 3D inversion workshop
- Maralinga Tjarutja Lands, Far West Coast, National Parks SA, traditional owners and numerous pastoralists, WPA for land access
- Goren Boran for technical support of AuScope instruments
- Philippa Mawby, Bruce Goleby and Geoff Axford (AusLAMP core field crew, University of Adelaide), numerous students for field work
- Katherine Betschart, Ian Hopton and David Love (DSD) for liaison and access, AARD for native title liaison
- Stacey McAvaney (F work), Simon van der Wielen (SA Geophysical Reference Model), Tom Wise (Eucla), Karol Czarnota (GA)
- S.I. Karato (Yale U, mantle conductivity), Alan Jones (formerly Dublin Institute of Advanced Studies, mantle conductor) for discussions
- eResearch SA for HPC access, NCI
- AuScope MT equipment pool
Mineral systems footprint

UNCOVER – template for Australian mineral exploration

Themes
1. Characterising the cover
2. Australia’s whole lithosphere architecture
3. 4D geodynamic and metallogenic evolution
4. Characterising and detecting distal footprints

Scale
- Deposit scale
- Camp scale
- Regional scale
- Continental scale

MT images from a few tens of meters to hundreds of kilometers
AusLAMP - Australian Lithospheric Architecture Magnetotelluric Project

- Regular grid of long-period (10 – 10,000 s) MT data collected every half degree (~55 km), freely available
- Run by Geoscience Australia, University of Adelaide, State Geological Surveys and other research institutions, University of Tasmania
- ANSIR national MT instrument pool
- Map the lithospheric architecture of the continent
- Constraints on the tectonic evolution of the continent and the mineral exploration potential as part of the UNCOVER initiative

Magnetotellurics

- Measures time-varying electric (E) and magnetic (B) fields of the Earth
- Maps the electrical resistivity of the earth
- Sensitive to largely minor conducting phases
- Ability to map from a few metres to hundreds of kilometres

AusLAMP long-period MT time series recording over 3 weeks
Magnetotellurics - what is measured

- Measures time-varying electric (E) and magnetic (B) fields of the Earth
- Time series are converted to frequency domain using robust remote processing codes
- \[
\begin{bmatrix}
E_x & E_y
\end{bmatrix} =
\begin{bmatrix}
Z_{xx} & Z_{xy} \\
Z_{yx} & Z_{yy}
\end{bmatrix}
\begin{bmatrix}
B_x \\
B_y
\end{bmatrix}
\]
- Impedance tensor \( Z \) determines the behavior of the secondary electric field \( E \) given the primary source field \( B \)
- Each component of \( Z \) has an apparent resistivity \( \rho_a \) and a phase \( \phi \)

Typical AusLAMP MT responses

Areas of data quality improvement
Depth of investigation

- EM energy propagates into Earth to a depth ~ defined by the skin depth $\delta$
- $\delta = \sqrt{\rho \cdot T}$
- $\rho$ – bulk resistivity of subsurface, $T$ – period
- Less penetration in deep sedimentary basins or beneath conductors
- for long-period MT ($T>10,000$ s) typically between 100 km and 400 km
- Broadband MT (max $T=1,000$ s) about 40 – 100 km

AusLAMP status

- 664 long-period MT stations collected to date
- 2343 stations to collect
- Currently an instrument pool of 50 MT instruments (soon up to 75)
- 3 week deployment per site
- AMIRA roadmap suggested to accelerate AusLAMP MT acquisition
- If funding and land access available – 900 sites per year possible with 75 instruments
AusLAMP in South Australia

Joint project between GA, GSSA, UofA

Robertson et al., EPSL, in press

Crustal evolution of the Gawler Craton and margins

- Maximum age of the Archaean Gawler craton at 3.1 Ga
- Major Proterozoic reworking between 1.8 – 1.5 Ga
- Main mineralization occurred at around 1.59 Ga associated with Hiltaba Suite intrusives (red)
3D inversion

- 156 sites x 22 periods x full impedance tensor
- Periods from 10 – 10,000 s
- 72x94x75 cells plus air layers
- 1620 x 1910 x 1140 km
- Inner grid cell spacing at 13 km
- First layer at 50 m, with vertical increase factor of 1.12
- Tests with and without ocean, varying starting half spaces, model covariances

EW cross-sections

- Olympic Dam
- Gawler Craton mantle conductor

Department of State Development
AusLAMP MT data

Conduction mechanisms to explain high mantle conductivity

- Ionic conduction: saline fluids and melts (typically in tectonically active settings), e.g. Afar rift, Didana et al., 2014
- Sulfides and magnetite in typically crustal environments through shearing and interconnection
- In stable lithosphere: hydrogen diffusion in nominally anhydrous rocks
- Grain boundary graphite (only within its stability field, Wang et al, 2013)

Fullea, et al 2011
Global examples of mantle conductors (~10 Ωm) in Archaean lithosphere

- Slave Craton, Canada (Jones et al., 2001)  
  Graphite
- Kaapvaal Craton, S Africa (Evans et al., 2001)  
  Hydrated minerals
- Dharwar Craton, India, beneath Deccan traps (LIP) (Patro & Sarma, 2009)  
  Compositional changes

Heterogeneous mantle source

- SCLM beneath Gawler Craton likely enriched (high in HFSE and REE, Huang et al., 2016)
- Relation to fossil or active supra-subduction at 1590 Ma
- Lower P-wave velocity compared to other Archean Cratons (compositional changes?)
What causes the Gawler mantle conductor?

- Very conductive (<10 Ωm)
- Depth ~100 – 200 km (bottom may be shallower due to lack of sensitivity below conductors)
- Extends beneath the ~1590 Ma Gawler Range Volcanics and Hiltaba Suite granites
- Too conductive for just compositional changes
- Too conductive for hydrogen diffusion in nominally anhydrous minerals
- Occurs roughly in the graphite stability field

Wang et al., 2013

Role of fluorine in the GRV and Hiltaba related magmatism

- Fluorine abundant in magmatic fluids (up to 1.3 wt%)
- Capacity to transport diverse elements (metals and REE)
- Significance for electrical conductivity?

McPhie et al., 2011
Role of fluorine for mantle resistivity

- Similar responses beneath high F Snake River Plain, US
- 3D inversion results of USArray MT data across western US
- Depth slice at ~150 km

Meqbel et al., 2014, EPSL

Relationship of electrical LAB to thermal LAB - Rheology

- Extracted from SA Geophysical Reference Model (van der Wielen et al., 2016)
- Volumes – electrical resistivity ±2 std deviations
- Light volume – mantle resistor
- Horizontal slice: thermal LAB derived from shear wave model (Czarnota et al., 2014)
Conductive mantle anomaly - correlation to shear wave model

- Extracted from SAGRM (van der Wielen et al., 2016)
- Light isosurface of $V_s$ at 4.61 km/s derived from AusREM model (Kennett et al., 2013)
- Volume – outline of 10 Ωm isosurface of the Gawler Craton mantle conductor
- Olympic Dam located at intersection of vertical intersections
Comparison with isotopic composition of ~1595 Hiltaba granites

Mantle-crust connection beneath Craton margin

Fertile IOCG belt east of the Gawler Craton provides pathways for fluids to penetrate into the crust

Updated from Heinson et al., 2006
Flinders-Curnamona lithospheric reworking

- 74 AusLAMP stations
- Data available on SARIG
- 3D inversion and interpretation
- Kate Robertson et al., 2016, EPSL (University of Adelaide)

Flinders Curnamona lithospheric reworking

- Nackara Arc – failed rift signature
- At transition from Proterozoic to Phanerozoic Australia
- Coincident with diamond locations in kimberlites
Camp scale mapping – from 50 km to 1 km

Thiel et al., 2016, GRL
Metamorphic devolatilization reactions

- Enhanced strain in lower crust
- Fluid dissolution-precipitation reactions triggering dynamic permeable networks

Future data acquisition programs – Pace Copper

- AusLAMP MT completion of SA by end of 2017
- Complete mapping the regional scale of South Australia
- $750k funding by PaceCopper for completion of NE South Australia
- $500k NCRIS funding for AusLAMP coverage across Musgraves/APY lands
- Data collection in partnership with the University of Adelaide
Future data acquisition programs - Pace Copper

- Pace Copper Olympic Domain in-fill MT survey in planning to scale up into the upper crust
- Mapping mineral systems footprint for fluid pathways in 3D
- ~320 Broadband MT sites with site spacing between 1.5 km to 10 km across ~ 100 km x 100 km
- Data collection Q2 2017

Conclusion

- AusLAMP provides electrical resistivity distribution of the SCLM
- Insight into “fertility” and connection of mantle to crust processes
- AusLAMP continues in NSW and NT (GA)
- South Australia completed by end 2017 ($650k by GSSA, $500k NCRIS funding, University of Adelaide)
Disclaimer

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Integrating Public Geoscience and Industry Data for Building Structural Frameworks for Mineral Exploration

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1) Introduction:
   - Public Remote Sensing Datasets
   - Digital Mapping Apps

2) Case Study - QUEST Area, Central BC
   - Digital Elevation Models
   - Magnetic data
   - Gravimetric data

3) Case Study - Yukon Gold Project
   - Magnetic data
   - Gravimetric data
Introduction
Public Remote Sensing Datasets
and Digital Mapping

Public Remote Sensing Datasets
DEM, Satellite Images and Geophysical Datasets

- DEM
  - NASA Earth Explorer => GMTED2010 (42 to 26 m)
  - Open Topography => AW3D30 / SRTM GL1 (30 m)

- Satellite Images
  - USGS Earth Explorer => Landsat 8 (15, 30 and 100 m)
  - ESA Copernicus => Sentinel (10, 20 and 60 m)
  - ESA Earth Online => RapidEye (5m), Spot 1 to 5

- Geophysics
  - USGS and DGGS datasets
  - GSC, NRCan, BCGS
  - Geoscience BC
Datasets

- Geoscience BC’s Bouguer and IR gravity
- Natural Resources Canada regional RTP aeromagnetic data

Aeromagnetic, Gravity and topographic datasets

1:300,000 scale interpretation of RTP magnetics (100m grid) and IR gravity (2km cell size)

Datasets

- Geophysical grid
  - Source data sets from the USGS, DGGS, and GSC
  - RTP magnetic grid
  - IR gravimetric grid

- Topographic data
  - GEBCO_08 DEM
Digital Mapping

Avenza Maps
Fieldmove Clino

Efficient and Reliable
- Digital Pen
- GPS
- Excellent size
- High resolution screen
- No cellphone signal required
- Easy data access
- Easy to share data
- Fast battery charge

Maps and Field Book

Export Georeference information using ArcGIS/QGIS
Case Study

Structural Frameworks

QUEST Area, Central British Columbia

GEO SCIENCE BC REPORT 2015-15


M. Sanchez, T. Bissig and P. Kowalcyzk
Interpretation and Analysis of Magnetic and Gravity Datasets, QUEST Area, Central British Columbia (NTS SHEETS 093A, B; 093F - K, 093M - O; 094C, D)

BCGS Geology

MINFILE database

Cui et al. (2013) and Massey et al. (2005)

Approximately half of the work area is covered by superficial sediments

Datasets
- Geoscience BC’s Bouger and isostatic residual (IR) gravity
- Natural Resources Canada’s (NRCan) regional reduced-to-pole (RTP) aeromagnetic data

Processing
- Transformations and filters
- Upward Continued Residuals representing depth surfaces
- High- and Low-Pass filters

Exploration in Regions of Poor Rock Exposure
High-Pass Filters and Transformations

Representation of depth surfaces with a series of upward-continued datasets

- 1000 m to 500 m (depth slice from ~250 m to ~500 m): Suppress the magnetic signal of the Chilcotin Group and Quaternary drift

Upward Continued Residual Filters
Aeromagnetic RTP UpRes 5 km - 1 km

Anomalies Axis 1VD Interpretation

Anomaly Axis
- High (>500 nT)
- Inter (0-500 nT)
- Low (<0 nT)

Azimuth
- 0 - 14 (N)
- 15 - 70 (NE)
- 71 - 109 (EW)
- 110 - 160 (NW)
- 161 - 194 (N)

100 km
Field Validation
Northwest- and northeast-trending, steeply dipping brittle structures of the Eaglet Lake area
Mount Polley - Woodjam
Relatively high magnetic intensity in Nicola Group volcanics

Case Study
Structural Frameworks
Yukon Gold Project

Intermontane Terranes of eastern Alaska and western Yukon


M. Sánchez, M. Allan, J. Mortensen and C. Hart
Geological and Structural datasets

After various authors
Reliability index map based on data set-stacking methodology

All geological and geophysical datasets

Collisional orogen with doubly vergent fold-and-thrust belt

Late Jurassic orogenic gold mineralization

Modified after Cook et al., 2004
Magnetic Domains
Magnetic Triassic - Jurassic plutons and erratic Cretaceous intrusions

Mineralization ages
Allan et al. 2013
Gravity Domains
Mass excess Late Triassic to Early Jurassic plutons

Gravity Domains
Low density felsic mid-Cretaceous to Early Tertiary intrusive rocks
Spatial Analysis
Length, azimuth and density analysis

Kechumstuck fault
Fortymile District, Alaska

Big Creek fault
Dawson Range, Yukon

Main Commodities
- gold
- silver
- copper
- copper-molybdenum
- lead-zinc
- copper-gold-silver

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Orogen-parallel fault systems
The Big Creek Fault

Northern Freegold Property

Fault scarp and triangular facets

Nucleus
Revenue

Big Creek fault
Orogen-perpendicular fault systems

The Sixtymile – Pika Fault
Connaught polymetallic (Pb, Ag) veins
Fault-fracture zone

Sixtymile - Pika fault
RTP anomalies over IR gravity
Key Aspects - Interpretation

- Understand the basic physical concepts which drive geophysical signatures
- Recognize the uncertainties related to data interpretation
- Integrate geological maps with rock parameter data
- Develop multi-dataset interpretation workflows
- Base the interpretation on pattern recognition
- Understand the tectonic setting and geological history
- Knowledge on structural styles and architecture
- Ground truth
Regional geophysical datasets for effective geological interpretations of remote terranes: examples from northern Canada

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DMEC workshop series
March 8, 2017

Regional geophysical datasets in Canada

- Regional geophysical datasets at a variety of scales and resolutions are available over most of Canada
- Operating under NRCan programs such as Geo-mapping for Energy and Minerals (GEM), Targeted Geoscience Initiative (TGI) and United Nations Convention on the Law of the Sea (UNCLOS) geophysical datasets are acquired to support research projects
- High quality, modern geophysical datasets are increasingly available
- Datasets provide important information to support mapping projects and assess the resource potential of remote tracts of land
Geoscience Data Repository (GDR)

- In Canada, public geophysical datasets are distributed and accessible through by the Geoscience Data Repository (GDR)
- ‘The GDR is a distributed collection of standardized, digital, thematic geoscience data holdings managed and accessed in accordance with the Earth Science Sector Information Management Plan.’

On-line access to GSC’s geoscience data holdings

gdr.agg.nrcan.gc.ca/

GDR for geophysical and geochemical data

Discover, evaluate and download magnetic, gravity, radiometric, seismic, magnetotelluric, geochemical, and rock property (density, magnetic susceptibility) data

‘Seek Data’ in Geosoft and ArcGIS plug-in

gdr.agg.nrcan.gc.ca/
**Canadian Gravity Anomaly Database (CGADB)**

**Regional gravity data**
- 1944 – present
- >700,000 observations
- Data spacing 200 m – 20 km
  - Targeted and/or detailed transects in strategic locations

**Current Products**
- 2 km Bouguer, Free Air and Isostatic Residual grids
- CGADB point data

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**Canadian Aeromagnetic Database (CADB)**

**Regional aeromagnetic data**
- 1947 – present
- 12+ million line km
- Line spacing 200 – 1600 m
- 600+ surveys

**Current products**
- 200 m national grid
- All digitally acquired surveys
  - Profile and gridded data
  - 349 surveys
- New surveys are being flown each year to infill or upgrade existing coverage
Regional airborne radiometric data

- Gamma-ray spectrometry data (K, eU, eTh and TC)
- 1970 – present
- >360 surveys
- Line spacing 200 m – 25 km

Current products

- 250 m national grids (K, eU, eTh and TC)
- Recent survey profile and gridded data

Rock property information

- 2,901 acoustic properties (M. Salisbury)
- 16,525 density measurements (Earth Physics Branch); 5542 magnetic susceptibility measurements
Regional geophysical datasets for terrane-scale studies

- When used with geological information regional geophysical datasets help answer fundamental questions about the tectonic framework, geology, and structure.
- Publically available datasets are particularly useful in remote locations where it is prohibitively costly to visit and explore.
- Remote regions often have sparse geological information but ample geophysical coverage – link available geological data to geophysical signatures and extrapolate.
- Making the most out of your situation - assess what is publically available, the scale of the problem, and the accuracy and resolution needed for meaningful results.

This presentation aims to provide examples of using regional geophysical datasets to solve geological problems at a variety of scales.

What can we do to get the most out of each dataset?
Tehery Lake – Wager Bay, Nunavut

- One of four identified regions in the Rae Province that had little exploration
- Reconnaissance mapping in 1950’s-1960’s
- Detailed studies in 1980’s-1990’s (Wager Bay area/Daly Bay Complex)
- Remote predictive mapping and isotopic dating in 2000’s
- Geo-mapping Frontiers 2012, detailed field mapping 2015-2016

Key questions:
What is the orogenic architecture of the Rae Province and how does it determine the distribution of mineral resources?

What is the nature, distribution, and significance of 2.6 Ga events in the Rae Province?

Background

Geological setting
- Archean gneissic and granitoid basement overlain by panels of folded Archean and/or Paleoproterozoic supracrustal rocks
- Intruded by 1.83 Ga granite and syenites
- Chesterfield fault zone and Wager shear zone transect the northern margins of the study area

Geophysical datasets
- 400 m line-spaced aeromagnetic data; 805 m line-spaced aeromagnetic data
- 10 – 15 km spaced ground gravity data
- Two targeted gravity transects across major faults
- Density and magnetic susceptibility measurements on ~150 samples
Panels of folded supracrustal rocks defined by prominent linear magnetic anomalies correlated to metaironstone

Potential for base and precious metals (Ag, Cu, Au/safflorite in surficial sediments; Day et al., 2013; McMartin et al., 2013)

Variably magnetic 2.6 Ga granites

Erosional surface

2.6 Ga Snow Island Suite

Mylonitized porphyry

Migmatite with pegmatite and disseminated molybdenite

2602 ± 2 Ma

2603 ± 3 Ma

Mylonitized porphyry melt cap

Model from T. Peterson

Euler deconvolution - depth to magnetic source

~200 – 500 m to magnetic sources

Tonalitic wall rocks
Kummel Lake domain
Shallow gradient
Bouguer gravity anomaly extends beyond domain boundary
Metamorphic core complex?

Daly Bay complex
Steep gradient coincident with domain boundary
3D modelling suggests inward dipping body (Gordon et al., 1995)

Granulite-facies rocks at depth defined by co-located linear gravity and magnetic anomalies

Northeast Thelon Basin, Nunavut
- Host to Kiggavik, End and Andrew unconformity related U deposits and additional prospects
- Focus of extensive study in GEM-1 (NUC); southwest Thelon Basin studied in GEM-2 South Rae

Geological Setting
- >1000 m of sedimentary rocks unconformably overlie early Paleoproterozoic felsic intrusions, Paleoproterozoic supracrustal rocks and Archean crystalline basement

after Jefferson et al., 2007
Available datasets

- Eight industry aeromagnetic surveys (200 – 300 m spaced lines)
- Three 400 m spaced lines aeromagnetic and radiometric surveys
- 21 DDH or seismic refraction depth estimates
- Densities and magnetic susceptibilities
- Two bedrock mapping field seasons (2010-2011) and targeted field visits/sampling (2007-2009, 2012)
Rock property information provides the fundamental link between the geophysical signature and geology.

Identification of key magnetic-lithologic units and their textural characteristics.
Structural interpretation

- Distribution of faults and folds
  - Orientation
  - Spacing
- Fault displacement
  - Relative displacement
- Fault timing
  - Fault-fault offsets
  - Displacement of marker units
  - Relative ages
- Fault characteristics
  - Width of alteration zone (+ or – anomaly; linear or curved)
  - Demagnetization

Source edge interpretation

Identify areas of similar magnetic-lithologic character and extrapolate below sedimentary cover

Lineaments and discontinuities (‘structure’)
Predictive geological map

- White lines – interpreted and mapped faults
- Yellow lines – faults in fertile basement units
- Red lines – intersecting faults in fertile basement units

Check magnetic-lithologic interpretation with gravity data

Tschirhart et al., 2017

Montresor belt, Nunavut

- 1982 field work mapped simple syncline comprising early Paleoproterozoic Rae cover group sedimentary rocks unconformably overlying Archean basement
- 2012 GEM reconnaissance identified hydrothermal breccia with anomalous Cu-Au-Ag
- 2014 field mapping aimed to delineate the extent and nature of the alteration zone and tectonic setting of the belt

What is the orogenic architecture of the Rae Province and the nature, extent, and temporal evolution of its Neoarchean crust and how do they determine the distribution of its mineral resources?

Percival and Tschirhart, 2017
Southwest Montresor belt

Geophysical and geological datasets
- 1982 maps and legacy samples (yellow circles; Frisch, 2000)
- 3 week fly camp in 2014 (red circles)
- 400 m line-spaced magnetic data oriented perpendicular to strike

K-spar-scapolite-epidote-biotite-hematite-quartz breccia

Extrapolated breccia/Alteration zone

Breccia observed in outcrop

Apparent susceptibility
- Apparent susceptibility calculation (Silva and Hohmann, 1984)
- Series of vertical, square ended prisms of infinite depth extent approximate the observed magnetic field
  - BUT not necessarily realistic values
- Assuming known and similar geometries calculated apparent susceptibility values can be scaled to a designated interval (e.g. 0 SI and the maximum measured magnetic susceptibility)

Tschirhart et al., 2015
Magnetic forward modelling

- From geological mapping, the magnetic units are steeply dipping and extend up to ~2000 m below surface
- Measured magnetic susceptibilities and structural information constrain southern limb of the synform
- Scaled apparent magnetic susceptibilities constrain centre and northern limbs
- Accentuates magnetization variations

Northeast Montresor belt

- Structurally more than just a simple syncline
- Distinct magnetic horizons approximate stratigraphic units
- Deviations from concentric pattern interpreted to represent structural complexities

Tschirhart et al., 2017
Magnetic forward modelling

- Structural information extracted from magnetic forward models
- Reveal low angle faults consistent with foreland fold and thrust belts
- Piggy-back thrust hypothesis accounts for dip variability of northern limb

Regional reconstruction

Percival and Tschirhart, 2017
Conclusions

- Interpretations of publically available regional geophysical datasets provide information to add value to the geological interpretations
- Use appropriate regional geophysical dataset to solve the geological problem
  - Gravity data for large scale crustal structures; magnetics for predictive geological mapping and structural interpretations
- Effective geological interpretations require collaboration between geologists and geophysicists. The geophysical solution must reside within geological constraints
- Important to consider the geological setting, physical rock properties, and potential ore deposit models when analyzing regional geophysical data
- At the end of the day it's about getting the most out of your available data - use regional datasets as a starting point for more targeted studies

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Looking at Geophysical data with geological eyes: Using "Structural geophysics" to understand mineral systems.

Peter Betts, Robin Armit, Laurent Ailleres, Mark Jessell*

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Faculty of Science, Monash University
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Thanks to Barry Murphy, David Giles, Caroline Forbes, Alan Aitken, John Stewart, Helen Williams, Mark McLean, Oz Minerals Prominent Hill team.

Regional geophysics used to target mineralisation directly – anomaly targeting.

Regional potential fields is effective in terms cost and value because it images data at multiple scale, and in 3D.

Tells you about things you might be interested in if you are exploring for an ore body – not just the target.

More powerful and predictive (if you look at the data with geological eyes).
  - Terrane selection (tectonics setting, major structures/sutures) - up to continental scale.
  - Terrane context (what is the structural architecture/geological evolution/tectonic setting).
  - Predictions (what is the movement, where is the dilation, alteration).

The role of geophysical interpretation – down scaling and predicting.

Take home messages
Career defining feedback.

“Shame you are doing structural geology. You would have made a good geophysicist” Jim Cull 1992.

“It’s a pity you like geophysics because you would make a good structural geologist.” Gordon Lister 1994.

Another influential quote

“I am sick and tired of forking out $100,000 a year to graduates who are too scared to put a line on a piece of paper. I don’t care if the line is right or wrong I just want something to F#$%#*g work with!”

Mark O’Dea (Frontier Group 2007)
What is structural geophysics?

What is structural geophysics?

"The application of analysis of geological structures and applying these approaches to regional (and local) geophysical datasets”

• Geophysical data tells you about 3D geometry.
• You can determine overprinting.
• You can do kinematic analysis.

• At all scales
• Transition to from structural analysis to geophysical analysis is not that big of leap.

What is structural geophysics?

The transition – is it an education challenge????
It’s all about confidence (and knowledge)!

If you’re a structural geologist/geologist.
- Where do I start?
  - Understanding the data - how it is processed
  - Converting a dataset that tells me about one physical property of the Earth into a geological observation or process.

If you’re a geophysicist
- Not knowing enough about geology
- How can you interpret something if you don’t know what it looks like?
Tectonics and mineralisation – a starting point

- From a mineral system approach there are more favourable environments.
- The overriding plate is significant because in an active convergent margin this is where the most of the important ingredients that allow for an orebody to form.
  - High fluid fluxes
  - High heat flow and flux
  - Active and intense deformation and tectonism.
  - Transient switches in tectonic modes (extension to shortening or vice versa).
  - Intense magmatism.
  - Better preservation.

Groves et al. 2005

2 Challenges!

- Exploration success at surface or shallow cover.
- Limited success at depths >50m
- Most deposits are structurally controlled – several scales.
- Not about making a map under cover but actually making a structural map.
  - 3D
  - Kinematics
  - Predictive – vectoring to a target

From the map of our largest mineral systems spatial patterns are not obvious. That’s a big haystack and a lot of drilling!
Geophysical data

Predict the position of the arc, overriding plate (back arc).

Opportunity to reduce exploration risk.
A significantly important step in understanding the mineral system.

Need to be on the right side suture for the time of mineralisation.

To understand this:

- Need a method for selecting the position of the plate/terrane boundary and a way to determine the geometry (combination of seismic and potential fields).
- Need to understand the depth extent (long wavelengths)
- Need a method to map the distribution near the surface (combination of aeromagnetics and gravity).

Mapping sutures is not easy in ancient terranes because they often have a cryptic signal in the geological record.

Some of the characteristics that you might expect in region geophysical data.

- A. Step in the Moho (ie are crustal penetrating) (best in seismic data but will have a long wavelength gravity signal).
- B. Big structures usually have large strike-lengths (it was a plate boundary after all ☺☺☺).
- C. In the absence of seismic data, gravity data is likely to assist in constraining the scale and the
- D. Major change in geophysical response in terms of the texture or the orientation of the structural grain of the boundary.
- E. *The interpretation will be ambiguous and lithospheric scale structures could have the same signal.*
- F. Geology on either side of the boundary will have different histories or have different geochronology inheritance in the magmatic rocks.
There have been a series of alternative interpretation about what has influenced the development of IOCG systems in the Gawler Craton.

1. Plumes – heat driver and potential source of metal.
2. Proximal to plate boundary
3. Crustal- to lithospheric scale faults (ancient suture).
4. Craton scale fault controls.
5. Lower metamorphic grade metasedimentary rocks in the basement (promote fluid flow, multiple fluid sources) (Reid et al.)
6. Mesoproterozoic sedimentary basin (host to the IOCG, brecciated, fluid mixing) (McPhie and students- UTAS and Prominent Hill).
7. Unconformity at the base of the GRV – chemical boundary.
8. Tectonic switching is significant (drive high fluid fluxes).
Continental scale – IOCG province

- Eastern Palaeo- to Mesoproterozoic Provinces of Australia host the highest density of IOCG mineralisation on the planet.

- This mineral system is over 100 km in length and hosts mineralisation that formed during a 90 million year interval between ca 1590 Ma and 1500 Ma.

- The oldest deposits occur in the Gawler Craton and the youngest occur in the Eastern Fold Belt of the Mount Isa Inlier.

- There is a strong spatial and temporal association with A-type granite and lithospheric scale structures.

- The process of orebody formation is very different between the Gawler Craton and the Mount Isa Inlier.

*PH: Prominent Hill; OD: Olympic Dam; CPT: Carapateena; OSB: Osbourne; EL: Eloise; EH: Ernest Henry.*

1600-1500 Ma hotspot track in eastern Australia: implications for Mesoproterozoic continental reconstructions

Peter G. Bird, G. Bruce Snelling, Bruce F. Schuiling, and Gudrun Mair

Monash University, School of Earth Sciences, Victoria, Australia.
Gawler Craton

- Hiltaba-GRV Silicic Large Igneous Province
- The Hiltaba Suite granites GRVs emplaced over an area of $\sim 320,000\text{km}^2$
- Large sub-circular felsic igneous province $\sim 500$ km in diameter
- Mostly buried

Regional kinematics

- There are a variety of kinematic criteria that are commonly used to determine the movement picture.
- Usually determined using micro-to-meso-scale features
  - porphyroclast morphology
  - S-C fabric in shear zones
  - mica fish structures
  - Reidel faults/shear zones
  - asymmetric fold trains
  - Foliation deflections
- Usually rely on foliations and other fabric elements (not observable in regional geophysical data).
Regional kinematics

The geological patterns of many of the kinematic criteria are the same. Geological processes can be very different. The major difference between structural geology and structural geophysics:

- approaches is the planar fabric elements
- volumetric elements
- driving forces
- rheological contrasts.

A significant difference is the scale of observation. Up to several hundred kilometers rather than microns to meters. Large-scale movements of major shear zones and terranes.

### Regional kinematics

#### S-C’ Foliation

- C’ – bands defined by foliation characterised by magnetite depletion
- S – foliation defined by a magnetic foliation - lithological (?)
Regional kinematics

Plutons

• granite “porphyroclast
• rigid bodies in a matrix that essentially flows around them
• state of the granite - rigid

Regional geophysical datasets provide valuable information about the large scale movement of rocks.

Many of the geometrical criteria that we use to understand rock kinematics at the micro-scale is also observed at the regional scale in geophysical datasets.

To understand the kinematics we rely on using planar features in rocks that are observed in geophysical datasets such as magnetite rich or poor units.

The criteria is most effective at determining faults that have a large relative strike-slip component.

From a mineral system perspective – it can be used to predict sites of dilation and therefore fluid flow.
- The architecture of the faults active during the Hiltaba Mineralisation Event
- Mineralisation located along Yerda SZ or second order splay
- Intersection with suture zone (Kimban or earlier architecture)
- Mineralisation and magmatism focussed at dilation sites.

Olympic Dam

After Nick Direen
Objectives of the project:

To make a geological map that would assist the exploration group:

A. Understand the crustal architecture and setting.
B. Constrain the distribution of rocks types.
C. Assist in identifying the structural architecture of the Prominent Hill orebody and map this to under explored regions.
D. Identify areas of alteration.
E. Determine the geological/tectonic evolution.
F. Predict the location of mineralisation.

Maps are the language of Geology - they are an effective way to communicate between the different geoscience disciplines

- Make sense and have predictive capability
- Exploration success requires an exploration geoscientist to make a call with the information.

- Geophysical data
  - Geometry
  - Kinematics
  - Overprinting
  - Alteration
  - Map format
Mount Woods Inlier

Image Processing
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Stratigraphy

Prominent Hill Group

Host mineralisation

Blue Duck Group

Hiltaba Suite

Gawler Range Volcanics

Structural evolution
Targeting

1. Gravity anomalies important: *Alteration vector*
2. Magnetic anomalies less important with hematite targets more desirable: *magnetic interpretation required.*
3. Fault intersection and location of dilation zones: *kinematic analysis.*
4. Unconformities: *understanding the stratigraphy and this narrowed the search area.*
5. Proximity to Hiltaba Granites: local heat engines to drive fluid flow: *magnetics important constraint for mapping these bodies.*
6. Proximity to a crustal scale fault (or large fault system).
7. Crustal Level (i.e. if the target is in the upper or lower plate). Targets in the upper plate were viewed more favourably: *putting the interpretation into tectonic context.*
1. **Contiental and Craton scale** - Tectonic modes switches – during one of the largest intervals of mineralisation on Australian continent (extension-shortening drives fluid flow at a crustal scale).

2. **All scales** - Switches driven by complex plate interactions and the likely interaction with the plume at the margin (heat flux, metal source?, halogens - HF to assist with brecciation (post emplacement).

3. **Craton scale** - There is a spatial association between terrane scale faults and IOCG's - high angle to an older plate margin – focused fluids and created dilation zones.

4. **Craton to Province scale** - Syn-extensional sedimentary basins – synchronous with the GRV’s or slightly older appear to host deposits. Preconditioned the environment - porosity, multiple fluid sources, and redox boundaries. DO and PH – converging in their environments of deposition.

5. **Province scale** - map the distribution of favourable stratigraphy, structural elements, and zones of dilation

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**Summary**

- Structural geophysical analysis – kinematics, 3D geometry, overprint
- Informs structural control, alteration, tectonic setting
- Importantly can be used at multiple scales.
- Kinematic analysis allows prediction of dilation and fluid flow.
- Communication of the data is key and it has to be digestible to your audience. Maps are the language of geology – assist in decision making.
- Need to understand what the purpose of the interpretation is – super critical for focus.

- Conceptually things are quite similar to the approaches initially proposed by David Boyd 50 years ago. I think we’ve just become more sophisticated in the manner in which we interpret higher resolution data.
Become a global leader in the development and application of disruptive technology and scientific solutions integrated across the mining value chain.

- Disruptive technology (drones & instrumentation) integrated with artificial intelligence for rapid, high-resolution data acquisition and real-time interpretation. [Exploration, Development, Production, Environment]
- Supercomputing & synchrotron big data, to build workflows for rapid, large through-put ore characterisation & mineral chemistry data. [Exploration, Production Scheduling, Design Optimisation, Processing]
- Mineral Systems Analysis using supercomputing and mineral chemistry big data, applied to predict the deposit types of the future. [Exploration]
- Drill core data and Artificial Intelligence for real-time interpretation and rapid updating of resource models. [Exploration, Design, Production, Processing]
- Geology from geophysics, 3D visualisation, mineral systems analysis & quantification of model uncertainty. Application of artificial intelligence (machine learning) to accelerate data interpretation. [Exploration, Geomechanical Modelling, Production]
- Forward modelling mm-scale big data for ground-control, safety and risk management. [Design, Development, Production]
- Disruptive technology (immersive visualisation) for:
  - collaborative interpretation,
  - collaborative reporting,
  - simulation training. [Exploration, Development, Production, OH & S]
- Disruptive technology (drones & instrumentation) integrated with artificial intelligence for rapid, high-resolution data acquisition and real-time interpretation. [Exploration, Development, Production, Environment]
- Supercomputing & synchrotron big data, to build workflows for rapid, large through-put ore characterisation & mineral chemistry data. [Exploration, Production Scheduling, Design Optimisation, Processing]
- Mineral Systems Analysis using supercomputing and mineral chemistry big data, applied to predict the deposit types of the future. [Exploration]
Porphyry Copper Deposits: What do we (really) know?

The Porphyry Copper System is arguably the most studied and best understood ore deposit type.

The model has proven a significant aid in deposit-scale vectoring, yet still provides little guidance at the district scale.

Fundamental questions remain regarding what factors control deposit distribution, metal tenor and relative size.

These are regional issues that require examination of datasets that extend beyond the alteration halo.
The Scale Problem (and the Known Unknowns)

The scale of most PCD studies is very small with respect to the processes that govern their emplacement.

How do we explore for covered porphyry deposits?

Porphyry exploration has historically relied almost solely (and been highly successful!) on a “hammer and hand-lens approach”. However, if we are to pursue covered and deeper orebodies, we will need to develop more integrated geological and geophysical models.

Few studies have attempted to fully integrate regional geophysical data, either to examine the regional controls on porphyry emplacement, or to characterize geophysical responses beyond the alteration halo.

Here we document examples from the Chilean Andes (La Escondida), the Laramide Province of Arizona (Resolution) and the Canadian Cordillera (Highland Valley).
‘Cordilleran’ verses ‘Orogenic’ Geologists

Exploration geologists -like normal people- tend to be strongly biased by their past experiences and successes. As we move to deeper and less exposed search spaces, the tried-and-tested methods (and models) may no longer be effective.

Exploration philosophies should be determined by the operating environment!

District-scale Structural Controls on PCDs

• In many districts, the intersections between arc-parallel fault zones and continental-scale, transverse lineaments has long been recognized as a fundamental deposit control.

• Such studies, many dating from the 1960s to 1980s, have been largely restricted to ‘lineament analysis’ based on the alignment of geological and topographic features.

• In most cases, the geological nature and exact location of such ‘lineaments’ remains unclear (commonly not observed in the field), and hence are not widely accepted by the exploration community and rarely used in targeting.
La Escondida: Geology

Northern Chile is one of the best examples of spatial and temporal coincidences between deposit clusters and intra-arc fault zones.

- The Eocene-Oligocene belt spans the Domeyko fault system for >1000 km, yet deposits are largely restricted to clusters approximately 100 to 200 km apart.
- A series of NW-trending arc-transverse lineaments are postulated to control the distribution of these clusters.
- However, at Escondida, no evidence of these structures is apparent on the geological map.

La Escondida: Magnetics

Magnetic data is consistent with much of the surface geology but also reveals the deeper extent of intrusive bodies and the presence of additional structural fabrics:

- N-S continuity of the Domeyko fault system, comprising the Escondida and Sierra de Varas faults (bounding a Mesozoic graben);
- A strong NE-structural fabric that largely reflects the Paleozoic basement – also apparent beneath Mesozoic cover west of the Escondida fault; and
- NW-trending fabrics manifest as alignments of prominent magnetic highs (corresponding to Eocene dioritic intrusions) and linear magnetic lows (probably reflecting faults).
La Escondida: Magnetic Worms

‘Worms’ derived from the magnetic data show two orthogonal (deep?) fabrics that suggest a complex intersection zone coincident with the deposit.

The NW-trending fabric intersects the Escondida Main Pit as well as the Chimbarazo deposit.

Vein / dyke orientations mapped in the pit are confirmed by the regional magnetic fabrics.

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La Escondida: Geology and Magnetics

Geology on Magnetics*

Eocene dioritic rocks
(Cerro Rincones Plutonic Complex)

Pre-mineral to coeval volcanics
(Augusta Victoria Fm.)

La Escondida Cu resource

breccia

10 km

Alteration on Magnetics*

inferred lithocap
(Herve, 2012)

propylitic alteration
(Richards, 2001)

phylllic / argilllic alteration
(Richards, 2001)

10 km

Long wavelength (‘deep’) magnetic transforms coincide with the geology and alteration at Escondida and could (and should!) be used to predict their extent beneath cover.

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* Pseudogravity Transform

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La Escondida: Magnetics (Upward Continued)

Long-wavelength magnetic transformations also reveal a deep, coherent anomaly that probably defines a NW-trending Parent Batholith.

Modeling suggests a source with dimensions of about 30 x 15 km, at a depth 5-10 km.

Older intrusions and other Eocene-age bodies are no-longer apparent (limited by depth extent?).

La Escondida: Bouguer Gravity

Gravity shows a steep gradient on the Escondida fault. This probably reflects the edge of the Mesozoic back-arc basin.

The main deposits are positioned in an anomalous, low-density zone on this gradient.

The takeaway here is that regional geophysical data at Escondida significantly adds to our understanding of deposit empacement.
The distribution of porphyry copper deposits in the Laramide Province of SW USA is similarly controlled by the intersection of regional transverse lineaments.

The Laramide Province in Arizona is oblique to the main trend of the Northern Cordillera. The district is aligned on a NW-trend, with deposit clusters on NE-trends. Both trends follow basement fabrics and appear to be unrelated to the subduction vector.

Major domain boundaries are clearly reflected in the regional geophysical data. These data reveal a first-order control on deposit distribution.
District-scale controls on PCD distribution are also apparent in the regional geophysical data. Gravity suggests a deep fault coincident with the Jemez Lineament. Magnetics reveals the probable parent batholith (50 x 25 km) responsible for the deposit cluster.

The geology of the Superior/Globe-Miami districts is characterized by a basement uplift that parallels the Jemez Zone. However, few faults of this orientation are evident. Note that ‘productive’ Laramide-age intrusions are confined to the Jemez Zone.
Superior & Globe-Miami Districts: Magnetic Inversion

A susceptibility isosurface of the regional magnetic data, colored by elevation, shows the probable extent of the parent batholith and its relationship to the deposits.

Miami-Inspiration positioned on the apex of the magnetic feature
Pinto Valley & Resolution positioned in a marginal position

Superior District: Geology and Magnetics

Regional magnetic data (c. 1976) shows the probable extent of Schultz Granite under younger volcanic cover and at depth. Note that the Resolution deposit is positioned on the interpreted margin of the parent pluton.
Resolution Copper Deposit: Geology

Resolution is a giant, high-grade deposit buried under >1500 m of post-mineral cover (dacite tuff and conglomerate).

A ZTEM and magnetic survey was flown by Freeport in 2013 and reprocessed by Condor Consulting in 2016.

Resolution: Geology and Magnetics

The high-resolution magnetic data over Resolution is dominated by near-surface responses but bounding faults of the Cretaceous graben are still well-resolved. Also apparent is an anomalous magnetic low that overlaps the resource area - typical of a Laramide-age porphyry.
The ZTEM data over Resolution indicate anomalous conductivities associated with the Cretaceous volcano-sedimentary graben-fill, and an apparent plume extending into cover rocks above the deposit.

The core of the ZTEM response at Resolution is positioned at a depth of 1500 m directly over the 1% Cu shell. This response can largely be attributed to a pyrite halo (~10%) above the deposit.
This belt consists of several accreted volcanic arcs that underwent major strike-slip displacements and rotation, resulting in a complex deformation history that remains poorly resolved.

Deposits are generally older (Mesozoic) and less well-endowed than the aforementioned belts.

Highland Valley is arguably the most significant copper deposit in the region.

The Highland Valley PCD cluster is hosted by a compositionally-zoned, well-exposed pluton known as the Guichon Creek Batholith.

- Productive porphyries are confined to the innermost, youngest and most felsic phase(s) of the batholith.

- The deposits are hosted by, or locally dissected and displaced by through-going faults (e.g. the Lornex and Highland Valley faults).
Looking Deep: Regional Magnetic Transforms

Long-wavelength transforms of the magnetic data help to identify the deeper, large-scale features of the belt.
Looking Deep: 3D Inversion Depth Slices*

A combination of 3D inversion outcomes reveals that the HVC cluster is positioned in arguably the largest, 'deep' anomaly in the belt. Combinations of 3D inversion potentially provide an effective means of belt-scale targeting.

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Guichon Creek Batholith: Magnetics & Gravity

At the batholith scale, a close relationship is evident between discrete intrusive phases and their geophysical character.
Magnetic and gravity inversion outcomes potentially provide targeting criteria to within several kilometers of the major deposits of the Highland Valley cluster.

Such outcomes are consistent with local structural controls on the emplacement of individual deposits.

Note that apparent asymmetries suggest a clockwise-rotation of the batholith (i.e. more of the eastern flank of the isosurface is visible than the western flank).

Limiting the isosurfaces to their lowest coherent values highlights a close spatial association with the largest deposits in the district – (particularly with respect to the density inversion).

(Note that remanent magnetism and errors in density corrections are suspected, potentially complicating such outcomes)
Targeting PCDs using Regional Data: The Takeaway

Regional geophysical data have revealed significant new insights regarding porphyry copper deposits, both at the belt- and district-scale; and potentially can provide direct targeting criteria to within several kilometers of individual deposits.

The world is awash in such (neglected) data! Much could still be learned about porphyry deposits that is not readily apparent at the outcrop scale. So perhaps,

...it’s not always about boots on the ground!