DMEC workshop series:

Developing the tools and techniques to explore undercover; a global initiative

Wednesday, March 4, 2015
Program Schedule

14:00-14:10  Introduction - Ken Witherly, Charles Beaudry

14:10-14:40  1. A CMIC industry perspective on sector requirements for step change; Alan Galley

14:40-15:10  2. Exploring Under Cover: NSERC-CMIC Exploration Footprints Network; Mike Lesher

15:10-15:30  Break

15:30-16:00  3. Targeted Geoscience Initiative: New public geoscience knowledge to support enhanced effectiveness of deep exploration; Mike Villeneuve

16:00-16:30  4. Mineral Exploration Geophysics for the Future — A Mineral Exploration Geologist’s View; Murray Hitzman

16:30-17:00  5. Mineral Systems: Key to Exploration Targeting; Cam McCuaig

17:00 -17:30  6. Coiled Tubing Drilling and Real-Time Sensing: Enabling ‘Prospecting Drilling’; Richard Hillis

17:30 – 18:00 Discussion

18:00  End of Workshop
Introduction

Decennial Mineral Exploration Conferences (DMEC) is an outgrowth of the very successful Exploration 07 symposium held in Toronto (September 2007) that drew together over 1,300 delegates to review the state of the art in minerals exploration technology. This year’s workshop will be the fifth DMEC-sponsored event under the theme “Developing the tools and techniques to explore undercover; a global initiative.” With the dual challenges of a declining inventory of quality mineral deposits in mature terrains and the an uncertain transition through the ‘great crew change’ (baby boomers retiring from the work place), the minerals industry must develop new technologies and processes to effectively explore for deposits under much greater cover than has been required in the past. This is particularly a challenge in mature terrains such as Canada, the US and Australia which were some of the first countries to benefit from the advent of modern exploration and mining practice. Concurrent with this challenge is the linked issue of maintaining a vigorous next generation of employees to drive the increasingly technology-focused exploration and extractive industries. In both Canada and Australia, major initiatives have been started in the past five years to address the technological challenges being faced with an increased focus on undercover exploration. Less clear is how the human capital story will unfold. While efforts to train up a new generation of explorers is underway in both countries, their future in the minerals business is less clear as the entire sector has undergone a major downsizing in the past 5 years with little indication this trend will be reversed in the short term. These initiatives will be reviewed and the short and longer term trends examined by the speakers, all who are directly involved with major technology and education initiatives.
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Short Biographical Notes

Charles Beaudry

Charles Beaudry is a Professional Geologist with over 30 years experience in project generation, business development, exploration geochemistry and hands-on project management. Charles was previously President and CEO of Xmet Inc., a Junior focused on advanced gold projects in the Abitibi region of Quebec. He held the position of General Manager of new business opportunities with IAMGOLD Corporation from 2008 to 2009, after having spent nearly 17 years in various positions for Noranda-Falconbridge-Xstrata. His newest venture is focused on gold and base metal exploration in the Timmins region of Ontario. Charles holds a Bachelors of Science in Geology from the University of Ottawa and a Masters of Geology from McGill University. Charles is also a QAQC specialist, having spent several years in Six Sigma and Quality Systems training, and gives a 3-day short course on Quality in Mineral Exploration and QAQC. He is also a Qualified Person as defined in NI43-101.

Ken Witherly

Ken graduated from UBC (Vancouver Canada) with a BSc in geophysics and physics in 1971. He spent 27 years with Utah/BHP Mineral 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.

Alan Galley

Alan Galley received his MSc in Geology at Western University and his Phd in Geology at Carleton University. After a brief stint in the consulting business he spent the next 27 years as a mineral deposit researcher at the Geological Survey of Canada focusing on greenstone hosted gold and then volcanogenic massive sulphide systems. In the latter part of his career at the GSC Alan switched from being a senior research scientist to the role of GSC Minerals Director. In 2011 he left the GSC to become exploration director for the Canada Mining Innovation Council, an industry-led, not for profit organization that brokers research, development and innovation for the Canadian mining industry.

Mike Lesher

Michael Lesher is Professor of Economic Geology and Research Chair in Mineral Exploration at the Mineral Exploration Research Centre and Department of Earth Sciences in the Goodman School of Mines at Laurentian University. He has worked on banded iron formations in Labrador-Quebec, Au deposits in Western Australia and the southern Appalachians, Ni-Cu-PGE deposits in Brazil, China, Western Australia, Manitoba, Ontario, and northern Quebec, and chromite deposits in northern Ontario. He is presently serving as Principal Investigator and Director of the CMIC-NSERC Mineral Exploration Footprints Research Network.
Mike Villeneuve

Mike Villeneuve started at the Geological Survey of Canada (GSC) in 1987 as a U-Pb geochronologist before becoming head of the Noble Gas Laboratory in 1996. From 2004 until 2011, he was Manager of the Scientific Laboratory Network, responsible for the planning and operation of national laboratories located in the five GSC offices located across Canada. Currently he is Program Manager for Targeted Geoscience Initiative, a five year, $25 million, federal government program focused on increasing effectiveness of exploration for deeply buried mineral deposits.

Murray Hitzman

Murray Hitzman’s current research focuses on deposit- and district-scale studies of metallic ore systems. Deposit-scale studies examine the genesis of ore deposits through detailed fieldwork and careful laboratory research to characterize the geologic setting of the deposits and determine alteration and mineralization events. Much of his recent work has dealt with iron oxide-copper-gold systems and with sediment-hosted stratiform copper deposits, primarily in the Central African Copperbelt (Democratic Republic of Congo and Zambia). Prior to arriving at CSM in mid-1996, Murray spent 11 years in the minerals industry. When with Chevron Minerals, Murray was a key contributor to discovery of the carbonate-hosted Lisheen Zn-Pb- Ag deposit in Ireland.

Cam McCuaig

Cam McCuaig is currently the Director for the Centre for Exploration Targeting (CET), a joint venture between The University of Western Australia, Curtin University of Technology, and the Minerals Industry that is focussed on advancing the science of exploration targeting. Cam received his Honours degree in Geology and Energy and Fuel Science from Lakehead University in 1988, and his PhD in Geology from the University of Saskatchewan in 1996. In the subsequent employment with the international firm SRK Consulting, Cam rose to the position of Director in the Australasian practice, where he garnered 10 years experience in providing solutions to the mining and exploration industry, from greenfields exploration to mine-based geology and valuations of projects. Cam’s experience spans 6 continents and numerous commodities in geological terranes ranging from mid-Archaean to Eocene in age, including Au deposits of all styles, polymetallic intrusion-related and skarn deposits, volcanic-hosted massive-sulphide deposits, Archaean komatiite-hosted Ni, sediment-hosted Cu, amongst others. In August 2005, Cam left SRK to take up the Directorship of the CET.

Richard Hillis

Richard Hillis is CEO of the Deep Exploration Technologies CRC which is developing transformational technologies for drilling and logging in mineral exploration. He graduated BSc (Hons) from Imperial College (London) and PhD from the University of Edinburgh. Richard was previously Mawson Professor of Geology and Head of the Australian School of Petroleum (University of Adelaide). He has published ~200 papers in petroleum geomechanics and basin tectonics. Richard and colleagues recently sold technology spin-off company JRS Petroleum to Ikon Science and he also has interests in geothermal energy, being previously a director of ASX-listed Petratherm. Richard is a director of AuScope, a company charged with developing earth sciences research infrastructure in Australia, and is a Fellow of the Australian Academy of Technological Sciences and Engineering (ATSE).
Decennial Mineral Exploration Conferences Organization

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Canada Revenue Agency Business Number 85158 8756

Website: www.DMEC.ca

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A CMIC industry perspective on sector requirements for step change

Alan Galley

PDAC/DMEC 2015
Toronto CA

Contents

• Market driven step change
• Developing an exploration RDI roadmap:
  – Where to look
  – How to look
  – Data to knowledge (How to use it!)
• LOM linkages through ore characterization
• Mechanisms for incubating required step change
Keeping pace with advances

- Service providers driving advances in order to survive the market
- Mechanisms to keep service providers aware of market requirements
- Mechanisms to allow users to develop flowsheets for better use of new technologies and techniques

Can’t do it alone: RDI Consortia

- Companies are divesting themselves of research and development capacity: not economic
- Not a bad thing: More opportunities for pooling investment in RDI in the pre-competitive space
  - Mitigates investment risk
- Sharing market intelligence makes for more innovative use of new knowledge and technologies.
- Fastest off the mark instead of striving to be second through risk aversion
### Exploration Innovation Consortium
#### 10 Year Roadmap

<table>
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<tr>
<th>Themes</th>
<th>Discovery Criteria</th>
<th>Discovery Technology</th>
<th>Data to Knowledge</th>
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<td><strong>Focus</strong></td>
<td>Knowledge and models</td>
<td>Detection</td>
<td>Interpretation</td>
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</tbody>
</table>
| **Key Question** | • Where to look?  
• What to look for? | • How to detect? | • What does it mean? |
| **Challenges** | • Terrane selection  
• Area selection  
• Vectoring to ore | • Mapping and detection tools  
• Cheaper drilling | • Visualization and integration  
• Using physical property models |

**Education & Technology Transfer**

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### CMIC-EIC Roadmap

<table>
<thead>
<tr>
<th>Deep Mature Camps</th>
<th>Remote &amp; Covered Areas</th>
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</table>
| **1.** Mult-parameter footprints and 3D vectoring  
• Detecting edges and vectoring to ore | **1.** Characteristics of fertile terranes and districts  
• How do we select fertile ground? |
| **2.** Techniques to unravel deep 3D geology  
• Deep penetrating detection and mapping techniques | **2.** Techniques to map subsurface geology  
• Drilling, data integration  
• Data density for detection |
| **3.** Real-time down-hole data collection  
• Real-time decision | **3.** Secondary dispersion  
• Understanding mechanisms  
• Developing techniques |

[www.cmic-ccim.org](http://www.cmic-ccim.org)
Discovery criteria

• Better metallogenic contexts at the geologic domain scale
  • Better characterization of mineral systems?
• Better fertility indicators at the domain and ore system environment scales
• Better definition of ore system footprints using multi parameter data sets

Responsibility for new discovery criteria: filling the gaps

• Domain scale mapping and potential/fertility studies should be supported by provincial and federal surveys
• Mineral systems studies by surveys, minerals institutes
• Ore deposit environment studies by universities and mineral institutes

Linkages!
Discovery technology

- Automated remote sensing platforms for greenfields and LOM monitoring
- Looking deeper with greater certainty and lower costs
- Stripping away the geophysical signatures of surficial cover
- Better multi parameter quantification of secondary ore system footprints in the surficial cover

From Mars to Earth: Entrepreneurs!

- Power source
- LBS-based Chemcam
- High def. video and navigation cameras
- Drill and Sample collectors
- 3 m

http://science.nasa.gov/missions/msl/
http://groundtruthexploration.com/
asrl.utias.utoronto.ca
Discovery Technologies: Exploring Covered Terranes

- Secondary dispersion of indicator minerals
- Better understanding of element migration and detection
- Genomics (bacterial barcoding)
- Gas detection and barcoding (Drone-based surface and aerial)
- Cheap and effective isotopic tracers
Discovery technology protocols

- More efficient drilling technologies and protocols (DET CRC)
- Real time, or near real time data and knowledge return during drill campaigns

Responsibility for new discovery technology and methods

- Lead taken by service providers (instrument developers, analytical firms, geophysical companies). Survival innovation!!
- Important role played by academic institutions for developing new methodologies and process reasoning
- Leverage funding through non profit RDI brokers
Data to knowledge

- Data rich and knowledge poor
- Better data management systems
  - Cloud-based?
- Data integration and 4D visualization
- Big data interfaces with analytics
- Better constrained 3D joint inversion models
- Proxies to replace sparse data with richer data sets

Data to knowledge

- Better protocols on the use of multi-instrument platforms
- Better linkage of advanced exploration results into the LOM flowsheet
Managing your data

- Reflex Hub®, Geosoft Oasis®, Mira Integrator®
  - Spatially aware data repositories with attached analytics
  - Linked with 3D GIS-based spatial analytics packages
  - Interoperability (gOcad® and ioGas®)
- Access to great computing power for free form (non deterministic) data analysis

Constraining inversion= Data integration

1D ➔ 2D ➔ 3D EM ➔ Mag-Gravity

Petrophysics + Geochemistry + Mineralogy + ?
Ore characterization

- No longer just the purview of mineral processors
- Becoming an integral part of discovery evaluation
- Linked with rock property assessment
- Field-based, multi parameter sample and drill core analysis
- Key linkage between essential geological and geotechnical information

Photonic Knowledge’s “Picasso” mineral mapping technique overlain on a high resolution photographic catalogue of the drill core

Linking exploration to the LOM flowsheet

- Better ore characterization during exploration telescopes development decisions

NEW PORTABLE AND AUTOMATED TECHNIQUES FOR DETECTION AND MONITORING OF BASE AND PRECIOUS METALS AND POTASH

- Exploration (Outcrop, Drill Core)
- Geochemistry
- Geochemistry
- Assay Geochemistry
- Geochemistry
- Terraformer, Terraformer, Terraformer
- Monitoring (Till, Biosphere, Outcrop, Drill Core)
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Ore characterization responsibility

- Requires the ability to “map” physical rock properties and mineral chemistry
- Development of niche specialty firms using multi-parameter tools based largely on hyperspectral analysis
- Field-based analysis (Raman spectrometry?) could take the place of lab-based MLA and Qemscan technologies.

Technology transfer?
Avenues for incubating step change

- Understanding the knowledge gaps and how they affect your company’s exploration strategy
- Better understanding of AMIRA, CMIC, CAMIRO as leverage vehicles for research, development and innovation
- Better fusion of academic and industry intellectual capacity
- Moving from the laboratory into the field for real time decision making
- Loosening up tight or misdirected funding avenues

Getting our acts together

- How can we stay ahead of the innovation curve in such a cyclical industry?
- Lack of long term planning result in exploration and related R&D budgets to be the first to go
- How can we better support/inform the service industry to allow the required technological changes?
Getting our acts together

• Developing flowsheets to understand how to use the new technologies in a multi-parameter fashion
• Better integration of exploration as part of the life of mine continuum
• Looking outside the mineral sector for solutions through modification of existing technologies and techniques

THANK YOU!
Research Network

- One of the largest and strongest research teams ever brought together in Canada for a project of this type
  - 60+ researchers from 24 universities across Canada
  - 60+ industry collaborators from 30 mining, mineral exploration, and mining service companies
  - Collaborations with GSC-TGI-4, Ministère des Ressources naturelles du Québec, Geological Survey of Saskatchewan, and Geological Survey of British Columbia
  - Includes geologists, mineralogists, geochemists, petrophysicists, geophysicists, and computer modelers
- 5-year funding (Phase 1: April 2013 - April 2018)
  - $7.8M cash and cash-equivalent in-kind funding from industry
  - $5.1M matching funding from NSERC (largest Collaborative Research and Development grant ever awarded by NSERC)
  - Total = $12.9M
Network Organization

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- Dr. Colin Farquharson (Memorial) – Inversions
- Dr. Bill Morris (McMaster) - Data integration
- Dr. John McGaughey (MIRA) - Data integration
**Current Numbers**

- 24 Universities
- 43 Faculty Researchers
- 8 Research Scientists (1 more to be added)
- 7 PhD Students (more to be recruited as project progresses)
- 11 MSc Students (1 completed, more to be recruited)
- 9 BSc Hons Students: (more to be recruited as project progresses)
- 4 BSc Summer Students: (more to be recruited as project progresses)
- 30 Sponsors:
  - 4 Geochemical Service Companies: Actlabs, ALS, SGS, SRC
  - 5 Geological and Geophysical Service Companies: Abitibi Geophysics, CGG, DGI, PGW, SRK Consulting
  - 6 Software Service Companies: Geosoft, Geovia, MIRA Geoscience, Paradigm, Pitney-Bowes, Reflex
- **Collaborators:** GSC TGI-4, MRNQ, SGS, GSBC

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**Footprints Project Objectives**

- **Develop comprehensive and robust models of the footprints of large-scale ore-forming systems at three integrated study sites**, combining geological, mineralogical, geochemical, and physical rock properties from the local to the camp scale
- **Develop novel methods for integrating and interrogating multiple data sets** that will enhance the exploration process and, at the same time, answer fundamental questions about the origins of large-scale ore-forming systems
- **Identify the best combinations of geological, geophysical, petrophysical, mineralogical, and geochemical tools** to detect the footprints of major ore-forming systems
Often acquired ... but in this project they will be integrated

What is needed are models where geology, structure, mineralogy, and geochemistry are completely integrated with rock properties and their geophysical responses:

Most models include only a few characteristics and are layered, but not truly integrated

This project will produce genuinely integrated multi-parameter models
Integrated Study Sites: Phase I

- McArthur-Millennium
- Highland Valley
- Canadian Malartic

Integration Matrix

- Work at each site focussed through Site Working Groups
- Research methods focussed through Integrative Science (Technology) Groups that include service providers
- Ensures multi-disciplinary collaboration and best practices across all sites
Research Methodologies

- **Full ore systems from distal edges to ore zones**, both at surface and at depth, and including the highest density of data and sampling opportunities
- **New and legacy data**, with emphasis on high-quality multi-parameter measurements on the same samples at each site
- **Focus on a limited number of representative cross sections and surface/level plans** through each ore system (e.g., encompassing no more than 10 km by 10 km)
- **Same teams of researchers will work on all three sites** to ensure a uniform approach to defining the ore-system footprints

Common Focus of Subprojects

- **Collate and integrate existing data sets**
- **Identify key sections to characterize the deposit footprint**
- **Select new analyses to fill critical gaps in multi-parameter data sets**
- **Identify unique combinations of parameters at the appropriate scales**
Common Data Integration Model

Essential common framework for 2D (cross-sections), 3D GIS, physical properties, borehole logs, structural modeling, advanced geophysical modeling and inversions

Major Deliverables

- **Fully integrated, multiparameter footprint models** of three major types of ore systems in Canada and the methods for creating models of other ore deposit types
- **Maps and sections of the detectable features of the ore-system**, including full geological, mineralogical, geochemical, geophysical and derived attributes
- **Database of physical rock properties** linked to the mineralogical and geochemical attributes of ore-hosting lithologies and alteration
- **Geophysical survey data reprocessed** with new software and constrained by new geological information and **physical property measurements specific to the ore system**
- **Modifications of existing tools or methods** to enhance the measurement and detection of footprints at a range of scales
Current Status

- Officially started in April 2013, presently near end of Y2
- **Au Site**: two seasons of field/structural/geophysical work and sampling completed; one round of lithogeochemical/mineralogical/petrophysical work completed
- **U Site**: one partial and one full season of field/surficial/structural/geophysical work and sampling completed; first round of lithogeochemical/mineralogical/petrophysical work completed
- **Cu Site**: one season of field/structural work, geophysical work, and sampling completed; first round of lithogeochemical/mineralogical/petrophysical work in progress
- **Data Integration**: workflows planned, legacy data being compiled, preliminary gOcad models completed

White Papers

1. **Lithogeochemical Processing** (Piercey)
2. **Lithogeochemical QCQA** (Piercey)
3. **Lithogeochemical Sampling and Analytical Protocols** (Piercey et al.)
4. **Mineralogical Analytical Methods** (Beaudoin & Layton-Matthews)
5. **Hyperspectral Comparison** (Layton-Matthews)
7. **Data Analysis Methods** (Feltrin et al.) – in preparation
8. **Surficial Geochemical Methods** (Hattori-Leybourne-Ross-Winterburn) – in preparation
Targeted Geoscience Initiative: New public geoscience knowledge to support enhanced effectiveness of deep exploration.

Mike Villeneuve

Presentation to DMEC
Exploring Under Cover
March 4 2015

Since 2008, Mineral Discovery Rate No Longer Tracks Exploration Spending

Note:
Discoveries are based on deposits > 100k oz Au, >10M/t Cu, >250k/t Zn+Pb, >10k/t Ni, >50k/t U3O8 or equivalent size
Excludes Bulk Mineral discoveries and satellite deposits found within existing camps
Source: MinEx Consulting, February 2014
An Alternate View of the Problem

Global Gold Discovery Costs

For reasonable probability of success:
Greenfields - need to test 200 to 3000 targets to find a discovery
Brownfields – need to test 20 to 100 targets to find a discovery

And only 50% of discoveries ever go into production (Schodde, 2014)
Deposits are getting deeper

- Recent discoveries occur at depth and at existing mining camps (brownfields)

The Need for New Exploration Approaches to Discover Deep Ore Deposits

Traditional geoscience mapping methods such as electromagnetic geophysical surveys and field mapping, work well in the top 300m below surface
There are two types of Canadian exploration environments:

<table>
<thead>
<tr>
<th>Remote and Expansive</th>
<th>Active Mineral Regions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mostly in the “North”</td>
<td>National, but concentration in “South”</td>
</tr>
<tr>
<td>Opportunity for new economic development</td>
<td>Need economic sustainability for mining-dependent communities</td>
</tr>
<tr>
<td>Greenfields</td>
<td>Brownfields</td>
</tr>
<tr>
<td>Possibility of significant near-surface deposits</td>
<td>Near-surface deposits likely exploited</td>
</tr>
<tr>
<td>Primary interest of “Juniors”</td>
<td>Primary interest to “Miners”</td>
</tr>
<tr>
<td>No infrastructure</td>
<td>Well developed infrastructure</td>
</tr>
<tr>
<td>In areas of inadequate geoscience knowledge</td>
<td>In data rich, well-studied mining camps</td>
</tr>
</tbody>
</table>

Geo-mapping for Energy and Minerals (GEM)  
Targeted Geoscience Initiative

Effectiveness of Prediction versus Detection

HIGH  
prediction  
Mine Camp  
Brownfields

LOW  
detection

Greenfields  
Regional  
Prospect Scale

Modified from Thébaud et al. (2014)
Supporting Innovation in the Canadian Mineral Exploration Industry

Invest in **public geoscience** that creates a **platform** for development of innovative, deep exploration approaches by industry.

Targeted Geoscience Initiative (TGI) is a **collaborative** federal geoscience program that provides industry with the **next generation of geoscience knowledge and techniques**, which will result in more effective targeting of buried mineral deposits by exploration industry.

---

**TGI-4 Objectives**

**Geoscience knowledge to support enhanced effectiveness of deep exploration**

Develop **new geoscience knowledge** and **innovative techniques** to model and detect Canada’s major mineral systems.

Develop more robust measures of whether a geological system may contain deeply buried ore (**system fertility**), as well as the indicators that provide the direction to that ore (**exploration vectors**), in order to reduce exploration risk.

**Train and mentor students** to increase the number of HQP available to the mineral industry.
TGI-4 projects seek to **integrate knowledge** by comparing multiple similar ore systems, and unlike previous TGI programs, are **not geographically isolated**.

Ore Systems, which focuses on **processes** of formation, not **characteristics** of ore deposits, defines program design.

**Scientific hypotheses underpin** the program and define the critical knowledge gaps within ore systems.

All TGI-4 work is **collaborative** and lever the expertise of federal and provincial geological surveys, professors, industry experts, and students.

---

TGI-4 uses a “**Supply-push**” model to support widest possible innovation

<table>
<thead>
<tr>
<th>Supply-push</th>
<th>Demand-pull</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Arising from basic research and knowledge</td>
<td>• Arising from the demand for new goods and services</td>
</tr>
<tr>
<td>• End-user not defined</td>
<td>• End-user defined as consumer</td>
</tr>
<tr>
<td>• Independent of the demand</td>
<td>• Demand driven</td>
</tr>
</tbody>
</table>

*From Sharpe and Long, Centre for Study of Living Standards, 2012*
TGI-4 Uses a Thematic Approach that Allows Knowledge Application Anywhere

Targeted Geoscience Initiative:

...Increasing Deep Exploration Effectiveness

Ore systems focus on processes of formation, not characteristics of ore deposits

DMEC workshop series: Developing the tools and techniques to explore undercover; a global initiative
### Ore Systems Research Leading to Better Targeted/Lower Risk Exploration

- Ore system knowledge gaps being filled lead to...
- Definition of targets/markers that extend beyond a deposit which leads to...
- New exploration methods and technologies

![Diagram of ore systems research](image)

#### TGI-4 has over 200 Participants Collaboratively Delivering Public Geoscience

<table>
<thead>
<tr>
<th><strong>Provincial – Territorial Geological Surveys</strong></th>
<th><strong>Academia</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Role: Science, technical and regional expertise (47 participants)</td>
<td>Role: Science expertise and student training (63 professors + 133 students)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Exploration Industry and Industry Associations</strong></th>
<th><strong>GSC/ TGI -4</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Role: Guidance and site-specific data, collaborative studies (58+ companies)</td>
<td>Role: Program management, science and technical expertise (43 participants)</td>
</tr>
</tbody>
</table>

All TGI-4 work is collaborative to leverage the expertise of federal and provincial employees, professors, industry experts, and students.
TGI-4 Results:

- Over 45 TGI-4 methods and scientific results have been incorporated by industry in their exploration approaches (Duke 2014):
  - **Advanced Ore System Modelling:** Studies change industry understanding of the genesis of economic deposits (e.g., Uranium deposits).
  - **New Areas of Mineral Prospectivity:** Defining new regions that were previously not considered for exploration (e.g., new model for gold transport in Abitibi region of Quebec and Ontario).
  - **New Methodologies supporting Ore System Knowledge**

Advanced Ore System Modelling:
Revised exploration criteria for lode gold

**New model:** Synorogenic extension, not compression, is the overall “engine” that leads to gold deposits

- Caused listric, extensional faults that functioned as the main conduits for Au
- Caused the alkaline magmatism
- Generated a heat pulse
- Decreased post-orogenic uplift
- Caused differential erosion of “hanging wall”, preserving “footwall”
- Explains why >99% of historic Au production is from north of the fault, i.e., the structural footwall
Advanced Ore System Modelling: Revised exploration criteria for lode gold

Markers of Fault-related Au Mineralization:
Alkaline Magmatism coeval with Extension

New Areas of Prospectivity: A Chrome “Superdomain”?

- **McFaulds Lake Greenstone Belt, ON**
- **La Grande & Eastmain Domains, QC**

Recognition of several generations of ultramafic rocks within the eastern part of the La Grande domain. Hosts Cr-PGE, Ni-Cu-PGE, and Fe-Ti-V mineralization similar to those recognized in the McFaulds Lake area.

Oxford-Stull-LaGrande Superdomain
Major methodology development project

Integrating:
- Active Seismic (requires seismic source; i.e. dynamite)
- Passive (Interferometry) Seismic (uses ambient noise as seismic source)
- 3D modelling of buried ore
- Geological Interpretation

Research site: Lalor mine, Northern Manitoba
Lalor: simultaneous, integrated geology-geophysics-modeling

Inputs to 3D modelling

- Lithofacies AND alteration zones from logs and geochem analysis
- Correlation using pre-defined discrimination geochemical ratios for units and for alteration zones (Interpolated Zr/TiO₂ ratio shown below)
- 3D geologic surface model Lalor
- Integrated visualization: seismic amplitude-lithofacies property

3D Seismic Experiment: Interferometry Component (Passive Seismic):

- This example is from Los Angeles Basin
- 5000 geophones installed (for three weeks) in the Los Angeles basin
- Huge processing exercise looking at correlations between recordings over time
- Environmentally friendly: no requirement for artificial seismic source (explosives)

Lin et al. (in press)
Results of Active Seismic with potential ore bodies highlighted:

Hanging wall: Upper Chisel Sequence
Footwall: Lower Chisel Sequence

Results of Passive Seismic with potential ore bodies highlighted:

Hanging wall: Upper Chisel Sequence
Footwall: Lower Chisel Sequence
TGI-4 Outcomes

- TGI-4 has stimulated **private-sector innovation** in exploration for deeper mineral deposits by providing Canadian mineral exploration industry with new geoscientific knowledge and cutting-edge tools.

- TGI-4 has already produced over 350 **interim scientific publications** and made over 450 **presentations** at workshops and conferences and helped train 133 students.

- TGI-4 activities have generated more than $13 million of in-kind support from industry, academia and provincial-territorial geological surveys.

- Nevertheless, a survey of companies and anecdotal evidence supports increasing uptake and use of TGI results by industry. As part of the survey, all companies stated they are already or would be using TGI results.

  - “TGI [is] critical to the efficient, effective and responsible development of new mineral deposits and mines” (PDAC in Canadian Journal of Mining, August 2013).

- TGI-4 is releasing the first synthesis publication on Uranium ore systems that brings together in one place the new knowledge generated under TGI-4.

  - This will be followed, over the next few weeks, by synthesis publications on the rest of the ore systems studied in the program (Lode Gold, Nickel-Copper-PGE-Chrome, VMS, SEDEX, Intrusion Related and Specialty Metals).

  - These integrate the results of five years of scientific studies by over 200 government, academic and industry participants, as well as 133 students (83 at post-graduate level) making it publicly available to serve as a platform for future development of new deep exploration approaches by industry.
Access to TGI-4 results

- Over 350 publically-available knowledge products at:
  WWW.NRCAN.GC.CA/TGI
- USB or CD-ROM available at Booth to link to latest publication list
- A primary focus is to ensure that data and products are publicly available

HQP:
- Over 133 students (including 83 MSc, PhD and PDF) trained
Mineral Exploration Geophysics for the Future —
A Mineral Exploration Geologist’s View

Murray W. Hitzman
Colorado School of Mines, USA

How do we Explore?

Primary search method used at the project-scale for base metal discoveries

Percentage of total discoveries (by Number)

Source: Richard Schodde, MinEx Consulting, 2014

Increasing use of geophysical methods.
Until recently the discovery rate moved in tandem with exploration expenditures — recent trend towards much more expensive discovery costs.

What is Causing this Disconnect?

Progressively exploring under deeper cover

Source: Richard Schodde, MinEx Consulting, 2014
## Mineral Exploration

We will increasingly be utilizing geophysical techniques.

Therefore we need:

- Better geophysical techniques and technologies;
- Better understanding of the geophysical properties of geologic materials (both ore and waste);
- Integrated geological/geophysical models of ore deposits.

## Better understanding of the geophysical properties of geologic materials

Geologists can help geophysicists with the data so they can develop the best tools:

- Better ore deposit models that distinguish rock/alteration types by petrophysical properties.
Model tells me rock types (mineralogy) but not petrophysical properties.
We need to determine mineralogy and texture on many rocks at micro- to hand specimen scale through CT scanning technology with QEMScan and then determine bulk averages.

We can use this data to calculate petrophysical properties and compare these values with test measurements.

This is doable NOW.

Better understanding of the geophysical properties of geologic materials

Geologists can help geophysicists with the data so they can develop the best tools:

• Better ore deposit models that provide accurate scales for different ore and alteration types.
Different IOCG Models

Alternative Models Based on Principal Fluid Sources

- Magma-derived
- Surface or basin-derived
- Metamorphic-derived

Different geological models have very different implications for how we might explore. Geologists need to get their act together!

Traditional Geophysical Anomaly - IOCG

Prominent Hill IOCG target (Gawler Craton) — but orebody is between major anomalies — drilling “bulls-eye” resulted in misses.
Traditional Geophysical Anomalies - IOCG

Gawler Craton —
MANY coincident mag-gravity anomalies – which are worth testing?

We need to better understand (geologically) what the target hydrothermal system is?

www.minerals.pir.sa.gov.au

Moving into the Third Dimension


We need to better understand (geologically) what the target is and understand the third dimension.

3D visualization of the subsurface has revolutionized hydrocarbon exploration and should do the same for mineral exploration – though there are challenges!
Better anomalies with deeper “roots”. This is a 3D inversion model of gravity at a prospect in the Gawler Craton. Even better would be to do a joint inversion of gravity and magnetic data. Best anomalies with deepest roots – deeper than this 4 km.

<table>
<thead>
<tr>
<th>Olympic Dam</th>
<th>150km x 150 km</th>
</tr>
</thead>
</table>

But even this technology is giving us too many anomalies to drill test effectively.

1.5% “magnetite”
Includes all susceptible minerals as their magnetite equivalent

0.5% “hematite”
Includes hematite, sulfides, gold, other dense minerals, and remanent magnetisation
The largest deposits (OD) have a “root” extending to the base of the crust — is this how we should really be exploring for these types of systems (at least first pass exploration)?

Perhaps IOCG exploration should be done with inversion of high quality magnetic and gravity data together with magnetotelluric surveys and if possible large-scale seismic for a 3D look. Such integrated geophysical programs are not now the norm.
Geologists Need to Work with Geophysicists to Get Rock Properties (Petrophysics) for both Footprints and Footpaths

Modified from Australian Academy of Sciences (2010)

---

Geophysical Techniques in the Range 250m – 1.5km

<table>
<thead>
<tr>
<th>METHODOLOGY</th>
<th>TECHNIQUE</th>
<th>AIRBORNE</th>
<th>SURFACE</th>
<th>BOREHOLE</th>
<th>MARINE</th>
</tr>
</thead>
<tbody>
<tr>
<td>POTENTIAL FIELDS</td>
<td>Magnetics</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>Gravity</td>
<td>X (limited bandwidth)</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>ELECTROMAGNETICS (EM)</td>
<td>active source</td>
<td>X (limited bandwidth)</td>
<td>X</td>
<td>X</td>
<td>limited</td>
</tr>
<tr>
<td></td>
<td>passive</td>
<td>X (limited bandwidth)</td>
<td>X</td>
<td>?</td>
<td>limited</td>
</tr>
<tr>
<td>ELECTRICAL</td>
<td>resistivity</td>
<td>ϕ</td>
<td>X</td>
<td>X</td>
<td>limited</td>
</tr>
<tr>
<td></td>
<td>chargeability</td>
<td>X (limited bandwidth)</td>
<td>X</td>
<td>X</td>
<td>limited</td>
</tr>
<tr>
<td>SEISMIC</td>
<td>active</td>
<td>ϕ</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>passive</td>
<td>ϕ</td>
<td>X</td>
<td>?</td>
<td>limited</td>
</tr>
</tbody>
</table>

ϕ = not applicable  X = nominal

We have a wide range of technologies available — we need to be better at integrating them together to tease out different aspects of complex hydrothermal systems.
Geologists Need to Work with Geophysicists to Get Rock Properties (Petrophysics) for Footprints and Footpaths

It will be critical for geologists and geophysicists to work much more closely together to develop forward models for different deposit types — much more similar to the way petroleum teams (geology-geophysics-reservoir engineering) work today in the petroleum industry.

Better understanding of the geophysical properties of geologic materials

Geologists can help geophysicists with the data so they can develop the best tools:

- Better ore deposit models that provide geological models setting out the real problems.
A Potential Use of Geophysics to Solve a Real Problem?

The real problem — how to explore under Tertiary gravel or ash flow cover?

A Potential Use of Geophysics to Solve a Real Problem — Passive Seismic for Porphyry Exploration

Utilize 100’s to 1000’s of seismometers to collect large amounts of seismic information to map the base of cover rocks.

This technology is being utilized by academics (and increasingly the oil industry) to image the upper 1 km of the crust.
Another issue: Conventional Mining

Mining today focuses on relatively low-grade deposits and commonly involves large-scale earth moving operations. These operations result in significant land disturbance and production of relatively large amounts of waste.

Change

But are we really looking for what we should be finding?

How might what we look for change in the (not too) distant future?
### Change?

> Based on history we can expect societal and environmental considerations to move away from this type of mining in the future (as has happened with coal mining in the USA).

### Unconventional Mining

| In-situ extraction of uranium at the Crow Butte deposit, Nebraska |
| In-situ extraction of copper at the Santa Cruz (now Florence) deposit, Arizona |

We will probably move to less invasive styles of mining.
Conventional vs. Unconventional

The energy sector has moved strongly into “unconventional” sources including coal bed methane, hydrofracking for both oil and gas, and is examining the possibility of hydrate production on land and in the oceans.

Unconventional energy production has relied on new technology — we must consider possible technological developments to change the face of mineral exploration and mining.

We should be developing integrated geological/geophysical models NOW for deposit types that we will need in the future.

I see little of this happening at the moment.
The Bottom Line on Mineral Exploration Geophysics for the Future

• Mineral exploration geologists and geophysicists must work more closely together to develop better geologic/geophysical/petrophysical models of the many different and complex metallic mineral systems.

• We need to better integrate the tools we have and develop new tools (stealing shamelessly from other sectors)!
Takeaway Messages

Mineral systems are complex dynamic systems exhibiting self-organised critical (SOC) behaviour.

Critical elements of mineral systems are whole lithosphere architecture, transient geodynamic triggers, fertility, and preservation of primary depositional zone.

In application of the mineral system concept, SCALE of decision must be matched to scale of relevant geological process.
The Problem

2.7–2.6 Ga Ni and Au in the Yilgarn WA
How to predict location and geometry of new high quality mineral districts – camps – oreshoots?

Deposit scale

2km

St. Ives Au (Miller et al. 2010)

400km

Craton / district scale

150km

New Holland Au (Henson, 2008)

Camp scale

400km

Oreshoot scale

100m

Scale Dependent Targeting

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

McCuaig et al. (2010)
Deposit Models

Our current view of deposit ‘footprints’

A New View on Footprints

In exploration for new high quality mineral districts under cover, it is the largest scale footprint of the deposits that is relevant to our targeting models.

These large scale footprints differ substantially from the local expressions captured by traditional analogue models.
An Example of a Large Scale Footprint

After Harper & Borrok (2007)

Understanding large scale mineralisation footprints quickly narrows the search space for large mineral districts.

We Need Non-Traditional Datasets to See Large Footprints

Need to understand the entire system.

Magnetotelluric Section through Olympic Dam

Modified after Hayward, 2004; Magnetotelluric section provided R. Gill, Uni. Adel; “hotter” colours are more conductive.
Mineral Systems Science

Mineral deposits = expressions of multiscale earth processes focusing energy and mass transfer at a range of scales
Process based, rather than analogue based
Substantial predictive power compared to traditional approaches based on analogue deposit models

Examples: Yeelirrie Calcrite U, Olympic Dam Cu-U-Au, Nebo Babel NiS

Mineral Systems - Some Constraints

Take elements at low concentration from large volumes of rock to high concentration in small volumes of rock
Only plausible mechanism is through advective mass flux - needs a fluid (fluid/magma)
Ore deposits therefore are foci of large scale advective mass and energy flux
Fluid needs to be low viscosity, available in large quantities over short timeframes, highly organised (focussed in space and time)

Mineral systems are dynamic complex systems
Understanding Dynamic Complex Systems

Structure and Pattern in Earth Systems

e.g. Power-law size frequency distributions (scale invariant) in Earth Systems

Example: Gutenberg-Richter earthquake scaling.

Example: Fault size populations

Example: Superior craton, greenstone-hosted lode gold

Malamud & Turcotte 2006

Needham et al., 1996

Robert et al., 2005

Understanding Dynamic Complex Systems

A new understanding of physics of complex systems

The tendency of complex systems to order around a critical point is termed self-organised criticality (SOC; Bak et al 1987)

Key drivers of SOC behaviour are:

- Energy is added slowly over long timeframes
- A barrier (threshold barrier) to energy flux is present that stops dissipation into the energy sink, forming extreme energy gradients
- Energy is released over very short timeframes in dramatic pulses termed ‘avalanches’

These systems will remain SOC systems as long as the energy flow is maintained, and the threshold barrier is intact.
Ore formation as a product of self-organising critical systems

**Understanding Dynamic Complex Systems**

**Critical Elements of Mineral Systems**

McCuaig and Hronsky (2014)
Critical Elements of Mineral Systems

Fertility

Favourable Whole-lithosphere Architecture

Preservation (of primary depositional zone)

Favourable (Transient) Geodynamics

Ore Genesis

Whole Lithosphere Architecture

A Multiscale Fluid (incl Magma) Delivery System

McCuaig and Hronsky (2014)

McCuaig and Hronsky, 2013
**Whole Lithosphere Architecture**

Isotopic maps as ‘paleogeophysics’ to image paleoarchitecture

Time slices can provide insights into spatial distribution of multiple mineral systems through time—**PREDICTIVE TOOL**

NiS (red), Fe (blue), Au (gold) deposit distributions

NiS deposits (stars) and komatiite Mg# (red) at 2.9Ga

Antamina, Peru

After McCuaig 2003 (courtesy of Antamina); Love et al., 2004
**Antamina VLR fault equivalent (NE-strike, subvertical) along strike to NE of the mine.**

Classic example of upper crustal brittle fractures overlying a fundamental, vertically accretive lithospheric flaw at depth.
**Common Characteristics of Large Scale Ore-Controlling Structures**

- **Strike-extensive.**
- **Depth-extensive** (often lithospheric mantle) with relatively steep dips (as imaged in geophysics).
- Commonly juxtapose distinctly different basement domains (as imaged by isotopes and magma chemistry).
- Multiply-reactivated (commonly with variable senses of movement) with a very long history.
- Vertically-accretive growth histories.
- These are not the obvious structures at or above the level of mineralisation – an important message for targeting.
Anastomosing Near-Surface Pattern Overlying Fundamental Structure at depth

Cryptic Near-Surface Pattern Overlying Fundamental Structure at depth

Carlin and Battle Mountain–Eureka trends not obvious in surface geology
Cryptic Near-Surface Pattern Overlying Fundamental Structure at depth

Bouguer gravity minus basin effects, up 5 km
Bouguer data processes to image deep architecture – trends much clearer!

Critical Elements of Mineral Systems

Fertility
Favourable Whole-lithosphere Architecture
Favourable (Transient) Geodynamics
Preservation (of primary depositional zone)

McCuaig and Hronsky (2014)
In recent years increasing availability of high-resolution geochronology and better understanding of global geodynamics is increasingly indicating that major ore-forming events occur in narrow time windows, often over broad areas. These critical time horizons must reflect unusual regional-scale geodynamic settings that are favourable for mineralisation. These favourable settings must be transient, lasting for only short periods of geological time.

**Focused system with little lateral dispersion**

McCuaig and Hronsky (2014)
Transient Geodynamic Triggers

Eocene Magmatic events in SW USA

Bingham, Carlin and Cripple Creek all form associated with this event

Very different deposit styles, same geodynamic trigger?

Tosdal (2009)

Large Orogenic Au deposit
Large Porphyry Cu-Au deposit

All these major deposits formed at 440 Ma (as did North Kazakhstan Gold Province)

Squire & Miller (2003)
Favourable Transient Geodynamic Events

Empirically we recognise three common scenarios:

**Incipient Extension** (VMS, Akalic LSE Au, LSE Au, NiS)

**Transient Compression** (Porphyry Suite deposits, Mafic Intrusion NiS)

**Switches in Far-Field Stress** (All?)

During these events:

- Active permeability creation is stopped, or
- Vertical permeability is clamped
- Energy and fluid input to the system continues
- Extreme energy and fluid pressure gradients are formed
- The system self-organizes to form ore as long as the geodynamic threshold barrier remains intact.
Threshold Barrier
Incipient Extension
e.g. VMS-epithermal

McCuaig and Hronsky 2014

Threshold Barrier
Transient Anomalous
Compression
e.g. porphyry

McCuaig and Hronsky 2014
Threshold Barrier
Stress Switches
e.g. orogenic gold

Goldfarb et al., 2005

Critical Elements of Mineral Systems

McCuaig and Hronsky (2014)
Fertility

A geological region or time period systematically better-endowed than otherwise equivalent geological environments

4 components
- Secular Earth Evolution
- Lithosphere fertility (e.g. Au)
- Geodynamic context (e.g. magmatic-hydrothermal Cu)
- Paleolatitude (Zn-Pb, U, Fe, others?)

Fertility

Secular Earth Evolution

Cooling of earth through time
- e.g. komatiite-hosted NiS

Evolution of biosphere-atmosphere-hydrosphere
- Controls availability or mobility of metals
- E.g. U, sediment hosted Pb-Zn

Evolution of lithosphere and geodynamic cycles
- E.g. Orogenic Au at terminal stages of supercontinent assembly
Fertility - Lithosphere Enrichment

Retreating arc

Advancing arc

Small volume melts trapped in mantle lithosphere

Au transferred to crust by subsequent tectonic and thermal trigger

Hronsky et al., 2012

3 periods of subduction

potential enrichment of mantle lithosphere pre-Mesozoic Au in North China Craton

allows gold introduction into previously metamorphosed terrane

Goldfarb et al., 2012
Implications of lithosphere enrichment

McCuaig and Hronsky (2014)

Fertility - Geodynamic Context
Andean Cu since the cretaceous - anomalously compressive margin

Spreading Rate on the MAR increased rapidly in Cretaceous
Nested scales of Threshold barriers

Transitory extreme anomalous compression causes ore

McCuaig and Hronsky 2014

Paleolatitude Control

Observed in basin-hosted deposits

Probably relates to availability of evaporites to provide salinity for ore-transporting fluids

Arid environments restricted to between about 20 and 40 degrees from equator

e.g. SEDEX, Hypogene BIF upgrade, uranium

Leach et al (2010)
Links Between Mineral Systems

One advantage of the Mineral Systems Method is that it enables us to recognise common underlying controls that link apparently different deposit types.

This enables us to focus our targeting on those common underlying controls.

It also helps us be more predictive about the deposit types we might find in a particular environment.

A good example is the Alexander Triassic Metallogenic Belt of Alaska-British Columbia.

Modified from Taylor et al (2008)
Challenge in practical application is in keeping scale of decision matched to scale of relevant mineral system process:

At all scales, processes at site of deposition get heavy weighting, despite their lower relevance to regional targeting decisions. Bias is to data rich areas at expense of data poor areas.
Collect evidence (fertility, whole lithosphere, architecture, geodynamics) to predict the location of the mineral system.

Collect evidence (architecture, local geodynamics, preservation) of the zones of mass and energy flux and locate the mineral system through detection (geochemistry, alteration, geology).

Vector to find the deposit/oreshoot through systematic detection (alteration, high-res geophysics, geochem, drilling).

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**Scale Dependence of Critical Elements for Orogenic Au**

<table>
<thead>
<tr>
<th>CRITICAL ELEMENTS</th>
<th>FERTILITY</th>
<th>FAVOURABLE GEODYNAMICS</th>
<th>FAVOURABLE ARCHITECTURE</th>
<th>DEPOSITIONAL PROCESS</th>
</tr>
</thead>
<tbody>
<tr>
<td>ORE-SHOOT</td>
<td>Null at this scale</td>
<td>Null at this scale</td>
<td>Located adjacent to or within structures</td>
<td>Breakwater, pressure dome, fault center, favourable substratum (chemical or mineral)</td>
</tr>
<tr>
<td>DEPOSIT</td>
<td>Null at this scale</td>
<td>Null at this scale</td>
<td>Major heterogeneity (e.g., cross structures, intersections), among areas of increased lithospheric activity or (multi-phase) test with associated structural complexity or pipe of enriched lithospheric material</td>
<td>Intrusion - upper Ekman of crust, ATHE SIM of MASH, SALS, EXOS where fluid pressures (P-h) gradients are present</td>
</tr>
<tr>
<td>CAMP</td>
<td>Null at this scale</td>
<td>Null at this scale</td>
<td>Major heterogeneity (e.g., cross structures, intersections), among areas of increased lithospheric activity or (multi-phase) test with associated structural complexity or pipe of enriched lithospheric material</td>
<td>Intrusion - upper Ekman of crust, ATHE SIM of MASH, SALS, EXOS where fluid pressures (P-h) gradients are present</td>
</tr>
<tr>
<td>PROVINCE</td>
<td>Null at this scale</td>
<td>Null at this scale</td>
<td>Located outside or within structures</td>
<td>Located outside or within structures</td>
</tr>
<tr>
<td>CONTINENTAL</td>
<td>Null at this scale</td>
<td>Null at this scale</td>
<td>Located outside or within structures</td>
<td>Located outside or within structures</td>
</tr>
</tbody>
</table>

McCuaig and Hronsky (2014)
Scale Dependence of Critical Elements for Orogenic Au

Takeaway Messages

Mineral systems are complex dynamic systems exhibiting self-organised critical (SOC) behaviour.

Critical elements of mineral systems are whole-lithosphere architecture, transient geodynamic triggers, fertility, and preservation of primary depositional zone.

In application of the mineral system concept, SCALE of decision must be matched to scale of relevant geological process.

McCuaig and Hronsky (2014)
Coiled Tubing Drilling and Real-Time Sensing — Enabling ‘Prospecting Drilling’

- DET CRC and its context
- prospecting drilling
- progress on drilling and sensing technologies
- field testing: Brukunga, Victoria and SA drilling
Technologies Will Enable ‘Prospecting Drilling’
• more cost-effective, safer and more environmentally-friendly methods for mineral exploration focusing on coiled tubing drilling complemented by downhole and top-of-hole sensing
• incorporated entity with independent board
• $58M cash & $88M in-kind support over 8 years (2010-2018) from Australian government and participants
• participants include miners, research providers and service companies
• unique model of commercialisation of IP via service sector
• Participants: $450k pa (~33x leverage)
• Affiliates: $10k pa with colleges for junior explorers, service providers and geological surveys
80% Australian production from mines >30 years old

Source: Richard Schodde, 2010
Copper Exploration

Primary copper deposits >0.3Mt found in western world: 1950-2009

Average gold grade (US, Canada, Australia & SA)
- > 10g/t in 1970
- ~7 g/t in 1980
- < 3 g/t in 2000
- ~1 g/t currently

Source: Mudd, 2009
Productivity Challenge

Source: Australian Bureau of Statistics

Source: EY 'Productivity in Mining', 2014

Productivity Challenge

Source: Topp et al., 2008
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Prospecting Drilling

- build out from initial targets using 5km grid and resampling prior holes for consistent geochemical data
- real-time downhole & top-of-hole sensing tools define petrophysics and geochemical halos
- anomalies re-modelled and followed up during single campaign
- targets based on broad bandwidth of geophysical and geochemical data reduces false positives and allows recognition of new deposit types
- start to map entire mineralising system with regional scale vector potential

Current Practice

- IOCGs, Gawler Craton, South Australia
- drill through deep cover based on gravity and/or magnetic anomalies alone
- many false positives
- many anomalies tested by only one hole
- sparse data collected with little knowledge to inform follow-up drilling

Source: Simon van der Wielen
Quantitative Mineralogical Mapping of IOCG Alteration Halo: Emmie Bluff


Emmie Bluff Inversions

Gravity

Magnetics

Source: Simon van der Wielen

Source: van der Wielen et al., 2013
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Coiled Tubing Drilling (CTD) for Minex

- 2-3 hours move in and rig up time and penetration rates up to 100m/hr
- improved cost, safety, environmental impact and hole stability in minex
- $15.6M Phase II project involving Boart Longyear, Teakle Composites, Imdex, Curtin Uni. & CSIRO
  - in Phase I prototype CT rig was commissioned with initial drilling at DET CRC’s Brukunga Facility
- CTD lab facilities commissioned in:
  - percussion and rotary drilling
  - CT material testing
  - cuttings return
- numerical modelling and lab work undertaken on the above topics and field trials at Brukunga

## Example Drilling Costs

remote 5,000m Australian greenfield mineral exploration drilling program in covered environment to 250m depth
test cover sequences and target basement

<table>
<thead>
<tr>
<th>Metres Drilled</th>
<th>Diamond 5,000</th>
<th>RC 5,000</th>
<th>Coiled Tubing 5,000</th>
<th>DD $650/m total program costs*</th>
<th>RC $350/total program costs*</th>
<th>CT $50/m metre rate, $100/m total program costs*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metre Rate Cost</td>
<td>$2M</td>
<td>$0.75M</td>
<td>$0.25M</td>
<td>DD 50m/day; RC 200m/day; CT 250m/day</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Addtl. Costs</td>
<td>$1.25M</td>
<td>$1M</td>
<td>$0.25M</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Drill Program Cost</td>
<td>$3.25M</td>
<td>$1.75M</td>
<td>$0.5M</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time (Days)</td>
<td>100</td>
<td>25</td>
<td>20</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*total program costs include: metre rate, failed holes, mob/demob, drill pads, rehab, surveying, supervision/field salaries and analytical costs (assay, mineralogy & petrophysics)
**Downhole Sensing: Logging-while-Drilling**

- In situ, real-time downhole rock characterisation will improve productivity of conventional DD and RC and enable CT drilling
- AutoSonde™ pumped down inside rods and logs as rods pulled (no separate wireline crew, no extra rig time)
- Modified sonde for RC tested in the Pilbara
- Commercialisation of AutoSonde™ gamma logger with BLY
- V.1 autonomous shuttle built and tested (hosts sensor package at back/top of DD inner tube and ‘shuttled’ to and from surface with each core pull)
- Focus for Phase II’s $4M project involving Curtin University and Globaltech adding new sensors to sonde and shuttle

**Press Release on AutoSonde™ available at:**
detcrc.com.au/category/media-releases/
Top-of-Hole Sensing: Lab-at-Rig®

- Downhole sensing of petrophysical properties and structure/fabric (images) will be complemented by top-of-hole sensing of geochemistry and mineralogy from cuttings by DET CRC’s Lab-At-Rig® analytical system.
- Geochemical accuracy and depth-fidelity of Lab-At-Rig® supported by recent results on cuttings.
- Lab-At-Rig® is a $10.1M Phase II project involving CSIRO, Olympus & Imx
Analysis of DET Brukunga-1 Rock Powders

Press Release on Lab-at-Rig® available at:
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Brukunga Drilling Research & Training Facility

- located in disused mine near Adelaide
- critical to testing DET CRC’s new technology
- researchers access state-of-art drill rig, drilling crew and fully logged and assayed test holes

Stavely Drilling with GA/GSV

- DET CRC project managed GA/GSV’s Stavely drilling program in western Victoria mid 2014
- Cambrian Andean-type collisional margin
- Boart Longyear sonic pre-collars and diamond tails
- 147 days, 14 holes and 2796 m
- deployed DET CRC’s new sensing technologies: notably Lab-at-Rig® and AutoSonde™
- key step in planning – design – manufacture – lab testing – Brukunga DRTF testing – field testing of DET CRC technology

Top-of-Hole Sensing: Lab-at-Rig® from GA/GSV Stavely Drilling Program
Mineral Systems Drilling:
GSSA / Minotaur / Kingston / DET CRC

- ~16 holes / 7 km to map mineral system under cover
- applying DET CRC’s new technologies
- commencing May 2015

Education and Training

- target of 40 postgrad completions
- 51 postgrads commenced
- 6 completions to-date
- 49 Hons projects
- 7 coursework Masters projects
- VET: 343 driller trainees have accessed the Brukunga site
Technologies Will Enable ‘Prospecting Drilling’