DMEC workshop series:

Making technology work; the importance of time and patience

Wednesday, March 9, 2016
2:00pm to 6:00pm
DMEC workshop series: Making technology work; the importance of time and patience

Agenda
Wednesday March 9, 2016
2:00pm to 6:00pm

2:00pm - 2:10pm  Welcome  Charles Beaudry /Ken Witherly

2:10pm - 2:45pm  Pathfinder elements in a Porphyry Copper system that are not where they are supposed to be found - Dick Tosdal

2:45pm - 3:20pm  Geochemical Exploration for Skorpion-Style Oxide Zinc Deposits - Peter Winterburn

3:20pm - 3:40pm  BREAK

3:40pm - 4:15pm  The Six Faces of Innovation - Leigh Freeman/Mary Poulton

4:15pm - 4:50pm  Exploration Technology- The Missing Pieces - John Gingerich

4:50pm - 5:25pm  Exploring for High Conductance Targets with EM Methods: Successes and Challenges - Alan King

5:25pm - 6:00pm  The Evolution in the use of EM in the Search for Porphyry Copper-Gold Deposits - Ken Witherly

6:00pm  CLOSE
SPEAKER/CHAIR CONTACT DETAILS

Ken Witherly
Condor Consulting, Inc.
Lakewood Colorado
303-423-8475
ken@condorconsult.com
Skype: ken.witherly1

Charles Beaudry
Consultant
Toronto, Ontario
beaudrycha@hotmail.com
647-668-3512
Skype: beaudrycha
Biographies

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.

Leigh Freeman is a Principal in Leigh Freeman Consultancy providing strategic consulting in the minerals industry. He co-founded and serves as Chairman of Fondo Santa Barbara, a newly-formed international, non-profit organization working with marginalized communities around the world to create enterprise value with mineral materials to help eliminate poverty and mitigate conflict. Over the course of his 40-year career he has worked with major and junior companies in exploration, research, mine development and production in over twenty-five countries. He has been directly involved in raising in excess of $100 million for three exploration companies as well as an innovative technology commercialization company working in the alternative energy sector. A geological engineer by education, early in his Mr. Freeman served as Chief Geophysicist for Placer-Dome (now part of Barrick Gold). In the mid-80’s with initial funding from Rio Tinto Mining, he co-founded Orvana Minerals to explore for world-class mineral deposits in countries outside Rio’s primary focus. For the last fifteen years his focus has been on the development and utilization of talent. He serves on industry minerals advisory boards for four universities. He recently published an opinion paper for the National Academy of Engineering on The Future of Mining.

John Gingerich, P. Geo is a professional geophysicist (APGO) with over 30 years’ experience in exploration and mining industry technology. As a past Director of Research, Technical Innovation and Exploration within the Noranda group, John was part of the senior management team and involved in the evaluation, acquisition, and development of mineral opportunities with Canada and around the world. In 2002, John founded Geotechnical Business Solutions (GBS), a company dedicated to the development and financing of exploration opportunities and related technology. He is also a co-founder and former director of East Asia Minerals Corporation and serves as a director of the Niskibi Group of companies that are focused on business development opportunities with the Aboriginal communities. He has also been involved in Advanced Explorations and its predecessors since September 2004.

As a recognized leader within the mining and technology communities, John is a member of several industry and government boards and committees including the Exploration Division of the Canadian Mining Industry Research Organization (Chairman) and the Ontario Geological Survey Advisory Board (Chairman).

Alan King received a B.Sc. in geology from the University of Toronto in 1976 and an M.Sc. in geophysics from Macquarie University in 1989. From 1976 to 1984 he worked as a geophysicist in exploration and resource development in Canada and Australasia. In 1985 he joined GeoPhysiCon Co. Ltd. in Calgary Canada where he was involved in mining, geotechnical, oil sands and environmental applications for a variety of commodities. In 1990 he was employed by Inco Exploration and Technical Services Inc. as a senior geophysicist and in 1995 was promoted to Manager of Geophysics with responsibility for global exploration.

With the takeover of Inco by Vale in 2007 he moved to Brazil to assist with Vale’s geophysical work in Brazil and moved back Canada in 2011. From 2009 to 2012 Alan was Chief Geophysicist for Vale Global Exploration working on geophysical applications for base metals, iron, manganese, coal and fertilizers (potash and phosphate) as well as target generation using regional and global data sets.

Alan is currently working as a consultant with his own company Geoscience North. His professional interests include the use of geophysics and new technology (and ideas) in exploration, mining, environmental, geotechnical and other applications.
Dr. Mary Poulton is a University Distinguished Professor in Geosciences, Mining Engineering, Law, and Public Health. She was the first woman to lead an engineering department in the history of the University of Arizona, serving from 2000 to 2014. She founded and directs the interdisciplinary Lowell Institute for Mineral Resources (IMR), the largest minerals research and education center in the US. Dr. Poulton directs the Western Mine Safety and Health Training Resource Center. She created the Latin American Natural Resources Academy with US State Department support to promote student exchange in mineral resources. She is also a founding member of the Pan American Hub for Compatible Mining. Poulton is co-founder of 4 startup companies. Dr. Poulton has more than 90 publications on the application of computational neural networks to pattern recognition problems in the earth sciences, including geophysics, mining, mineral and petroleum exploration, hydrology, and atmospheric science. She is the author of a book on the use of neural networks for geophysical data analysis. She has led or participated in nearly $30 million in research funding. Poulton chairs the Committee on Earth Resources for the US National Academies. She is a distinguished member of SME.

Richard Tosdal received a Bachelors degree from the University of California, a M.Sc. from Queen’s University and a Ph.D. from the University of California at Santa Barbara. He worked for the U.S. Geological Survey from 1978 to 1999, and was the Director of the Mineral Deposit Research Unit at the University of British Columbia from 1999 through 2008. He currently is an independent consultant to the minerals industry, serves on technical advisory boards to mining companies, and maintains an adjunct appointment at UBC. He helped establish the CMIC Exploration Innovation Council and currently serves as Chairman of the Board for the joint NSERC-CMIC Footprints project, a national initiative aimed at mapping and understanding how to detect the distal expression of porphyry, uranium, and orogenic gold deposit.

Peter Winterburn is the NSERC-Bureau Veritas Minerals Industrial Research Chair in Exploration Geochemistry, based at the Mineral Deposit Research Unit at UBC. With expertise in regional geochemistry and exploration methodologies, Peter has previously served as Regional Geochemist in South America and Africa with Anglo American. His research interests centre on innovation of cost-effective, robust geochemical exploration methods for concealed deposits.

At MDRU, he is establishing a fully funded research team comprising to undertake collaborative industry relevant research to develop a deeper understanding of the processes by which inorganic and organic geochemical anomalies form and are retained over concealed mineralisation. This research is intended to lead to the development of industry appropriate geochemical tools and applications with a clear understanding of their geological and environmental constraints.

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.
Decennial Mineral Exploration Conferences Organization

Head Office:
Suite 1710, 155 University Avenue
Toronto, ON, M5H 3B7

Incorporated in Ontario, June 5, 2007, Ontario Corporation Number 1735699
Canada Revenue Agency Business Number 85158 8756

Website:  www.DMEC.ca  www.exploration17.com

Officers and Directors

President and Director
Mr. Stephen Reford
98 Wychwood Park
Toronto ON M6G 2V5

Vice-President and Director
Ms. Micki Allen
80 St. Clair Avenue East, Apt. 1610
Toronto ON M4T 1N6

Secretary-Treasurer and Director
Mr. Charles Beaudry
187 Hanson Street
Toronto ON M4C 1A7

Director
Mr. Ken Witherly
President, Condor Consulting, Inc.
St 150 2201 Kipling St.
Lakewood CO USA 80215

Director
Mr. Chris Nind
Chairman Exploration 17
Suite 1710, 155 University Avenue
Toronto, ON, M5H 3B7
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.

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

6th Decennial Conference on Exploration Technology October 2017

Frank Arnott Award

Innovation in Data Visualisation & Integration

The exploration industry faces the challenge of finding mineral deposits to support a global population expected to grow beyond 9 billion in 2050. Geoscience data is critical to exploration success, yet increased expenditure on acquiring more data has not translated into higher discovery rates. Exploration organizations are therefore seeking to maximize the value of their existing data and technology to prioritize opportunities and select the best drill targets. As projects move deeper underground, modern exploration scenarios require explorers to integrate and access all available data, gain even greater insights and build improved exploration models. In recognition that effective data integration and visualization of our data sets remains one of our greatest challenges, we are hosting the Frank Arnott Award as a ‘collaborative’ challenge, focused on innovation in data integration and visualization.

www.frankarnottaward.com
Presentations

- 14:00-14:10 – Welcome: Charles Beaudry/Ken Witherly
- 14:10-14:45 - Dick Tosdal
- 14:45-15:20 – Peter Winterburn
- 15:20-15:40 - Break
- 15:40-16:15  - Leigh Freeman*/Mary Poulton
- 16:15-16:50 - John Gingerich
- 16:50-17:25 - Alan King
- 17:25-18:00 – Ken Witherly
Pathfinder elements in a porphyry Cu system that are not where they are supposed to be found

Richard M. Tosdal
PicachoEx LLC

Presented at DMEC sponsored workshop
Making technology work; the importance of time and patience
(with geologic knowledge)
March 9, 2016

Reko Diq, Baluchistan, Pakistan

• Soil and rock chip samples for geochemistry is a tried and true method of exploration

• New field based technology (SWIR and pXRF) can permit the smart exploration group to quickly vector toward a deposit in “real time”.

• Advances in analytical technology permits expansion of ore deposit footprint

• However, the use of geochemical data is uneven, may be restricted to just a few elements, and may, but not always, assume that the pathfinder elements behave in a hydrothermal system the way they are supposed to behave, that is distributed along temperature and pH gradients.

• Geology is sometimes forgotten or ignored, and the approach is “drill the anomaly”.
Multiple fluid sources and evolution paths characterize a porphyry Cu system

- Two fluids are present:
  1) magmatic hydrothermal and
  2) external thermally driven

- Each capable of transporting and precipitating pathfinder elements

Mt. Milligan — Jago and Tosdal, 2009

Distribution of alteration facies and mineral assemblages in porphyry Cu system

Thermally driven external fluid circulation may transport significant volume of elements in a brine

Water: rock reactions release protolith trace elements to fluid
Common hydrothermal mineral reactions

**Potassic mineral reactions**

\[ 2\text{CaAl}_2\text{Si}_2\text{O}_8 \text{ (anorthite)} + \text{K}^+ \Leftrightarrow \text{KAISi}_3\text{O}_8 \text{ (Kspar)} + \text{SiO}_2 + 2\text{Ca}^{2+} \text{ (anh.)} + [3\text{Al (bio)}] + 8\text{O} \]

\[ \text{NaAlSi}_3\text{O}_8 \text{ (albite)} + \text{K}^+ \Leftrightarrow \text{KAISi}_3\text{O}_8 \text{ (Kspar)} + \text{Na}^+ \]

Hornblende / pyroxene + K⁺ + H⁺ + SO₂ ⇌ Biotite ± Rutile – sulfide

\[ \text{Ca}_2\text{(Mg,Fe)}_3\text{AlSi}_3\text{O}_10\text{(OH)}_2 \text{ (hnb)} + \text{K}^+ + 6\text{H}^+ \Leftrightarrow \text{K(Mg,Fe)}_3\text{AlSi}_3\text{O}_10\text{(OH)}_2 \text{ (bio)} + 1.5\text{Fe}^{3+} + 2\text{Ca}^{2+} + 4.5\text{SiO}_2 + 3\text{H}_2\text{O} \]

**Hydrolytic reactions in sericitic and intermediate argillic reaction:**

\[ 1.5\text{KAISi}_3\text{O}_8 \text{ (Kspar)} + \text{H}^+ \Leftrightarrow 0.5\text{KAISi}_3\text{O}_{10}\text{(OH)}_2 \text{ (musc)} + \text{K}^+ + 3\text{SiO}_2 \]

\[ 1.5\text{NaAI}_{\text{Si}_3\text{O}_8} \text{ (albite)} + \text{H}^+ + 0.5\text{K}^+ \Leftrightarrow 0.5\text{KAISi}_3\text{O}_{10}\text{(OH)}_2 \text{ (musc)} + 1.5\text{Na}^+ + 3\text{SiO}_2 \]

\[ 1.5\text{CaAl}_2\text{Si}_2\text{O}_8 \text{ (anorthite)} + 2\text{H}^+ + \text{K}^+ \Leftrightarrow \text{KAISi}_3\text{O}_{10}\text{(OH)}_2 \text{ (musc)} + 1.5\text{Ca}^{2+} \]

\[ 2\text{K(Fe, Mg)}_3\text{AlSi}_3\text{O}_{10}\text{(OH)}_2 \text{ (bio)} + 4\text{H}^+ \Leftrightarrow \text{KAISi}_3\text{O}_{10}\text{(OH)}_2 \text{ (musc)} + \text{Mg}^{2+} + \text{Fe}^{2+} \text{ (pyrite)} + \text{SiO}_2 \]

\[ 2\text{KMg}_2\text{AlSi}_3\text{O}_{10}\text{(OH)}_2 \text{ (bio)} + 4\text{H}^+ = \text{Mg}_2\text{Al}_2\text{Si}_3\text{O}_{10}\text{(OH)}_2 \text{ (chl)} + \text{Mg}^{2+} + 2\text{K}^+ + 3\text{SiO}_2 \]

**Na-Ca mineral reactions**

\[ 2\text{NaAlSi}_3\text{O}_8 \text{ (Ab)} + \text{Ca}^{2+},\text{aq} \Leftrightarrow \text{CaAl}_2\text{Si}_2\text{O}_8 \text{ (An)} + 4\text{SiO}_2 \text{ (Qz)} + 2\text{Na}^+,\text{aq} \]

\[ \text{Ca}_2\text{(Mg,Fe)}_4\text{(Al, Si)}_8\text{O}_{22}\text{(OH)}_2 \text{ (hnb)} + \text{Fe}^{2+},\text{aq} \Leftrightarrow \text{Ca}_2\text{(Fe, Mg)}_5\text{Si}_8\text{O}_{22}\text{(OH)}_2 \text{ (act) [or chlorite + epidote]} \]

Trace element hosted in common rock forming minerals

**Intermediate Argillic** ↔ **Chlorite-Sericite** ↔ **K-Silicate**

Mafic silicates (pyroxene, hornblende) — Mn, Zn, Cu, Sr, Co, Ni, As, Sb, Li

Feldspar — Pb, Sr, Rb, Cs, Ti, Ba

Hydrothermal reactions will therefore release these elements to the fluid, depleting them from one area, to be transported and then enriched elsewhere in other alteration assemblages together will elements exsolved from a magma

Element abundances will depend upon magma and host rock compositions
Elemental dispersion in rocks

- Relative elemental abundances will vary based upon magmatic compositions.
- A good starting point is 10x average crustal abundance.

Elemental distribution and alteration assemblages at different levels in a PCD

**Above Mineralized Zone**
- PROPYLITIC
- ADVANCED ARGILLIC
- SERICITIC
- Polymetallic veins
- 1 km

**Top of Mineralized Zone**
- Li, Zn, V, ± As, Sb elevated compared to core
- Increasing Ti, As, Bi, Se, Te
- 1 km

**Deep Environment**
- SODIC-CALCIC
- Mo + Bi-Se-Te
- Na, Ca, and Sr enrichment, K, Fe, Mn, V, Pb, Zn, Ca, Cu depletion
- 1 km

**Elevation of Highest Grade Cu**
- Depletion in As, Mn, Pb, Zn, Cs, Sb, Ti in K silicate core
- Localized Ti, As, Bi
- 1 km

**Zone of external fluid alteration**
- Return to background or slightly elevated Zn, Mn, Pb, Sr, Co, Ni, Li, ± As, Sb

Halley et al. 2015
Temperature control on elemental distribution

Element precipitation in sulfides, largely pyrite and to lesser extent in sheet silicates, is temperature controlled. Their distribution is predictable. Because many pathfinders form oxyanion compounds, they are stable in weathered terranes, whereas the metals, which form chloride compounds generally are not stable and are leached.

What does it mean when low temperature elements are coincident with higher temperature elements?

- Sb > 8 ppm
- Tl > 1.2 ppm
- Tl > 2 ppm
- As > 25 ppm
- Mo > 4 ppm
- Zn > 250 ppm
- Cu > 100 ppm

Top of bedrock (base of till) geochemical map of porphyry Cu district with multiple centers
Or low temperature pathfinder elements are coincident with Cu and elements usually stripped from the Cu core is enriched

Top of bedrock (base of till) geochemical map of porphyry Cu

Red Chris, British Columbia

Look at the geology along a section through part of the anomaly

Geology courtesy of Imperial Metals and from Rees et al., 2015
Alteration Zonation
From Norris (2012)

- Propylitic
- K-Silicate
- Chlorite-Sericite
- Sericitic/Phylllic
- Intermediate Argillic
- Carbonate

Alteration – K-Silicate

Secondary Biotite – Magnetite – K-Feldspar

- Secondary biotite and magnetite alteration of hornblende
- K-feldspar alteration of groundmass
- Plagioclase phenocrysts unaltered
- Extended much shallower in system

From Norris (2012)
Alteration – Chlorite-Sericite

Chlorite ± Sericite

- Transitional between K-silicate and Phyllic
- Retrograde alteration of secondary biotite to chlorite
- Altered to sericite (muscovite)

From Norris (2012)

Alteration – Sericitic/Phyllic

Quartz – Sericite (muscovite) – Pyrite

- Groundmass altered to quartz
- Plagioclase phenocrysts altered to high T sericite (muscovite)
- Secondary biotite altered to pyrite and quartz

From Norris (2012)
Alteration – Intermediate Argillic

**Illite - Kaolinite**

- Illite-kaolinite alteration of phenocrysts and groundmass
- Pervasively overprints all other alteration zones and diminishes with depth
- Where less pervasive, K-feldspar is stable
- Common ‘pale greasy green’
- Kaolinite common in upper 300m

From Norris (2012)

**Ore related elements associated with porphyry Cu related alteration**

- Low concentrations of Mo associated with sericite and will like most proximal to Cu
- Zn depleted from ore zones, but present in distal assemblages
Bi, Te and Se are biased towards the sericite, intermediate argillic and argillic groups. These three elements are generally a little more distal than the highest Mo values, but are still indicators. Porphyry core are generally strongly depleted in As, high As values are associated chloritic assemblages (reflects superposition of assemblages). Kaolinized sericitic rocks may have high Sb contents, so distal is now superimposed on the ore zone.

Li is generally depleted in ore zone and phyllic assemblages are depleted in Li, but the kaolinite is enriched (normally this would be far distal). Even though the absolute values are low, W and Sn also appears to be a good proximal indicator. Mn, Pb, and Zn are depleted from the ore zone.
Geochemical pattern reflects the telescoping of the porphyry Cu system

Note that low temperature pathfinder elements are coincident with intermediate temperature and with Cu.

In weathered soil profile, Cu and Zn would be depleted as they are acid soluble, but the pathfinders would remain.

Bethlehem, Highland Valley District, British Columbia
Na-Ca alteration overprint K silicate in core of Bethlehem but peripheral at Valley

View (looking south) of East Jersey (left pit) and Jersey open pits

Na-Ca altered rocks
Trace elements associated with alteration assemblages

- Magmatic derived elements associated with magmatic hydrothermal fluid plume
- Na-Ca alteration adds Sr, Sb, (also P, U, etc); represents influx of saline external fluid and overprint on the magmatic-derived elemental distribution

Sr depletion in magmatic-hydrothermal plume but enrichment in Na-Ca externally driven saline fluid, commonly at depth below to same level as Cu
Localized enrichment of acid-soluble pathfinder elements within Na-Ca alteration assemblages at same level as porphyry Cu system

Elemental dispersion in rocks

- Elemental distribution in a porphyry Cu system is a function of rocks, fluids, and geology
- Pathfinder elements may be in odd places, but they can be explained in the context of the hydrothermal alteration assemblages
- Understanding the geology helps immensely

Halley et al. 2015
Geochemical Exploration for Skorpion Style Oxide Zinc Deposits

Peter Winterburn  MDRU, UBC
John Barr  Anglo American
Markus Schaefer  Vedanta Resources

AngloAmerican  vedanta

Google Earth

NAMIBIA
Skorpion Zn-Oxide Mine
Rosh Pinar VMS Mine
10km
Discovery History

• Anglo American (1976)
  • Target VMS - Style Mineralisation,
  • Stream Sediment Anomaly (115ppm Zn),
  • Zn-Pb-Ag-Ba Gossan,
  • Deep drilling for VMS,
  • Fortuitously assayed bland hanging wall,
  • 8.3Mt @ 10.9% Zn (oxide),

• Reunion Mining (1996) JV
  • Resolved Metallurgical Issues,
  • 17.5Mt @ 10.4% Zn (oxide),

• Anglo American (1999)
  • Commenced Mining 2002 ($454M investment)
  • 24.6Mt @ 10.6% Zn (oxide)

• Vedanta Resources (2010)
  • 11.4Mt @ 9.5% Zn (oxide)

Geology

West East

Discovery Outcrop Orebody (Zn oxide only)

Leached Gossan (high Fe, Pb, Cu)

Sulphides (Zn, Pb, Cu)

Schaefer 2008
Deposit formation

- VMS deposit formed ~ 740-750 Ma
  Sea floor

- Unroofing and oxidation < 65 Ma
  Humid- sub-tropical

- Formation of supergene deposit ~ 37-14 Ma
  Semi-arid

- Burial < 14 Ma
  Arid

K. Kerner 2006

Geology

Schaefer 2008
Exploration

• Classic residual geochemistry inappropriate
  • Buried deposit
• Regional Outcrop Lithogeochemistry
  • too wide scale

• Geophysics
  • EM
  • Mag
  • Gravity
  • IP

• Geochemistry through cover

Sampling – Orientation Survey 2000

Shallow – 30cm
Deep – on Calcrete
Calcrete – Cores.
Deep Sample AR-ICPMS -180 micron

Profile sampling 2001 - Pre-stripping & 30yr old Anglo pit
Skorpion Index

- Elevated values of Zn, Cd, Ba, Mn, Cu, Pb, Y, Ti, Hg, Ag, Au, As, Bi, and Sb in the basal gravel and bedrock along strike from Skorpion.

- Elements combined into an Empirical Geochemical Index, applied as a geochemical exploration tool.

- Coefficients calculated for each element correcting for differences in absolute concentration values.
RAB Sampling Program

- Routine XRF screening of bedrock + 10m of deep overburden
- Best 2-m interval for:
  - (i) bedrock and
  - (ii) deep overburden
- Selection of sample intervals for 52-element ICP-MS assays

Deep Overburden Sample
Bedrock Sample

Palaeo-topography

Current Topography (SRTM data)
Overburden Thickness (from drill data)
Pre-Overburden Palaeo-Topography (SRTM topo less overburden thickness)
1. RAB drill grid
2. Palaeo-topography Modelling
3. Sub-outcrop Geology
4. Bedrock & deep overburden Geochem
5. Follow-up

Did we see a response in 2000?

- Calcrete Formation
- Insects
- Re-activated faults
- Active wind blown sand surface
West – East Profile, Zn.
Six Faces of Innovation
DMEC 2016
Making Technology Work
The importance of time and patience

March 2016
Leigh Freeman - Consultant
Mary Poulton - Director Institute of Mineral Research, University of Arizona

Three Planes - Six Faces Plus Time

• Solution - Technology
  – Basic Research
  – Delivery to Market
• Execution - People
  – Starters
  – Finishers
• Driver – Need
  – Profit
  – Society
• **Innovation ‘Language’**
• Resource Example - Geology/Geophysics
• Defining Three Planes – Six Faces
• The Mining Case
• What does it all mean?

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**Language of Innovation**

• A new idea, more effective device or process

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*Modified From P. Wright, Invtech*
Language of Innovation

Modified From A. Treloar, 1999

Modified From D. Norman & R. Verganti, 2012

A. Human-Centered design and design research
B. Maximum quality for this stage
C. Incremental Innovation to "B" is assumed to be higher quality
D. Higher value necessary from incremental innovation
• Innovation ‘Language’
• Resource Example - Geology/Geophysics
• Defining Three Planes – Six Faces
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• What does it all mean?
A Geology/Geophysics Example
‘3D Seismic’

‘3D Seismic’ - an euphemism for Innovation responsible for transition from high discovery costs in the ‘70s and ‘80s to low discovery costs in this century

From S. Holbrook, 2015

Financial Driver
Supply/Demand Imbalance

CRUDE OIL PRICES SINCE 1861

1974

Modified From Wikipedia
Evolution of ‘3D Seismic’
Five Supporting Innovations Build to One Radical Outcome

- Birth of 3D Seismic, too expensive
- Birth of Sequence Stratigraphy
- 3D revealing targets
- 5% of wells in Gulf use 3D
- Horizontal wells cost competitive
- Most wells directional
- 80% of well is Gulf use 3D
- Fracking-horizontal

Finding Cost $12-16/bbl
Finding Cost $4-8/bbl

3D Seismic Computing Cost
$8M/km² $1M/km² $0.09M/km²

1970 ... 1975 ... 1980 ... 1985 ... 1990 ... 1995 ... 2000 ... 2005 ... 2010 ... 2015

Information Heavily Drawn from J. Rauch, 2001

US Shale Reservoirs
Resources Recognized – Needed Innovation to Move to Reserves
Summary ‘3D Seismic’

- Stimulus in 1974 (Social/Political Issue ‘permanently’ disrupts supply).
- +10 Fold increase in price ($2 to +$20/bbl) for 40+ years.
- Five ‘Innovations’ over next 30 years (1975-2005)
  - 3D Seismic
  - Sequence Stratigraphy
  - Efficient computing
  - Directional drilling
  - Fracking applied to horizontal wells
- Result
  - 25 years after ‘stimulus’ ... innovation cut discovery cost in half
  - 40 years after ‘stimulus’ ... innovation oversupplied the market .... Price drops 75%

Plot ‘3D Seismic’ Innovation

1. 3D Seismic
2. Sequence Stratigraphy
3. Efficient Computing
4. Directional Drilling
5. Fracking Horizontal
A. Human-Centered design and design research
B. Maximum quality for this stage
C. Incremental Innovation to ‘B’ is assumed to be higher quality
D. Higher value necessary from incremental innovation

- Innovation ‘Language’
- Resource Example - Geology/Geophysics
- **Defining Three Planes – Six Faces**
- The Mining Case
- What does it all mean?
Six Faces on Three Planes

- Three Dimensions, each with two faces
- The Puzzle: Six scrambled colors

Execution: People
- Starters
- Finishers

Solution: Technology
- Basic Research
- Delivery to Market

Driver: Need
- Profit
- Society

Colors represent each face

Six Faces of Innovation
Rubik’s Cube

- Success requires that we work with all faces: Technology, People, and Need
- In Mining we focus on the Technology face
- 43 Quadrillion possible configurations ... can always be solved in 20 moves or less
Solution - Technology

Basic Research
Develop new technologies with First-Principles science or uniquely adapting technologies and methods from other disciplines

Bring to Market
Refine and optimize technologies, methods, and costs, develop markets

Basic Research
Discover and Adapt

Bring to Market
Refine Product and Develop

Execution - People (Diversity)

Starters
Creative, unconventional
Undisciplined, break rules
Idea-focused
Not afraid to make mistakes
Non-linear
Reluctant Project Managers

Finishers
Rigorous, conventional
Disciplined, make rules
Process-focused
Abhor mistakes
Linear, efficient
Good Project Managers

Starters
Right Answer-Wrong Question

Finishers
Efficiency Practical and Market

Freeman and Poulton

Freeman and Poulton

Freeman and Poulton
Driver - Need

- **Profit**
  - Commodity Price driven by Supply/Demand imbalance
  - Available multi-disciplinary Technology and methods drive Incremental Innovation to reduce costs

- **Society**
  - Population and affluence determine Demand
  - Evolving Beliefs and Values affect costs and access to resources via laws and regulations

- Innovation ‘Language’
- Resource Example - Geology/Geophysics
- Defining Three Planes – Six Faces
- **The Mining Case**
- What does it all mean?
Mining Example
Three-Fold Increase in Price Due to Supply/Demand Imbalance
Lead to Oversupply in Ten Years

Commodity Price suffers and Society benefits from Incremental Innovation oversupplying Markets with commodities

Why Oversupplied in 10 Yrs

- Constant Incremental Innovation. Minerals sectors historically have the highest reinvestment of revenues into Innovation. (Upstill and Hall 2006)
Mining Heavily Invests in Innovation
Contrary to Convention Thought

• Upstill and Hall (2006)
• Conventional thought ... Basic Materials and Other Metallic Products (1997) 0.7% and 0.9% ‘reinvestment’. Well below pharmaceuticals and information processing.
• Recalculate to include engineering, exploration and R&D in applicable capital goods. Re-Stating ‘reinvestment’... 2.85% and 2.89, highest of all sectors.
• Conclusion ... in Mature sectors such as Mining a substantial component of R&D in manifested in support sectors (example Caterpillar spends $2B/yr in R&D. A substantial component benefits mining, but is not captured in traditional sector R&D reinvestment numbers).
• QED ... we haven’t Needed Radical Innovation, yet.

Price a Weak Driver of Innovation
Price Increases in the Minerals Sectors ‘Find’ Addition Metal at Zero Cost

Double the Price = Half the break-even cut-off grade
‘Find’ 200% more gold.
• Zero cost of discovery
• Can be ‘realized’ with existing plant, permits infrastructure
• Or, allow expansion of production rate

Supply shortfalls quickly mitigated by additional production

Modified From International Tower Hill Mines, Livengood Deposit, SEC Filing 2008
Innovation and the Mining Case

- Incremental Innovation will continue to serve the mineral industry more-than-adequately.
- The Need Driver (Profit) via higher prices unlikely to exist long enough to support development of Radical Innovation.
- Social Developments are capable of ‘permanently’ sterilizing significant existing Reserves

Examples
- Resource Nationalism
- Social License including threat of Cultural Globalization

Innovation ‘Language’
Resource Example - Geology/Geophysics
Defining Three Planes – Six Faces
The Mining Case
What does it all mean?
Increasing Demand Drives Incremental Innovation

- Because ... it is slow, steady, predictable and dependable
- The rate of change of consumption is systemic, steadily increasing (or decreasing) demand in the context of supply
- Too much innovation – For +100 years Incremental Innovation increased supply in excess of constantly rising demand.

Freeman and Poulton

Social Initiatives (Decreased Supply) Drive Radical Innovation

- The consequences of a major ‘Social Decision’ can create long-lasting supply/demand imbalances that could necessitate and support Radical Innovation.
- ‘Social Decisions’: Evolving Beliefs and Values drive Legislation and Regulations and other Political Initiatives. Accordingly, they are capable of ‘permanently’ sterilizing a large proportion of mineral reserves.

Freeman and Poulton
Multi-Disciplinary Incremental Innovation Leads to Radical Innovation

Freeman and Poulton

1. 3D Seismic
2. Sequence Stratigraphy
3. Efficient Computing
4. Directional Drilling
5. Fracking

Multi-Disciplinary Incremental Innovation Lead to Radical Innovation

Freeman and Poulton

1. Geophysics
2. Geology
3. Computer Sciences
4. Mechanical Engineering
5. Mechanical Engineering, Rock Mechanics, Hydrology
### Innovation Starts with a Need – A Driver (Supply/Demand Balance)

- The **Need** establishes the characteristics of the Innovation and directly or indirectly incentivizes its cost of development.
- Society is the most important aspect of Innovation:
  - Consumption drives commodity price via the demand side of the supply/demand balance.
  - Evolving Beliefs and Values drive legislation and regulations via the supply side of the supply/demand balance as well as affecting costs.

### Three Planes - Six Faces Plus Time

- **Solution – Technology** *(Diverse Hard Sciences)*
  - Basic Research
  - Delivery to Market
- **Execution - People** *(Diverse Soft Sciences)*
  - Starters
  - Finishers
- **Driver–Need** *(Diverse Soft Science and Business)*
  - Profit
  - **Society** *(The critical driver for Radical Innovation)*
The Six Faces of Innovation
Exploration Technology
The Missing Pieces

PDAC: DMEC Workshop
March 9, 2016
John Gingerich, Geotechnical Business Solutions Inc.

Déjà vu
The mineral Industry in crisis ~15 years later
- Exploration expenditures continue to slide, below <50% of 2012 levels ($21.5B)
- Commodity prices in decline – marginal projects not economic
- Investor fatigue, frustration, disillusionment
- Declining discovery record!
- Abysmal time to be in exploration

Looking for Change
- Corporate restructuring, strategic planning, revised strategies
- Regain investor/management confidence
- Find a Technology/Innovation Solution?

Why will it be different this time?
What happened to the Previous initiatives?

- **Pre-2003** Industry pressured by Boards & Investors to Improve Performance, reduce cost
  - Downsizing, Strategic Planning, TQM, Six-Sigma, Risk Management, etc.
  - Major technology initiatives (looking for the magic bullet).

- **Then Metal Super-Cycle hits** and every marginal play is now “economic” (Price masks Risk)
  - Industry Leaders abandon discipline – Growth at all cost – you could fund anything, and we did
  - Geoscientists: Everything can be a mine (Prospector Myth at Play)

- Global Exploration spending goes from $2.5B to $15B in 5 years peaking over $21B in 2012.

- Impact of Metal Price that encouraged this spending: Waste converted to Ore
  - e.g. Average grade of gold mines fell from 4.6 gpt in 1998 to 1.2 gpt in 2013

- Technology becomes just another tool and exploration practices reverts to old practices.

Do we need more technology now?

- **What are the attributes of the ore body that we cannot adequately measure?**
  - Ore bodies typically have a dimension in kilometres and volumes in excess of 5 million cubic metres (delta - R, M, V, γ, ρ, μ, ε, φₚ, σ, etc.)
  - Is there a mine discovered which is truly blind to current methods? Case history publications certainly do not support this possibility

- Increases in commodity prices and processing technologies have done more to create ore resources than discovery.
  - Average gold grade mined around the world only 1.2 g/t
  - $100/B oil led to fracking and current surplus

- **Why does exploration continue to fail?**
  - Not enough technology and we need more?
  - Why can’t we seem to find that magic technology bullet?
There has been Substantial Advances in Exploration Technology
The Industry has enjoyed 15 years of Targeting Excellence

From 1990 to 2002 industry invested heavily into Exploration Technology (BHP, Noranda, etc.)

- AGG (Falcon)
- UTEM (Squid receivers)
- MegaTEM
- HEM – time domain
- Hyperspectral
- 3D Siesmic
- Common Earth Models – Gocad
- Distributed Array – Titan 24
- Inversion/modelling software – UBC
- Expert systems
- Partial Extraction Geochemistry

Since then we have seen orders of magnitude improvement in our ability to measure, acquire and analyse data – e.g. Analysis from PPM – PPB - PPT

Did Improved Targeting lead to Improved Discovery? - No!

What happened?

Why did it Fail?

What needs to change?

Information from BHP, Noranda and others concluded that while significant technology advances were achieved, there are no significant economic discoveries that can be directly attributed to these initiatives
Will a Technology Initiative make a Difference Now?

*Definition of Insanity:* Doing the same thing over and over again and expecting different results

While continuous improvement will increase efficiency and precision within the geosciences, it will not impact the way geoscience is being applied without fundamental changes in the approach to mineral exploration!

---

From Wikipedia

“**Mineral exploration** is the process of finding *ores* (commercially viable concentrations of minerals) to *mine*. Mineral exploration is a much more intensive, organized and professional form of mineral *prospecting* and, though it frequently uses the services of prospecting, the process of mineral exploration on the whole is much more involved.”
Measuring the wrong performance

- At Noranda/Falconbridge geophysical drill targeting had >97% success rate: Exceptional!
- However, outside of existing mine infrastructure, no new economic discoveries were made.

![Understanding the Difference: Chance of discovery, versus the chance the discovery is economic](image)

Technical excellence is a professional requirement
- Reviews assess expertise and professional development
- Industry expects surveys meet or exceed industry standards (NI 43-101)
- Technological advances set standard for best practice

Project Reviews
- Post Mortems – why did it fail?
  - Wrong geology?
  - No alteration?
  - Wrong model?
  - Misinterpretation of the data?
  - Etc.

The Industry Accepts Poor Performance

- Numerous models have been presented all pointing to the same conclusion – thousands of targets, and hundreds of millions per discovery.
- Gov. Canada AANDC: “About 1 out of every 200 projects that reaches the discovery stage moves to development. This is equivalent to about 1 out of every 10,000 grassroots exploration projects”. [Link](https://www.aadnc-aandc.gc.ca/eng/1100100023711/1100100023711)

### Exploration Success Model
(Andy Green – CSIRO)

- ~ 5% of targets are mineral occurrences
- Of those, 1-2% will evolve into economic deposits
- 1000-2000 targets need to be tested!

If the above is true – exploration not much better than gambling. Certainly a reason not to invest
Does the Industry have a clue how to fix Exploration Performance?

- Since we do not know whether there is an ore body to be found. The probability of success depends on a number of factors;
  - Chance our database contains sufficient information to identify the minimum required pathfinders (a)
  - Chance we are in a productive belt (b)
  - Chance we had the right ore forming processes (c)
  - Chance ore body within detection limits of our geoscience (d)
  - Chance we have the right deposit model (e)
  - Chance we have adequate targeting methodology (f) = >95% based on Noranda experience

- Probability of success = a\times b\times c\times d\times e\times f = small* (explains the 1/10,000 projects)

- Which factors present the highest risk and can we improve on them?

---

**e.g. Porphyry Mineral exploration.**

**Chance of a successful “Cu Porphyry Prospect” In Chile**

Risk Model derived from Team Discussions

<table>
<thead>
<tr>
<th>Geologic Requirement</th>
<th>Chance of Success</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geology (age)</td>
<td>(0.7 - 0.95)</td>
</tr>
<tr>
<td>Structural controls</td>
<td>(0.6 - 0.95)</td>
</tr>
<tr>
<td>Cu porphyry intrusive</td>
<td>(0.05 - 0.15)</td>
</tr>
<tr>
<td>Phyllic Overprint</td>
<td>(0.1 - 0.5)</td>
</tr>
<tr>
<td>(preserved) supergene</td>
<td>(0.05 - 0.75)</td>
</tr>
</tbody>
</table>

Chance of a discovery = 0.9x0.8x0.1x0.3x0.6 = 1.3%

Chance of it being economic is derived from separate geostatistical analysis
**Chance of Success: Understanding Risk**

**Focusing on the Right Problem**

**Cost of target opportunity in Chile**
- Comparing costs from 1997-1998 using traditional methods to 1999-2001 period using hyperspectral, there was over a 15 fold decrease in the cost to identify a new porphyry and acquire a property.

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<td>(preserved) supergene enrichment</td>
<td>(0.05 - 0.75)</td>
</tr>
</tbody>
</table>

Chance of a discovery = 0.9x0.8x0.8x0.8x0.6 = 28%

72% chance the project will fail.

*Noranda - PDA 2001, AMIRA 4rth Biannual Managers meeting 2001*

---

**How do we get to a Project?**

If the ore body is there to be found
- Unequivocally, Best Practice Geoscience will find it! – tell you where to drill.
- Corollary; Best Practice Geoscience can tell you not to drill
- At what point do we know enough to drill or walk away?
- Once the Team is called into action – drilling is inevitable
  - Like a hunter with a loaded gun, something gets shot!
Exploration is a Process

**Exploration Process (simplified)**
- Selection of prospective areas
  - recognizing ore forming attributes
- Cost effective Geoscientific surveys to identify potential ore (targeting)
- Processing results - enhance predictable outputs (risk assessment)
- Discovery – economic models drive ore delineation

**Mine Process (simplified)**
- Ore delineation
  - Grade Control -manage dilution)
- Mining (cost effective Grade Control)
- Processing (maintaining inputs equals predictable outputs)
- Profitable product

When all else fails – change the definition of ore

---

Analyze the Process

**Things to be learned from Six Sigma**
- Build a statistical framework for analysis
- What are the major reasons for failure?
  - Permissive geology absent – wrong rocks
  - Incorrect exploration model
  - No ore forming process (alteration/mineralization)
  - Incorrect data interpretation
  - Abandoned exploration plan – drilling targets on contradictory evidence (loss of quantification)
  - Never know until you drill
  - Project needs another hole
  - Deposit has unique attributes (can ignore selective datasets)

Philosophy – 70% rate of improvement
Statistical measurement – you can control what you measure
Business strategy – Structured approach for charactering, then optimizing a business process
We cannot improve until we identify the priority problems

Until we properly analyze the entire process, we have no idea as to what are the key problem areas.

Once identified, whatever improvement method the industry chooses
  • It must be able to quantify the problem in order to prioritize and assess the nature of the impact.
  • It is here we will identify the research gaps in technology, management practices, etc.
  • It must be able to consistently report on it (statistics=measurements)
  • Identify means to improve specific processes and track change in performance
  • Audits/post mortems to review the model and try to identify and eliminate bias.

Motivational Bias – corrupts the best of intentions
  • The opportunity for sudden success drives the industry, but the emotional aspects can lead to less than optimal decisions
  • When Luck & Serendipity become factors, we are no longer in the “business of exploration”
One Option: Exploration Risk Management

After James MacKay 2003: Rose & Associates LLP

• Requires a consistent Process for the Accurate Quantification of Forecasts and Opinions
• These tools are to be used in an economic model for Decision Support
• Main Responsibility of Explorationists
  • Identify Commercial Prospects
  • Measure them Estimating
    • Chance of Success
    • Reserves contained
    • Profitability
• Unbiased Estimates
  • Post mortems and audits

From the business perspective of exploration, this is the only technical success

Chance of Failure

Conclusions

• Exploration Technology has no “Missing Pieces” that affects discovery.
• Nothing has changed in the industry in over 15 years. We are still terrible managers of the Exploration Process.
• There is no technology solution to fix the problem we are facing
• Our industry cannot quantify why we fail and because of this, we actually do not know what needs to be fixed and how.
• After researching what was being done in the Oil and Gas sector, I tracked down Peter Rose of Rose & Associates LLP in 2002 with the idea of championing the migration of Risk Management concepts into the Mineral Industry. Peter called me a “Lone Wolf” and expected little to come of my efforts;
  • Risk management is about making middle and senior management accountable for their exploration investment decisions. No one willing to surrender “their turn to make decisions (be the Hero)”. Not until the CEO’s and Boards invite you to present the message is your industry ready.
• Perhaps this time the Mineral Industry will respond appropriately
Perseverance Example

MegaTEM Linked to discovery – the magic bullet

- 100s of thousands of kilometres flown in the next 5 years
- Quebec, Ontario, other provinces added to the initiative
- Noranda follow-up drilling of conductors while drilling 98% successful in targeting, there was not even an economic intersection
- While all massive sulphide deposits are conductors, not all conductors are massive sulphides. Targets often lacked the other required attributes, but still drilled.

It has been reported that there was a similar experience with BHP Falcon surveys.
Exploring for High Conductance Targets with EM Methods:
Successes and Challenges

Alan King
Jan 2016

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• Duncan McNeill - Geonics
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• Inco/Vale Exploration teams
• Barry Krause and Eberhard Berrer
• Gord Morrison and Andy Bite
• Voisey’s Bay Nickel Exploration team – Steve Balch
• Falconbridge Exploration team
• Tony Watts
• Bill Ravenhurst – Crone Geophysics
• The Australians – Bill Amman, Andrew Duncan, etc.
• Anglo American Exploration team
• IPTH
• Dennis Woods
• …
The Problem

- Traditional 25-30 Hz Pulse type Time Domain (TD) EM systems, that measure when the transmitter is off, do not detect or resolve very good conductors well
- May miss large, excellent conductors entirely

Schematic of TEM Pulse system

Technical Note TN-7 Applications of Transient Electromagnetic Techniques, JD McNeill, 1980
Changing (Pulsing) Magnetic Field (B) at Rx coil (dB/dt) induces a voltage in the coil. (It’s all Faraday’s Law)

Note: At the Receiver we measure the voltage induced in a coil by the alternating/pulsing/changing secondary magnetic field B. This changing secondary magnetic field is dB/dt = rate of change of B with time.

Pulse AEM Response Diagram

Weak Conductors
Zinc, Alteration, Weakly conductive Overburden, Water.

Excellent/Slow Decaying Conductors
Magmatic Ni-Cu Sulphides
Very large VMS systems

Effective system Aperture

Pulse Receiver Voltage response
dB-dt nomogram for vertical conductive plate
Conductance = Conductivity x thickness
The problem in more detail

• Most modern deep penetrating EM surveys use high power Time Domain (TD) EM systems

• EM target quality is proportional to conductivity, thickness, and lateral dimensions

• Target quality is best represented by the Tau parameter which is a measure of the rate of decay of the secondary EM signal from the target where

\[ \text{Tau} \sim \text{Conductance} \times \text{diameter} \text{ (units milliseconds)} \]

• Where Conductance = Conductivity*Thickness in Siemens (S) (McNeill, 1980)

The problem in more detail

\[ \text{Tau} \sim \text{Conductance} \times \text{diameter} \text{ (msec)} \]

Where Conductance = Conductivity*Thickness in Siemens (S) (McNeill, 1980)

• Most traditional TD pulse type Airborne, Ground and Borehole (BH) TEM systems measure the time rate of change of the secondary magnetic field or dB/dt

• Hence if Tau is >> than the measurement time window of the system (~8 msec for a 30 Hz TDEM system) the secondary currents don’t decay much during the measurement period and the measured dB/dt signal goes to zero

• Translation - For the best quality large targets the measured dB/dt signal, measured in the offtime, goes to zero!

• The problem is actually with large Tau not just high conductance
Why do we care?

The Ovoid
(and all other very conductive and/or large deposits)

- The Ovoid deposit at Voisey’s Bay is a large, bowl-shaped, accumulation of massive iron, nickel and copper sulphides that contains about 32 million tonnes of ore grading 2.83% Ni, 1.69% Cu and 0.12% Co.
- The conductivity of pure Pyrrhotite (or Pentlandite) is about 100,000 S/m.
- Approximating the deposit with a 100m radius sphere and 100,000 S/m conductivity yields an estimated time constant Tau of 120 seconds! (McNeill, 1980)
- A 50m radius and 10,000 S/m yields tau \( \approx 3 \) seconds = 3000 msec. versus 8 msec. reading window for \( 3 \) Hz system.
Synthetic Model study of BHEM Pulse type (dB/dt receiver) TDEM system in Maxwell EM modelling software 500S (low grade) and 5000S (ore) targets with Low Transmitter Frequency (4hz)

BHEM synthetic Model 500S (low grade) and 5000S (MSU ore) targets Side View

dB/dt Late Time Ch17-20 Data – almost no apparent response from 5000s target
**BHEM synthetic Model**
500S (low grade) conductor +5000S (MSU ore)
Plan View

Horizontal component gives wrong direction - points to weaker not best conductor

**Solutions**
Optimizing TEM Systems for High Conductance/Slow Decay

- System Geometry
- Transmitted Waveform
- Measured Parameter
- Receiver Type
- Data Processing
Solutions

1) Do it the old way. Measure while the transmitter is on using traditional Frequency Domain (FD) EM systems.

2) Measure or calculate the B field at the TEM receiver instead of the traditional dB/dt.

3) Use modern high power TEM systems that include on time measurements.

4) Go to very low frequencies with TEM and wait for decay.

EM Transmitter waveforms

Frequency Domain (FD)
Only one frequency at a time

Time Domain (TD)

Receiver time windows
Frequency domain (FD) EM systems

- Do it the old way
- Measure while the transmitter is on using traditional Frequency Domain (FD) EM systems like the MaxMin HLEM system, the original Inco AEM system, the GTK AEM system, DIGHEM style helicopter EM system, the Boliden BHEM system or any other FD EM system
- Problems - low power and shallow penetration especially in conductive overburden.

Inco FD AEM Thompson Discovery Manitoba (Dowsett 1970)

Measure (Ground TEM) or calculate (AEM) the B field at the receiver

- This can help as the B field response to a non decaying current in an excellent conductor has 100% signal (for a single pulse)
- It can add about a decade to the conductance aperture of a pulse type EM system. The B field can be measured with AC magnetometer receivers such as the EMIT or Crone flux gate AC magnetometers
- The B field can be integrated from dB/dt field measurements

Problems
- If dB/dt is < noise then B field calculated from measured dB/dt isn’t much good
- For measured B field repeated, opposite polarity, non decaying, B field pulses from a very good conductor cancel each other out resulting in little or no signal again for very slowly decaying targets.

TEM – Decay Rates dB/dT versus B field

(a) Primary B Field

(b) Primary + Secondary B Field at receiver

Can go to zero for excellent conductor!

(c) dB/dt at Receiver

(after West et al., 1991)
B-field data processing for AEM
First done by Fugro on Inco VBN Geotem data

The advantage of the B-Field data compared with the normal voltage data (dB/dt) are as follows:

1. A broader range of target conductance that the system is sensitive to (the B-Field is sensitive to bodies with conductance as great as 100,000 S) (AK Note this highly size and noise dependent);
2. Enhancement of the slowly decaying response of good conductors;
3. Suppression of rapidly decaying response of less conductive overburden;
4. Reduction in the effect of spherics on the data;
5. An enhanced ability to interpret anomalies due to conductors below thick conductive overburden;
6. Reduced dynamic range of the measured response (easier data processing and display).

Fugro HELIGEOTEM® II Logistics and Processing report 2008

B-field data processing for AEM
Give about decade in high end Aperature
But is highly dependent on noise levels

dB-dt vertical plate nomogram (left), B-field vertical plate nomogram (right).

Fugro HELIGEOTEM® II Logistics and Processing report 2008
Measurement of the B field
3 component Fluxgate AC magnetometers (EMIT)

• Low noise, 3-component fluxgate magnetometer sensor
• Automated nulling and recording of the Earth’s DC magnetic field
• Sensor noise level: maximum 6 pT/root Hz @ 1Hz on all components
• Noise level: approximately 3 picoTeslas on late time window
• Bandwidth DC - 4 kHz


SQUIDS

• A SQUID (Superconducting Quantum Interference Device) is a very sensitive AC magnetometer (=EM receiver) used to measure extremely subtle magnetic fields, based on superconducting loops containing Josephson junctions
• High temperature SQUIDS – LandTEM - CSIRO and Crone
• Low temperature SQUIDS – IPHT LTS TEM SQUID

Limitations
• Need liquid Nitrogen (HTS) or liquid Helium (LTS)
• Not good for on time measurements due to large dynamic range required
LandTEM

A SQUID system developed for use in TEM surveys by CSIRO in Australia and commercialized by Crone Geophysics

IPHT HTS TEM SQUID system

IPHT HTS TEM SQUID system:

Cryopara and electronics on top
Power supply and control unit
Filling LTS with liquid nitrogen

Liquid Nitrogen Cooled SQUID Magnetometer for TEM* Chwala et al, 2009 Search and Discovery Article #40407
SQUIDS other EM sensors and the Magnetic Field Spectrum

Remember EM sensors measure changing or AC Magnetic fields. Regular Magnetic surveys measure constant or DC Magnetic fields.

Signal from the human brain

picoTeslas
femtoTeslas

Fridge Magnet
Earth's Magnetic field

Induction dB/dt coil
Fluxgate 3C AC Magnetometer
SQUID AC Magnetometers

Recent Discoveries with Measured B Field Very Low Frequency TEM

- Sakatti, Finland Anglo American
- Nova, Western Australia, Sirius
- ....
Anglo-American announces major mineral discovery in northern Finland 11-04-2011

- The deposit was discovered 2009
- The area was initially selected using regional geological correlations and thoroughly assessed utilising the excellent base data generated by the Geological Survey of Finland.
- A number of additional airborne survey systems were flown and ground follow-up using Base-of-Till geochemical sampling together with Anglo American’s LT SQUID TEM geophysical system refined and prioritised the targets.

Anglo American and Geological Survey of Finland

Sirius Nova massive Nickel Sulphide Deposit Albany-Fraser Belt WA

Sirius Nova massive Nickel Sulphide Deposit JULY 2012

- Sirius Resources in conjunction with Newexco’s Geophysical Principal Bill Amann, designed and implemented the geophysical programme from which the discovery hole, SFRC0024, was targeted.
- The current resource at Nova-Bollinger is 14.6Mt @ 2.2 % Ni and 0.9% Cu.
Sirius Resources “a 100-bagger”
Good news in tough times

Sirius went from 5c to $5... New Upstart Explorer Has More Land, More Drilling Targets

• Sirius Resources sparked “The Great Nickel Rush” in WA’s Fraser Range when it hit two mammoth Nickel Deposits, resulting in the share price rocketing from 5c to $5 in matter of months.
• That’s a 100-bagger. (100x initial stack price)

http://www.nextsmallcap.com/sirius-went-from-5c-to-5-new-upstart-explorer-has-more-land-more-drilling-targets/

The Discovery Story – “EM too good to be true” (following up Geochem)

EM Late Time Channel 32
Cu in soils

Mark Bennett- CET Discovery Sirius The psychology of exploration – those that talk about it, and those that do it
Nova Discovery

- Sirius Resources NL's Nova main conductor was modelled with a conductance of $5,144 \, \Omega^{-1}$ (SIR ASX release 18 April 2012).

![Plan view of plate model of EM conductor, based on anomalies defined on three 200m spaced lines](image)

Forrestania WA

EM Test Range (GEM Geophysics)

barren, semi-massive to massive sulphides (Po-rich), ~5000-10000S

Use modern high power TEM systems that include *On time* measurements, B field data and Late time/Very low frequency

- Lamontagne UTEM 3, 4 and 5
- Crone TEM with clever STEP processing

---

**Why do *On time* measurements work so well?**

- **Frequency Domain (FD)**
  - Is an on time Measurement
  
  Bakch 1995

- **Time Domain (TD)**
  - Offtime Pulse Measurement
  - On-time (STEP) Measurement

Ravenhurst 2001
Why do *On time* measurements work so well?

When the transmitter current is changing (*on time*) the primary EM field is continuously inducing a secondary current in the conductor. This creates a secondary magnetic field that acts to cancel the primary (Lenz's Law). When the primary field is cancelled or subtracted out the secondary field is always present for any conductor quality. *There is no decaying signal just different responses at different frequencies (or time windows) that can be used to characterize conductor quality.*

**Potential Problems**
- The accuracy of the key Late time/Low frequency measurement is highly dependent on accurate control of the system geometry from ppm to % scale
- The primary EM field also induces non decaying secondary magnetization in magnetic rocks. This will show up as a non decaying secondary signal in the EM receiver. The response from magnetic sources is another source of noise in on time measurements.

Wave of new, deep, high-grade discoveries at Sudbury

1989 to present

- By the end of the 1980’s Sudbury was considered by some to be a mature or declining camp (i.e. no more large high grade deposits to be found at economic depths)
- In 1989 improved geological model (high grade footwall deposits) and the introduction of on time BHEM surveys led to the deep high grade Victor discovery
- This methodology – closely integrated geology, Drilling and BHEM have led to a continuing series of new high grade discoveries at depths up to 2200m including:
  - Victor ~ 20Mt
  - Coleman 153 zone ~9Mt at 9% Cu, 1% Ni and substantial PGE’s
  - Kelly Lake 10.5 Mt 1.77%Ni, 1.34% Cu and 3.6 g/tonne PM
  - Totten ~ 10Mt
  - Nickel Rim 13.7 million tonnes grading 1.7% Ni, 3.6% Cu, 0.04% Co, 0.8 g/t Au, 2.0 g/t Pt and 2.2 g/t Pd. The deposit is open up-dip (2005-02-01)
  - Podolsky - 3,238,200t (2006)
  - Levack West Footwall - current NI 43-101 Probable Mineral Reserves of 1.3 million tons at 7.4% Cu, 1.5% Ni, 0.20 ounces per ton platinum, palladium and gold. The Morrison Deposit is open in most directions
  - Victoria 14.5 million tonnes of ore were documented in the category of inferred resources, with the grade of 2.5% of copper, 2.5% of nickel and 7.6 g/t of precious metals (2002)
  - Plus numerous ore extensions in existing mines

➢ >70Mt High grade ore at ~ $US300/ton ore (Cu$2/lb/Ni $5/lb US) or about $27 billion in gross value! (not 43-101 compliant!)
Not Only Magmatic Ni-Cu, PGE Deposits

- Very Large VMS deposits can produce long time constant targets due to their large size which contributes equally to tau well as conductance.
  
  \[ \text{Tau} \sim \text{Conductance} \times \text{diameter (msec)} \]

- Neves Corvo, Portugal (Lamontagne Geophysics Case History)

- Lalor, Northern Manitoba
Lalor Lake Deep VMS discovery

• The recent Lalor VMS discovery in Manitoba at 750m depth which has been discussed in detail at recent special KEGS Geophysics symposia

• Recognized deep geological potential and targeted and improved, deep penetrating, large fixed loop TEM surveys
Hudbay Lalor EM Case Studies
The Hudbay Lalor Case Study in the paper: Then and Now: UTEM3 and UTEM5 Comp

• Having the UTEM5 0.24Hz 3 component data available allowed for modelling responses out to just over 2 seconds - the latest 2 time channels are - Ch1 @~1.54s and Ch0 @~2.09 seconds.
• This is a factor of ~16 later in time than the 4Hz latest Ch.
• In order to match the responses seen in the later time channels @0.24 the conductivity of the main plate had to be increased appreciably.

The Lalor model:
1) a single 4000S plate modelling mineralization ~along the Upper Chisel/Lower Chisel contact surface. Note this is ~10x more conductive than the modeling results based on the 4Hz data.
2) a broader, 50m deeper, 50S plate modelling the response of the footwall alteration/mineralization package
3) Zinc-rich Base Metal Zones -10,11,20,30,31,40 - are roughed in as 300S plates (from the 43-101 information) From the modelling results shown we feel that the Lalor deposit would be detectable to a depth of 1500m, possibly more...

Hudbay Lalor EM Case Studies
ElectroMagnetic Imaging Technology

• In June, 2010, DigiAtlantis TEM data was collected in 2 boreholes (DUB33 and DUB 178) at the Lalor VMS Deposit near Snow Lake, Manitoba.
• Data was collected mainly at 1 Hz transmitter frequency and some data was also collected at 0.5 Hz.
• The transmitter loop used was HudBay's Loop 5 — a 2500m x 2000m loop that has been used for a great deal of borehole and surface TEM work at Lalor.
• The low frequency TEM data confirms that the late-time decay constant for the most conductive parts of the deposit is in excess of 100 msec.
Late Time, B field, On Time EM
It’s a bit harder but it’s worth it
Discoveries

On time B field with UTEM
• Sudbury – Vale/Inco and Falconbridge/Xstrata/Glencore
• Reid Brook at VBN
• ....

Low to Very low frequency B field
• Raglan - Falconbridge/Xstrata/Glencore – Crone LandTEM SQUID B field
• Sirius Nova – EMIT Flux gate B field
• Sakatti – IPHT Anglo Low temperature B field SQUID
• Lalor VMS – Crone Late time TEM discovery. All systems show larger slow decaying main current system.

Problems to solve - AEM

• Need lower frequency and or/on time AEM
• Hard but not impossible

On time AEM
• Main problem is system geometry control. There are a number of solutions for this.
• ZTEM is an interesting solution

Lower frequency AEM
• We need to break the 30Hz barrier
• Main problem is Receiver bird movement in the earths magnetic field
General Problems

- No AEM TEM system less than 25 Hz
- On-time low frequency AEM not generally available
- Very low frequency (less than 1Hz) ground or BHEM TEM is very slow
- Need better, cheaper TEM receiver sensors
- SPM – Super Paramagnetic Magnetic responses that look like very good deep conductors are being seen in the best recent high power Helicopter TEM surveys.

Closing Comments

1. The problem is worst for large distant/deep current systems and these are the ones we want to find.
2. If you are close to a large excellent conductor you see smaller scale currents but these don’t reflect the full size or quality of the system
3. The largest current systems have the slowest decay. We need to be able to detect these current systems to see large orebodies at depth
4. You can use AEM for very high conductance targets (see 2) but you need high power B field/LT/On time ground followup
5. One Hz EM systems are getting into the typical range of IP systems and we are seeing IP responses in EM data
Moral

- EM systems are like golf clubs
- Make sure you use the right one
The Evolution in the use of EM in the Search for Porphyry Copper-Gold Deposits

Geophysical surveys over Pima Deposit, Arizona 1951
Idealized Porphyry Alteration/Mineralization
(Lowell and Gilbert, 1970)

Metal Zonation in Porphyry Systems

Bingham

Mineral Park
Supergene enrichment

Leached zone – acidity creation
\[ \text{FeS}_2 + \text{H}_2\text{O} + \frac{7}{2}\text{O}_2 = \text{Fe}^{2+} + 2\text{SO}_4^{2-} + 2\text{H}^+ \]
\[ \text{CuFeS}_2 + 4\text{O}_2 = \text{Fe}^{2+} + \text{Cu}^{2+} + 2\text{SO}_4^{2-} \]

Oxidized zone – Fe and Cu oxides, acidity creation
\[ 2\text{Fe}^{2+} + 2\text{H}_2\text{O} + \frac{1}{2}\text{O}_2 = \text{Fe}_2\text{O}_3 + 4\text{H}^+ ; \quad 2\text{Cu}^+ + \text{H}_2\text{O} = \text{Cu}_2\text{O} + 2\text{H}^+ \]

Enriched zone – reduction and sulphide deposition
\[ 2\text{Cu}^+ + \text{SO}_4^{2-} = \text{Cu}_2\text{S} + 4\text{O}_2 \]

INPUT Mk IV over
Cactus deposit, Arizona, 1964
PORPHYRY COPPER DEPOSITS SW UNITED STATES

MISSION PORPHYRY COPPER DEPOSIT. This is a true dissemination of sulphides which on the basis of ground surveys is not notably inductive. An INPUT testing of the Mission pit area produced the airborne record shown. Two closely spaced but clearly recognizable anomalies have been resolved. The more left handed of these is due to surface mine installations. The second anomaly, however, is identifiable with the pit mineralization proper and is a good response exhibiting a non-exponential decay through the full six channels.

Ground EM Newman Deposit, BC, 1965

© Condor Consulting 2016
IP-resistivity over Lakeshore Deposit; circa 1967

IP over Safford District, Arizona 1970s

Image courtesy M Thoman
Borehole resistivity log and airborne EM response
Escondida Norte, Chile
Noranda Airborne EM Trials
Arizona 1993

Regional airborne EM response over Kerman region, Iran
Airborne EM response over Sar Chesmah Deposit, Iran

Ground mag response over Reko Diq Deposit, Pakistan
Ground EM response over Reko Diq Deposit, Pakistan

Porphyry copper deposits
COLLAHUASI GEOPHYSICS
2005 Rosario EM in 3D

Looking North & Down

Rosario Oeste
Untested Zone
Untested Deep Zone

1 kilometre

% Cu Grade
>10%  
3% to 10%  
1% to 3%  
<1%

EM Inversion Resistivity
< 25 ohm-m

Pit shell Exploration Potential
Based on Xstrata Copper Geophysics Result

Rosario Reserve:
1,062 Mt @ 1.02% Cu

Rosario Oeste
Inferred Resource:
500 Mt @ 1.00% Cu

Rosario Oeste
Exploration Potential
4 X 248 Mt ???

300m Depth Slice
ZTEM modeling over porphyry-style target and field data from Arizona

Figure 3 - perspective view of the inphase Vs Tipper over a "porphyry" deposit.

Z-UP

Figure 4 - perspective view of the inphase Vs Tipper over a "porphyry" deposit.

ZTEM over porphyry deposit,
NW USA
ZTEM over Babine Deposit
central BC

ZTEM over El Cobre Deposit
Panama

**ZTEM Results**

System appears to be mapping near surface sulphides
Large untested anomaly northwest of Cuatra Crestas prospect
Deep response also present at known deep sulphides at Botija

- Very low resistivity
- Low resistivity
- High resistivity
- Very high resistivity
ZTEM over El Cobre Deposit Panama

4 holes on 400m step-outs were proposed

Hole #2 hit 0.80% Cu, 0.21 g/t Au / 240m
Including 0.92% Cu, 0.42 g/t Au / 114m

Hole #1 intersected 0.28% Cu / 209m
and 60m below 2.9% Cu/ 2.0g/t Au / 6.4m
In sheeted quartz-chalcopyrite-bornite veins

EM and Porphyry Copper Exploration 1950-2016

Documentation
P-professional
C-commercial
N-nothing
??-??

1950 Stream sed
GX 1970 Reign of IP 1990 blanket model
1990
2010 ZTEM

Ground EM
Airborne EM
ZTEM
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