PDAC 2013 International Convention

DMEC workshop series:

Southern Andes Exploration; Challenges of Searching Under Cover in Elephant Country

Wednesday, March 6, 2013
DMEC workshop series: Southern Andes Exploration; Challenges of Searching Under Cover in Elephant Country

Chairs - Ken Witherly, Condor Consulting, Inc.
Charles Beaudry, Xmet Inc.

Introduction

Decennial Mineral Exploration Conferences (DMEC) is an outgrowth of the very successful Exploration 07 symposium held in Toronto (Sept 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 third DMEC-sponsored event under the theme ‘tools and techniques to explore undercover’. In the first workshop, we focused on exploration issues related to a major VMS exploration program in the Abitibi and then in the second workshop, we examined the challenges of exploration undercover in the search for Cu-Au porphyry deposits in the Quesnel terrain, east central B.C. This year the theme remains exploration undercover but the geographic focus has shifted to the northern copper belt of Chile. Presentations will examine the geological, geochemical and geophysical methodologies being used to search for new deposits particularly in the pediment-covered areas of the Atacama fault zone.

The Andean mineral belt of northern Chile represents one of the most prolific mineral districts in the world and hosts several giant and supergiant deposits that range in style from porphyry to epithermal and IOCG in nature. However much of the prospective structures are buried under variable thickness of gravel rendering the generation of drill targets very difficult. How players in the region are dealing with the issue is the main focus of the next DMEC workshop. We bring together a total of five presentations that will look at different aspects of the problem with contributions from metallogeny and deposit studies, geophysics, geochemistry and remote sensing. The workshop is aimed at experienced explorationists and is meant to provide the audience with a better understanding of how the various geoscience disciplines must come to bear on the problem of generating high quality drill targets in areas that are known to be highly prospective but which are covered by post-mineral cover that effective renders direct detection impossible.
Program Schedule

14:00-14:05 Welcome and introduction to workshop - Ken Witherly, Condor Consulting, Inc.

14:05-14:15 Exploring undercover in a world-class copper belt of Chile - Charles Beaudry, Xmet Inc.

14:15-15:00 Cenozoic and Mesozoic copper & gold deposits of the Chilean Andes - Peter Hollings, Lakehead University

15:00-15:35 Deposit scale geology: what can we expect to find? - Jeremy P. Richards, University of Alberta

15:35-15:45 Break

15:45-16:25 Exploration undercover in a world-class copper belt - Chile Contributions from Regional Geophysics Hernan Ugalde, Paterson, Grant & Watson Limited

16:25-17:00 Seeing Deep and Staying Focused Challenges for Exploration in Northern Chile - Ken Witherly, Condor Consulting Inc.

17:00-17:40 Mining Exploration in the Andes New Challenges for Geochemistry - Brian Townley, University of Chile

17:40-18:00 Panel discussion
**Ken Witherly**

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Short Biographical Notes

**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 until 2009, after having spent nearly 17 years in various positions for Noranda-Falconbridge-Xstrata. His newest venture is called Gold Crossing, just launched and focusing 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.

**Ken Witherly** has been involved in minerals exploration for over 40 years, spending 27 years with Utah/BHP Mineral during which time as Chief Geophysicist, he championed BHP’s development of what became the MegaTEM and Falcon airborne 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 discovery success.

**Dr. Peter Hollings** completed his Ph.D. at the University of Saskatchewan in 1998 where he investigated the geochemistry of the 2.7-3.0 Ga Uchi Subprovince from Red Lake to Pickle Lake. After a one-year postdoctoral fellowship at the University of Saskatchewan where he worked on the characterisation of waste rock associated with uranium mines, Dr. Hollings moved to the Centre for Ore Deposit Research (CODES) at the University of Tasmania, Australia in 1999 for a two-year NSERC funded postdoctoral fellowship. At CODES Dr. Hollings participated in a multidisciplinary research project investigating the genesis of giant copper-porphyry deposits in Chile.

In 2008 Hollings was awarded the William Harvey Gross medal by the Mineral Deposits Division of the Geological Association of Canada. Hollings has published 43 peer-reviewed publications in internationally recognised journals, 21 of those as first author and has been successful in securing major research funding. As a faculty member at Lakehead University since 2001, Dr. Hollings is continuing his research into the relationship between igneous petrogenesis and mineralisation in Northwestern Ontario, the Philippines and S America.

**Dr. Jeremy Richards** is a Professor of Economic Geology at the University of Alberta, and is a registered professional geologist in Alberta. He received a BA in geology from Cambridge University in 1983, an MSc from the University of Toronto in 1986, and a PhD from the
Australian National University in 1990. He was appointed as Lecturer at the University of Leicester, UK, in 1992, and joined the University of Alberta in 1997.

His research interests focus on the genesis of hydrothermal mineral deposits, and in particular regional tectonic and magmatic controls on porphyry and epithermal mineralization. He is also pursuing research in sustainable development as applied to the minerals industry.

He is currently an associate editor of the journal Economic Geology, and was previously editor of the journal Exploration & Mining Geology and associate editor of the Economic Geology 100th Anniversary Volume, and Mineralium Deposita.

**Dr. Brian Townley** earned a Bachelor of Science degree in Geology (1989) at the University of Chile, a Professional Geologist title (PGeo) and a Master of Science degree in Geology (1991) at the same University, and a Philosophy Doctor of Science degree in Geology at Queen’s University at Kingston, Ontario, Canada (1997). During 1990 – 1991 he worked for industry, in mineral exploration programs in Chile. In 1992 he joined the Department of Geology, University of Chile, where he has worked as professor until present, currently an Associate Professor and former Head of the Department (2010-2012). Since 1993 he has worked in various applied research projects, in Chile and abroad, with many international publications resulting from research and national and international patents for new developments applied to exploration geochemistry. He has also worked as a part time consultant geologist/geochemist since 1997, with SRK Consulting during 2001 – 2002 and since 2003 as an independent consultant. He has recently formed his own consulting company, associated with former graduate students. He lectures Ore Deposit Modelling, Applied Geochemistry, Field Geology I and Field Economic Geology courses at the University of Chile, also short courses for industry and for the Diploma Programs “Geologic Evaluation of Ore Deposits” and “Geo-Mineral-Metallurgy” of the Department of Mining Engineering of the University of Chile. He was leader of the Chilean component of project AMIRA P778, and now leads three privately funded applied geochemistry research projects for industry, these through the Fundación para la Transferencia Tecnológica (UNTEC). He is an associate researcher for the Advanced Mining Technology Center, in particular for the Geo-resources and Sustainable Development research group, as well as for the Geomineral Metallurgy characterization research group.

**Dr. Hernan Ugalde** obtained a BSc and MSc in Geophysics at University of Chile in Santiago. After 3 years at the Geological Survey of Chile (Sernageomin) he joined Paterson, Grant & Watson Limited’s Santiago office in 1997. In 2001 he moved to Canada to pursue a Ph.D. at University of Toronto. He obtained his PhD in Geophysics in 2006. Then he went to McMaster University as a postdoc/research scientist from 2006-2011, where he worked with Bill Morris mostly in Bathurst, NB, Sudbury, ON and Newfoundland while keeping his links to PGW as a
part-time consulting geophysicist. In 2011 he returned full time to PGW, where he has been doing processing, interpretation and modelling of geophysical data with geological tendencies.
Decennial Mineral Exploration Conferences Organization

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Exploring undercover in a world-class copper belt of Chile

DMEC Annual Workshop
PDAC 2013 Annual Convention
K. Witherly and C. Beaudry
Toronto, 6 March, 2013

What does DMEC mean?
Decennial Mineral Exploration Conferences

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

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

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

PDAC 2011 - Focus on Abitibi VMS Exploration-Quebec/Ontario

PDAC 2012 - Focus on Quest Undercover Porphyry Cu-Au, British Columbia

PDAC 2013 - Exploring undercover in a world-class copper belt in Chile

6th Decennial Conference on Exploration Technology September 2017

Introduction

- Exploration in Southern Andes (Primarily Peru and Chile) is fairly mature in areas where Cenozoic sequences outcrop.
- However many parts of major metallogenic trends are covered by post-mineral sequences (gravels and ignimbrites primarily).
- As exploration in covered areas has been much less successful the question of how to generate legitimate economic threshold targets becomes acute.
- This workshop along its 2 predecessors is meant to deal with the issue of cover and the problems and risks inherent with targeting in these areas.
- How do we deal with risk in exploring areas under cover where the target deposit is not directly observable?
Exploring Under Cover 101

- Since the target deposit is not directly observable we must assess the likelihood of its presence given some objective criteria.
- These criteria are derived from the metallogenic model of the deposit type (theoretical model) applied the dataset to derive observable criteria (exploration model).
- Each of these criteria may be low probability by themselves but when combined together can very significantly increase the odds of discovery.

Probabilistic Risk Assessment in Exploration

- According to Brian Mackenzie, based on a study of base metal exploration in the Canadian Shield in the late 70’s it was necessary to invest, over a 5-10 year period, about 2.3 times the cost of an economic discovery to have a 90% chance of discovering an economic deposit.

- The cost of discovering a mineral occurrence was estimated at $335,000 (all amounts 2013 currency).
- The probability of a mineral occurrence turning into an economic deposit was estimated at 0.018 or one in 50.
- The cost of an economic discovery was estimated at $19M.
- So the amount on average that would be required for a 90% chance of making an economic discovery would be about $44M spread out over a 5 to 10 year period.

- Obviously this way of doing things does not work for most of us, particularly if you are a Junior Miner.
**Mineral Exploration Process**

This is the classic Exploration Process Diagram.

It assumes numerous concurrent and sequential instances of the process for the previous conclusions to be valid.

However we know that grass roots exploration simply does not lead to exploration success except under certain conditions:
- Large poorly explored area (i.e. Anglogold in Colombia in early 2000).
- Introduction of new technology (i.e. airborne EM in 1950’s)
- Identification of a new deposit model (i.e. IOCG in 90’s)
- Can we think of other examples?

From Snow and Mackenzie (1981)

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**Exploration under cover**

- Imagine what happens to the cost of discovering a showing when you explore areas that are covered like northern Chile.
- Although the probability a showing will be economic may be similar (say 1/50) the cost of discovering a showing will be much larger than the Snow-Mackenzie base case both in $ and in time, two commodities in short supply.
- So what is the solution?
Project vs Decision-based risk assessment

- The problem with Snow and Mackenzie's approach is that it is "Frequentist" in nature. It requires many instances of the process over a long period to reach some sort of satisfactory outcome.
- This is simply not the way we do exploration.
- What we want are some guidelines regarding probabilities all through the process itself.
- We want to ask questions like the following:
  - What is the risk of taking on a particular project?
  - How much decrease in risk will I get if I do a certain type of survey?
  - What are the odds that my drill target will result in the discovery of a mineral occurrence?
- These are questions more appropriate to "Bayesian" statistical approach.

How do you avoid the Failures?

Understanding where/when to explore

Understanding how/why to explore

Chance of Failure

Most Exploration Projects - Failures

The chance a discovery is commercial/economic

Exploration failure and exploration success (economic, commercial, and geologic).

(Gingerich et al. 2002; from Rose, 2001)
Implications for Exploration Targeting

- Bayesian Inference is particularly well suited to estimate the probability of discovery of an orebody given the presence of a set of observable characteristics that are correlated with mineralization.
- Some requirements are necessary to avoid biased interpretation:
  - The characteristics must not be correlated (e.g., magnetite may be important but in such a case magnetics and gravity anomalies may be correlated).
  - The evidence must be obviously related to the event (i.e. the evidence is a bedrock response and not from overburden).
  - The prior probabilities must be reasonable and not arbitrary. In doubt we can use a whole series of priors and evaluate their impact on probabilities.
- Note that as the number of observations increases the impact of the prior decreases. With more data the problem merges into a classic hypothesis testing scenario.

Multi-Disciplinary Exploration in Covered Areas

- Considering the weak evidence that must be used to generate economic threshold drill targets in the target area, it is not surprising that only a multi-disciplinary approach is susceptible of providing enough confidence in targets.
- In that case what are the datasets that are available (or desirable) that can help to generate the exploration targets for the exploration models derived from our metallogenic models?
- This is the question that this DMEC workshop is trying to answer.
Metallogenic and Exploration Models for Northern Chile

- Porphyry Cu-Mo-Au Deposits
- Epithermal Deposits
  - High sulphidation, low sulphidation, intermediate sulphidation
- IOCG Deposits
- VMS Deposits
- Skarn Deposits
- Others?

Datasets

- Regional Geology
- Structural Model of the construction of Andes
- Regional Geophysics
  - Magnetics
  - Radiometrics
  - Gravity
  - EM
  - Others
- Regional Geochemistry
  - Stream
  - Soil
  - Rock
- Remote Sensing
  - Hyperspectral
  - Ground-based spectrometry
  - DEM
- Deposit Geology
Key Questions in Covered Areas

- How deep is the target (i.e. open pit possible or only underground mine)?
- How can we interpret the geology in the covered areas from the geology of the adjacent exposed areas?
- What remote detection methods are known to work for the deposit of interest and what are the odds associated with these anomalies? How “sensitive” and “specific” is the evidence?
- What are the “priors” when attempting to estimate the early risk associated with any particular land position?
- What is the best sequence of exploration tools that should be applied to generate the best drill targets?

Presentations

1) Regional geology-intro/theme setting – Pete Hollings: Lakehead University, Thunder Bay, ON
2) Deposit scale geology; what can we expect to find? Jeremy Richards: University of Alberta, Edmonton, AB
3) Regional geophysics: Hernan Uglade, PG&W, Toronto, ON
4) Deposit scale geophysics: Ken Witherly Condor Consulting, Denver, CO
5) Geochemistry: Brian Townley, Universidad de Chile, Santiago CL

These Presentations will be Followed by a Panel Discussion
Genozoic and Mesozoic copper & gold deposits of the Chilean Andes

Pete Hollings, David R. Cooke and Huayong Chen
Lakehead University
CODES, University of Tasmania
Guangzhou Institute of Geochemistry

Collapse Zone & Braden Pipe, El Teniente Underground Cu-Mo Mine

Thanks to...

Francisco Camus and Jorge Skarmeta, CODELCO Exploration

John Walshe & Paul Gow, CSIRO DEM

AMIRA INTERNATIONAL
Sponsors & other team members of AMIRA P511 and P765/765A

Esperanza vein, Cerro la Grande, Colahuasi district, Chile
Giant epithermal deposits

- Low sulfidation deposits
- High sulfidation deposits

Modified after Sillitoe, 1997

Porphyry provinces

- In any given province, porphyry deposits are typically emplaced within a time interval of a few million years
- Similar magma suites characterise individual provinces
- Similar metal suite characterise each metallogenic event
- There is a general relationship to subduction environment
- Specific relationship to tectonic change
Porphyry ore genesis

- Tectonic trigger (e.g., ridge subduction)
- Incompatible behaviour of metals and volatiles allows magmatic transport of metals and sulfur
- Multiple phases of intrusive activity – one or more of which efficiently concentrates and releases metals
- Fluid exsolution may be triggered by mafic magma underplating of felsic magma chamber
- Cycles of volatile accumulation and release at the apex of the mineralizing intrusion (multiple seismic events)

Favourable geodynamic settings

- Island arc
- Andean arc
- Accreted arc
- Post orogenic belt
- Behind-belt magmatic centres (shoshonitic)
Architecture of an Oceanic Island Arc

Post-collisional porphyry deposits

PCDs in SW China
- Collision commenced ~65 Ma
- Porphyries cluster at ~40, ~35, ~25 Ma
Post-collisional geodynamic settings

(a) SUBDUCTION
(b) POST-COLLISIONAL THERMAL REBOUND

(c) SCLM DELAMINATION
(d) POST-COLLISIONAL EXTENSION

Reproduced from Richards (2011)

Arc magmatism and porphyry deposits

- Porphyry deposits form at discrete moments in the evolution of magmatic arcs
- What are the tectonic triggers?

Reproduced from Richards (2011)
Convergent margin tectonism and porphyry mineralisation

- Compressional tectonic regimes inhibit volcanism, promote plutonism and can be favourable for porphyry ore formation
- Mineralisation occurs when fluid pressures exceed lithostatic load + the rock tensile strength, producing stockwork veins
- Seismic ruptures that occur late in the porphyry life-cycle result in epithermal mineralisation under hydrostatic conditions

Unmineralised Mt Ngauruhoe stratovolcano, Taupo Volcanic Zone, New Zealand

Ridge subduction

Source: www.noao.org

Tectonic trigger for Miocene porphyry and HS mineralisation in central and northern Peru, and central Chile
Peruvian flat slab segment

- Slab buoyed by subduction of anomalously hot oceanic crust
- Shallowing of subduction angle puts overriding plate into compression

Image from Gutscher et al. (1999)

Ridge subduction - side effects?

- Flattening of subduction zone
- Cessation of voluminous andesitic volcanism ($\text{La/Yb}$)
- Thrust stacking and crustal thickening
- Giant earthquakes
- Sediment subduction in shadow zones
- Hydration & oxidation of the mantle, sulfur & boron flux
- Propagation of deformation fronts
- Opening of slab windows?

Cerro Aconcagua, Central Chile
Geodynamics and porphyry deposits

- Geodynamic processes control ore deposit locations in space and time \textit{(i.e. processes that are fundamental to ore genesis)}
- Understanding tectonic triggers may assist in exploration targeting
  \textit{But far-field events can be difficult to link to district-scale processes}

South America

- Central Andes of Chile, S. Peru & Argentina contains at least eight belts of porphyry copper deposits that have formed since the Early Cretaceous
- \textit{Also contains important Fe-oxide Cu-Au, HS and LS epithermal deposits}
Mesozoic Mineralization in the Central Andes

Coast near Montoverde, Chile

Mesozoic IOCG – Major Epochs

Late Jurassic
(170 to 150 Ma)

and

Early Cretaceous
(130 to 95 Ma)

Paleocene – early Pliocene
**Major IOCG deposits – Central Andes**

- **Candelaria Cu(-Au) Deposit, Chile:**
  - 470 Mt at 0.95% Cu, 0.22 g/t Au
- **Mantoverde Cu(-Au) Deposit, Chile:**
  - 400 Mt at 0.52% Cu, 0.11 g/t Au
- **Mina Justa Cu(-Ag) Deposit, Peru:**
  - 347 Mt at 0.71% Cu, 3.83 g/t Ag

*Early Cretaceous*  
(130 to 95 Ma)

Associated with CIB, Manto-type and some small porphyry Cu deposits

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**Model for Mesozoic IOCG mineralisation of the Central Andes**

*Late Jurassic*  
(170 to 150 Ma)

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Model for Mesozoic IOCG mineralisation of the Central Andes

Early Cretaceous
*(130 to 95 Ma)*
Stage I: Tethyan Period
180 – 165 Ma
Aalenian – Bajocian

Sinistral transtension and extension - basin formation
Lower Rio Grande, Chalcolite and La Negra Fm.

No economic mineralization

Stage II: Tethyan Period
165-155 Ma
Bathonian-Oxfordian

Stronger plutonism, varied tectonic environments:
extension - Marcona - upper Rio Grande Fm.
(Marcona magnetite deposit)
Compression - Cocachacra - granitoid intrusions
(small Porphyry Cu-Mo-Au deposits)
extension - Rio - Guanero Fm.
(No economic mineralization)
Sinistral transtension - N. Chile - granitoids and extrusives
(IODC veins and small porphyry deposits)
Stage III: Transition Period

155-145 Ma
Kimmeridgian-Tithonian

Weak transtension and magmatism
(Jahuay and Yauca Fm.)

No economic mineralization

Stage IV: South Atlantic Period

145-135 Ma
Berriasian-Valanginian

Generally transtension, but strong
magmatism only focused on N. Chile 21-26°,
weak in Peru and south of 26° in Chile

Mantos Blancos Cu in 21-26° section;
K-Fe metasomatism in Marcona
Stage V: Pacific Period

135-120 Ma
Hauterivian-late Aptian

Dextral transtension and strong magmatism — regional extension, basin formation
(Casma-Copara-Punta del Cobre Fm.)
No economic mineralization

Stage VI: Pacific Period

120-80 Ma
Albian-Campanian

Dextral transtension, compression and strong plutonism — regional uplift, basin inversion

Coastal Batholith in Peru
(IOCG mineralization)
Granitoids and extrusives in N. Chile
(IOCG, CIB, Manto-type, small porphyry Cu)
Could this relationship be applied to breakup of other supercontinents?

### Supercontinent breakup and IOCG mineralization?

<table>
<thead>
<tr>
<th>Supercontinents</th>
<th>Kenorland (2.7 Ga)</th>
<th>Columbia (1.9 Ga)</th>
<th>Rodinia (1.1 Ga)</th>
<th>Pangea (0.3 Ga)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assembling (compressional arc magmatism)</td>
<td>3.1 – 2.7 Ga Orogenic Gold: 3.1; 2.8-2.5 Ga</td>
<td>2.4-1.9 Ga Orogenic Gold: 2.1 – 1.7 Ga</td>
<td>1.5 – 1.1 Ga</td>
<td>615-280 Ma Orogenic Gold: 500 – 0 Ma</td>
</tr>
<tr>
<td>Break-up (anorogenic magmatism, extensional arc magmatism)</td>
<td>2.7 – 2.4 Ga (anorogenic/extensional arc ?) Carajas district Salobo-Igarape-Sossos (2540 Ma)</td>
<td>1.9 – 1.5 Ga (anorogenic/extensional arc ?) Kiruna district-A Pahdetavare-Tjärnöjkärr (1890 Ma); Artik (1770 Ma) Great Bear district-B Nico-Sue Diarre (1860 Ma); Olympic Dam (1600 Ma)-C Werneck (1600 Ma)-D Concordy district-E (1540-1500 Ma) SE Missouri district-F Boss IOCG (1480 Ga)</td>
<td>1.0 – 0.6 Ga (extensional arc) Grenville belt-I Kewjibio IOCG (970 Ma) Bafe district, Iran (6750 Ma) Guellib, Mauritania-II (5720 Ma ?) Kheti, North India-III (850-750 Ma) Lufluian, SE Africa-IV (5880 Ma ?)</td>
<td>200 – 60 Ma (extensional arc) Southern Peru Mina Justa-Raul Condestable (115-95 Ma) Northern Chile La Candelaria-Mantoverde (120-110 Ma) Baja California, Mexico (95 Ma)</td>
</tr>
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</table>
Porphyry deposits: tectonic setting

Compressional tectonism dominant after Mid-Cretaceous transition from Mariana to low angle Chilean-style subduction (opening of Atlantic Ocean)

Box folds & thrust faults
Domeyko Fault System

Early – Middle Cretaceous:
Porphyry Cu and Fe-oxide Cu-Au

- 132-118 Ma: Porphyry Cu deposits intruded along Atacama fault after Atlantic Ocean opening
- 121-115 Ma: Iron-oxide Cu-Au deposits
- 106-91 Ma: Porphyry Cu-Au-Mo cluster (Andacollo: 540 Mt @ 0.45% Cu, 0.25 g/t Au, 0.01 % Mo)
- 90-73 Ma: PCD cluster in southern Chile (not shown)
Cretaceous metallogenic belts - Chile

Cretaceous PCDs
4.57 Mt Cu
135 t Au
0.07 Mt Mo

Cretaceous IOCGs
6.88 Mt Cu
121 t Au
1,919 t Ag

Paleocene:
Porphry Cu-Mo and LS Au-Ag

- Incaic orogeny triggered Paleocene porphyry Cu-Mo mineralisation in Southern Peru and northern Chile
- Largest deposits formed in Southern Peru on the Incapuquio & Micalaco Faults
- Smaller deposits formed in Northern Chile (importance of convergence angle? – Sillitoe 1999)
- Less deeply eroded arc segment in Chile preserves LS epithermal mineralisation at El Penon and San Cristobal

Paleocene: NNE convergence
Cretaceous metallogenic belts

Peruvian PCDs (4)
39.1 Mt Cu
? Au
1.19 Mt Mo

Chilean PCDs (7)
12.7 Mt Cu
162 t Au
0.19 Mt Mo

Paleocene PCDs Total
51.8 Mt Cu
162 t Au
1.38 Mt Mo

Eocene – Oligocene:
Porphyry Cu-Mo

- Most prolific and aerially extensive porphyry copper belt in Chile (extends into S Peru)
- Formed post-peak Incaic orogeny along the Domeyko fault zone: three main periods of activity:
  - 43-41 Ma (Early stage): Seven deposits – lowest total contained Cu and Au
  - 39-36 Ma (Intermediate stage): 16 deposits – highest abundance of contained gold
  - 34-31 Ma (Late stage): 6 deposits – most prolific copper event
Eocene – Oligocene metallogenic belt

Early
43-41 Ma (n = 7)
15.6 Mt Cu
147 t Au
0.21 Mt Mo

Intermediate
39-36 Ma (n = 16)
78.0 Mt Cu
402 t Au
0.83 Mt Mo

Late
34-31 Ma (n = 6)
126.4 Mt Cu
352 t Au
3.30 Mt Mo

Eocene-Oligocene porphyry Cu-Mo – Total
220.2 Mt Cu
901 t Au
4.35 Mt Mo

Chalcocytite veins cutting cataclasite in phyllic-halocite Chuquicamata porphyry

Early – Middle Miocene, Chile
Porphyry Cu-Au and HS Au-Ag

- Nine gold-rich porphyry and several HS epithermal systems have been identified in the Maricunga belt

- Mineralisation triggered by contractional deformation in the Quechua orogenic cycle

- 25-20 Ma: Western sub-belt of Au-rich PCDs & HS Au-Ag deposits

- 15-12 Ma: Eastern sub-belt of Au-rich PCDs (most prolific)
Early to Middle Miocene Belt – Chile

**Western Sub-belt**
- 25-20 Ma
- 0.24 Mt Cu
- 312 t Au

**Eastern Sub-belt**
- 15-12 Ma
- 7.06 Mt Cu
- 1,607 t Au

**Miocene PCDs Total**
- 7.30 Mt Cu
- 1,919 t Au

**Early – Middle Miocene:**

**Granite-related Sn-Ag (Bolivia)**

- Porphyry Sn-Ag-Bi deposits formed in a back-arc setting in Bolivia in the Middle Miocene (20 – 12 Ma)

- The Sn deposits formed synchronous with porphyry Cu-Au and HS deposits in the Maricunga belt of Chile

- Tin mineralization is related to peraluminous, ilmenite-series, and locally S-type magmas

- A thick prism of reduced, siliciclastic marine sedimentary rocks of early Paleozoic age appears to have influenced the redox state of the crustally derived magmas (*Sillitoe, 2008*)
Late Miocene – Pliocene
Porphyry Cu-Mo and HS epithermal Au

- Flat slab subduction triggered by the arrival of the Juan Fernandez Ridge (Quechua Orogeny)
- Argentina: Porphyry Cu-Au-Mo systems form at eastern flexure from shallow to steep subduction
- El Indio belt: High sulfidation Au-Ag deposits (limited exhumation prevents exposure of PCDs?)
- Central Chile belt: Giant Cu-Mo porphries form at southern flexure from flat to steep subduction

Late Miocene - Pliocene Belts – Chile

NW Argentina
- 8 – 4.5 Ma
- 8.63 Mt Cu
- 693 t Au
- 1.65 Mt Mo

El Indio Belt
- 8-6 Ma
- 0.93 Mt Cu
- 1,362 t Au
- 25,541 t Ag

Central Chile
- 10 – 4.5 Ma
- 327.8 Mt Cu
- 653 t Au
- 3.87 Mt Mo

Late Miocene - Pliocene Total
- 337.4 Mt Cu
- 2,648 t Au
- 5.52 Mt Mo
- 25,541 t Ag

El Teniente – mindelized massive in breccia breeicles
Summary

Eight episodes of PCD formation in Chile, S Peru and Argentina since 130 Ma (contractional tectonic regime)

Major copper ore-forming events in the Early Oligocene and Late Miocene-Pliocene

Major gold-rich PCD and HS ore-forming events were in the Middle Miocene and Late Miocene-Pliocene

Ridge subduction and slab flattening triggered ore formation in the Miocene and Pliocene systems

Tectonic triggers for older systems not yet determined

Exploration for porphyry deposits

Discoveries since 1992

Map source: http://www.gebco.net
Exploration successes and challenges

- New porphyry deposits continue to be discovered, but the costs of discovery continue to rise
- New deposits are deeper and harder to find
- Some of the new discoveries are among the largest known deposits

Discoveries since 1992 – giant PCD

- Pre-1992 discovery
- Post-1992 discovery

Behemothian

Super-giant
Discoveries since 1992 – Au-rich PCD

Porphyry discoveries since 1992

- More discoveries have been made in covered geological settings than in the past
  - Spence
  - Toki
  - Cadia East
  - Pebble East
  - Hugo Dummett
  - Resolution

- These covered deposits are mostly being discovered in near-mine (brownfields) areas rather than virgin (greenfields) areas

Biotite alteration halo in albite-sericite altered quartz monzonite porphyry, E48, NSW
Observations on recent porphyry discoveries

- Deposits are being found at greater depths based on vectoring information only obtainable by drilling (e.g.: Ridgeway, Resolution, Los Sulfatos)
  - suggests an increasing use of drilling for data gathering rather than specifically for target testing
- Exposed deposits are discovered predominantly only in provinces that are very under-explored because of less-favourable geo-political setting
- Some recent discoveries have unusually high hypogene grades
  - Ridgeway, Hugo Dummett, Resolution

Trend in recent porphyry discoveries

- Exploration techniques have not been revolutionised
  - no surge in exploration successes
  - no refocusing of exploration approaches
- Discoveries are still made using tried and true techniques that evolve naturally with developments in technology and accumulating industry knowledge
- The main trends of this evolution are:
  - Drill hole vectoring using down hole geological, geochemical and geophysical information
  - Geophysics methods appear to be increasingly important in obtaining exploration success
Deposit scale geology: what can we expect to find?

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PDAC 2013

View of Volcán Llullaillaco (~1 Ma) from La Escondida (38 Ma)
Lowell and Guilbert's classic model of porphyry alteration and mineralization zoning:

1. Alteration

Fig. 3 in Lowell, J.D., and Guilbert, J.M., 1970, Lateral and vertical alteration-mineralization zoning in porphyry copper ore deposits: Economic Geology, v. 65, p. 373-408.

2: Mineralization

The link with volcanism

Sillitoe (1973) was one of the first to suggest that porphyries are overlain by composite volcanoes.


Yerington porphyry, Nevada

Relationship between regional crustal structure and mineralization in Chile

Based on maps from Sillitoe (1992) and Sillitoe (1985)

© Richards (2013)

Magma emplacement in the upper crust

Fault intersections and offsets on major strike-slip fault systems offer ideal extensional loci for magma emplacement.

© Richards (2013)
Magma emplacement in the upper crust

- Upper crustal magma chambers develop by rooflifting and/or floor depression.
- Location controlled by magma buoyancy and/or crustal rheology.

Examples of structural controls on localization of magma emplacement: Argentine Puna

El Queva volcano:
Epithermal Pb-Ag and low-grade porphyry mineralization
Located within zone of intersection of major NE- and WNW-trending structures

Cerro Galán ignimbrite caldera:
Minor epithermal mineralization
Located within zone of intersection of major NNE- and NW-trending structures
Bajo de la Alumbrera: Major porphyry Cu-Au deposit + epithermal Au
Located within zone of intersection of major NE- and NNW-trending structures

Chemicoff et al. (2002)

Hydrothermal Alteration

Hydrothermal alteration can affect very large volumes of rock, and can provide a much larger exploration target than an individual ore deposit. Correct identification of distal alteration styles and their relationship to ore-forming processes is therefore crucial to successful exploration.
Andean volcanic centres are large and long-lived — a single connected system may run for up to 10 m.y., and span an area of hundreds of km².

Hydrothermal alteration zones associated with rhyolitic tuffs and domes in the Antofalla volcanic complex, Argentina.

© Richards (2013)

Landsat bands 5/7 showing water/ice and argillic alteration on Volcán Antofalla: each alteration zone is several km wide.

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Potassic alteration associated with Cu mineralization in porphyry deposits

The fluids responsible for potassic alteration are typically saline (initially ~10 eq.wt.% NaCl) and hot (up to 700° C). As a result, they have the potential to carry high concentrations of metals, including Fe, Cu, and Au.

Alteration minerals include K-feldspar, biotite, and magnetite. As such, potassic alteration may generate small positive magnetic anomalies, but low conductivity anomalies (relative to pyrite-rich, magnetite-destructive phyllic alteration).
Potassic alteration
(K-spar and biotite)
(Chuquicamata, Chile)

Intense secondary biotite
(potassic alteration)
associated with magnetite
and Qz-magnetite veining
in andesite country rock to
porphyry system

Dallij porphyry Au deposit, Iran

© Richards (2013)
Secondary biotite-magnetite alteration in andesite country rock to porphyry system
Dallii porphyry Au deposit, Iran

Potassic alteration (biotite with later Qz-sulfide veins)
(Bingham Canyon, Utah)
Potassic (K-feldspar) alteration with phyllic stockwork overprint (Silver Bell, AZ)

Feldspar-destructive phyllic alteration (sericite-quartz-pyrite) (La Escondida, Chile)
Advanced argillic alteration: Vuggy (residual) silica with alunite (NW Argentina)

Advanced argillic alteration in upper parts of Chimborazo porphyry system, Chile
La Escondida area
as an example

Three significant porphyry Cu deposits (La Escondida, Zaldívar, Chimborazo) all began formation at the same time at ~38 Ma (Late Eocene), and were coeval with a regional suite of dioritic plutons.

Regional scale (>100 km²)
alteration around the Escondida-Zaldívar-Chimborazo porphyry triplet, Chile

Light orange: Eocene porphyry
Yellow: Eocene tuff
Purple: Eocene andesite
Green: Eocene diorite
Brown: Mesozoic sediments
Dark orange, red: Paleozoic felsic volcanics

Phyllic alteration
Propylitic alteration

Fig. 3 in Richards, J.R., Boyce, A.J., and Pringle, M.S., 2001, Geological evolution of the Escondida area, northern Chile: A model for spatial and temporal localization of porphyry Cu mineralization: Economic Geology, v. 96, p. 271–305.
Escondida aeromagnetic anomaly

Behn et al. (2001) showed that the Escondida, Zaldívar, and Chimborazo PCDs are located within a ~30 km-diameter magnetic low, which they interpret to represent an underlying source plutonic system of batholithic proportions.


Chuquicamata, El Abra aeromagnetic anomalies

Behn et al. (2001) showed similar large magnetic lows associated with the Chuquicamata and El Abra porphyry systems.

Importance of supergene processes in the Atacama Desert. Formed by intense tropical weathering during the Oligocene and early Miocene, followed by dessication and preservation since ~11 Ma.

Cu-oxide and Cu-carbonate minerals (brochantite, malachite) formed above paleo-water table.
(Zaldivar porphyry Cu deposit, Chile)

Supergene chalcocite and cuprite (red) coating and replacing primary pyrite in phyllic alteration: formed below paleo-water table.
(Escondida and Zaldivar porphyries, Chile)
La Escondida
P&P reserves of 4.32 Gt
@ 0.72% Cu (2010 data)

Features of deposits that are most likely to lead to detection under cover in Chile:

- Magnetic features associated with high-temperature magnetite alteration (porphyry and IOCG deposits).
- Chargeability of disseminated pyrite in phyllic alteration zones around porphyry systems; should correlate with magnetic low (magnetite destruction).
- Extrapolation of regional structural trends (lineaments) and intersections beneath cover to define possible locations of magmatic centres.
- Interpolation (beneath cover) between distally exposed alteration zones, to predict system centres.
- Epithermal levels of systems unlikely preserved if deposits have been eroded and then covered; unlike in the Laramide belt, tilting is not significant.
Exploration undercover in a world-class copper belt – Chile

Contributions from Regional Geophysics

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March 6, 2013
PGW

Contents

• Motivation: the case of Chile
• Data review: the regional picture
• A localized example – some implications for data use
• Add-on: topographic effects on magnetic data
• Conclusions/Final remarks
The case of Northern Chile:
Hosts 10/25 of the largest known Porphyry-Cu deposits

<table>
<thead>
<tr>
<th>Deposit</th>
<th>Province</th>
<th>Age (Ma)</th>
<th>Tenorage (Cu)</th>
<th>Cu (wt %)</th>
<th>Mo (wt %)</th>
<th>Au (g/t)</th>
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<td>0.85</td>
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</table>

(Cooke et al, Economic Geology 2005)

Main deposits/belts

(Camus & Dilles, Economic Geology 2001)
Now the big question...

How do we find more of these, especially when the terrain is covered and the main mineralized bodies are deeper?

Let's see this from a geophysical point of view...

(Behn et al, Economic Geology 2001)
Let's see this from a geophysical point of view...

Abstract

The compilation of a large aeromagnetic high-resolution dataset acquired for base metals exploration in northern Chile between lat 19° 45' S and 27° 15' S revealed a pattern of transversely regional magnetic anomalies. These anomalies occur as generally east-west strips of negative residual magnetic intensity of more than -100 nanotesla (nT). They have an east-west extension of some tens of kilometers and a north-south width of some 5 to 10 km. Some of them can be observed continuously from the coast to the volcanic belt. Their residual intensity is typically more than -100 nT. They also show a loose north-south spacing. It is observed that all known porphyry copper deposits of the investigated segment are spatially related to these transverse magnetic anomalies. We propose that the transverse magnetic anomalies are the magnetic response to the loci of emplacement of intrusive bodies of batholithic size along paths of the advancing magnetic front of the active continental margin. The occurrence of several important porphyry copper deposits in clusters within a district is explained as being related to a common parental intrusive complex, which is geophysically signaled by a corresponding transverse magnetic anomaly. A possible implication of the observed relationship between porphyry copper deposits and transverse magnetic anomalies is the quasideterministic restriction of porphyry copper deposits to certain orogens transverse loci (necessary condition) and the corresponding consequences for future exploration strategies.

(Behn et al, Economic Geology 2001)
A closer look at this model

Data compilation: courtesy of Codelco Chile (proprietary data, JVs and other acquisitions)

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Different approach: focus on structure instead

Data compilation: courtesy of Codelco Chile (proprietary data, JVs and other acquisitions)

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This is not new...

(Tosdal & Richards, 2001)

So...can we use Magnetics?

Data compilation: courtesy of Codelco Chile (proprietary data, JVs and other acquisitions)
Behind the lines, there must be geology...

(Tosdal & Richards, 2001)

A more objective analysis with actual data

SAMMP data
1-4 km spacing; flown “quite high” (Sernageomin + other sources; compiled by PGW 1995)

Calama W multiclient
500 m line sp; 100 m elev (Courtesy of Fugro G & M)
Reminder: exploration under (sedimentary) cover!

“Structural” mapping

(Actually..."Lineament" mapping, because "lines" without geological context are not really structures...yet!)
"Structural" mapping

(Actually..."Lineament" mapping, because "lines" without geological context are not really structures...yet!)

"Structural" mapping:
How are we doing...?
Structural mapping? Not yet...

- Our interpretation is still just lines
- We need to provide sense of movement, strike & dip
- ...And most importantly, we need to integrate geophysics with geology

Hold it!! .......Geology???

- What do we need:
  - Structure (strike/dip, faults, folds)
  - Lithology (rock type, and more than that, physical properties)
- Normally we have a few scarce strike/dip points and no susceptibility at all
- We must obtain these constraints from somewhere else
Strike and Dip

Worms: used to determine relative dip direction

12 km

Strike and Dip

Worms: used to determine relative dip direction

From Archibald et. al., 1999
Strike and Dip

Worms: used to determine relative dip direction

From Archibald et. al., 1999

---

Worms: used to determine relative dip direction:

*upward continuation implementation*

12 km
Application of worms

Strike and Dip
Three point solutions: if we know the location of a contact on 3 \((X,Y,Z)\) points, we can solve for the equation of a plane \(\rightarrow\) strike, dip

Requires topographic relief and confidence on the location of contacts
Strike and Dip
Three point solutions: require topographic relief and confidence on the location of contacts.

Strike and Dip
Three point solutions: a case where geophysics and topography could make a difference
Strike and Dip
Three point solutions: a case where geophysics and topography could make a difference

Caveat...
• The above algorithm works when topographic surfaces are related to the bedrock geology
• In this situation (highly covered area), it is quite likely that the method is not always applicable
Vertical displacement? 1VD

We can highlight areas of "vertical displacement", or where magnetic sources are deeper

Hold it!!

......Geology???

- What do we need:
  - Structure (strike/dip, faults, folds)
  - Lithology (rock type, and more than that, physical properties)
- Normally we have a few scarce strike/dip points and no susceptibility at all
- We must obtain these constraints from somewhere else
- Or...we use 2.5D modelling to test geological hypothesis
2D geophysical modelling to obtain geological structure

- A series of sub-horizontal bodies
- Folds and faults
  - However: this requires a priori knowledge of the structure/geology

Testing geological hypothesis (2D Modelling)

Geologist provided 2D section + physical properties + ground mag survey. We then plug it into modelling software and see whether the model holds...
Testing geological hypothesis (2D Modelling)

A localized example

- So far we have examined the big picture
- Let’s focus on a smaller area where we can appreciate the advantages of geophysics & structural geology combined
A localized example: "Baquedano East"

A localized example: "Baquedano East" – Regional Geology & Deposits

15 km

March 6, 2013

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A localized example: "Baquedano East" – RTP Mag, Geology (structure), deposits

15 km

A localized example: "Baquedano East" – Regional Mag interpretation

15 km
Regional mag interp done @ 1:1M
This window is @ 1:400k
A localized example:
"Baquedano East" – "Detailed"
(1:400k) Mag interpretation

15 km

Fault
Normal
Str-slip dextral
Str-slip sinistral

A localized example:
"Baquedano East" – "Detailed"
(1:400k) Mag interpretation

15 km
Apparent displacement
directions compatible with:
- NW-SE shortening
- E-W shortening
Implications

- "Orange" offsets "green"
- Main area of known deposits coincide with NW-SE shortening
- Thrust at known deposits is offset by "orange"
- Where to go next: we need to know age of mineralization relative to deposits

NW-SE shortening?

(Rothe et al, 2006)
A localized example: “Baquedano East” – Detailed interpretation & geology

Let’s backtrack a bit...

- Regional geophysics?
  - It depends on the scale of the program
  - For a 5x5 km prospect, “regional” could be a 10-15 km scale feature
  - For a 40 x 40 km area, “regional” would be a 100+ km feature
  - However, in broad sense “regional” refers to a survey collected with spacing >500 m and usually from the air
Let's backtrack a bit...

- Methods
  - Usually magnetics, due to its lower cost/benefit ratio
  - With magnetics, we can usually get radiometrics ("2 for the price of 1")
  - Gravity: involves large (continental) scale data compilations (in Chile: SFB-267)
  - Large MT/AMT & 2D seismic transects

---

A localized example: "Baquedano East" – Ternary radiometrics

![Image of mineral sample with scale: 15 km]
A localized example: "Baquedano East" – Regional Geology & Deposits

Use of radiometrics?

- Refine geology
- Zonation of intrusives
- Structural mapping
- Sometimes definition of (K) alteration zones

...all this on a covered zone where we thought that radiometrics would not work!
Radiometrics vs Structure...

Potassium content for potential alteration zones?
A localized example: “Baquedano East” – Regional Geology & Deposits

Can we “see” alteration?

- Not always...
- High K anomalies could also be related to rocks naturally high in K (e.g. rich in K-feldspar)
- However, not all is lost:
  - Th is less mobile than K. Thus, areas that have been enriched with K, will not show a corresponding Th high
Can we “see” alteration?

- By plotting Th/K ratio, we can discriminate areas that underwent K-enrichment (Th/K lows)

Potassium content for potential alteration zones?

15 km

End of Calama \textit{W} survey
A localized example: 
"Baquedano East" – Detailed interpretation & geology

We’ll stop (this exercise) here...However:

- Regional geophysics on covered areas can provide with a wealth of information
  - Structure (not just lineaments, we must relate these to geology and give sense of movement and/or strike/dip)
  - Lithology refinement: we focused on structure, but we can certainly refine lithological mapping by using magnetics & radiometrics
  - Potential alteration zones
What about 3D inversions of mag data?

- Let’s take a quick peek at that...

What about 3D inversions of mag data?

- We know that modelling of geophysical data is not-unique
- Unless we have proper ground control (boreholes, mapping, physical properties), 3D inversions are very risky
- Building a “proper” 3D model (including all the above) is very time consuming, and it requires data that we can use as a control
- Rock properties!!
Geologically Constrained Inversion
Surface geology and boreholes

Convert Maps to geologic models
Then assign physical properties to units...

Rambler Structure
Baie Verte, Newfoundland

From BILL SPICER
(McMaster, then Quadra FNX)

Convert Drill-hole information into voxels

3D Grids (voxel models) of physical properties

From BILL SPICER (McMaster, then Quadra FNX)

5m voxels with a 100m elliptical buffer
Final Reference Model

Check model by comparison with published geological models
In short...

- We should NOT invert data in 3D without proper geological control.
- Period.

Another application of 3D modelling

- We have been focusing on how to obtain **geology** out of geophysical data
- Topography might or might not be related to the geology that we want to highlight
- A topographic source (even without physical property contrast) will produce a magnetic anomaly
Topographic effects on magnetic data

- Regular assumption on magnetic based exploration is that the observed field is purely a representation of magnetic mineral variations in the subsurface

- However, topography can have strong effects on the observed magnetic data, which are usually neglected

Topographic effects on magnetic data

- Early results of topographic effects on magnetic data shown as early as 1971 (Gupta & Fitzpatrick, Geophysics, 1971), but hardly ever applied.
- Topographic corrections are a big deal in gravity...what about magnetics?

*Topographic effect: magnetic anomalies induced by topography, no matter the magnetic mineralogy of the associated rocks*
Main sources of topographic effects

The topographic effect on magnetic data is a function of:

1) Large magnetic susceptibility contrast on surface (air – rock)
2) Source-sensor separation
3) Amount of topographic relief
4) Total magnetic inclination
5) TMF angle vs Topographic slope

In practical terms...

Uniform susceptibility $k=0.001$ SI
Sinusoidal shape
Observation surface flat at $Z=2$ km
Bottom flat at 5600 m

EMF: Intensity, 60000 nT
Inc = 90°; Dec = 0°
Source – sensor separation

---

Drape vs not-drape

1. Flying as low as possible certainly improves resolution of sampled anomalies
2. Flying surface parallel to the ground: normalizes amplitudes, so that all anomalies are comparable

The above does NOT get rid of topographic effects on the data.
Inclination of the EMF

- $F = 60,000 \text{ nT}$
  - Inc = 90
  - Dec = 0

- $F = 40,000 \text{ nT}$
  - Inc = 45
  - Dec = 0

- $F = 28,000 \text{ nT}$
  - Inc = -45
  - Dec = 0

Exploration undercover in a world-class copper belt of Chile
March 6, 2013
PGW
Consequences for interpretation routines

Same model as before, host with $k=0.005$ and with the addition of dikes ($k=0.01$ SI)
Where are the dikes?

Consequences for interpretation routines

PGW
Consequences for interpretation routines:

Any interpretation routine based on derivatives (Euler, ASIG, Tilt, etc.) or a plain inspection of TMI without accounting for topography will be biased.

Application: Southern Andes (Central Chile)

Andina:
- Eocene-Miocene volcanics (Abanico Fm 1st, then Farellones Fm)
- Diorites and granodiorites controlled by structures striking N30W

28 km
Application: Southern Andes (Central Chile)
Application: Southern Andes (Central Chile)

TMI: Before

TMI: After

Application: Southern Andes (Central Chile)

RTP Mag (Before correction)

Geology

Exploration undercover in a world-class copper belt of Chile

March 6, 2013

PGW
Application: Southern Andes (Central Chile)

RTP Mag (After correction)

Geology

Detail

RTP Mag (After correction)

Andesite

Diorite

Geology

Intrusive

RTP Mag (Before correction)
Summary of Topographic correction

- Topographic effects on magnetic data can be quite misleading before doing a “map” interpretation
- This will affect any semi-automatic routine that is based on TMI/RTP or its derivatives (e.g. Euler, Tilt, SPI, etc.)
- Combination of 3D inversion & 3D forward model techniques allow to compute the topographic effect on magnetic data, and produce a much cleaner data set
- If we are modelling the data, model must incorporate topography. Then the software takes care of the topo effects
- Computation requires 5 pieces of software and detailed, case by case analysis

Summary & Conclusions

- The starting question was, can we use regional geophysics on a sedimentary covered area? What can we do to improve our detection rate?
Summary & Conclusions

- From our analysis on the Northern Chile:
  - We **must not** use geophysics as a direct detection tool
  - Standard "lineament mapping" is not sufficient
  - Integration with geology really helps on determining areas of follow-up
    - Further mapping
    - Hyperspectral alteration mapping
    - Detailed ground geophysics that allows a further refinement of the exploration model

---

Summary & Conclusions

- Each geological problem is unique, therefore we can’t treat them all as a uniform case
- Therefore, we can’t push data through a black box and pretend to have decent results without inspection
- Geological mapping (structural data, contact locations) and rock properties are the main control for the success of any geophysical interpretation/modelling program
Acknowledgements

• Iris Lenauer (SRK Consulting) for structural input
• Data:
  – Fugro Gravity & Magnetics (A CGG Company)
  – PGW
  – Codelco Chile
Seeing Deep and Staying Focused Challenges for Exploration in Northern Chile

Ken Witherly-Condor Consulting, Inc.
DMEC workshop March 6 2013

The Target-Porphyry Coppers/IOCGs

Location of major copper deposits

(courtesy MinEx Consulting 2012)
The Target - Getting deeper

Depletion of the residual search space
Depth of cover for base metal discoveries (>0.1% Cu-equiv) made in the western world

Again, a shift the petroleum industry made decades ago.
Source: BHP Billiton January 2007

The Target - Getting better at going deeper

• "We need paradigm shift in exploration and exploration technology. Where is the equivalent of 3d geophysics that they’ve got in oil and gas? We haven’t got that in our business. Why not?"
  • Pierre Lassonde Round Up 2013
The Prize-WORTH looking deep

If we can find Deep High-Quality Orebodies we can mine them

![Graph showing IRR vs. NPV depth to top of orebody]

Hinesky (2005)

Modeling for a VMS-style orebody in remote WA (30 Mt @ 2.5% Ni, 2.0% Cu, 20m thick 60 degree dip)

The Prize-Evolution of Cave mining

![Diagram showing evolution of cave mining techniques]

1898 - First Block Cave, Prwobit Mine (Iron Ore)

Contemporary caves

Strong rocks at moderate depths

Massive footprints

Lower grades

Deep deposits

Panel caving

Beyond Super-caves

Emergence of Super-caves

In-situ metal recovery??

After Wood 2012
The Prize

‘Deep Earth’ Environment

- >500 m – >1000 m to top of ore
- Obscuring post-mineral rocks
- Science-based risk-taking essential
- Robust deposit-halo models needed (aka foot prints)
- Geophysics for ‘sulfur’ anomaly

After Wood 2012
The Prize

The Present

The Future

[Courtesy P. Bratt]

The Search for foot prints

Era of Intelligent Subsurface Mapping

© Cimbor Consulting 2013
Cuajone Peru

First commercial IP survey - Newmont 1956 (after Brant 1966)

Quebrada Blanca Chile

Figure 9. QB chargeability anomaly at 4100 meter elevation.
Rosario-Ujina Chile

1990 Resistivity Survey a=300 m, n=2

Ujina Chile

Geology and TEM survey results over Ujina deposit
Kemess BC

Chargeability Model

Depth (m)

0 367 733 1100

Kemess North Deposit Kemess North Offset Zone New Target

-intensive

75 62.5 50 37.5 25 12.5 (milliradians)

0 500m

IP section Kemess deposit

The Search

Hypothetic Northern Chile Search Model

greywacke: -30 shtn-m
greenschist + calc-silicate: -250 shtn-m
basement anastase: -700 shtn-m
polynorite: oxidized: -20 shtn-m
polynorite: unoxidized: -10 shtn-m
polynorite: hypogene: -500 shtn-m

1500

750 750 500 750 1500

0 km 15 km 30 km

S.L.

3000 m 2000 m 1000 m

© Golder Consulting 2013
The Search

Synthetic ZTEM section-Northern Chile

© Orford Consulting 2013
The Search

RTP of Total Magnetic Intensity

ZTEM 25Hz In-Phase TPR

ZTEM results at the Pampa Lirima geothermal district, Northern Chile

The Search

ZTEM 2D inversion

1.8 km

ZTEM 3D inversion

ZTEM mapping deep shale unit
The Search

MT sounding over Olympic Dam deposit-Australia

The Search

Comparison of Gravity & Magnetic Inversions to drill defined – TG-3 Deposit

3D magnetic and gravity models-Tambo Grande
The Search

The Tambo Grande FALCON™ AGG system survey was flown over a section of the Lancones Basin in Peru. Significant VMS deposits occur within the area.

The images show the good comparison between ground gravity and the FALCON™ AGG system data. The top image is the first vertical derivative of the ground gravity, and the bottom image is the FALCON™ AGG system vertical gravity gradient.

Three deposits are indicated: TG-1, TG-3 and BS. The BS deposit was detected by the FALCON™ AGG system even though it lies 450 m beneath the surface.

Falcon results over Tambo Grande

Where are we?

- We can see deep but things are fuzzy
- Joel Jansen-Teck
Where are we?

<table>
<thead>
<tr>
<th>Technique</th>
<th>Borehole</th>
<th>Ground</th>
<th>Airborne</th>
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<td>✔️</td>
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</tbody>
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© Condor Geosolutions 2013

Where are we?

Conductivity model for Noranda camp-Quebec

© Condor Geosolutions 2013
Where are we?

Acknowledgments

- Cam McCuaig-CET-University of Western Australia, Perth
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- Geotech Ltd.
- SJ Geophysics
Mining Exploration in the Andes
New Challenges for Geochemistry

Brian Townley
Academic & Researcher
Department of Geology &
Advance Mining Technology Center
University of Chile
Consultant & Associate
GeoAnalytical Vision - Geochemistry & Exploration

Introduction

- Chile & World High demand
  Mineral Commodities
- Impact on market
  Higher prices of metals &
  diminishing resources
- Much pressure on
  Mining Exploration
- New Challenges to
  Mining Exploration
How challenged are we?

- Mining exploration in Chile is mature, Peru not far behind and Argentina slowly picking up the pace.
- In northern Chile outcropping evident exploration targets are no longer available, new challenges for exploration being enormous expanses of transported overburden covered terrains and/or old drilled targets discarded due to low exploration potential based on models at the times of exploration.
- Despite such situation, much space is still open for exploration, yet these now require multiplicity of exploration tools (conceptual geology, geophysics, remote sensing imagery and interpretation and exploration geochemistry) and integration of all available information in new ore deposit and hydrothermal system conceptual models.
- Combinations of geology (lithology and structural geology), morphology, landscape evolution models, geophysics and geochemistry are likely the best opportunity at finding those new until present undiscovered targets, a large number under cover, or requiring deep drilling high risk exploration.
- Exploration geochemistry, aimed at studying geochemical dispersion processes, both primary and secondary, represents one additional tool that may assist the finer targeting of prospects, from regional, to district and finally local scale.

Exploration environments are ever more limited to concealed ore deposits
eg. Beneath transported overburden
or concealed deep within subtly altered rocks

Combine concealment by both overburden and deep within subtly altered rocks...

This would account for a large number of old past abandoned targets...

Nowadays, targets for renewed exploration in northern Chile

Deep drilling exploration has expanded as better knowledge and new technologies allow lower cost and more efficient exploration & deep mining

Geochemistry may assist in construction of hydrothermal system models, from regional to local scale
El Salvador Porphyry Copper

- Pyrite
- Chalcopyrite - Pyrite
- Chalcopyrite - Bornite
- Trace Sulfides
What exploration potentials do we have in northern Chile and southern Peru?

How much of it is under cover?

Metallogenic belts of the north Chilean and southeast Peruvian Andes & relation to evolution of magmatic arcs

Paleocene – Lower Eocene

Miocene – Pliocene

Eocene – Lower Oligocene
So how can we define exploration targets beneath cover?
How do we approximate from regional to local scale?
How do we optimize our drilling?

Geochemical signature of ore deposits – from source to surface

- Secondary geochemical dispersion processes occur at surface, from the moment any sulfide bearing altered rocks are exposed to groundwater & atmospheric conditions
- Sulfide minerals are exposed to oxidation, chemical & biological, generating acidic conditions, hydrolysis and redox reactions on rocks
- Minerals of all types are altered, degraded and thus geochemical dispersion occurs along chemical (redox – pH), hydraulic, barometric or other natural gradients
- Dispersion processes may incorporate mechanical degradation at surface, eluvial, colluvial, fluvial, alluvial and eolian
- Geochemistry, employing natural materials, must incorporate interpretation of secondary processes, these potentially of various types, commonly overprinted
From source to surface

Study of real time processes
What do we know?
What has been established?

3. Capture of ions and gases; natural regolith/cover geochemistry vs. development of a surface geochemical signal

2. Migration of ions and gases to surface. Transport mechanisms

1. Sulphide oxidation and bacterial processes => free metal ions and generation of non organic and organic gases

Experimental view
IDO case study
Other case studies
Overburden

Oxidation zone
Reduced zone
Water table

Experimental view

- Facts as determined from column and in vitro experiments
  - Processes at source generate free ions and gaseous hydrocarbon compounds, these susceptible to dispersion from source to surface
  - Microbiotic activity includes a vast community of chemolithotrophic autotrophic, heterotrophic and mixotrophic bacteria
  - Chemical and biochemical reactions generate thermodynamic gradients (T°, pH, Eh, composition, electro-chemical), these buffered by mineral - water - microbial activity equilibrium
  - Chemical and biochemical reactions, buffered by environmental parameters control the partitioning of elements among different phases, mineral, aqueous, gaseous
  - Thermodynamic and geochemical gradients so far detected include pH, Eh, EC and TDS
  - In other published studies, exothermic sulphide oxidation reactions have been documented and are capable of generating convection cells (Mann et al., 2005)
In vitro experimental research: copper sulphide mineralization

Experiments on shaker table at 100rpm
Room temperature at 30°C
Over a period of 3 months
Adsorbent materials analysed for SGH
162 reported compounds
Linking HGC to bacteria communities and specific iron and iron-copper sulphides

1. The Source
IDO CASE STUDY
IDO 3-D CONCEPTUAL MODEL
Hydrogeology and groundwater–rock interaction
- Water Table - Gravel - Rock Level at approx. 1550 m.

- Top of water table within copper oxidised and leached rock, mostly sericite altered andesite and PTO, with patchy chlorite, biotite and argillic alteration.

- Top of water table is only 25 m above deeper copper oxidised - leach - pyrite zone, and 50 m above back-end deepening secondary and primary copper mineralization.

Cangue and ore mineral buffers

Water table plan view of mineral zone, Total copper and soluble copper
SE to NW groundwater flow and geochemical – physico chemical modification of groundwater as product of water – rock – microbe interaction processes

- Metal and anion concentrations in groundwater
- pH drops slightly within rock hosted groundwater

SE to NW groundwater flow and mineral saturation indexes of groundwater as product of water – rock – microbe interaction processes

Higher saturation for copper sulphate minerals is observed along the front end of the deposit

Gypsum observes higher saturation towards the back end of the deposit
Groundwater – overburden (2.): Ore deposit oxidising processes and effects

- From field measured data, both from groundwater properties and characteristics of overburden, corroborated by experimental analogue trials, oxidising processes on sulphide ore deposits have the following effects:
  - Chemical and microbiological oxidation of sulphide minerals
  - Modification of groundwater chemistry and physicochemical properties, which propagate down flow through and out of the deposit
  - Development of subtle physicochemical and geochemical contrast anomalies both in groundwater and in overburden
  - Depending on hydrogeologic conditions, contrast anomalies may be asymmetric and displaced down flow from the underlying deposit
3. The surface expression of underlying ore deposit oxidation processes

Geochemical surface signature of ore deposit beneath overburden vs. regolith/ sediment geochemistry

Sedimentary deposits: main sources and flow directions
Detailed mapping of present and past sediments / regolith

Provenance and Geology

Mostly Basalt and andesitic rocks, minor limestone (La Negra and Punta Del Cobre Fm.)

Intra and extra caldera ignimbrite

Andesitic rocks with rhyolitic intrusions
Regolith/Sedimentary Units

- Units with south provenance mostly from andesitic basaltic rocks of La Negra Fm.
- Units with south-east provenance mostly from intracaldera ignimbrite

Geochemistry of Regolith/Sediments

- What is the relationship between regolith/sedimentary units and soil chemistry?
- Could we discriminate the regolith/sedimentary units with geochemistry?
Geochemistry of Regolith/Sediments

- To study the geochemical characteristics of regolith/sediments, a regular sampling grid of 252 samples was taken.
- Samples sieved at -80#.
- Total digestion -> ICP-AES 35 elements.
- QAQC carried out with sample duplicates (99%) and analytical standards (2%) = OK for most elements (<20% error).

30-40 cm

Geochemistry of Regolith/Sediments
Distribution of element concentrations in different Units

- South basaltic-andesitic provenance
- South-East andesitic rhyolitic provenance
- South-East ignimbrite provenance

% Mg

Sr ppm
Geochemistry of Regolith/Sediments

- Distribution of elements in different Units

![Graphs showing distribution of elements]

Geochemistry of Regolith/Sediments

- Distribution of elements in different Units

![Graphs showing distribution of elements]
3. Regolith/sedimentary units geochemistry/mineralogy

High geochemical variability of regolith/sediments reflects heterogeneity, highly dependent on source. This affects soil total, aqua regia and EL geochemistry.
Rock geochemistry vs. Regolith/sediment Unit geochemistry

- For all units, Ba, Ca, Co, Cr, Ga, K, La, Li, Mg, Mn, Na, Ni, Pb, Sc, Sr, Zn and Zr observe similar geochemical tendencies in rocks, compared to the respective regolith/sedimentary unit, representing geochemical criteria for provenance determination.

- Ratios between elements could help discriminate the different units based on geochemistry. Example, La/Mn
Rock geochemistry vs. Regolith/sediment Unit geochemistry

Geochemistry and Mineralogy

Relative abundance of Calcite in XRD show relation with Ca concentrations
Geochemistry and Mineralogy

Relative abundance of Albite in XRD show relation with Na concentrations

Other example:
- High Ti/Fe
- Higher concentrations of Magnetite and Oxides (probably Illmenite).
Real time integrated geochemical response: the collector device experience (3.)

- The objective of testing collector devices for the detection of hydrocarbon gaseous compounds, metals and other elements were to:
  - Test a sampling media which is independent of regolith/ sedimentary units
  - Detect an integrated real time signal as a response to present time on-going processes
  - Test gaseous transport mechanisms

Collector devices: SGH detection of real time processes?

SGH 006-C28 observes a negative contrast anomaly respect to background. Some high values over Cu, higher concentrations down water flow direction.
Collector devices: SGH
detection of real time processes?

SGH 005-C26 observes a negative contrast anomaly respect to background
Some high values over Cpy, higher concentrations down water flow direction

Collector devices: SGH
detection of real time processes?
Collector devices: SGH detection of real time processes?

Comments on SGH

- In vitro and column experiments have clearly demonstrated that sulphide microbiotic oxidation processes do indeed generate HCC's.
- SGH is a qualitative HCC's analytical technique, based on ppt detection levels of 162 HCC's.
- Collector devices concentrate up to one order of magnitude higher proportions of HCC's compared to the standard soil sample.
- For analytical purposes sample batches are randomly tested and analytical sample weights are determined.
- To keep analytical conditions within GC-ICPMS working range, very small proportions of samples are employed. Subsampling and sample weighing complicated.
- Different sample batches operate with different analytical sample weights, depending on initial evaluation.
- Different sample batches are not directly comparable;
- Field sample reproducibility is often poor, in many cases over 40% average relative difference (original - duplicate).
- Standard is represented by the off the shelf caolinite, analysed repeatedly as to define original analytical confidence range.
- Much to be learned about HCC's, alternative analytical techniques, specific microbe community - HCC's relation, among many.
Collector devices: Geochemistry detection of real time processes?
These elements, together with Ti, Sr, Rb, P, Ba, Al, exhibit a negative contrast anomaly over the oxidised SE portion of the deposit... In groundwater these elements increase concentration in the NW down flow direction, lowest concentrations to the SE.

Flow plume effect?

Cu in collector devices develops a good annular contrast anomaly, displaced to the NW of the deposit.

Elements: Co, Ni, Pb, Zn, Ga
REE (Lanthanides): In groundwater lanthanides observe decrease of concentration from gravel host into rock hosted GW
Summary (Collector Geochemistry)

- Na, K, Mg, Ti, Rb, P, Ba, Al, exhibit a negative contrast anomaly over the oxidised SE portion of the deposit, higher values occur to the west and northwest. In groundwater these elements increase concentration in the NW down flow direction, lowest concentrations to the SE.

- Base metals (Cu, Zn, Pb), Co, Ni and Ga exhibit a negative contrast anomaly just SE of and above the oxidised SE portion of the deposit, well marked positive contrast anomalies to the NW, displaced to the NW, in the direction of groundwater flow. Asymmetry of annular contrast anomaly displaced by groundwater effect?

- Th and REE (Lanthanides: La, Dy, Gd, Nd, Pr, Sm): develop discrete yet high contrasting annular anomalies above the deposit.

- Others: Nb, Sm, S, V: irregular annular contrast anomalies above the deposit. Tb, Yb, U, Y: subtle annular contrast anomalies above the deposit.

IDO 3-D Conceptual Model: from Source to Surface
Summary and Conclusions

1. Groundwater - rock - microbial interaction:
   - Generation of free ions and HCC's
   - Redox and hydrolytic reactions (ionic species, redox and electrochemical cells)
   - Groundwater down flow dispersion of ionic species and gaseous compounds
   - Dispersion enhanced and modified by redox cells and thermal convection
   - Groundwater flow -> physicochemical and chemical asymmetry of water table
   - Upward effects on overburden and surface soil and collector geochemistry
IDO 3-D Conceptual Model: from Source to Surface
Summary and Conclusions

2. Subtle yet discernable effects of deep sulphide oxidising processes on overburden:
- Slightly lower pH and absence of calcite above deposit
- Elevated TDS, Na, K, above deposit respect to gravels away from deposit
- Elevated TDS over back end of deposit
- Groundwater hydrochemical asymmetry reflected on overburden
- Transport mechanisms within water table mainly solution/dissolution processes enhanced by electrochemical (redox) and convection cells
- Transport from top of water table to surface, partial capillarity (as evidenced by elevated metals at depth) but mostly gaseous (as evidenced by gas collectors at surface).
- Migration to surface displaced NW by groundwater flow.

3. Deep sulphide oxidising processes and groundwater flow not only have subtle effects on overburden, these effects reflect at surface partially on soil geochemistry (aqua regia and enzyme leach), yet cloaked within regolith/ sedimentary unit natural geochemical variance.
High geochemical variance of regolith/ sedimentary units are documented from mineralogy and geochemistry of soils/sediments.
Collector device geochemistry register a time integrated accumulation of ionic species and HGC’s, adsorbed to collector device materials (over 100 - 120 days).
Surface HGC’s and geochemical patterns are influenced by groundwater flow, anomalous patterns displaced NW for metals, major elements and HGC’s, over the deposit for Th and lanthanides.
Groundwater
Evaporation - condensation

Water capillarity

Evaporation
Vapor rises and condenses, daily
Development of moisture zone
At surface, dried by arid conditions
Moisture does not reach surface, evaporates and precipitates minerals, in particular carbonates
Composition of moisture reflects composition of source (high copper, lead, sodium, potassium: these in groundwater only within ore rock)

Do metals break out to surface?
Do metals migrate through moisture?
Exploration considerations

- Seasonal variations suggest migration of elements and HGC's from source to surface may vary in time, location and intensity, hence not all seasons are best for geochemical exploration.

- Hydrological conditions may have profound effects on geochemical processes leading to a surface expression of underlying sulphide mineralised bodies, these conditions need to be established before data interpretation, as these will modify the expected surface geochemical patterns.

- Total, aqua regia and enzyme leach geochemistry: detailed mineralogical and geochemical characterisation of regolith may allow correction algorithms for partial extraction geochemistry as to minimise soil/sediment natural geochemical variance (mineralogy/geochemistry based regolith/ sediment based filter). Further data revision and data mining could shed understanding of effects of natural geochemical/mineral variance.

Other case studies (optional)