Geochemical Mapping: A Critical Tool in the Search for Mineral Deposits

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*Teck Corporation, Perth*

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*SRK, Cardiff*
The Technology Push

Cumulative Cu resources discovered in Chile (mt Cu)

Outcropping ore bodies
Porphyry model applied to outcrop
Exploration around known deposits
New technologies (e.g. SXEX)
Covered terrains

Source unknown
Economics Preliminaries

Exploration expenditures and **amount** of copper found

Primary copper deposits >0.3 Mt found in Western World: 1950-2009

![Graph showing exploration expenditures and amount of copper found, with axes labeled Mt Cu and Exploration Expenditures (2009 US$B).](Source: MinEx Consulting Sept 09)
Exploration expenditures and amount of uranium found
Primary uranium deposits >0.5 kt U$_3$O$_8$ found in the World: 1940-2008

Note: Chart include adjustment for deposits missing from the database
★ Olympic Dam (Cu-U-Au deposit) found in 1975 – contains 2405 kt U$_3$O$_8$

Source: MinEx Consulting May 09
Expenditures from OECD

From Schodde, 2010
DRIVER 1: District maturity and the need to chase deep targets

Depth to top of ore body for (>0.1 Moz) gold discoveries made in the Western World

Note: Chart refers to the initial discovery in a camp. – and so excludes subsequent brownfield discoveries which are often deeper

Source: MinEx Consulting Jan 10

From Schodde, 2010
DRIVER 2: Shift towards brownfields exploration
Total World gold discoveries: 1950-2009

Note: Includes By-Product gold (mainly from base metal deposits)
"Brownfield" is defined as exploration associated with conventional targets within an established mineral district. This includes exploration beneath/immediately along-strike from a known deposit. "Greenfield" is defined as all other exploration.

Source: MinEx Consulting Jan 10

From Schodde, 2010
What about geochemistry?!
<table>
<thead>
<tr>
<th>Deposit</th>
<th>Type</th>
<th>Discovery</th>
<th>Discovery methods</th>
<th>Primary Geol</th>
<th>Geochem</th>
<th>Drilling</th>
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*From data compilation in Holliday and Cooke, 2007*
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**Geochemistry**

**Geophysics**

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From data compilation in Holliday and Cooke, 2007
The ultimate utilitarian objective of geochemical exploration is to separate barren from mineralized rock and regolith.

Early stages of exploration need to rapidly identify areas of potential for follow-up to reduce overall risk.
Lithogeochemical Mapping

A long established in geochemical exploration and overlaps broader field of ore deposit geochemistry

Example:

Porphyry Cu deposit formation is favoured by hydrous melts containing elevated $\text{H}_2\text{O}$, $\text{SO}_3$ and $\text{Cl}_2$

Increase in $\text{H}_2\text{O}$ suppresses plagioclase ($\text{Sr}$) formation in favour of hornblende ($\text{Y}$) $\Rightarrow$ elevated $\text{Sr}/\text{Y}$ in fertile magmas

After Rohrlach and Loucks, 2005
From Urqueta et al, 2009
Alteration index of rocks in the Collahuasi area, Chile

From Urqueta et al, 2009
After Robertson and Taylor 1987, McQueen and Whitbread 2007
Mantoverde district (440) vs Regional samples (460)

Cu Proportional dot-plot

Na / Zr, molar vs Al / Zr, molar

Regional samples (460) From Benevides et al, 2008
From Benevides et al, 2008

Modified alteration index (%)

Cu (ppm)

Ba (ppm)

Na / Al, molar

K / Al, molar

Albite

K-feldspar

Muscovite
Regolith – Arid / Deeply Weathered Terranes

Weathered profiles typically have RESIDUAL and TRANSPORTED components of varying ages.

Several distinct phases of creation and destruction of secondary Fe, Ca, Si and Al minerals – each with total or partial resetting of trace element geochemistry.

⇒ Systematic approach to identifying regolith materials and landforms
⇒ Link evolution of regolith and its components to geochemical processes and sampling strategies

Anand and Smith, 2005
From Márquez-Zavalía et al, 2004
Pd-rich gold forming distinct rim around core, Brownstone (Cornwall).

Zonation of Cu-Au compounds surrounding Au-Pd grain core from Kraskov (Czech Rep), and Philip Burn (Lammermuir Hills, Scotland).

Placer Au grains derived from oxidising Cl-rich systems

After Chapman et al, 2009
Gold grain from Lively's Find, Flinders RA
A. SEM micrograph (BSE mode) showing rounded morphology of the Au grains.
B. Alloved nature of the grain and areas of higher purity Au.
C. Inner crystallinity of the grains via FIB with crystal size smaller on the exterior rim of the grains and larger towards the bulk of the Au grain.
D. SEM micrograph of a viable biofilm on the surface of the grains
E. Surface of grains and Au nanoparticles in interstices between the nano-wires.
F. Au precipitates distributed on the surface of the Lively's Au grains.

Morphology of Au, Donegal Runoff
B. SEM micrograph showing angular grains and layer composed of Si, Al, O, Na (arrow).
C. FIB-SEM micrograph showing a section through the layer of material shown in B.
From Scott and Radford, 2007

Big Bell Au Deposit
From Scott and Radford, 2007
The problematic terrains for geochemical exploration

- Glacial deposits
- Thick gravel and scree deposits
- Thick alluvium or colluvium + deep weathering
- Aeolian deposits
- Volcanic ash
- Ice

Significant mineral occurrences

Data: Australian Minerals Atlas
Waters in kimberlite
- B30
- 95–2
- C14
- A4
- Diamond Lk

Non–kimberlite groundwaters
- Diamond Lk
- Country Rock

Reaction modelling with kimberlite mineral suite
-

From Sader et al., 2007
Generalised geochemical profile, Mt Gibson Au deposit

**TRANSPORTED**
- Sand
- Hardpan
- gravelly sand

**RESIDUAL**
- Lateritic residuum
- Mottled saprolite
- Saprolite (quartz vein)
- Saprock
- Bedrock

Approx. depth 80m

ppm

Anand, 1991

Mt Gibson

Ag
Au
Cu
Bi
Anand et al., 1989

- Tobias’ Find (Au)
- Quartz veining
- Secondary Cu
- Sample sites

N = 109 samples
Anand, 1994

**Distribution of gold at Boddington**

- Breadth of laterite anomaly increases
- Soil anomaly
  - Gravelly soil
  - Loose pisoliths
  - Pisolithic duricrust
  - Fragmental duricrust
  - Bauxite zone
  - Clay zone
  - Saprolite
  - Saprocks
  - Bedrock

- Au decreases
- Leaching of Au from upper horizons
- Au stronger in non-magnetic nodules
- Depletion Zone (very low in Au)
- Enrichment zone

*Image credit: Anand, 1994*
Non-magnetic lag

Magnetic lag

Mrangelli, Cobar

Zn

150 ppm

50

RAB anom.

Zn

150 ppm

50

RAB anom.

Non-magnetic lag

215m

220m

225m
Geochemical data from irrigation well waters in the Casa Grande area, Arizona

From Taufen, 1997
From Carey et al 2003.
Does dispersion occur through deep, transported cover?

Osborne Cu-Au deposit, Qld

Dispersion mechanisms?

Dispersion timing?

Data from Lawrance, 1999
Dispersion models – dilatancy pumping

Cameron et al., 2004

Figure 5 - Model of Cameron et al.

WEST

Gravel

Water Table

Saline Water

Cu Deposit

Porphyry

Fracture Zone

Soil Copper Anomalies

EAST

Andesite Basement

Meteoric Water
Spence porphyry Cu deposit, Northern Chile

Surface regolith samples; weak selective extraction

Burial under 250m of Tertiary gravels

Vertical fracture with saline soil

500 m

Spence Deposit

Eastern Fracture Zone

Cu

0

15 ppm

0

2 ppm

0

0.6 %

0

Na
Dispersion models – gases and aerosols

Deployment arrangement

Collector assembly

polystyrene-coated glass slide

Clay in droplet

NaCl + Na$_2$CO$_3$

Amorphous silica

Rutherford et al., (2005)
Osborne Cu-Au deposit, Qld

Plus a range of other transition and group I and group II elements

Ore Zone

Cl

K

Fe

Cu

ng cm$^{-2}$

0 500 1000 1500 m
Dispersion models – electrochemical

Cathode: \(15O_2 + 30H_2O + 60e^- \rightarrow 60OH^-\)

Anode: \(4FeS_2 + 40H_2O \rightarrow 4FeO.OH + 76H^+ + 8SO_4^{2-} + 60e^-\)

Zone of increased cation conc. created by organic chelation of diffusive flux

Zone of increased cation conc. created by electrochemical migration

Equipotential lines

Govett, 1977
Smee, 1983
A horizon

B horizon

Clay

Volcanic Rocks

Zn

Cd

Oxidation Zone

Low pH

Carbonate Loss

Zn$^{2+}$ + Cu$^{2+}$ + Fe$^{2+}$

Reduced Column

Sulphide

Water Table

pH

Ca, REE

Hamilton, 1998
Mandamah, NSW

Transported Regolith

Lower Saprolite

Andesite

50 m

30 m

MACD 312

MHACD 228

206m @ 0.51 g/t Au
0.37 % Cu
+ Mo

Ser-py alt

Ser-ohmt-alb alt

Mandamah
30 cm depth, pH 5 K-acetate

Northern block

Central block

Southern block

ppm

Ca
Mg
Ce
Mo
Cu

mineralisation
Dispersed models - vegetation

McKinnons deposit, Cobar
- Alluvial fill
- Pediment
- Mixed pediment / alluvium
- Saprolite
- Au mineralised structure

Cypress pine needles

As (ppm)

Au (ppb)

Saprolite

Cohen et al, 1996
Case study at Pebble, Alaska
Total resources: 10.78 B tonnes
80.6 B lbs Cu
5.6 B lbs Mo
107.4 M oz Au
+ Pd, Re

Surface exposure

From Eppinger and Kelley, 2012
PW shallow, lower grade
PW covered by glacial deposits, 0-50 m thick
PE has Cover Sequence plus glacial deposits

From Eppinger and Kelley, 2012

After Gregory et al, 2012
From Eppinger and Kelley, 2012
Chimborazo porphyry Cu, Chile

**Cu**
- 0 ppm
- 0.8 ppm
- 1.2 ppm

**As**
- 0 ppm
- 0.0 ppm
- 1.0 ppm

**Ave**
- 0.0
- 0.8
- 1.2

7-point moving
- As average
- As variance

Aqua Regia

Gravel
- Libra zone
- Virgo zone
- Supergene enrichment
- Monzonite porphyry
- Porphyrytic andesite
Regional Geochemical Mapping

Copper in Topsoil

Aqua regia / ICPOES
837 samples

Cu mg/kg

0 500 km

Major Cu deposits

FOREGS
Geochemical Atlas of Europe
1 sample per 3,000 km²

Modified from www.gtk.fi/publ/foregsatlas/ and Plant et al. (2007)
Ammonium acetate/EDTA ("bioavailable")

Zn

- <0.13 mg/kg
- 0.13 - 0.28
- 0.28 - 0.57
- 0.57 - 1.17
- 1.17 - 2.15

Aqua regia ("total")

Zn

- <25 mg/kg
- 25 - 50
- 50 - 222

Till, fine fraction

Zn (mg/kg)

Atlas of Finland
Aqua regia ("total")
Zn

- <25 mg/kg
- 25 - 50
- 50 – 222

Ammonium acetate/
EDTA
("bioavailable")
Zn

- <0.13 mg/kg
- 0.13 - 0.28
- 0.28 - 0.57
- 0.57 - 1.17
- 1.17 - 2.15
Fine fraction
Top of sediment

Pb

max 1,090

- □ >53 mg/kg
- + 11 – 53
- • 7.3 – 11
- • 4 – 7.3
- ○ 0.8 – 4
- ○ <0.8
Geology of Cyprus (simplified)

- Quaternary
- Circum-Troodos Sedimentary Sequence
- Keryneia Terrane
- Mamonía Terrane

Troodos Ophiolite Complex & Arakapas Transform Sequence

- pillow lavas
- mafic units
- ultramafic unit
Sulphide, chromite & asbestos mines

Troodos Ophiolite Complex & Arakapas Transform Sequence

- Pillow lavas
- Mafic units
- Ultramafic unit

- Skouriotossa & Apliki
- Alestos & Memi
- Agrokipia, Kokkinoyia & Kokkinopesula
- Peristerka, Pytharochoma, Kokkinonero & Kapedhes
- Mathiatis Sth
- Sha
- Kalavasos
- Maghaleni
- Troulli
- Limni, Evloymeni, Uncle Charles & Kinousa
- Kannoures
- Hadjipavlou
- Amiantos
- Agios Minas
- Kokkinorotsos
- Kokkino-rotsos
- Kannoures
- Hadjipavlou
- Amiantos
- Agios Minas
- Kokkinorotsos
- Kokkino-rotsos

Cu (%)
- <1
- 1–2
- 2–3
- 3–4

Zn (%)
- <1
- 1–2
- 2–3
- 4–9

Chromite
Asbestos
Sampling site

- Polis
- Lemesos
- Lefkosia
- Keryneia
- Ayia Napa
- Ammochostos
- Larnaca

WGS84 36N

33 °E

34 °E

35 °N

440000 460000 480000 500000 520000 540000 560000 580000 600000 620000 mE

3820000 3840000 3860000 3880000 3900000 3920000 mN
Lead
Aqua regia ICP-MS

Top soil
(0 – 25 cm)

Sub soil
(50 – 75 cm)

Pb (mg/kg)

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530
Zinc
Aqua regia ICP-MS

Top soil
(0 – 25 cm)

Sub soil
(50 – 75 cm)

5,377 samples

Zn (mg/kg)

D_{int}

D_{targ}

400
110
93
85
76
64
58
55
45
36
25
Lefkara Fmn (deep marine chalks)

Top soil (0 – 25 cm)

Barium
Aqua regia ICP-MS

5,377 samples

\[ D_{int} \]
Cu*As*In*Pb*Zn index
Aqua regia ICP-MS

5,377 samples

Top soil
(0 – 25 cm)

Cu Mines

Skouriotossa

Limni, Evloymeni, Uncle Charles & Kinousa

Apliki

Alestos & Memi

Kokkinoyia & Kokkinopesula

Kokkinonero & Kapedhes

Agrokipia

Peristerka, Pytharochoma, Mathiati Sth

Kalavasos

Peristerka, Pytharochoma, Kokkinonero & Kapedhes

Lefkosia

Vassiliko industrial site

Lemesos

Limni, Evloymeni, Uncle Charles & Kinousa

Pafos

Larnaca

Sha

Maghaleni

Index

10,000
500
300
200
150
120
80
50
25
15
10
Cu ar-ICPMS (mg/kg)

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<th>All</th>
<th>50%</th>
<th>25%</th>
<th>10%</th>
<th>5%</th>
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1 sample per 1 km² (2 km² in Troodos)

1 sample per 4 km²

1 sample per 10 km²

1 sample per 20 km²

1 sample per 100 km²

1 sample per 2 km²

1 sample per 10 km²
Rock and regolith formation and modification processes

Geochemical behaviour of elements

Conceptual geochemical models

Geochemical mapping