Metal Dispersion around Porphyry Cu-Mo-Au Deposits: Implications for Fluid Flow and Exploration

Cerro Casale porphyry Cu-Au deposit, Chile

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Transitions and Zoning in Porphyry - Epithermal Districts:
Indicators, Discriminators and Vectors
7 industry sponsors

AMI RA P765A (2008 - 2010)
Geochemical and Geological Halos in Green Rocks and Lithocaps:
The explorer’s toolbox for porphyry and epithermal districts
18 industry sponsors

AMI RA P1060 (2011 - 2014)
Enhanced Geochemical Targeting in Magmatic-Hydrothermal Systems
21 industry sponsors
From Holliday and Cooke (2007), with inspiration from Sillitoe and Thompson (2006)

Epidote: basic field techniques

- Map epidote’s distribution
  - Largest deposits have the largest propylitic halos
  - Epidote veins are more abundant close to the deposit centre
  - Larger deposits have intensely developed epidote stockworks

- Map mineral associations
  - Epidote + actinolite – higher temperature (proximal)
  - Epidote + chlorite – lower temperature (distal)
  - Pyrite + epidote typically occurs close to mineralisation

- Watch for colour changes
  - Pink – high Mn epidote
  - Orange – high Pb epidote
**Epidote Chemistry**

Epidote group minerals:

\[ \text{A}_2\text{B}_3(\text{SiO}_4)_3(\text{OH,F}) \]

- A - Ca, Ce, Pb, Sr, Y
- B - Al, Fe, V, Mg, Mn
  + REE & other assorted “metals”

Solid solution:

- \( \text{Ca}_2\text{Al}_3\text{Si}_3\text{O}_{12}(\text{OH}) \) - \text{clinozoisite} to
- \( \text{Ca}_2\text{Fe}^{3+}\text{Al}_2\text{Si}_3\text{O}_{12}(\text{OH}) \) - \text{epidote}
Epidote LA-ICP-MS Analysis

Luzon Central Cordillera, Philippines

Baguio District
2.7 Mt Cu, 35 Moz Au

Mankyan District
7.69 Mt Cu, 37 Moz Au

Cooke et al. (in review)
Baguio District, Philippines

- Black Mt Kennon: 47Mt @ ~0.38% Cu, 0.35g/t Au & 0.01% Mo.
- Southeast: 15mt @ ~0.37% Cu & 0.26g/t Au.
- Nugget Hill: Rock chip assays up to 1.17% Cu and 4.58g/t Au.

Epidote Mineral Chemistry

- $n_{(max)}$ epidote = 3,521
- $n_{(max)}$ whole rock = 985

Legend:
- Whole rock – mean
- Whole rock – p. 75
- Whole rock – median
- Epidote – mean
- Epidote – p. 75
- Epidote – median
- Epidote – p. 25

Concentration (ppm)

- Na, Mg, K, Ti, Ba, Zr, Cu, Ce, Y, Nd, La, Yb, Mo, Bi
Epidote is significantly enriched in As, Sb and Pb in the distal halo to porphyry deposits.
Metal enrichment in epidote: lateral fluid migration and depletion of $H_2S$

Potassic zone ($H_2S, SO_4^{2-}$ available)
- High $T$ (> 450°C):
  - Deposition of Cu-sulfides and Au
  - Most other metals too soluble to precipitate
  - High aqueous sulfate contents cause Ca deposition as anhydrite
  - Epidote not stable

Pyrite halo ($H_2S$ abundant)
- Moderate $T$ (<450°C):
  - Deposition of pyrite, minor chalcopyrite
  - As, Sb and Pb scavenged by pyrite
  - Epidote enriched in Y and REEs
  - Epidote also incorporates Zr, minor Sn, trace Cu, Mo

Green rock halo ($H_2S$ exhausted)
- Moderate - low $T$ (220 – 350°C)
  - As, Sb and Pb substitute into epidote when sulfides are no longer being deposited
  - Mn substitutes into epidote due to the similar ionic radius to Fe$^{3+}$

The most highly productive porphyries flux the most metals

As (ppm)

![Graph showing As (ppm) distribution with various transects and alteration zones marked.](image)
Epidote chemistry (outside pyrite halo of productive porphyry):
- Pb, As, Sb, La, Y, Zr elevated
- Cu, Zn, Sn, Mo depleted

Epidote chemistry (inside pyrite halo of productive porphyry):
- Cu, Sn, Mo, Bi, Zn elevated

Lithocap (pyrite-rich stratabound domains of advanced argillic and residual silicic alteration: chargeability high, magnetic low, silica zone defines a resistivity high)

Enargite-rich high-sulfidation mineralization (Fault-hosted and/or stress-transported Cu-Au-Ag, potential EM anomaly)

Pyrite halo (root zones of lithocap - chargeability high, Zn-Pb-Mo geochemical halo)

The Lithocap Environment

Propylitic halo (epidote subzone)

The Green Rock Environment

Propylitic halo

Composite porphyry stock
 Alteration Assemblages

Lithocap & associated clay-altered root zones
argill: advanced argillic & phyllic-altered & silicified rocks

Propylitic (chlorite sub-zone: chl-py-ab-cblpy)

Propylitic (epidote sub-zone: epi-chl-py-ab-cblpy)

Propylitic (actinolite sub-zone: aci-epi-chl-py-ab-cblpy)

Potassic (bi-K-fsp-arth-bn-cp-Austpy)

From Holliday and Cooke (2007), with Inspiration from Sillitoe and Thompson (2006)
1) Acidic magmatic condensates cause AA alteration
2) Introduction of metalliferous metals

Lithocap Mineralogy

Unaltered Chlorite-rich rock
Montmorillonite-rich rock
Ferro-kaolinite rock
Vuggy/residual quartz
Quartz-alunite

Clay alteration zone
Magnetic brine (incl. HCl, SO2)

K-alteration
Vuggy quartz
Rocks and minerals (fluorite, clays, micas)
**AA Alteration Mineralogy**

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz</td>
<td>SiO₂</td>
</tr>
<tr>
<td>Alunite</td>
<td>KAl₃(SO₄)₂(OH)₆</td>
</tr>
<tr>
<td>Kaolinite</td>
<td>Al₂Si₂O₅(OH)₄</td>
</tr>
<tr>
<td>Halloysite</td>
<td>Al₂Si₂O₅(OH)₄</td>
</tr>
<tr>
<td>Dickite</td>
<td>Al₂Si₂O₅(OH)₄</td>
</tr>
<tr>
<td>Pyrophyllite</td>
<td>Al₅Si₄O₁₀(OH)₂</td>
</tr>
<tr>
<td>Diaspore</td>
<td>AlO(OH)</td>
</tr>
<tr>
<td>Topaz</td>
<td>Al₂SiO₄(F,OH)₂</td>
</tr>
<tr>
<td>Zunyite</td>
<td>Al₁₃Si₅O₂₀(OH,F)₁₈Cl</td>
</tr>
<tr>
<td>Dumortierite</td>
<td>Al₆.₅₂BO₃(SiO₄)₃(O,OH)₃</td>
</tr>
<tr>
<td>Corundum</td>
<td>Al₂O₃</td>
</tr>
<tr>
<td>Andalusite</td>
<td>Al₂SiO₅</td>
</tr>
<tr>
<td>Cordierite</td>
<td>Mg₂Al₄Si₂O₁₈</td>
</tr>
</tbody>
</table>

**Filter WR Geochemistry**

- use samples with < 0.1% Cu,
  < 0.1ppm Au and contain alunite

Mineralization at a later stage
Alunite Mineral Chemistry

KAl₃(SO₄)₂(OH)₆

Al > Fe  Fe > Al

alunite KAl₃(SO₄)₂(OH)₆  jarosite KFe₃(SO₄)₂(OH)₆
natroalunite NaAl₃(SO₄)₂(OH)₆  natrojarosite NaFe₃(SO₄)₂(OH)₆
minamiite (Na,K,Ca)₂Al₆(SO₄)₄(OH)₁₂  hydronium jarosite (H₃O)Fe₃(SO₄)₂(OH)₆
huangite Ca₂Al₄(SO₄)₄(OH)₁₂  argentojarosite AgFe₃(SO₄)₂(OH)₆
walthierite BaAl₆(SO₄)₄(OH)₁₂  beaverite Pb(Fe,Cu)₃Fe₃(SO₄)₂(OH,H₂O)₆
ammonioalunite NH₄Al₃(SO₄)₂(OH)₆  ammoniojarosite (NH₄)Fe₃(SO₄)₂(OH)₆
schloessmacherite (H₃O,Ca)Al₃(SO₄)₂(OH)₆  plombojarosite PbFe₆(SO₄)₄(OH)₁₂

Variations in K, Na and trace element contents (e.g., Pb, La, etc.)

Alunite 1480nm Spectral (SWIR) Feature

Higher Na/(Na+K) ratio indicates higher formation temperature

Correlation coefficient = 0.84
Trace Elements in Alunite

K, Na, Ag, Tl, NH₄, H₂O, Ca, Ba, Pb, Hg, Sr, Zn, Cu, Rb, Ag, Th, Bi, REE

DG₃(TO₄)₂(OH,H₂O,F)₆

Sn⁴⁺, Al, As³⁺, Fe³⁺, Cr³⁺, V³⁺, Ga, Mg, Mn, Cu²⁺

S⁶⁺, As⁵⁺, Cr⁶⁺, Sb, P⁵⁺

Mankayan

Linked porphyry and lithocap parts of system; lithocap hosts HS ore

Mineralisation 1.4 Mt
1.2 to 0.5 Mt
2.2 to 1.0 Mt
13 to 12 Mt
Cretaceous to Miocene
Chang et al. (2011)

Lepanto HS: >0.9 Mt Cu & 102 t Au Production
FSE porphyry: 650 Mt @ 0.65% Cu & 1.3 g/t Au resource
Victoria veins, 11 Mt @ 7.3 g/t Au + Ag-Cu-Pb-Zn

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Porphyry, lithocap and HS mineralization

Genetic relationship between porphyry and lithocap established (lateral flow to NW): alteration, dating, fluid inclusion, isotope geochemistry study


Dickite ± kaolinite

Quartz-alunite

Dickite ± kaolinite

Alunite absorption peak at ~1480 nm shifts to higher values closer to intrusive centre

Chang et al. (2011)
Alunite composition (LA-ICPMS)

![Sr Composition Map]

Chang et al. (2011)

**Sr**

17 - 545
545 - 1124
1125 - 1870
1871 - 3264
3265 - 6570

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Alunite composition (LA-ICPMS)

![Pb Composition Map]

Chang et al. (2011)

**Pb**

1 - 425
427 - 1207
1208 - 2259
2256 - 4531
4532 - 7868
**Increase:**
- Alunite 1480 pk position
- Alunite La, La/Pb, Sr, Sr/Pb
- Enargite: Au, Te, Ba, Th, As/Sb
- Whole-rock (alunite-bearing only):
  - La/Pb, Sr/Pb, Cu/Hg

**Decrease:**
- Alunite Pb, Ag/Au
- Whole-rock (alunite-bearing only): Pb, Ag, Ag/Au, Hg, Te, As/Zn
- All whole rock: Te, As/Zn

4 km long Lithocap

Mankayan lithocap and ore deposits - schematic cross section

Innovation and Exploration

**Lithocaps**
Fluid Flow: vapour vs brine transport into lithocap
- Exploration: alunite 1480nm peak position, alunite geochemistry and filtered whole rock geochemistry vector to intrusion (heat source) and potential sites for HS/porphyry ore

**Green Rock**
Fluid Flow: metal dispersion related to H2S availability
- Exploration: epidote geochemistry can detect productive porphyry deposits several km beyond the limits of conventional geochemical sampling (outside pyrite halo)
- Epidote texture and chemistry as vectoring tools
- Fertility assessment tool

Bingham Canyon, Utah
District, camp and deposit scale

Geological, mineralogical and geochemical

- VHMS
- SEDEX
- Sediment-hosted Cu
- Sediment-hosted Au (porous)
- Epithermal Au-Ag
- Porphyry Cu-Au-Mo

Gemmell (2007)