Lithocap alteration and sulfidation state evolution of ores over porphyry systems: Insight from volcanic-hydrothermal systems

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Thanks to Kinross Gold Corporation

White Island, New Zealand

- Evolution of hydrothermal alteration and mineralization
  - Advanced argillic alteration: Condensation of magmatic vapor
  - Mineralization of high & intermediate sulfidation state minerals
  - Evolution of magmatic-hydrothermal fluids

High-temperature hypogene vapors, ~850 °C (HCl, SO₂)
Formation of advanced argillic alteration

Lithocap formed by hypogene condensate

Hypogene alteration

HCl, SO2, CO2, H2S

H2SO4, HCl

HCl, SO2, CO2, H2S

Formation of advanced argillic alteration

4 SO2 + 4 H2O => 3 H2SO4 + H2S

H2O, NaCl,

SO2, HCl, CO2, H2S, ...

Schematic reconstruction of the lithocap environment

Early acidic vapor condensate forms leached lithocap, barren

Vuggy quartz

Arribas et al., 2000

(modified from Stilitio, 1999)

Structural root to lithocap

K-silicate alteration

Dense hypersaline liquid

Quartz-dickite/kaolinite

Quartz-alunite

Ilite out to illite/smectite

Porphyry stock

Steam-heated acid leached zone

Igneomprite
Residual (vuggy) qtz and qtz-alunite flares upward

Steven and Ratté, 1960

pH ~ >6 4 - 6 2 - 4 <2

10 - 100s m
Far Southeast – Lepanto, Phillipines: Linked porphyry and epithermal deposits

Mohong Hill quartz-alunite-pyrite lithocap

dacite pyroclastics
volcaniclastic basement

Lepanto cross section:

Early alteration flares upward along structure, and outward from feeder along unconformity

Lithology-controlled lithocap outcrop

Fresh dacite Qtz-alun-py halo Vuggy qtz ore

Enargite-Au ore in residual qtz host
Quartz-alunite-py ± Al-silicate halo

Gonzalez, 1956, 1959; Garcia,
Satsuma Iwojima, S. Kyushu: passive degassing

870 °C H₂O, HCl, SO₂

Summit crater

Sampling of 770 °C vapor with acidic gases, HCl, SO₂
Satsuma Iwojima, Japan

Residual (vuggy) qtz

Hedenquist et al., 1994

dissolved rock

pH 1.1

Satellite image of Satsuma Iwojima, Japan.
Dissociation and increased reactivity due to cooling

$$HCl \rightarrow H^{+} + Cl^{-}$$

$$H_{2}SO_{4} \rightarrow H^{+} + HSO_{4}^{-} + HSO_{4}^{2-}$$

~100 m

Muscovite overprint, transition up to pyrophyllite

150 C, 200 C, 250 C, 300 C, 350 C, 500 C

W:R <10

W:R >10

pH ~1.5, ~0.7, ~1

pH ~2

Long section along Lepanto fault

Lepanto - Far Southeast, Philippines:

(1 Mt Cu, 4 Moz Au; 5 Mt Cu, 20 Moz Au)

Offset of lithocap, and ore, from causative intrusion

Hedenquist et al., 1998

Hedenquist and Taran, 2011
Mankayan district, Luzon:

Lepanto enargite-Au, Far Southeast porphyry Cu-Au, and Victoria veins

Surface projections of Lepanto enargite-Au deposit, Victoria veins, & Far Southeast porphyry

Arribas et al. (1995); Clavera (2001); Hedenquist et al. (2001)
Sulfidation state evolution

Residual quartz (secondary quartzite)
No rock buffer left
e.g., Lepanto, Kochbulak, Bereznyaki

Magmas of bimodal extension

Kovalenker et al., 1997
Hedenquist et al., 1998
Plotinskaya et al., 2009

White Island, New Zealand: Quiescent eruption 1988

Vapor condensates cause acidic leaching.

What more can we learn from volcanic fluids?
Active and extinct volcanic systems

Giggenbach, 1987

Einaudi, Hedenquist, Inan, 2003

RMS-DPI: E2-2011-9-1
http://www.minsoc.ru/E2-2011-9-1
Epithermal deposit endmember chemical environments: Evolution affected by composition of magmatic fluid, and interaction with wallrock (many variations)

Geology of 3 end-member epithermal deposits: high-, intermediate- & low-sulfidation ores

Dr. Glen Masterman, Vice President - Exploration
Kinross deposits

Endowment of Kinross deposits that are >10 Moz (300 t Au)

<table>
<thead>
<tr>
<th>Deposit</th>
<th>Inferred Resource</th>
<th>M + I Resource</th>
<th>2P Reserve</th>
<th>Production (to 2010)</th>
<th>Total Endowment</th>
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<td>Cerro Casale</td>
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<td>3.2</td>
<td>23.2</td>
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<td>Paracatu</td>
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<td>Mansungu</td>
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<td>3.4</td>
<td>6.1</td>
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<td>14.5</td>
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<tr>
<td>Fruta Del Norte</td>
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<td>0.6</td>
<td>6.8</td>
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<tr>
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<td>2.2</td>
<td>3.6</td>
<td>4.9</td>
<td>10.9</td>
</tr>
</tbody>
</table>

Source: Kinross and Red Back Mining Annual Reports and other sources. Deposit figures are quoted on a 100% basis.

View over La Coipa Mine, Chile: to NW

Production: 1989-now, 108 t Au, 6030 t Ag; Resource: 57 t Au, 1770 t Ag
La Coipa, Chile:
Geological characteristics of a high-sulfidation deposit

- **Alteration**
  Steam heated, residual qtz, advanced argillic (alunite), argillic

- **Mineralization Styles**
  Disseminated, breccia, veins, mantos

- **Structural & lithological controls**

- **Hypogene mineralization**
  Native gold and silver, argentite, electrum, proustye, pyrargyrite, pyrite, enargite, tetrahedrite, tennantite, chalcopyrite, bornite, galena, sphalerite: high sulfidation

- **Supergene overprint**
  Native gold and silver, cerargyrite, embolyte, iodargyrite, argento-jarosite

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La Coipa: Ladera Farellón Cross Section

Qtz-alunite with roots of pyrophyllite ± zunyite, diaspore, APS (mica)

Pyrite-enargite (luzonite)-tennantite, pyrite-covellite/digenite, chalcocite/chalcopyrite, (+chalcopyrite, bornite, covellite, galena, sphalerite, tennantite)

(supergene overprint)
Discovery (2006) of the Fruta del Norte epithermal Au/Ag deposit, Ecuador

LOCAL CRUSTAL STRUCTURE
Suarez pull-apart basin

Suarez Fm
Misahuallí Formation (main vein host)
Setting of Fruta del Norte

Cretaceous 119-110 Ma

Fruta del Norte 158-156 Ma

Jurassic 170-190 Ma

FRUTA DEL NORTE – BLIND TARGET – PATH-FINDER GEOCHEMISTRY

Suarez Fm: silicified - As, Sb, Hg, marcasite, BM
Fruta del Norte MINERAL ZONES
Intermediate Sulfidation Epithermal System:
Reserves: 204 t Au (8.1 g/t) Au
LAMINATED SILICA SINTER/MUD POOL DEPOSITS

Stromatolitic texture Laminated silica sinter Mud pool deposit

Champagne Pool, Wai-O-Tapu, New Zealand Sinter terrace and geyser at Rotorua, New Zealand Mud Pool burst at Wai-O-Tapu, New Zealand

FDN-1 Mn-carbonate/rhodochrosite stockworks + BM

7.43 g/t Au, 7.54 M oz (55% of orebody)

TEXTURES: Crustiform-colloform-cockade-ginguro Diatreme breccia (dacite)
FDN-2 Chalcedony marcasite + base metal sulphide
7.31 g/t Au, 3.64 M oz (22% of orebody)

FEATURES: >1% SULPHIDE (marcasite) – blackened fine matrix

FDN-3 Upper silica low sulphide carapace
12.36 g/t Au, 0.4 M oz (2%) of orebody

FEATURES: Depleted in sulphide, enriched in celadonite, locally vuggy
FDN-4 Northern quartz vein zone
6 g/t Au, 2.1 M oz (18% of orebody)
FEATURES:- Bladed carbonate (replaced), adularia – intense stockworks - electrum

FDN1…. 2447 g/t Au

THE GOLD
Okhotsk-Chukotka metallogeny

Kupol regional geology

Initial Occurrence Discovered in 1966 during 1:200,000 Regional Mapping Program

“Orange Occurrence” 3.0 g/t Au, 660.0 g/t Ag
Kupol deposit discovered in 1995 on last prospecting traverse of the season

Slava Zagoskin Deposit Discoverer

Kupol Discovery

Very little outcrop of Kupol Vein. Big Bend was buried under talus and tundra. Vein float present in north and south.
Aerial View of Big Bend  (40% of all gold at Kupol)

Kupol area geology

- Andesite flows and fragmentals
- Trachyandesite flows
- Rhyolite
- Basalt
- Vein and stockwork zones
- Principal faults

Gently eastward dipping andesitic flows and pyroclastics, intruded by rhyolite dikes and flow dome complex
Kupol Longitudinal Section, 2007
(magenta = 100 g\textsuperscript{m} Au)

2003 to 2006, >150,000 m in 700 ddh define >180 t Au
Production, May 2008; development cost, $407 M
End 2010: 69 t Au equil.; Reserves, 75 t Au (10.7 g/t), 948 t Ag

Big Bend

- Single large vein
- Steepening toward surface
- Bisected by rhyolite dikes
North Zone

North and South Zones display near vertical multiple anastomosing veins

Kupol Deposit Section 92352N

Kupol mineralization stages

Early phase of quartz adularia (stained yellow) with minor gold and silver

Second phase of sulfosalts-rich quartz + adularia. Principal Au and Ag rich phase.
Kupol “Bonanza” styles of mineralization

289 g/t Au, 3336 g/t Ag

Examples of high grade sulfosalt-rich colloform & crustiform banded veins and breccias

237 g/t Au, 4291 g/t Ag

Main Ore Mineralogy

- Electrum, Native Gold, Native Silver
- Sulfosalts:
  - Stephanite (Ag$_3$SbS$_4$)
  - Pyrargyrite (Ag$_3$SbS$_3$)
  - Tetrahedrite (Cu$_{12}$Sb$_4$S$_{13}$)
  - Freibergite (Ag,Cu,Fe)$_{12}$Sb$_4$As$_4$S$_{13}$
  - Perceite (Ag, Cu)$_{16}$As$_2$S$_{11}$
- Sulphides:
  - Acanthite (Ag$_2$S)
  - Pyrite
  - Marcasite
  - Chalcopyrite
  - Sphalerite
Low sulfidation deposit indicators: Vein formation at neutral pH

Amorphous silica deposition
Cyclic crustiform and colloform banding

Sulfosalt rich (ginguro) bands abundant

Hishikari
Kyushu, Japan:
330 t Au, 40 g/t

1000-4000 g/t Au
~20 g/t Au
<1 g/t Au
Kyushu tectonic evolution

Y. Watanabe, 2004

- Tectonics influence type of epithermal Au deposit (early HS, IS, or later LS)
- Variable features, no single deposit type

Hishikani (LS) 0.7 Ma
Kushikino (IS) 3.7 Ma

Migration of volcanism

Epithermal deposit styles

- Endmember styles can have a wide range of characteristics
- Variations caused by:
  - Tectonic setting
  - Magmatic affiliation
  - Depth of formation and structural control
  - Degree of wallrock influence on paths of fluid evolution
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