Lithocaps and high-sulfidation epithermal deposits

- Principal characteristics
- Origin of features, background
- Case examples, variations

Types of epithermal deposits

3 endmember types

- **High sulf’n bodies**: Cu-Au-As, sulfide rich, andesite arcs
  - Hosted by lithocaps: advanced argillic zones over porphyry systems

- **Inter. sulf’n veins**: Ag-Au ± Zn-Pb, sulfide rich, andesite arcs
  - Zoned and/or complex mineralogy (intrusion related, diatreme)
  - Variable Au:Ag:bms (Mexican): transitional style, deep magma?

**HS (or lithocap) and IS locally affiliated; also deeper porphyry**

- Low S’n veins: Au-Ag bonanzas, sulfide poor, bimodal setting
  - LS veins: Au-Ag-Te, sulfide poor, alkalic association

Examples of epithermal deposits (w/ porphyry)

- **HS replacements**: Goldfield, Sumitvillie; Sauzal, Mulatos; Quimsacocha; Yanacocha, Pierina, Alto Chicama, Aruntani; El Indio, La Coipa, Pascua-Veladero; Chelopech, Bor; Chinkuashih, Lepanto
  - Barren lithocaps: common, W, US, Andes, Asia, etc. (Shuteen)

- **IS veins**: Comstock, Creede; Mexican Ag; Andean (“Cordilleran”), Quirivilca, Arcata; Fruta del Norte; San Jose; Victoria, Baquita; Kellian; Kushikino, Toyoha; Rosia Montana, western Tethys

- **LS veins**: Midas, Sleeper; El Peñón; Esquel; Hishikari; Kupol; Ovacik, Efemçukuru (?)
  - LS veins, alkalic: Cripple Creek, Emperor, Porgera, Ladolam

**Epithermal Au-Ag Deposits - Grade and Tonnage**

Epithermal deposits display inverse relationship between tonnage and grade with several small, very high grade deposits and other larger, low grade deposits, reflecting deposit form (veins vs disseminations).

**High grade**
- El Indio, Chile (E.Indo) 0.106B, 2.17B gramton Au
- Hishikari, Japan (H) 5.2 Mt, 69 gramton Au

**Low grade**
- Round Mountain, Nevada (RM) 90 Mt, 1.2 gramton Au
- Yanacocha, Peru (Ya) nearly 1 B, 1.2 gramton Au

Three epithermal deposit types to model / target:
I. Low-grade, disseminated, oxidized or leachable ore
II. Medium-grade, unoxidized and refractory deposit
III. Structurally controlled, high-grade veins or lodes
Geologic setting of HS (and IS) deposits

Circum Pacific, 44 deposits

Neutral - mild extension, calc-alkaline andesite-dacite arcs
- 22 Volcanic domes (single, complex, summit; not host)
- 12 Central vent volcanoes (including IS)
- 3 Calderas
- 4 Diatremes
- 10 Insufficient information

Hosts: A/D flows, bxs, ignimbrites, intrusions, seds

LS deposits: Bimodal (rhyolite domes-basalt dikes) in extensional settings:
- Intra, near, and backarc; postcollision rifts (non porphyry)

Arribas, 1995; White et al., 1995; Sillitoe, 1999; pers. obs.

Formation of advanced argillic alteration: hypogene & steam heated

Steam-heated blanket

Lithocap formed by hypogene condensate

H₂S + 2 O₂ → H₂SO₄  pH >2

H₂SO₄, H₂S  pH <1

4 SO₂ + 4 H₂O → 3 H₂SO₄ + H₂S

H₂O, NaCl, SO₂, HCl, CO₂, H₂S, ...

Steam-heated alteration

HCl, SO₂, CO₂, H₂S hypogene alteration

Arribas et al., 2000

Schematic reconstruction of the lithocap environment

Steam-heated acid leached zone

Vuggy quartz

Ignebrite

Quartz-dickite/kaolinite

Quartz-alunite

Structural root to lithocap

K-silicate alteration

Dense hypersaline liquid

Porphyry stock

CO₂, H₂S

H₂S + 2 O₂ → H₂SO₄

H₂SO₄, HCl

CO₂, H₂S

HS ore deposits

Inferred depth of formation

Shallow
Intermediate
Deep

Sillitoe, 1999

Lithological control

Hydrothermal breccia control

Structural control
Epithermal alteration, gangue minerals

- **HS replacements:** silicic host, quartz-alunite halo
  (kaolinite, dickite, pyrophyllite, diaspor, topaz, etc.); alunite, barite, anhydrite
- **Barren lithocaps:** silicic core, quartz-alunite halo
- **IS veins:**
  "sercite" (muscovite); quartz, rhodochrosite, barite, anhydrite
- **LS veins:** illite, clays; chalcedony, adularia, calcite

**Mineral:**
- Alunite
- Jarosite
- Halloysite
- Kaolinite
- Dickite
- Pyrophyllite
- Diaspor
- Zhurilite, topaz
- Muscovite
- Anhydrite
- Covellite, Quarts Pyrite
- Muscovite
- Sphalerite
- Illite-smectite
- Chlorite-smectite
- Illite
- Chlorite
- Epidote
- Biotite
- Adularia
- Calcite
- Monticellite
- Larimarite
- Wavellite

**Epithermal ore deposition**

- **LS, shallow (<300-400 m):**
  - <220-230°C
- **IS, deeper (>300-800 m):**
  - >220-230°C

**Schematic reconstruction of the lithocap environment**

- Steam-heated acid leached zone
- Early acidic vapor condensate forms leached lithocap, barren
- Vuggy quartz
- Iilite out to illite/smectite
- Quartz-dickite/kaolinite
- Quartz-alunite

**Schematic reconstruction of a high-sulfidation deposit**

- Steam-heated acid leached zone
- Later metal-rich phyllic stage; liquid may ascend to lithocap
- Disseminated Au-Ag in vuggy quartz
- Iilite out to illite/smectite
- Quartz-dickite/kaolinite
- Quartz-alunite
- Au-aurichalcite in vuggy quartz
- Au-tennantite in vuggy quartz
- Barren intermediate argillic alteration (sercite up to pyrophyllite)
- Late dense lower salinity fluid
- Chalcopyrite in K-silicate alteration

**Image credits:**
- Hedenquist et al., 1996, 2000
- Arribas et al., 2000
HS and IS deposits: sulfide assemblages

- Lithocaps and high sulf'n: Cu-Au-Ag
  - Initial leaching: vuggy qtz, qtz-alun lithocap w/ crs py, <50 ppb Au
  - Barren lithocap

  - Stage 2a: py (fn)–enargite–Iz-fm

- Intermediate sulf'n veins: Ag-Au ± Pb-Zn
  - Py–low-Fe sph–tn/td–ccp–gn, ± Te

Close similarity between HS and IS fluids, distinction from LS related to volcanotectonic setting

Barton et al., 1977, John, 2001, Einaudi et al., 2003
**Summitville, Colorado:**

Alteration zoning and ore bodies within dome; strong structural control

*after Gray and Coolbaugh, 1994*

**Residual (vuggy) quartz and quartz-alunite flares upward**

**Steven and Ratté, 1960**

**pH ~ 4-6 2-4 <2**

**Residual quartz, vuggy: Summitville Quartz-alunite, Summitville**

*Arribas et al., 2000*

**Residual quartz, vuggy: Pierina**

**Quartz-alunite, Summitville**

**Residual quartz, vuggy: Tucar**
White Island, New Zealand: High to low T fumaroles

Steam-heated acid sulfate waters: can also occur over hypogene acidic fluids

~110 °C

High-temperature hypogene vapors, ≤850 °C with HCl, SO₂

Steam-heated zone, ~100 °C (CO₂, H₂S)

La Coipa, Chile: Looking NW; sedimentary host to residual quartz

Coipa Norte: Steam-heated cristobalite-alunite-Kaolinite blanket over residual quartz zone

H₂S + 2 O₂ = H₂SO₄
Steam-heated alunite-kaolinite

Puren, Chile

Puren Norte, 1.5 Moz Au eq.

Vadose zone: steam-heated blanket

Shallow geochemical anomalies (Ag, ...)
Supergene alunite, Rodalquilar

Rodalquilar, Spain: looking ~east

Arribas et al., 1995

Drilling beneath supergene alunite blanket; a mistake here....

Arribas et al., 2000

Steam-heated advanced argillic blanket, La Coipa

Supergene alunite, Rodalquilar

Massive supergene alunite, Rodalquilar; post-mineral weathering oxidation

Supergene oxidation critical to economics!
Sonomi volcano

Inset: qtz-alun halo, sharp ctc with vuggy qtz, to r.)

Urashima et al., 1981

Tuff breccia
Nansatsu Group

Arabira rebody: Structural control to alteration and ore (in feeders)

Iwato, S Kyushu, looking east: Iwato HS deposit, Maruyama pit

Inset: qtz-alun halo, sharp ctc with vuggy qtz, to r.)
Mulatos, Mexico:
"Residual quartz is steep", and must be sampled
Exploration and discovery histories: Use of models

EL DEPOSITO EPITERMAL DE Au, Cu, Ag
QUIMSACOCHA, PROVINCIA DEL AZUAY, ECUADOR

Strong lithologic control to residual quartz lithocap: tuffs

“Stacked” lithocaps!

“Stacked” lithocaps, upper barren...!

Diatreme breccia w/ porphyry Cu fragments

Quimsacocha

Vuggy Qtz: IQD 122
235.9m 3.87 gr/t Au

Vuggy Qtz: IQD 122-136 m
16.95 gr/t Au, 68.5 gr/t Ag
Quimsacocha, ~ 3.3 Moz Au (2.1 Moz at 6.5 g/t Au, UG): drill sufficiently deep to test system

Longitudinal section, N-S

Pierina, Peru:
Yanacocha oblique aerial to NE

Chouinard et al., 2005

Alteration sections, NW-SE and SW-NE

Chouinard et al., 2005

Mineralization sections, NW-SE and SW-NE

Chouinard et al., 2005
Cajamarca District

Tertiary volcanic rocks

Perol-Cocanes

Cerro Yancocha

Cajamarca District

Paleozoic-Mesozoic sedimentary rocks

40 km

Gustafson et al., 2004

Cretaceous-Tertiary intrusive rocks

Tertiary volcanic rocks

Yanacocha cluster

Cerro Yanacocha; 25 Norte, Oeste, Sur, Encajon (Verde - sulfide)

Cerro Negro; 1

Tapado-Corimayo; 4

La Quinua; 9

Oeste

Encajon

San Jose; 4

Kupfertal porphyry: KUP-3

Leach pad

Yanacocha ore bodies: Moz gold resources

Chiquindacta

Cerro Yanacocha; 25 Norte, Oeste, Sur, Encajon (Verde - sulfide)

Cerro Negro; 1

Tapado-Corimayo; 4

La Quinua; 9

Oeste

Encajon

San Jose; 4

Kupfertal porphyry: KUP-3

Leach pad

Yanacocha ore bodies: Moz gold resources

5 km

5 km

Cerro Regalado

Cerro Yancocha; 25 Norte, Oeste, Sur, Encajon (Verde - sulfide)

Cerro Negro; 1

Tapado-Corimayo; 4

La Quinua; 9

Oeste

Encajon

San Jose; 4

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Encajon

San Jose; 4

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Leach pad

Yanacocha ore bodies: Moz gold resources
From Longo, 2005; and Perol and Cocañez dates from Gustafson et al., 2004

- 8.2 – 9.2 Ma (Yanacocha Complex)
- 10 – 10.5 Ma (San Jose)
- 10.7 – 11.1 Ma (Corimayo-Carachugo-Tapado)
- 11.5 – 13.5 Ma (Cerro Negro, Quilish)
- 15.8-16.1 Ma (Perol porph, Cocañez litho)

Longo et al., 2010

- Late dacite
- Alunite

Yanacocha district: General stratigraphic column and petrogenesis
2 km

Hydrothermal breccia body
Lithologic horizon (70% of ore in welded pyroclastics)
Margin of dome intrusion

Yanacocha Norte

Gold deposited in leached core of deposits

Yanacocha Norte altertation section 9228200 N

220-ton haul truck
Dome moat, laminated siliceous sediments, paleosurface...

Chaquicocha, Carachugo

SAN JOSE SUR SCHEMATIC ALTERATION SECTION 9225000 N

San Jose Sur Schematic Alteration Section 9225000 N

Chaquicocha

Cross Section SW-NE
**Yanacocha district: geochemistry** (Bell et al., 2005; Teal, 2008)

**KUPFERTAL PORPHYRY**

- **Level of blind deposits** (Corinayo, Tapacito)
- **Level of outcropping deposits** (Carre Yanacocha, Canacheco, San Jose and others)

**Two origins (environments) of hypogene pyrophyllite:**

1) **Vapor condensation**
   - Lithocap environment (roots)
   - Silicic (vuggy), alunite halo, hotter pyrophyllite (below)

2) **Simple fluid cooling**
   - Cooling: muscovite (A) to pyrophyllite (B) (gusano replacement of silicide) to dickite (C)

\[ 2KAlSi_3O_8(OH)_2 + 2H^+ + 8SiO_2 = 3Al_2Si_5O_10(OH)_4 + 2K^+ \]

**Milagros Garcia, 2009**

**Fault contact between epithermal and porphyry alteration at Kupfertal**

- 185.3m: pyrophyllite, minor alunite
- 205.6m: pyrophyllite, alunite
- 210.6m: pyrophyllite, kaolinite
- 215.3m: Muscovite
- Breccia: from 181.5m

**DDH KUP-3**

- Epithermal
- Porphyry
- Porphyry-style quartz veins with phyllic alteration
Patchy texture outcrop

Milagros porphyry prospect, Alto Chicama, Peru

Garia, 2009

Residual quartz (silicic) and advanced argillic size matters...

...much of the time, cf. El Indio

Arribas et al., Gold in 2000

El Indio: Chile
El Indio: high-sulfidation massive enargite with late, high-grade (IS-type) quartz-pyrite-gold veins with white mica halos

surface at 4100-4200 m

Jannas et al., 1990

El Indio 3500 vein: quartz-pyrite-Au (tn-ccp) with mica halo, post enargite

DSO: 200 g/t Au average (cutoff 100 g/t, 1.5 Moz of 8 Moz)

Jannas et al., 1990, 1999

Bonanza ore in HS deposits: late IS stage, common creamy Qtz (chalcedony), i.e., silica gel due to sharp cooling (cf. LS bonanza)
Solubility of silica polymorphs in epithermal environment

High-grade HS hydrothermal breccia ore, associated with creamy chalcedony

NB: Mixing will not cause amorphous silica saturation and colloform gels

Variations on a theme: Huge (but barren) lithocap, Masupa Ria, Kalimantan

- Minas Conga: Perol porphyry (15.8 Ma), east of Yanacocha (5-12 Ma)
- Co. Cocañez: Barren quartz-alunite lithocap (16.1 Ma), related to Perol porphyry??
- Multiple porphyry vein generations (parallel to silicic ribs in lithocap)
Exploration: Lithocaps, high-sulfidation ores, and tops of porphyry deposits

- Regional: Tectonics, permissive geology (mines)
- District: Alteration, geochemistry
- Prospect: Map
  - Lithology (potential lithocaps), stratigraphy (favorable), structure (identify feeders)
  - Alteration (mineralogy, zoning), erosion level
  - Chip and channel silicic (barren lithocap?)
  - Geophysics: right tool in right place, integrate
  - Drill targets (integrate structure, stratigraphy, alteration, etc.)
  - Assess, reinterpret, drill again