**Formation of high- and low-sulfidation deposits**

**Tonopah, NV: 1901 to late 1920s+, 1.9 Moz Au, 174 Moz Ag**

Ag-Au intermediate-sulfidation vein

**Environments and variations of epithermal gold deposits**

1) Characteristics, active analogues
2) Au-rich veins (low sulfidation): Rifts
3) Au-Cu in residual vuggy quartz (high sulfidation): Arcs

**Exploration implications**

Champagne Pool
WaioTapu, New Zealand

Orange precipitates with hot spring sinter ~ 80 g/t gold

Jeffrey W. Hedenquist
Ottawa, Canada
Types of epithermal deposits

3 endmember types: two in volcanic arcs, 1 in rifts

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

- **Intermediate sulf’n veins**: Ag-Au ± Zn-Pb, sulfide rich, andesite arcs
  - Zoned and/or complex mineralogy (intrusion related, diatreme)

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

- **Low sulf’n veins**: Au-Ag bonanzas, sulfide poor; extensional, bimodal
  - **LS veins**: Au-Ag-Te, sulfide poor, alkalic association
Taupo Volcanic Zone, New Zealand: A missing link

Looking northeast: volcanic arc to east, rift to west

Waiotapu

Rotokawa

Broadlands geothermal system

FeS₂, CuFeS₂, + 5 wt. % gold
K.L. Brown, 1986

Pilot plant at well head

Broadlands, New Zealand: Missing link
Epithermal alteration, gangue minerals

- **LS veins:** ilite, clays; chalcedony, adularia, calcite
- **HS replacements:** silicic host, quartz-alunite halo (kaolinite, dickite, pyrophyllite, diaspore, topaz, etc.); alunite, barite, anhydrite
  - Barren lithocaps: silicic core, quartz-alunite halo
- **IS veins:** “sericite” (muscovite); quartz, rhodochrosite, barite, anhydrite

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Hedenquist et al., 1996

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Champagne Pool, Waiotapu: Silica sinter around vent

Diagnostic textures: evaporative growths, algal stromatolites
Fine laminations, plant fragments, lack of rock textures are only permissive...

Fruta del Norte, Ecuador
Another missing link
McLaughlin, California:
LS sheeted veins below sinter;
old Hg mine (trace Au)

Hydrothermal breccia with sinter clasts
Sheeted vein

Silica sinter

H₂S + 2O₂ = H₂SO₄
Steam-heated

Sheeted gold-quartz vein below sinter
Formation of high- and low-sulfidation deposits

Kyushu epithermal deposits: LS and IS veins

Tectonics and age determine type of epithermal Au deposits

Migration of arc (IS or HS), producing rift (LS)

Y. Watanabe (2004)

Hishikari, southern Kyushu

Footprint of 11 Moz Au deposit
Hishikari: Gold-quartz veins in greywacke basement

Izawa et al. (1990)
Outflow down valley to distant hot springs
Old surface, before erosion

Ascent along fractures

Boiling + gas loss = gold deposition

Smectite-chlorite, smectite, kaolinite

Hishikari
Kyushu, Japan

1000-4000 g/t Au
~20 g/t Au
<1 g/t Au

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**Formation of high- and low-sulfidation deposits**

**SEG Nevada: May 2013**

**Sleeper, Nevada: 1.7 Moz prod (>1 Moz on surface)**
Open pit, encircled by infrastructure (looking SE)

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**Sleeper mine blast hole Au contours**

*Courtesy of X-Cal*
Formation of high- and low-sulfidation deposits

SLEEPER PIT
Long section 16
(blast hole data, 50’)

1 cm

200 m

Opt

0.05 - 0.10
0.10 - 0.25
0.25 - 0.50
0.50 - 1.0
>1.0

Courtesy of X-Cal

Dendrites = colloidal Au
Colloform qtz = colloidal silica gel

COURTESY OF JIM SAUNDERS

Round Mountain, NV: Disseminated LS deposit, >13 Moz Au
(with high grade veins, both over and below)  Saunders and Einaudi, 1990
Formation of high- and low-sulfidation deposits

Saunder and Einaudi, 1990

2005 open pit

Round Mountain: Geology

Saunder and Einaudi, 1990
Formation of high- and low-sulfidation deposits

Saunder and Einaudi, 1990

Quartz-adularia-sericite

Argillic

Silicification

Round Mountain: Alteration

Round Mountain: Gold and model

Saunder and Einaudi, 1990
Formation of high- and low-sulfidation deposits

SEG Nevada: May 2013

J.W. Hedenquist

Sillitoe and Hedenquist, 2003

Porphyry systems: arcs

High-sulfidation Au-Cu

Intermediate sulfidation Au-Ag (Pb-Zn)

Base of lithocap

Replacement Zn-Pb-Ag

Sillitoe, 2010

Economic Geology

5 km

Sillitoe, 2010

Economic Geology
White Island, New Zealand: Quiescent eruption, 1988

≤800°C hypogene vapors, HCl, SO₂

Metal flux from magma, 10,000 yr life: 300 t Au, 1 Mt Cu

White Island, New Zealand: fumaroles

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

~110 °C

Steam-heated zone, ~100 °C (CO₂, H₂S)
Formation of high- and low-sulfidation deposits

Porphyry systems

Sillitoe, 2010

Base of lithocap

Early: High T magmatic
- Coupled brine + vapor
- Potassic (~500°C) + advanced argillic lithocap
- Wavy qtz veins, no halo
- Metal sulfides

pH 1-2, H₂SO₄, HCl

Quartz-alunite, barren

Residual quartz (vuggy), barren

Fluid:rock reaction

White Island, New Zealand: drowned fumaroles, 2007

Satsuma Iwojima, Japan

Residual (vuggy) quartz

pH~0.2

acidic stream, pH ~0.6
Satsuma Iwojima, S. Kyushu: passive degassing

Satsuma Iwojima, Japan

H$_2$O, HCl, SO$_2$

Sampling of 770 C vapor with acidic gases

pH 1.7 -- 1.1

Satellite: Hedenquist et al., 1994

Residual (vuggy) qtz

pH 1.1

dissolved rock

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Summitville, Colorado: Dome-hosted high-sulfidation deposit (0.7 Moz Au)

Steven and Ratté, 1960

\[ \begin{align*}
\text{pH} & \sim >6 \quad 4 - 6 \quad 2 - 4 \quad <2 \\
\text{residual} & \\
\text{qtz} & \\
pH & <2 \\
\text{qtz-alun} & \\
\text{qtz} & \\
\text{alun} & \\
\text{qtz (ore)} & \\
\text{qtz-alun} & \\
\text{alumino-silicates} & \\
\text{(kandites)} & \\
\text{Qtz-alunite rock} & \\
\text{Unaltered rock} & \\
\text{Chlorite-rich} & \\
\text{Montmorillonite-rich} & \\
\text{Ilite-rich} & \\
\text{Kaolinite} & \\
\text{Mineralized vuggy quartz} & \\
\end{align*} \]
Summitville, Colorado: Alteration zoning and ore bodies within dome; strong structural control

after Gray and Coolbaugh, 1994
Nansatsu district, S Kyushu, looking east: Iwato HS deposit, Maruyama pit
Inset: qtz-alun halo, sharp ctc with vuggy qtz, to r.)
Formation of high- and low-sulfidation deposits

**Iwato Deposit, Alteration Plan and Long. Section**

- Tuff breccia
- Nansatsu Group
- Mohong Hill
- quartz-alunite
- lithocap

**Mankayan district, Philippines**

- Mohong Hill quartz-alunite lithocap
- dacite pyroclastics
- volcaniclastic basement
Most ore (~70%) in root zone of lithocap, in Lepanto fault

Lepanto high-sulfidation ores

- Bato dacite
- Imbanguila dacite
- Unconformity
- Dickite-kaolinite
- Quartz-Albite
- Silicic ± enargite
- Lepanto metavolcanic rocks
- Late Oligocene to mid-Miocene Apaoan volcaniclastics
- Slightly younger Balili volcaniclastics

Mankayan: Basement

- Late Oligocene to mid-Miocene Apaoan volcaniclastics
- Slightly younger Balili volcaniclastics
- Qtz diorite porphyry
- Lepanto metavolcanics

Hedenquist et al., 1998; Chang et al., 2011

Chang et al., 2011
Formation of high- and low-sulfidation deposits

SEG Nevada: May 2013

J.W. Hedenquist

Pliocene volcanism
3.3 - 1.8 Ma, multiple eruptions

Chang et al., 2011

Young cover:
<1.2 Ma

Chang et al., 2011
NW end of lithocap: qtz-alunite cliffs at unconformity, with kaolinite halo

< 50 ppb Au

Chang et al., 2011
Formation of high- and low-sulfidation deposits

SEG Nevada: May 2013

Lepanto HS: 1 Mt Cu & 120 t Au

FSE porphyry: >650 Mt @ 0.65% Cu & 1.2 g/t Au

Guinaoang porphyry, 500 Mt @ 0.4% Cu & 0.4 g/t Au

Mohong Hill porphyry + HS

1 km

Chang et al., 2011

Lepanto - Far Southeast deposits

Bato dacite
Quartz-diorite porphyry
Imbangua dacite
Galili volcanioclastic rock

Outline of epithermal Cu-Au ore (>2.5% Cu eq.)
Outline of porphyry Cu-Au ore (>1.0% Cu eq.)

Concepcion and Cinco, 1989; Garcia, 1991

J.W. Hedenquist

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Formation of high- and low-sulfidation deposits

**SEG Nevada: May 2013**

J.W. Hedenquist

**Porphyry systems**

- Residual quartz (vuggy) ± enargite, Au

- Early: High T magmatic
  - Coupled brine + vapor
  - Potassic (~500°C) + advanced argillic lithocap
  - Wavy qtz veins, no halo
  - Metal sulfides

- Intermediate: **Lower T magmatic**, <10 wt% NaCl
  - Phyllic (chl-sericite, up to pyrophyllite) (~350°C)
  - Straight qtz veins, halo
  - Metals (remobilized?; shallow HS, marginal veins)

**Lepanto - Far Southeast deposits: Lithocap offset from porphyry**

- Basalt dacite
- Residual quartz
- Kaolinite
- Batio dacite
- Late Au
- 25% Cu eq.
- Dickite, diaspore
- Basement
  - 1) Residual qtz (early, barren)
  - 2) Breccia-hosted enargite + Au (sericite stage)

Long section along Lepanto fault

Garcia, 1991; Arelilas et al., 1995; Hedenquist et al., 1998
• 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)

Schematic reconstruction of the lithocap environment

(modified from Silitoe, 1999)

Arribas et al., 2000
Intrusion-centered systems: tectonic setting

<table>
<thead>
<tr>
<th>CONTINENT</th>
<th>OCEANIC RIDGE</th>
<th>BACK ARC</th>
<th>ACCRETED TERRANES</th>
<th>CONTINENTAL ARC</th>
<th>BACK-ARC EXTENSION</th>
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Intrusion-centered: ~40% of world Au
Porphyry: 70% of world Cu

after R. Goldfarb, from Groves et al. (2005)

Epithermal deposit types (arc vs rift endmembers)

Hedenquist et al., 2001

Sillitoe and Hedenquist, 2003

Intrusion-centered: ~40% of world Au
Porphyry: 70% of world Cu

Sillitoe and Hedenquist, 2003

Intrusion-centered: ~40% of world Au
Porphyry: 70% of world Cu

after R. Goldfarb, from Groves et al. (2005)
Exploration for epithermal Au-Ag vein deposits

- Large variations between deposit types and districts
- Model the prospect, do not fit prospect to the model
- Beware generalizations
- Paleosurface estimation, hydrology, erosion level
  - Lithology: volcanic (alteration) history, effect on permeability
  - Structure: relation to lithology, paragenesis (and ore)
  - Alteration mineralogy: assemblage, paragenesis, and zonation
  - Vein textures and mineralogy: shallow, barren levels
  - Distinguish style of deposit and hence possible morphology
- Use the right tool, at right time: orientation surveys

Comstock Lode, Nevada: IS veins

6000 t Ag, 257 t Au
Con Virginia: 1.13 Mt @ 87.4 g/t Au, 1834 g/t Ag

Alunite: 15-16.3 Ma
Adularia: 12.7-14.1 Ma
Ad overprint on AA