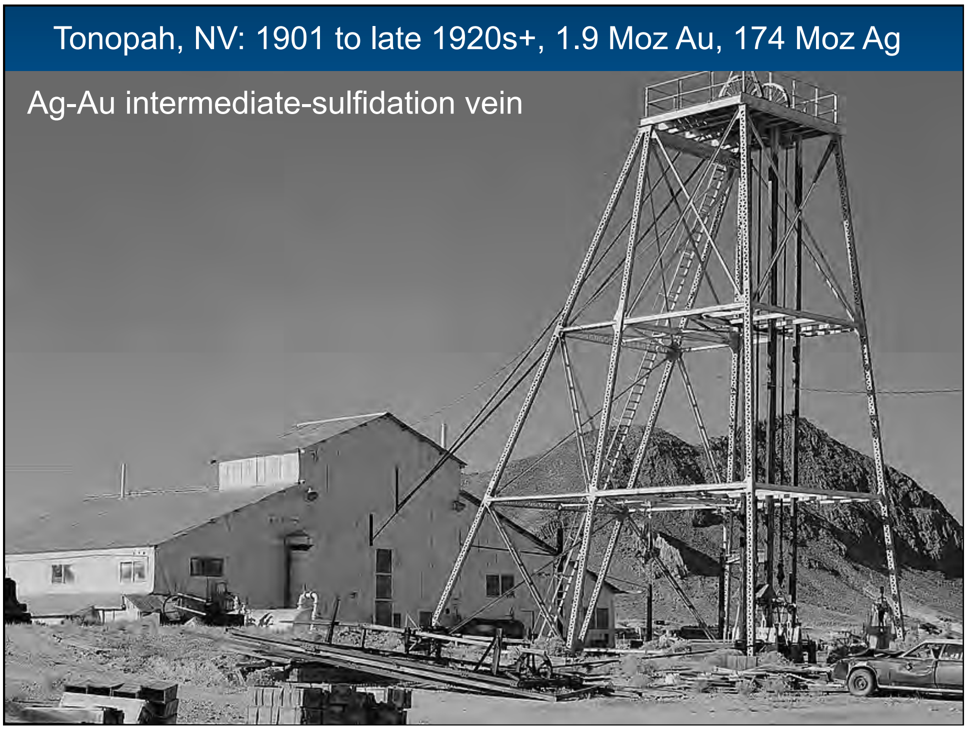
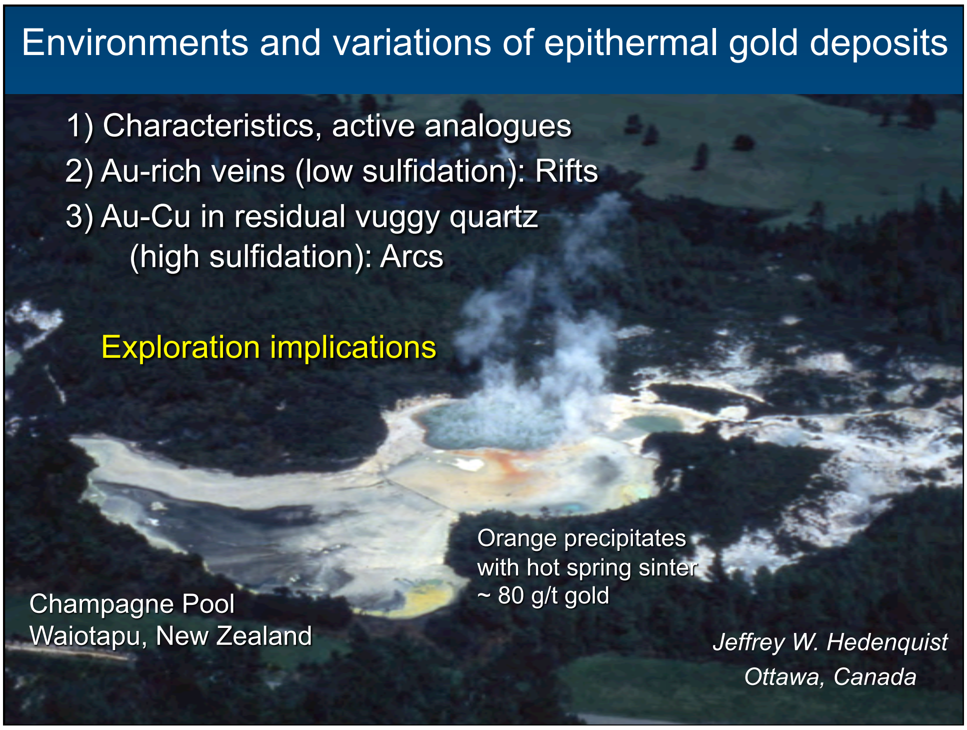
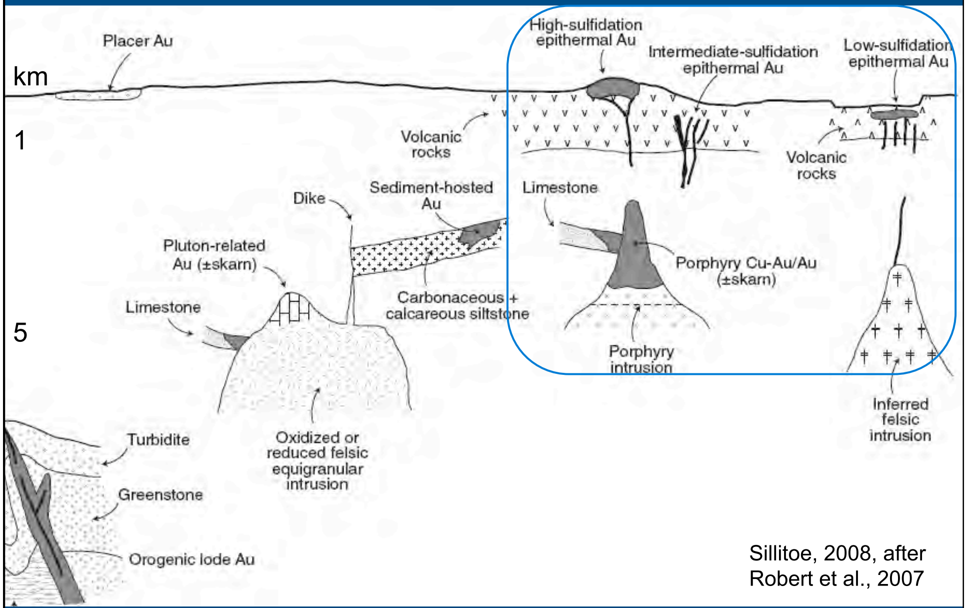

Tonopah, NV: 1901 to late 1920s+, 1.9 Moz Au, 174 Moz Ag
Ag-Au intermediate-sulfidation vein


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
Orange precipitates
with hot spring sinter
~ 80 g/t gold
Champagne Pool
Waiotapu, New Zealand
Jeffrey W. Hedenquist
Ottawa, Canada

Intrusion-related hydrothermal ore deposits in subduction settings



Types of epithermal deposits

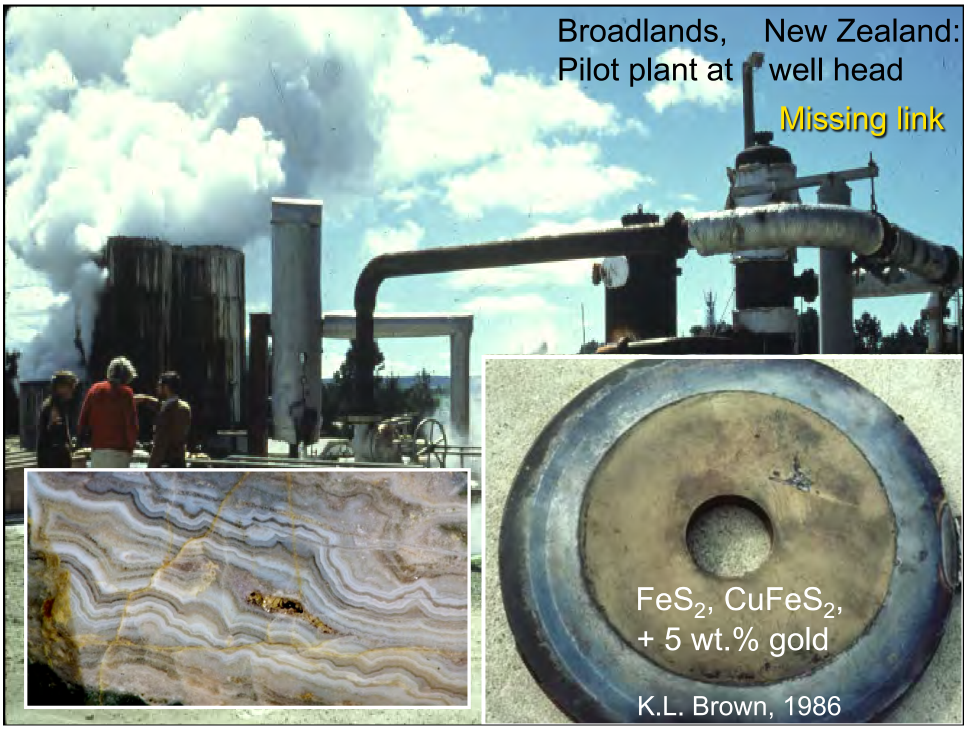
3 endmember types: two in volcanic arcs, 1 in rifts

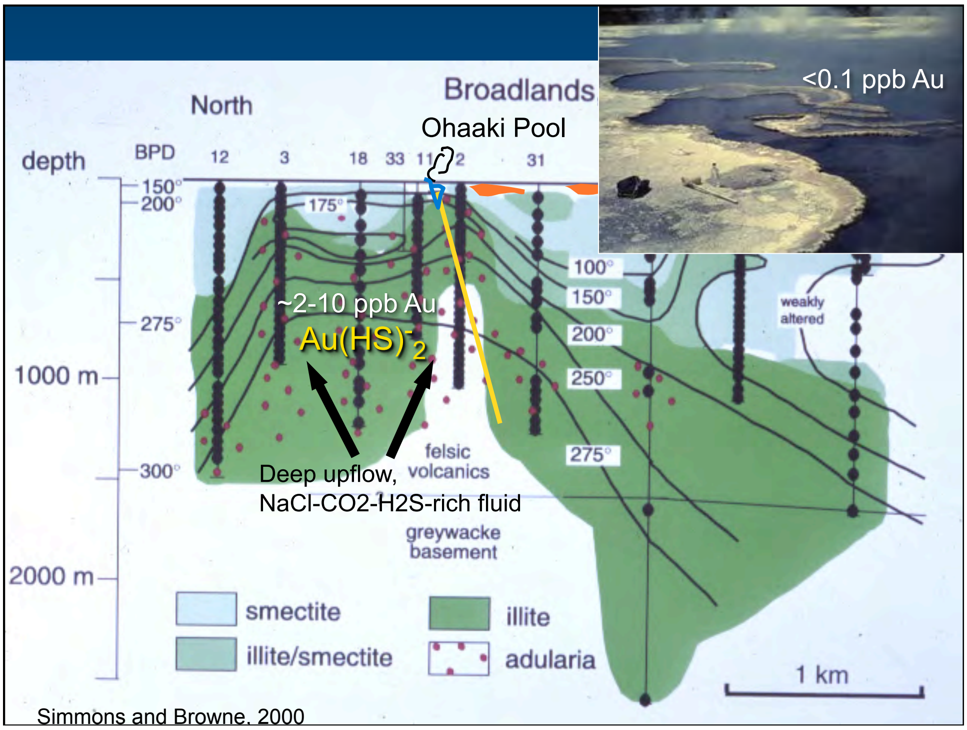
- **Hign sulf'n bodies:** Cu-Au-As, sulfide rich, andesite arcs
  - **Hosted by lithocaps:** advanced argillic zones over porphyry systems
- **Inter. sulf'n veins:** Ag-Au ± Zn-Pb, sulfide rich, andesite arcs
  - **Zoned and/or complex mineralogy (intrusion related, diatreme)**

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

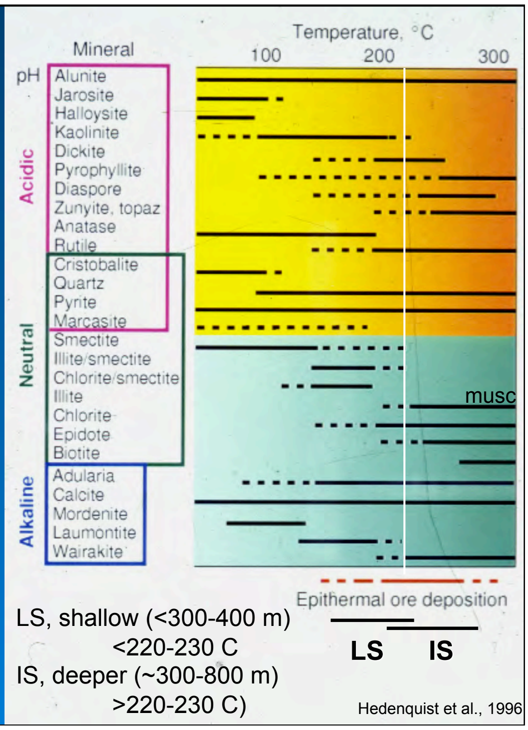

Taupo Volcanic Zone, New Zealand:
A missing link
Looking northeast: volcanic arc to east, rift to west
Waiotapu
Broadlands geothermal system
Rotokawa

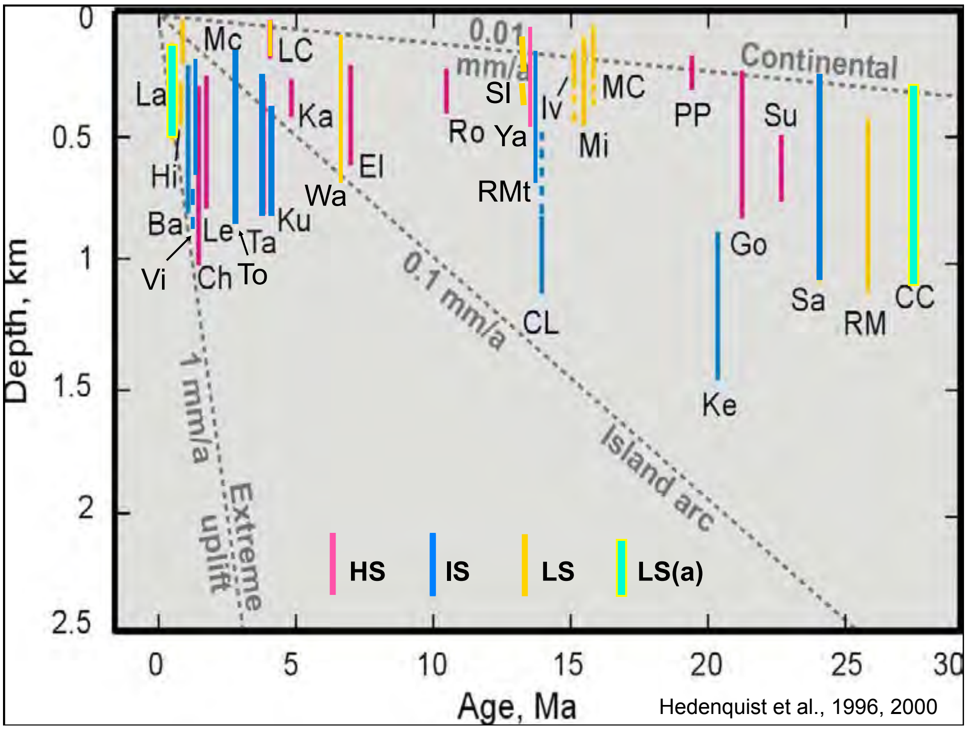

Broadlands, New Zealand:
Pilot plant at well head
Missing link
FeS_2, $CuFeS_2$,
+ 5 wt.% gold
K.L. Brown, 1986



Epithermal alteration, gangue minerals

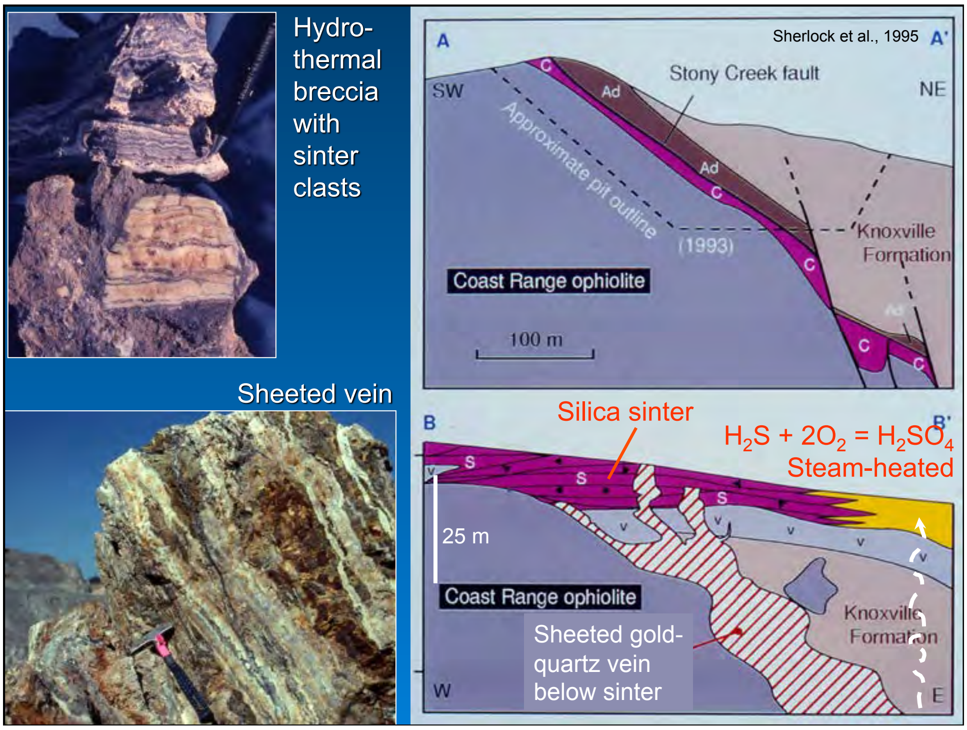
- **LS veins: illite, clays; chalcedony, adularia, calcite**
- **HS replacements: silicic host, quartz-alunite halo (kaolinite, dickite, pyrophyllite, diaspore, topaz, etc.); alunite, barite, anhydrite**
  - Barren lithocaps: **silicic core, quartz-alunite halo**
- **IS veins:** **"sericite" (muscovite);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

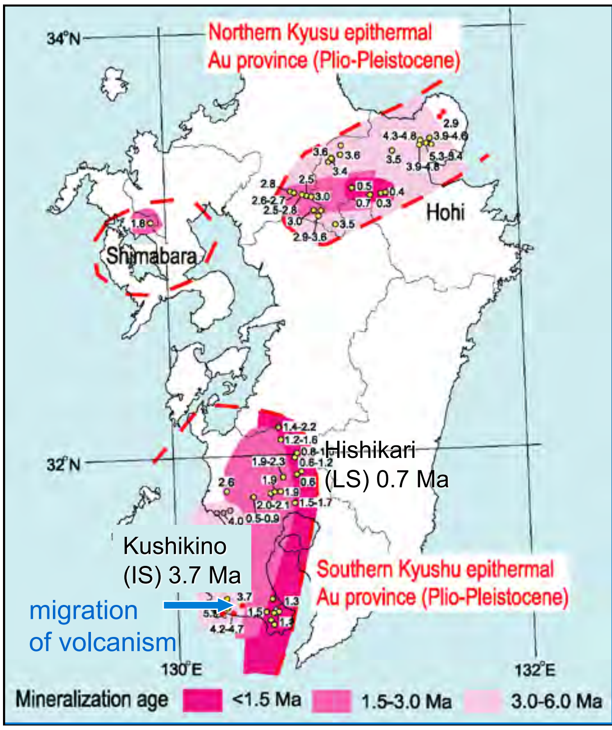



Depth, km
0
0.5
1
1.5
2
2.5
Age, Ma
0
5
10
15
20
25
30
0.01 mm/a
Continental
0.1 mm/a
Island arc
1 mm/a
Extreme uplift
La
Mc
LC
Ka
Hi
Ba
Le
Ta
Ku
Vi
Ch
To
Wa
El
Ro
Ya
Sl
Iv
MC
Mi
RMt
CL
PP
Su
Go
Ke
Sa
RM
CC
HS
IS
LS
LS(a)
Hedenquist et al., 1996, 2000


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)


Hydro-thermal breccia with sinter clasts
Sheeted vein
Sherlock et al., 1995
A
A'
SW
NE
Stony Creek fault
Approximate pit outline
(1993)
Knoxville Formation
Coast Range ophiolite
100 m
B
B'
Silica sinter
$H_2S + 2O_2 = H_2SO_4$
Steam-heated
25 m
Coast Range ophiolite
Sheeted gold-quartz vein below sinter
Knoxville Formation
W
E

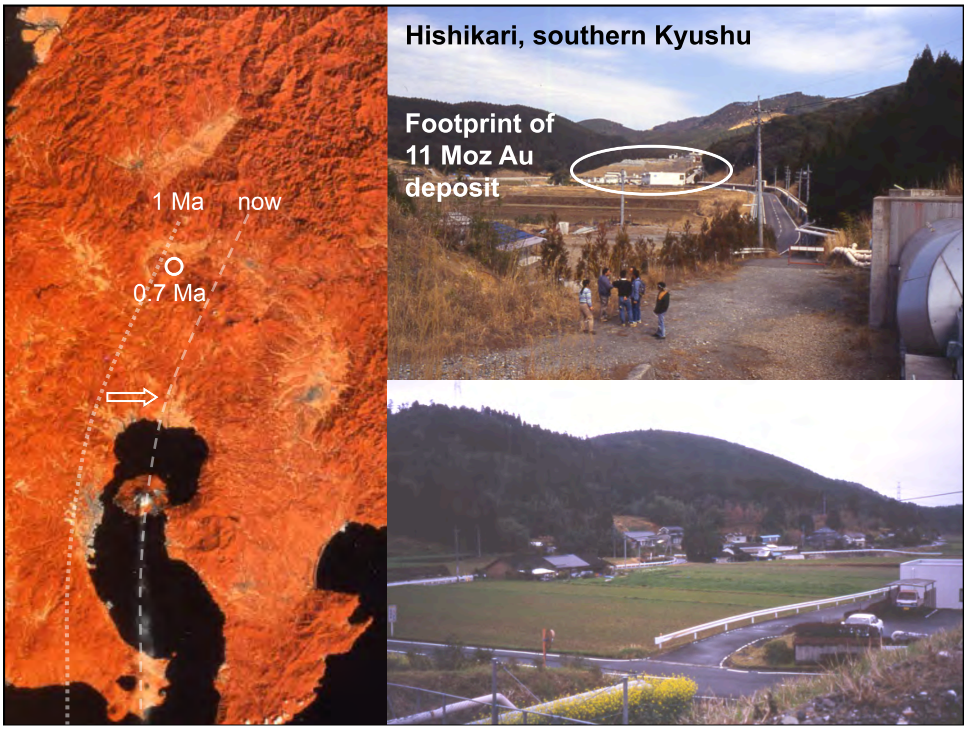


Kyushu epithermal deposits: LS and IS veins

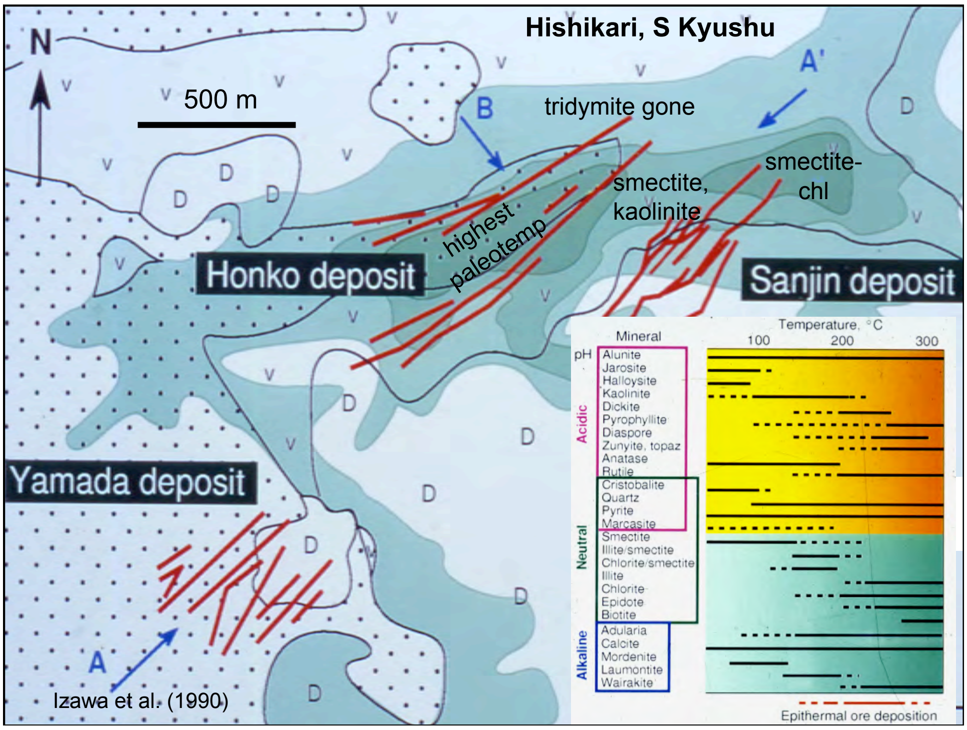
Tectonics and age determine type of epithermal Au deposits

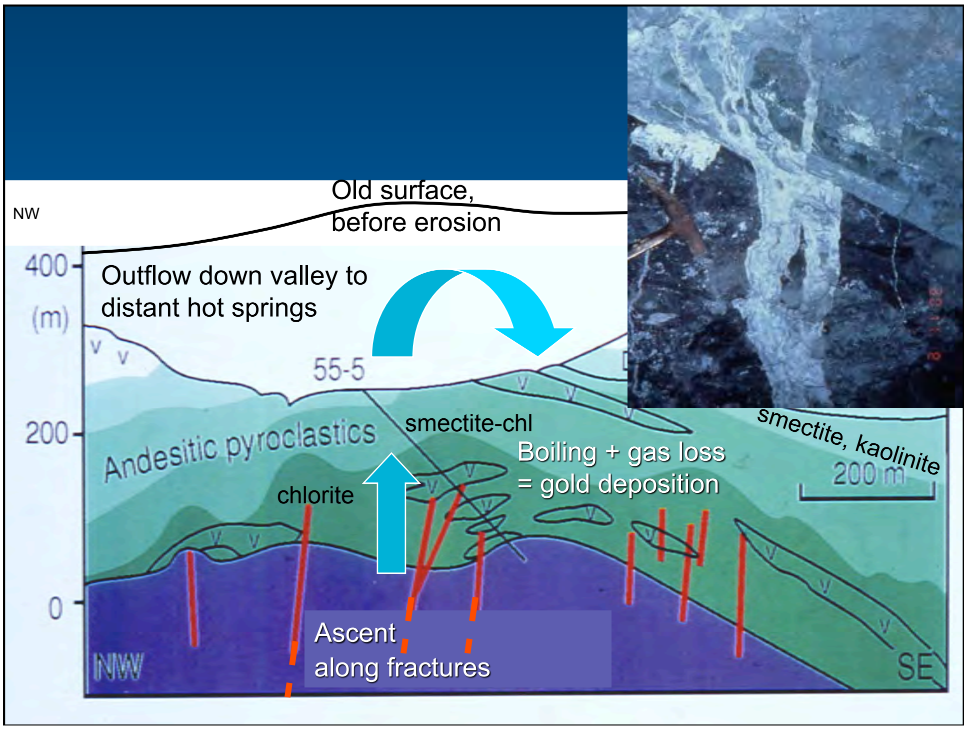
Migration of arc (IS or HS), producing rift (LS)

Y. Watanabe (2004)

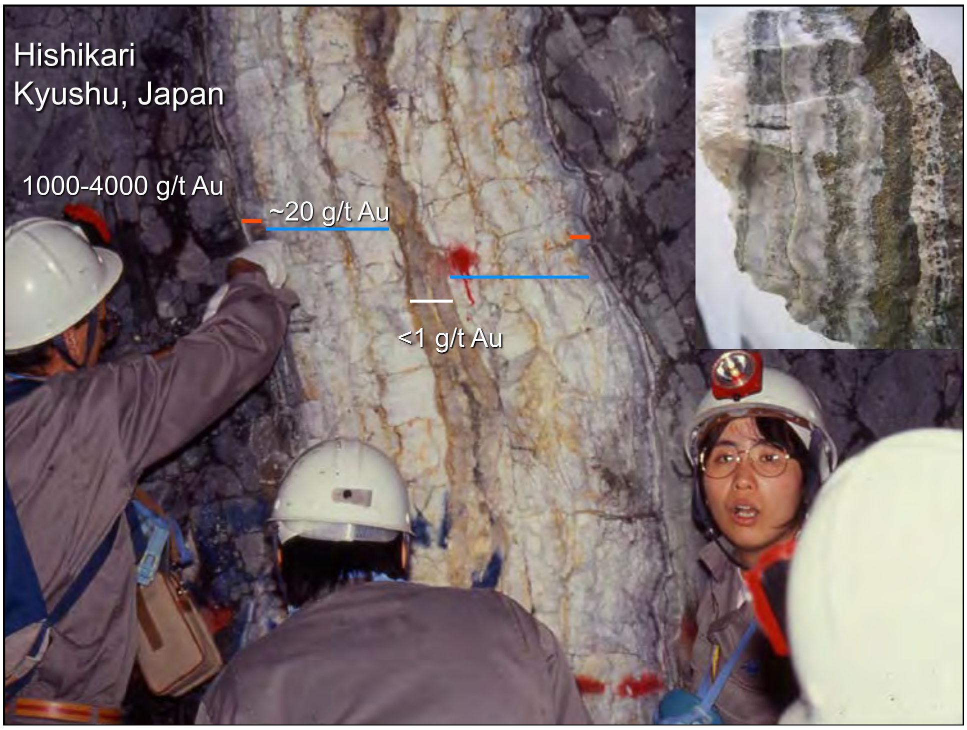



Hishikari:
Gold-quartz veins
in greywacke
basement


Hishikari, S Kyushu
N
500 m
B
tridymite gone
A'
smectite-
chl
smectite,
kaolinite
highest
paleotemp
Honko deposit
Sanjin deposit
Yamada deposit
A
Izawa et al. (1990)
Mineral
Temperature, °C
100
200
300
pH
Acidic
Neutral
Alkaline
Alunite
Jarosite
Halloysite
Kaolinite
Dickite
Pyrophyllite
Diaspore
Zunyite, topaz
Anatase
Rutile
Cristobalite
Quartz
Pyrite
Marcasite
Smectite
Illite/smectite
Chlorite/smectite
Illite
Chlorite
Epidote
Biotite
Adularia
Calcite
Mordenite
Laumontite
Wairakite
Epithermal ore deposition

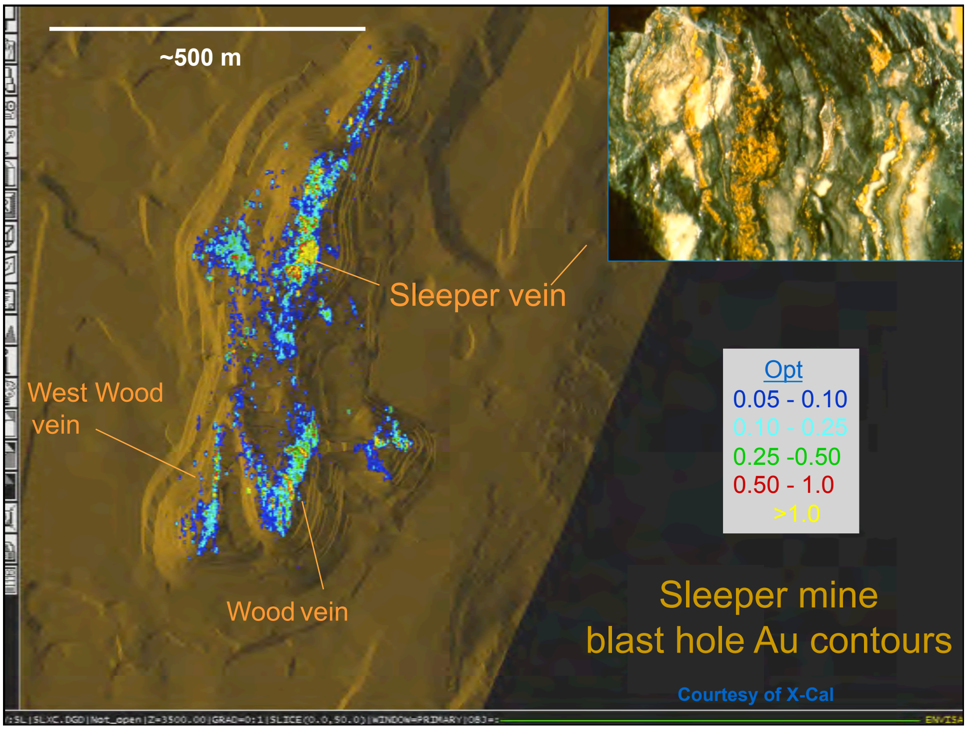


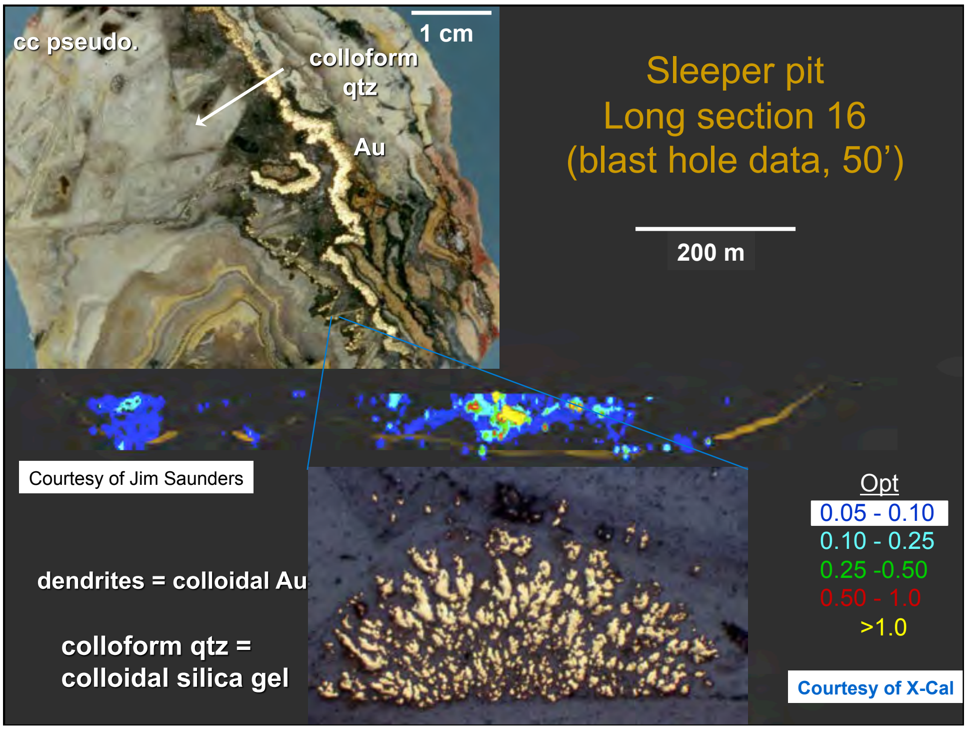
NW
Old surface, before erosion
400
(m)
200
0
Outflow down valley to distant hot springs
55-5
Andesitic pyroclastics
smectite-chl
chlorite
Boiling + gas loss = gold deposition
smectite, kaolinite
200 m
Ascent along fractures
NW
SE

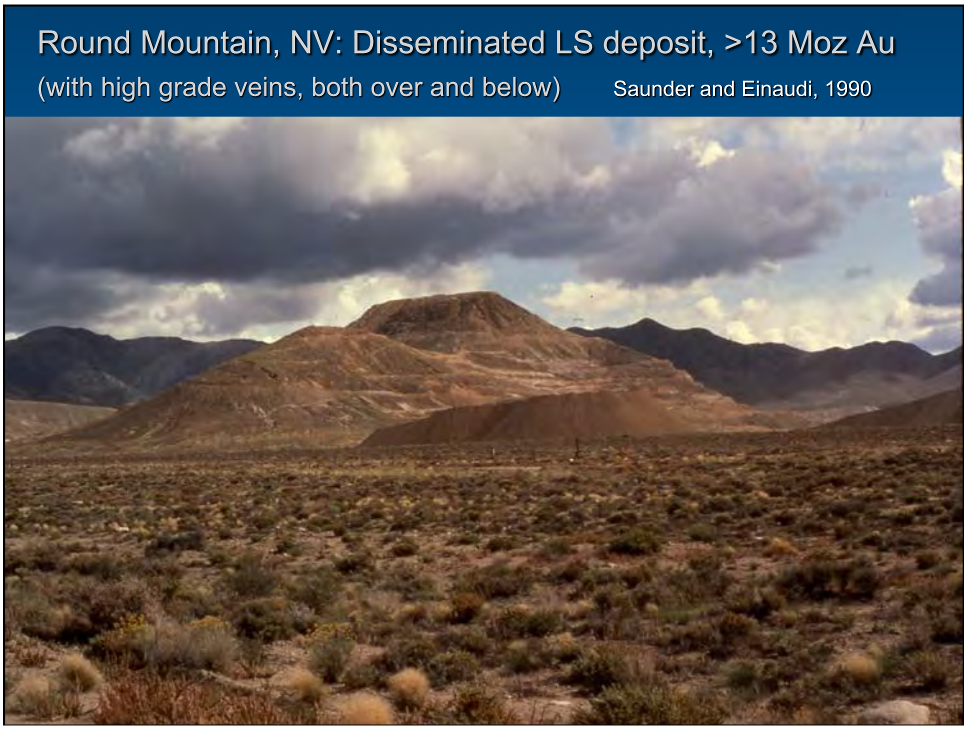


Hishikari
Kyushu, Japan
1000-4000 g/t Au
~20 g/t Au
<1 g/t Au

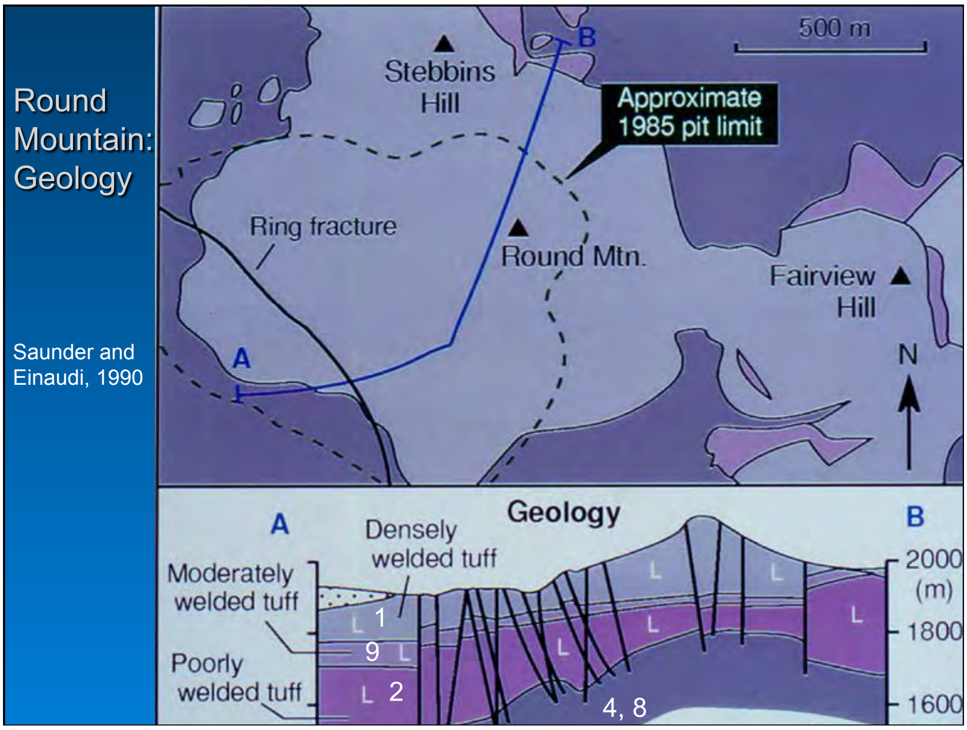

Sleeper, Nevada: 1.7 Moz prod (>1 Moz on surface)
Open pit, encircled by infrastructure (looking SE)

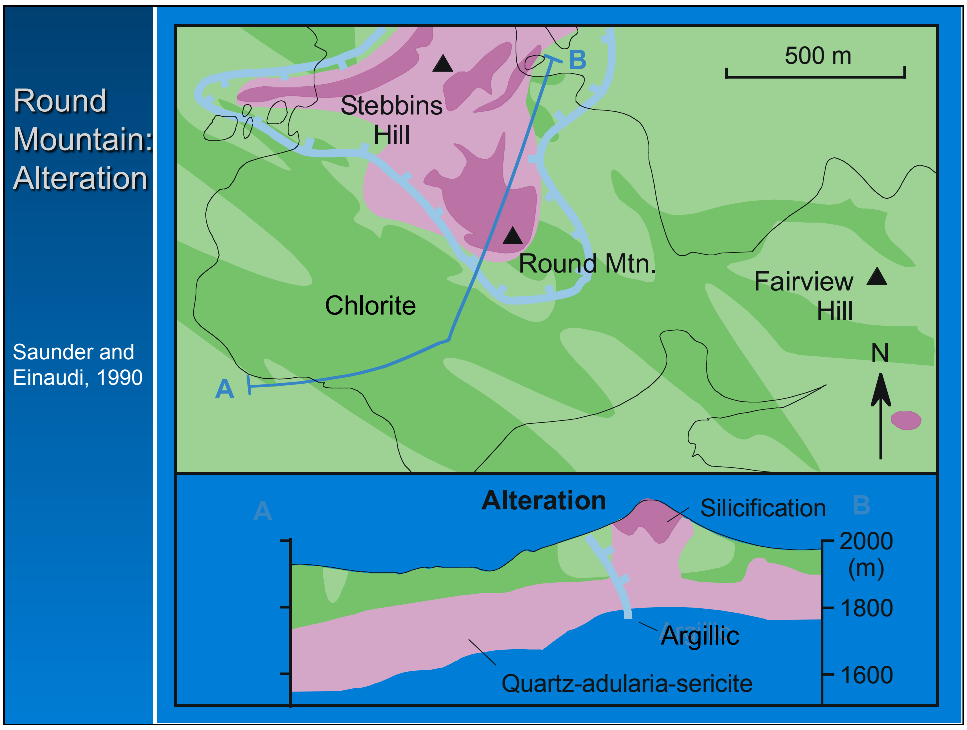

~500 m
Sleeper vein
West Wood vein
Wood vein
Opt
0.05 - 0.10
0.10 - 0.25
0.25 -0.50
0.50 - 1.0
>1.0
Sleeper mine
blast hole Au contours
Courtesy of X-Cal

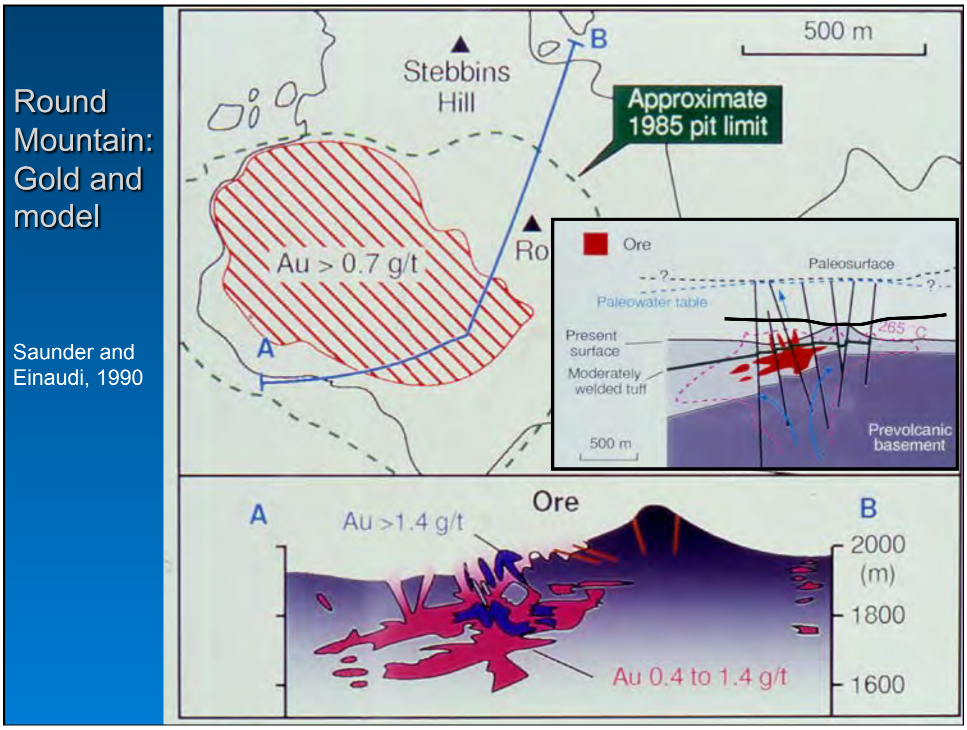

cc pseudo.
colloform qtz
1 cm
Au
Sleeper pit
Long section 16
(blast hole data, 50')
200 m
Courtesy of Jim Saunders
dendrites = colloidal Au
colloform qtz =
colloidal silica gel
Opt
0.05 - 0.10
0.10 - 0.25
0.25 -0.50
0.50 - 1.0
>1.0
Courtesy of X-Cal

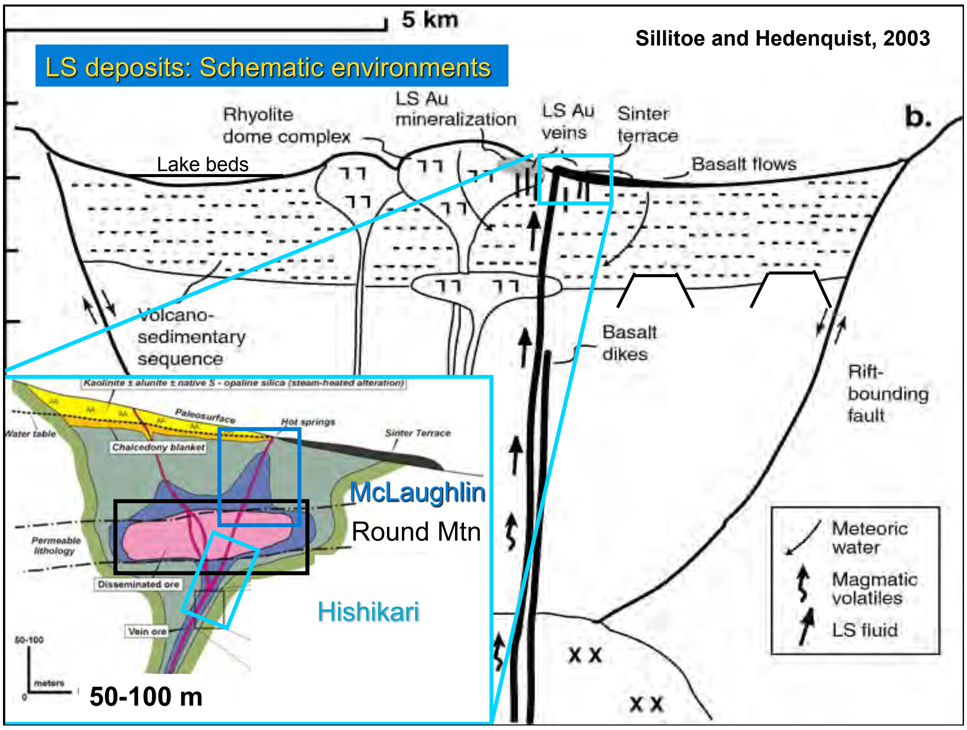

Round Mountain, NV: Disseminated LS deposit, >13 Moz Au
(with high grade veins, both over and below)
Saunder and Einaudi, 1990

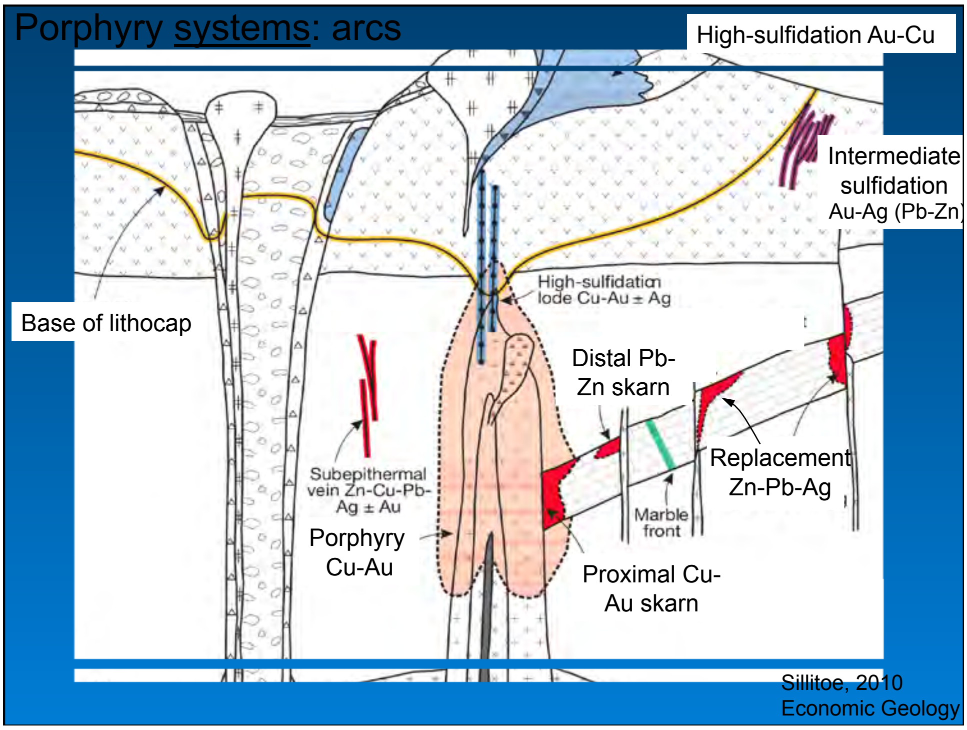

2005 open pit


Round Mountain: Geology
Saunder and Einaudi, 1990
500 m
Stebbins Hill
B
Approximate 1985 pit limit
Ring fracture
Round Mtn.
Fairview Hill
A
N
Geology
A
B
Densely welded tuff
Moderately welded tuff
Poorly welded tuff
1
9
2
4, 8
L
2000 (m)
1800
1600

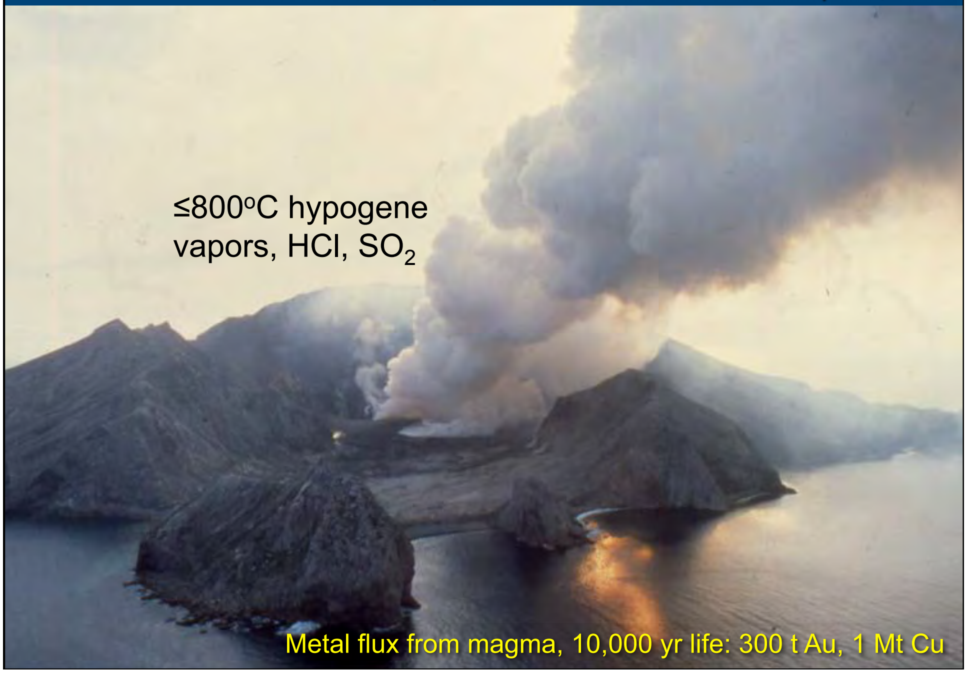

Round Mountain: Alteration
Saunder and Einaudi, 1990
500 m
B
Stebbins Hill
Round Mtn.
Fairview Hill
Chlorite
N
A
Alteration
A
Silicification
B
2000 (m)
1800
Argillic
Quartz-adularia-sericite
1600


Round Mountain: Gold and model
Saunder and Einaudi, 1990
Stebbins Hill
B
500 m
Approximate 1985 pit limit
Au > 0.7 g/t
A
Ore
Paleosurface
Paleowater table
Present surface
Moderately welded tuff
500 m
Prevolcanic basement
A
Au >1.4 g/t
Ore
B
2000 (m)
1800
Au 0.4 to 1.4 g/t
1600

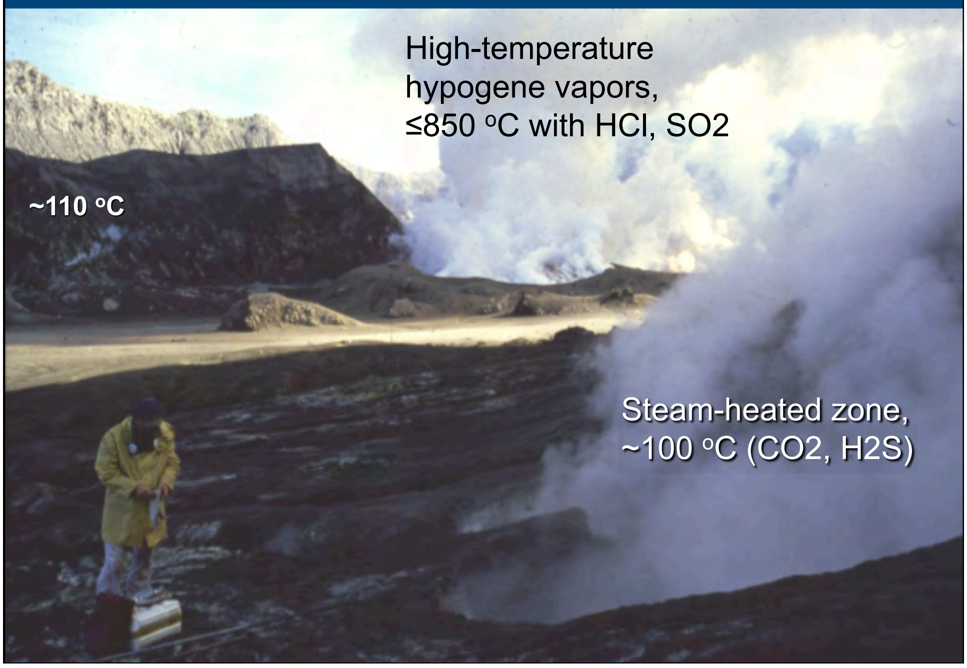

5 km
Sillitoe and Hedenquist, 2003
LS deposits: Schematic environments
b.
Rhyolite dome complex
LS Au mineralization
LS Au veins
Sinter terrace
Lake beds
Basalt flows
Volcano-sedimentary sequence
Basalt dikes
Rift-bounding fault
Meteoric water
Magmatic volatiles
LS fluid
McLaughlin
Round Mtn
Hishikari
50-100 m

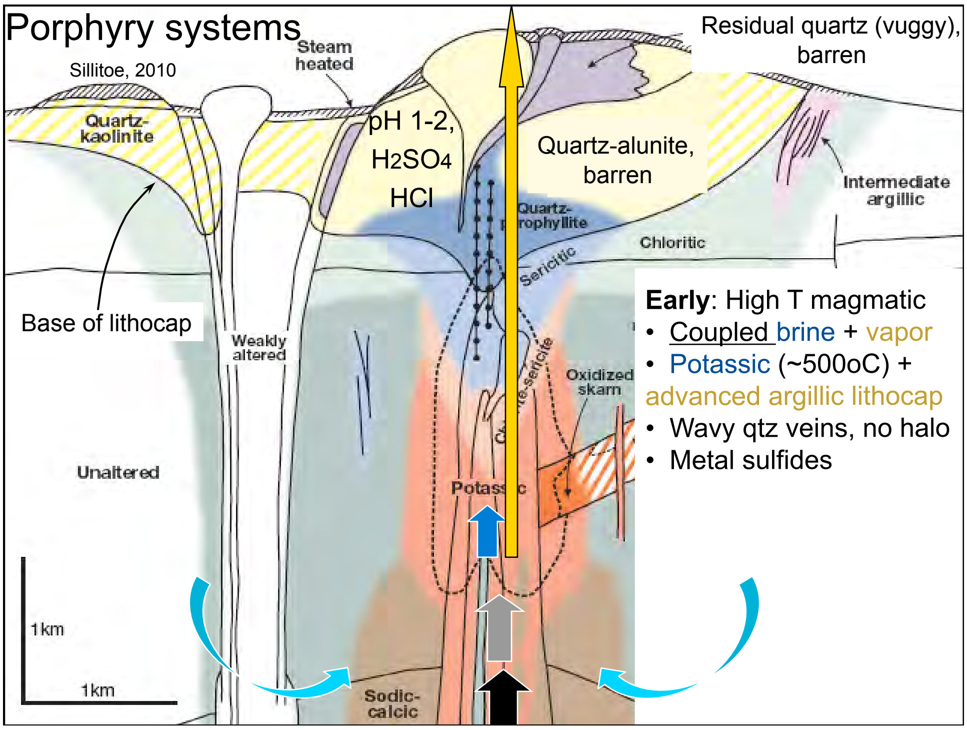

Porphyry systems: arcs
High-sulfidation Au-Cu
Intermediate sulfidation Au-Ag (Pb-Zn)
Base of lithocap
High-sulfidation lode Cu-Au ± Ag
Distal Pb-Zn skarn
Subepithermal vein Zn-Cu-Pb-Ag ± Au
Replacement Zn-Pb-Ag
Marble front
Porphyry Cu-Au
Proximal Cu-Au skarn
Sillitoe, 2010
Economic Geology

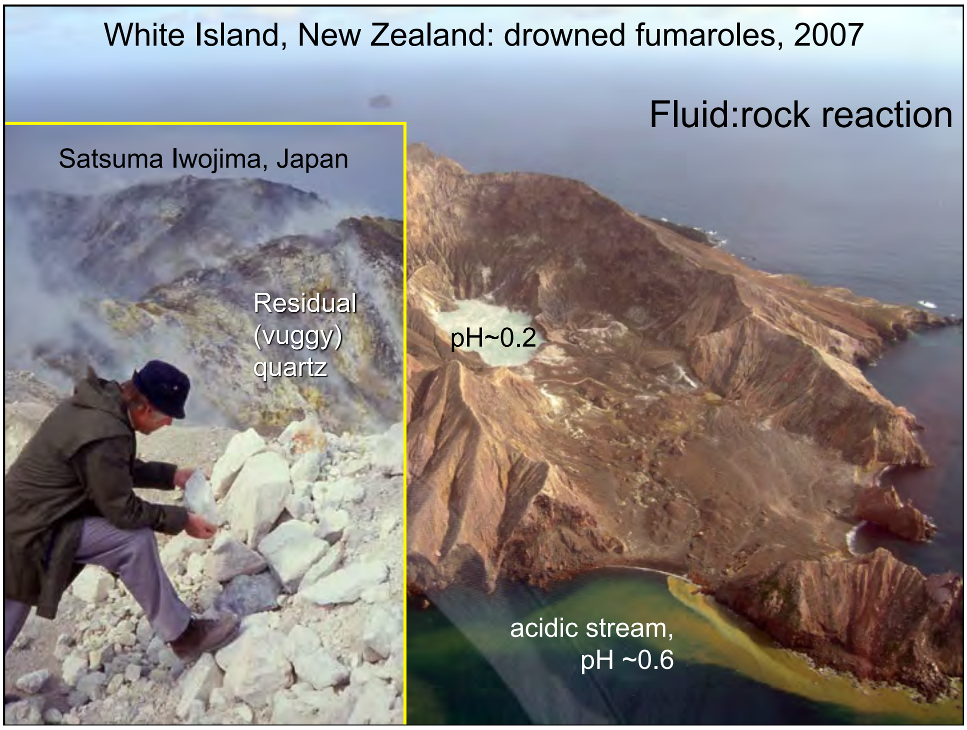
White Island, New Zealand: Quiescent eruption, 1988

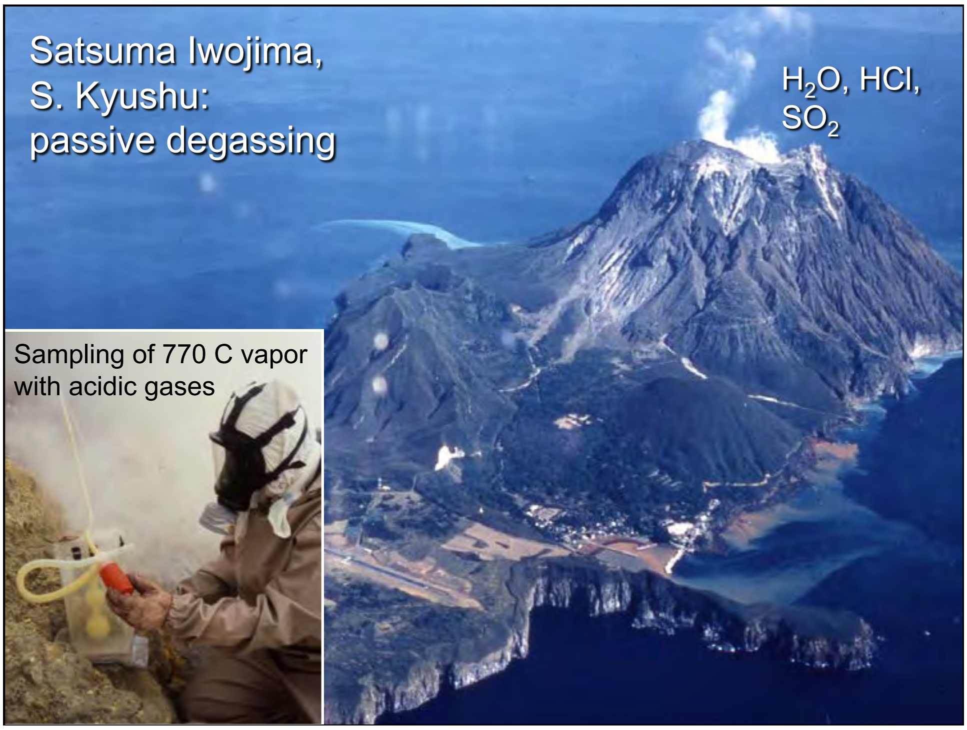


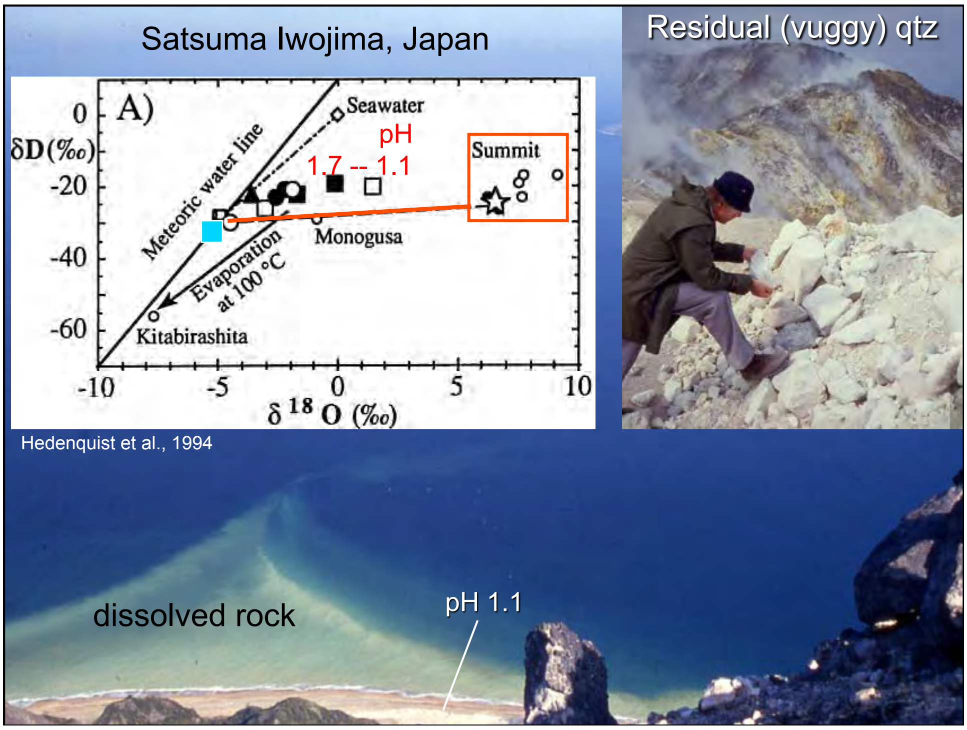
White Island, New Zealand: fumaroles

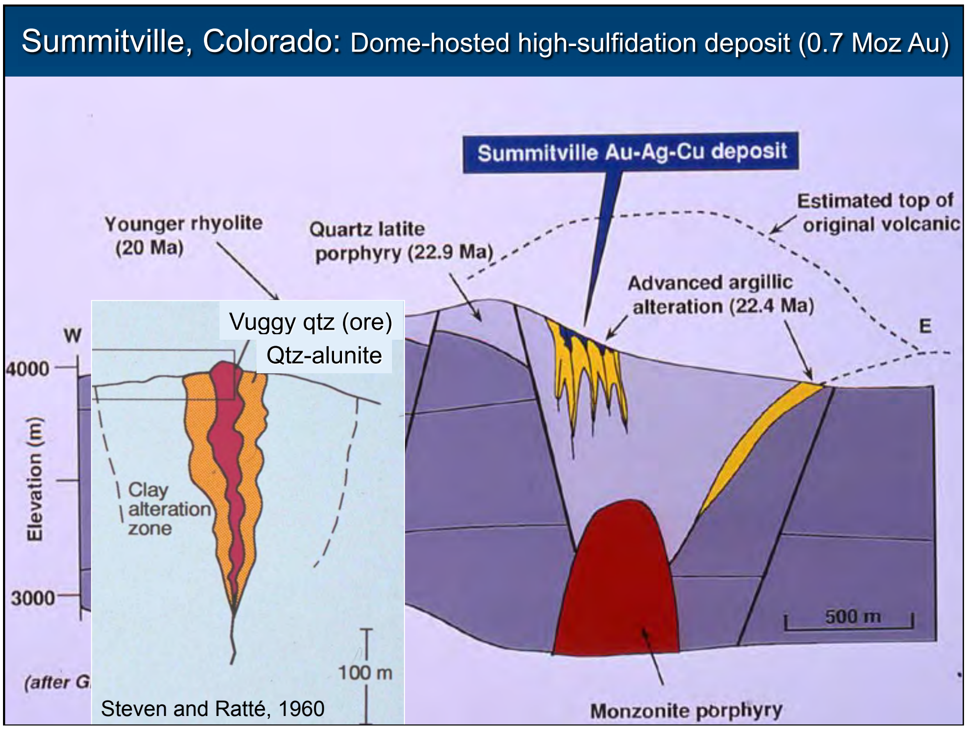


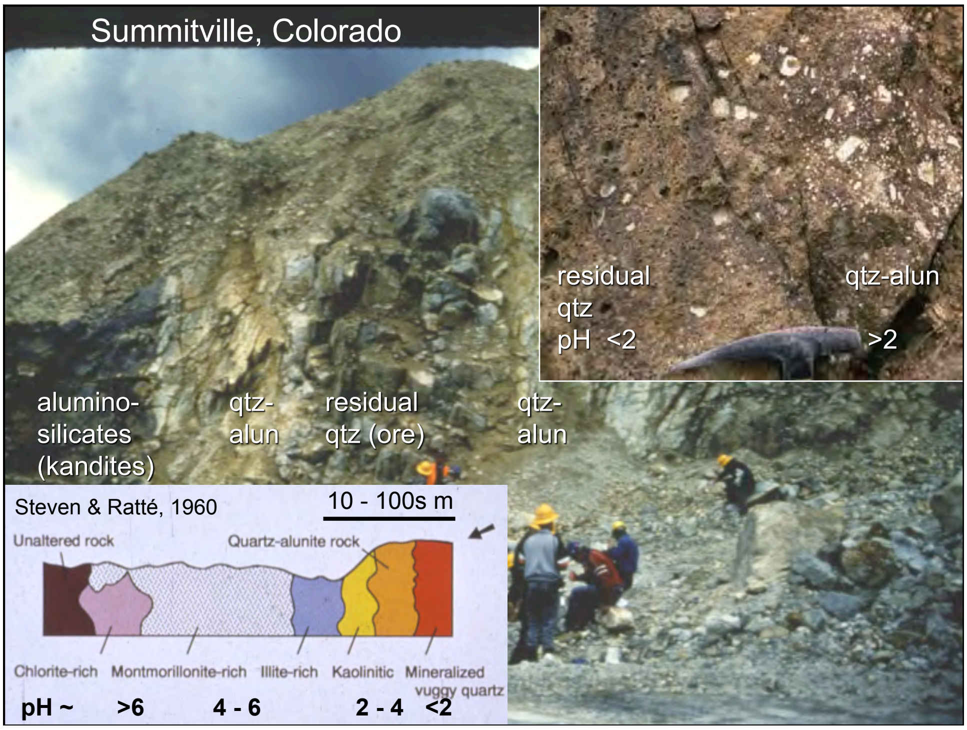

Porphyry systems
Sillitoe, 2010
Steam heated
Residual quartz (vuggy), barren
Quartz-kaolinite
pH 1-2, H2SO4 HCl
Quartz-alunite, barren
Intermediate argillic
Quartz-pyrophyllite
Chloritic
Sericitic
Base of lithocap
Weakly altered
Oxidized skarn
Early: High T magmatic
• Coupled brine + vapor
• Potassic (~500oC) + advanced argillic lithocap
• Wavy qtz veins, no halo
• Metal sulfides
Unaltered
1km
1km
Sodic-calcic


White Island, New Zealand: drowned fumaroles, 2007
Fluid:rock reaction
Satsuma Iwojima, Japan
Residual (vuggy) quartz
pH~0.2
acidic stream, pH ~0.6


Satsuma Iwojima,
S. Kyushu:
passive degassing
H_2O, HCl,
SO_2
Sampling of 770 C vapor
with acidic gases

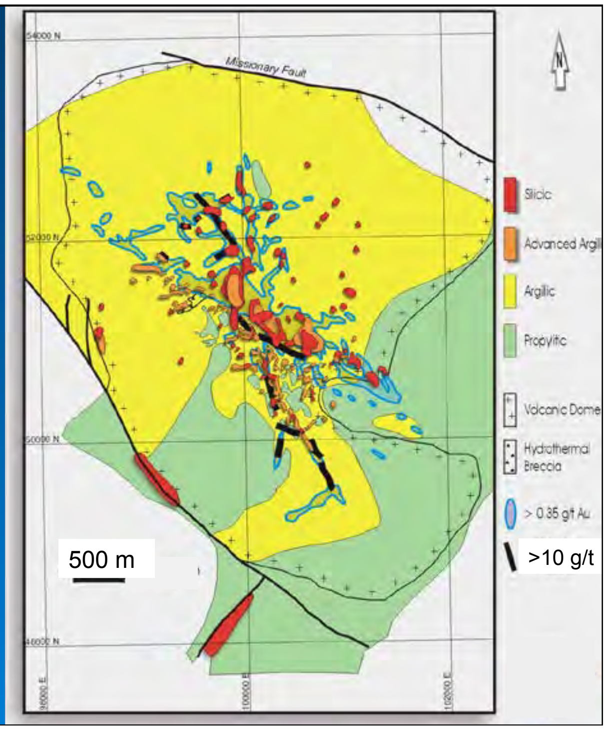

Satsuma Iwojima, Japan
A)
δD (‰)
0
-20
-40
-60
-10
-5
0
5
10
δ 18 O (‰)
Seawater
Meteoric water line
pH
1.7 -- 1.1
Summit
Monogusa
Evaporation at 100 °C
Kitabirashita
Hedenquist et al., 1994
Residual (vuggy) qtz
dissolved rock
pH 1.1

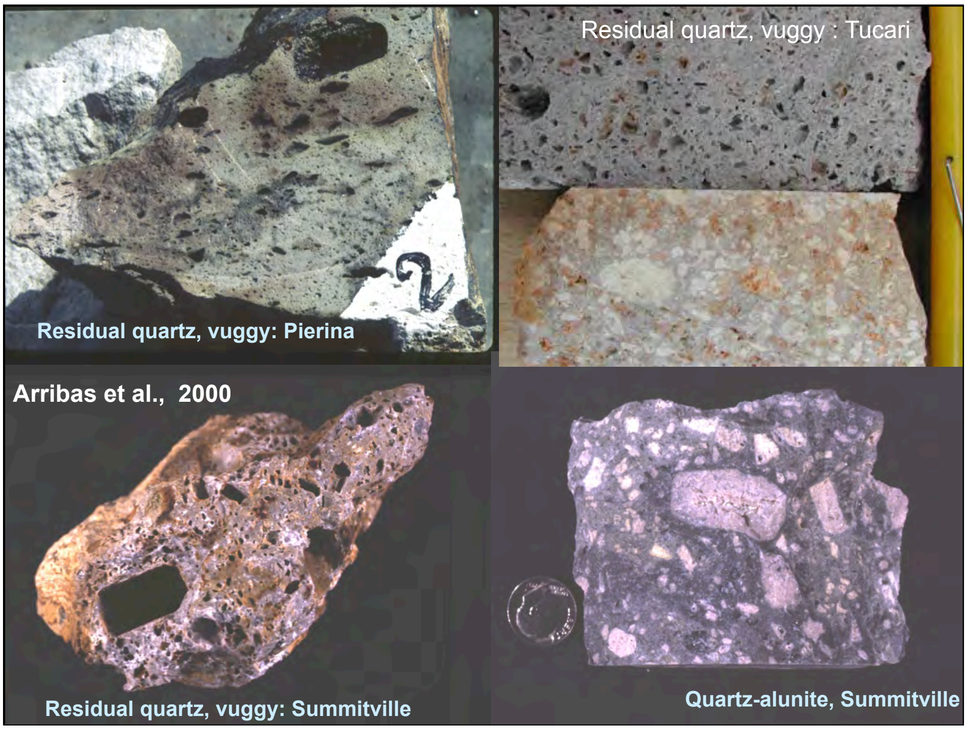

Summitville, Colorado: Dome-hosted high-sulfidation deposit (0.7 Moz Au)
Summitville Au-Ag-Cu deposit
Estimated top of original volcanic
Younger rhyolite (20 Ma)
Quartz latite porphyry (22.9 Ma)
Advanced argillic alteration (22.4 Ma)
W
E
4000
3000
Elevation (m)
Vuggy qtz (ore)
Qtz-alunite
Clay alteration zone
100 m
Steven and Ratté, 1960
500 m
Monzonite porphyry

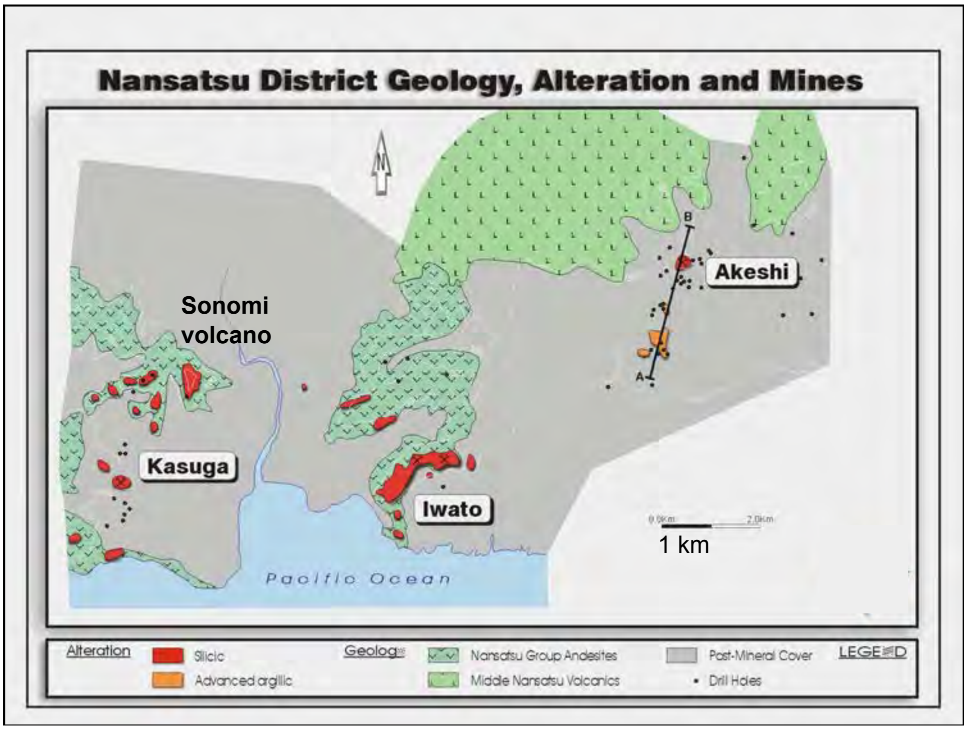

Summitville, Colorado
residual qtz pH <2
qtz-alun >2
alumino-silicates (kandites)
qtz-alun
residual qtz (ore)
qtz-alun
Steven & Ratté, 1960
10 - 100s m
Unaltered rock
Quartz-alunite rock
Chlorite-rich
Montmorillonite-rich
Illite-rich
Kaolinitic
Mineralized vuggy quartz
pH ~ >6 4 - 6 2 - 4 <2

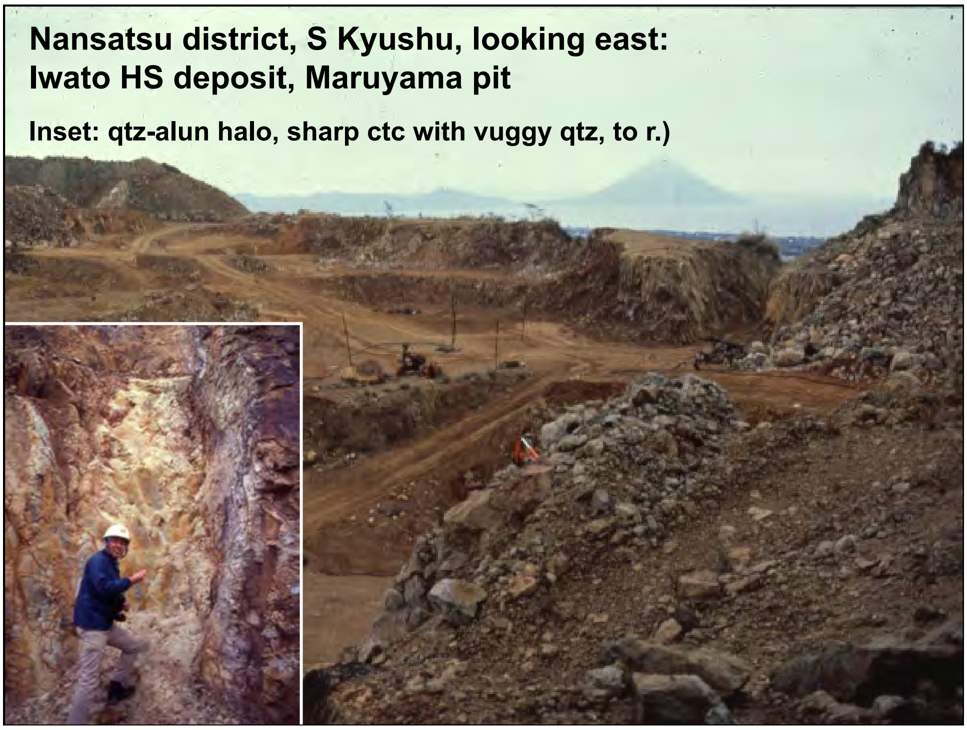
Summitville, Colorado:
Alteration zoning and ore bodies within dome; strong structural control

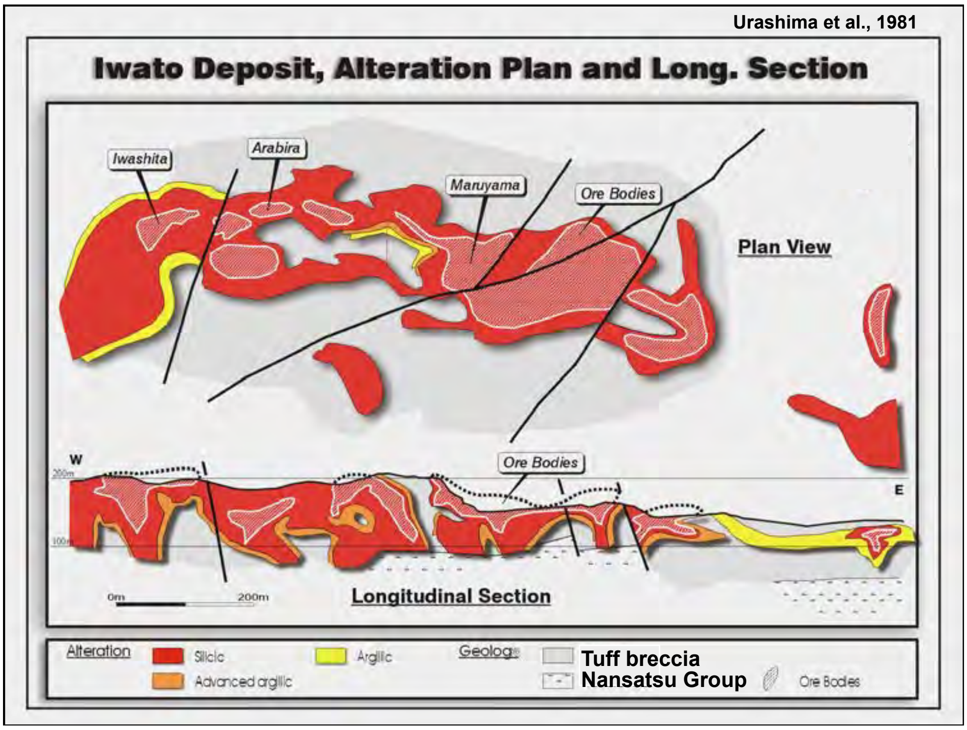
after Gray and Coolbaugh, 1994



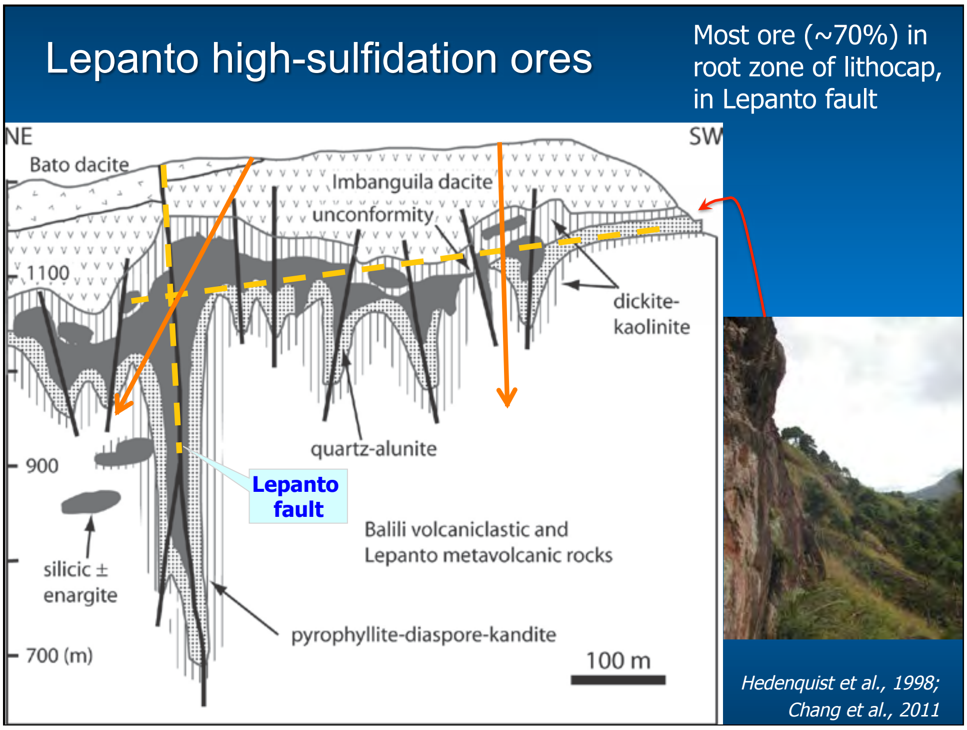


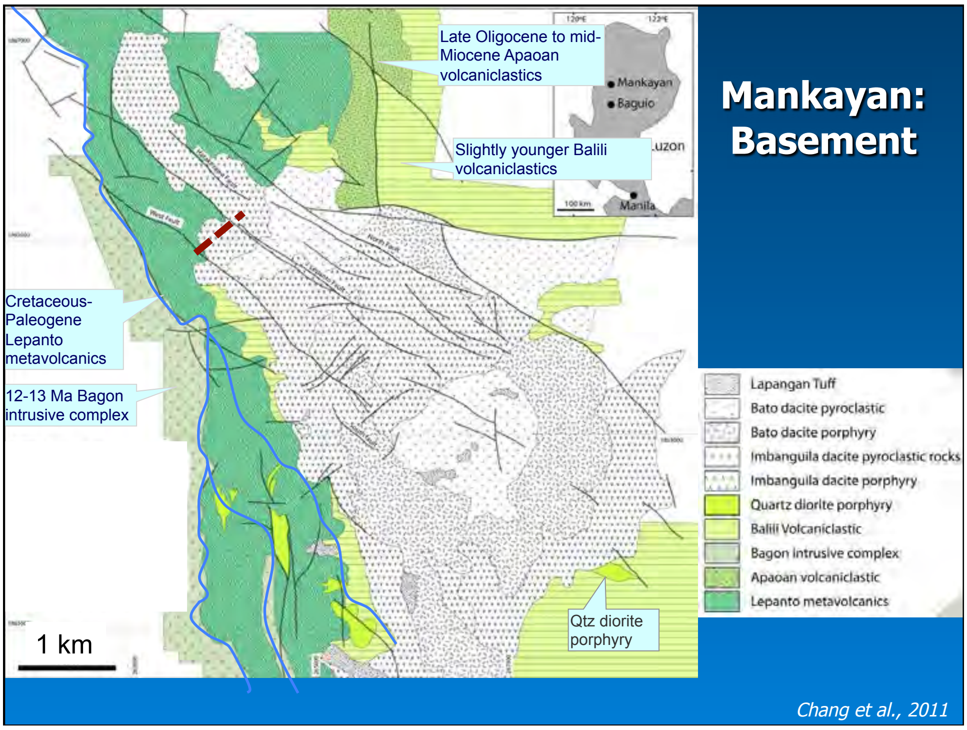

Nansatsu District Geology, Alteration and Mines
Sonomi volcano
Akeshi
Kasuga
Iwato
Pacific Ocean
1 km
B
A
Alteration
Silicic
Advanced argillic
Geology
Nansatsu Group Andesites
Middle Nansatsu Volcanics
Post-Mineral Cover
Drill Holes
LEGEND

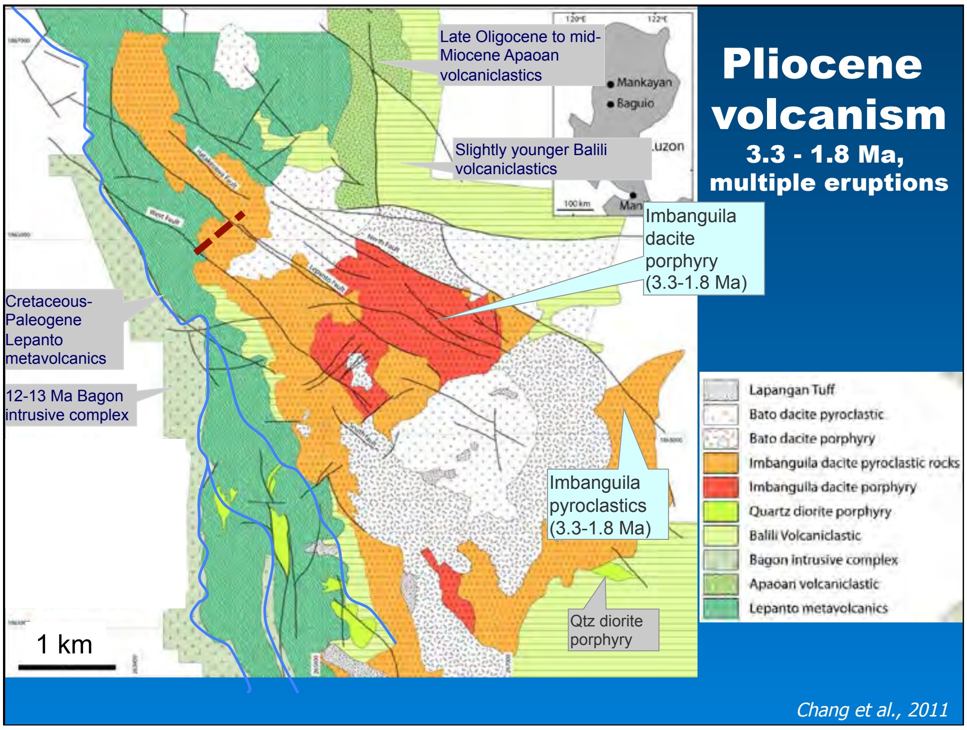

Nansatsu district, S Kyushu, looking east:
Iwato HS deposit, Maruyama pit
Inset: qtz-alun halo, sharp ctc with vuggy qtz, to r.)

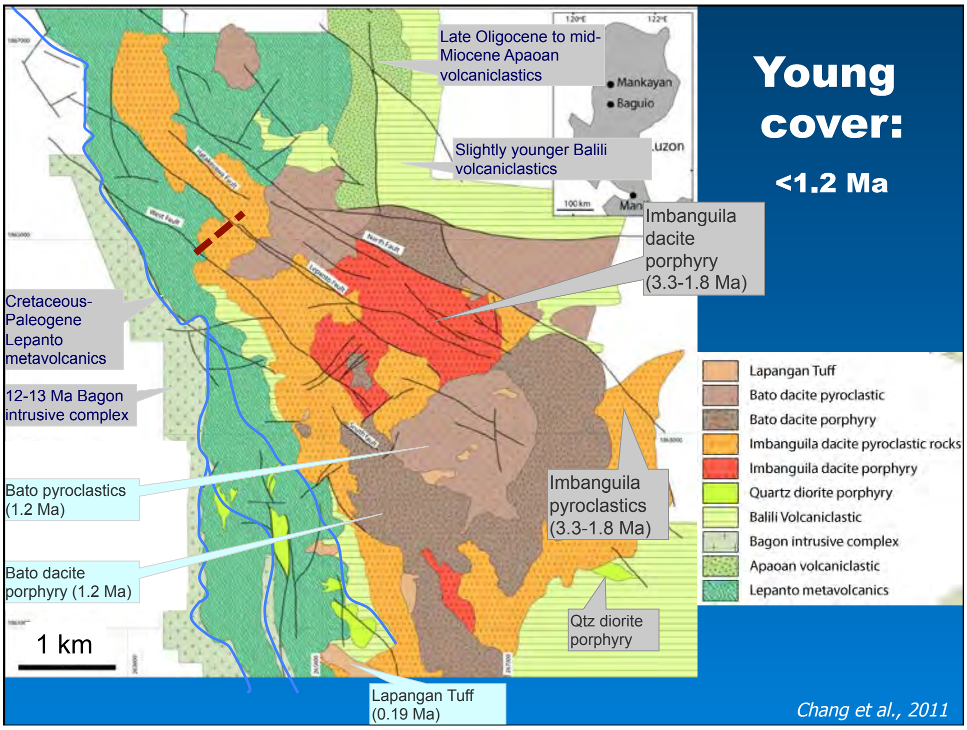

Urashima et al., 1981
Iwato Deposit, Alteration Plan and Long. Section
Iwashita
Arabira
Maruyama
Ore Bodies
Plan View
W
E
Ore Bodies
0m
200m
Longitudinal Section
Alteration
Silicic
Advanced argillic
Argillic
Geology
Tuff breccia
Nansatsu Group
Ore Bodies

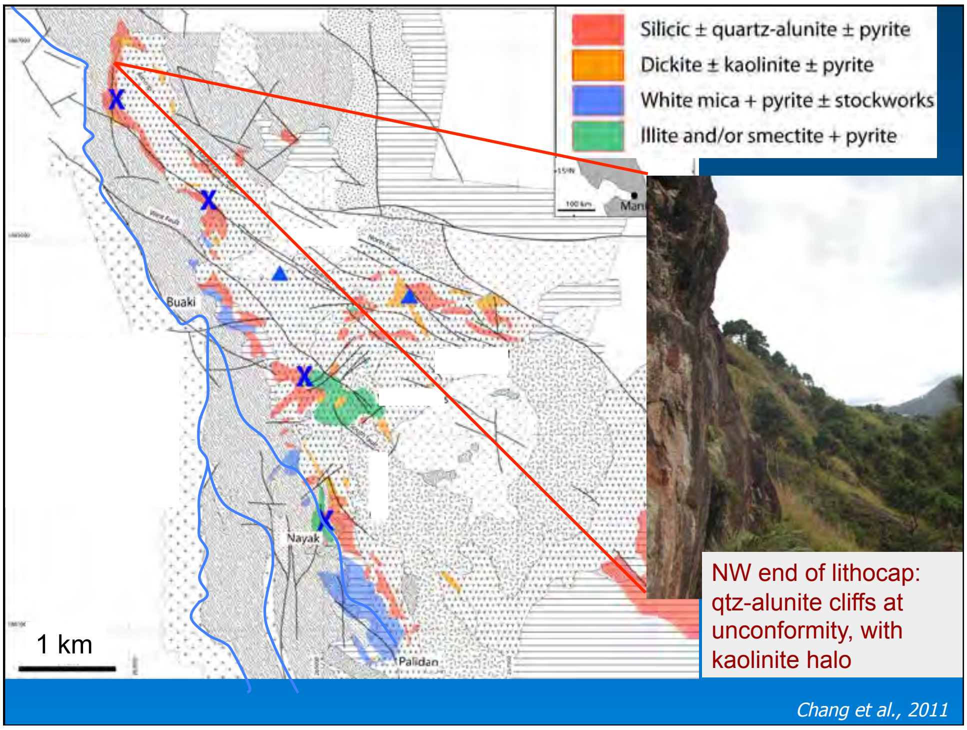

Mankayan district, Philippines
Mohong Hill
quartz-alunite
lithocap
dacite pyroclastics
volcaniclastic
basement

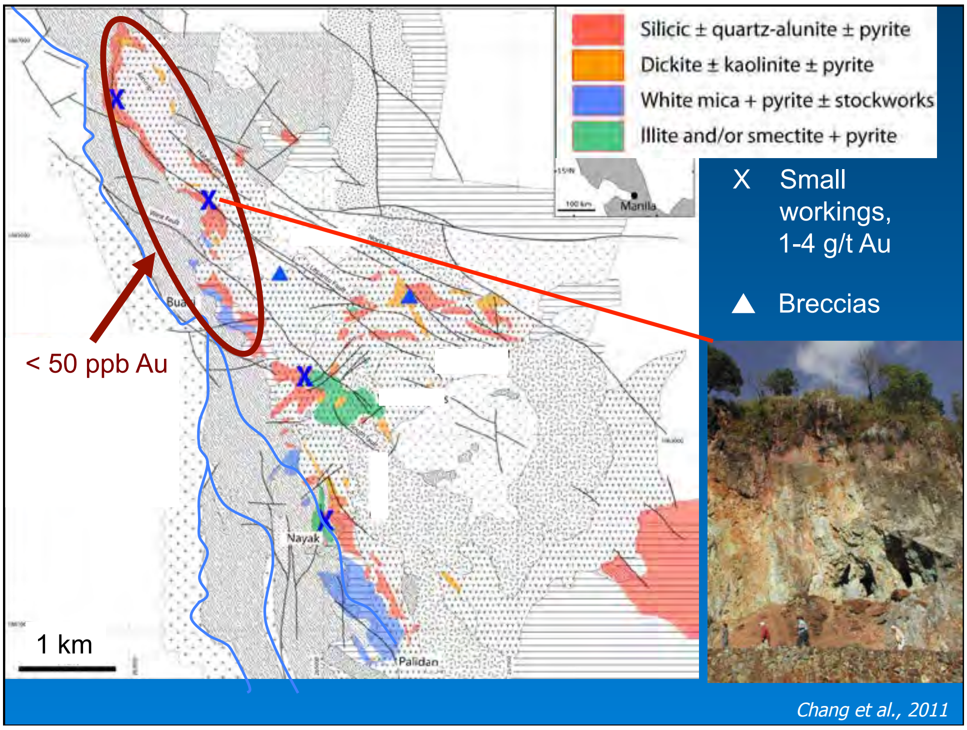

Lepanto high-sulfidation ores
Most ore (~70%) in root zone of lithocap, in Lepanto fault
NE
SW
Bato dacite
Imbanguila dacite
unconformity
1100
900
700 (m)
dickite-kaolinite
quartz-alunite
Lepanto fault
Balili volcaniclastic and Lepanto metavolcanic rocks
silicic ± enargite
pyrophyllite-diaspore-kandite
100 m
Hedenquist et al., 1998; Chang et al., 2011

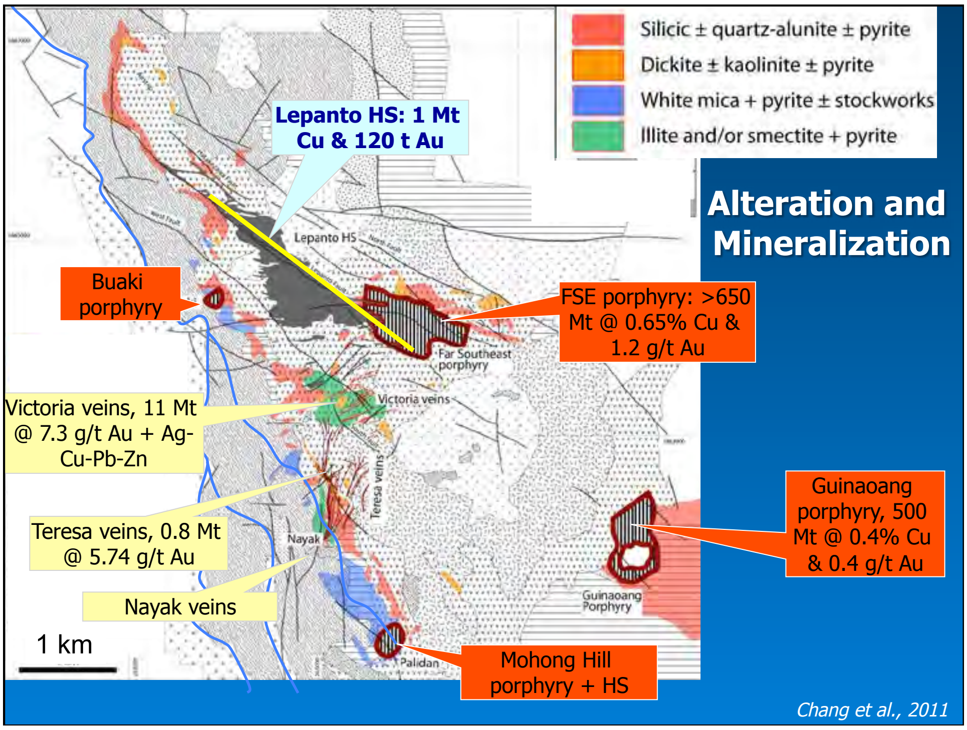

Mankayan: Basement
Late Oligocene to mid-Miocene Apaoan volcaniclastics
Slightly younger Balili volcaniclastics
Cretaceous-Paleogene Lepanto metavolcanics
12-13 Ma Bagon intrusive complex
Qtz diorite porphyry
1 km
Mankayan
Baguio
Luzon
Manila
Lapangan Tuff
Bato dacite pyroclastic
Bato dacite porphyry
Imbanguila dacite pyroclastic rocks
Imbanguila dacite porphyry
Quartz diorite porphyry
Balili Volcaniclastic
Bagon intrusive complex
Apaoan volcaniclastic
Lepanto metavolcanics
Chang et al., 2011

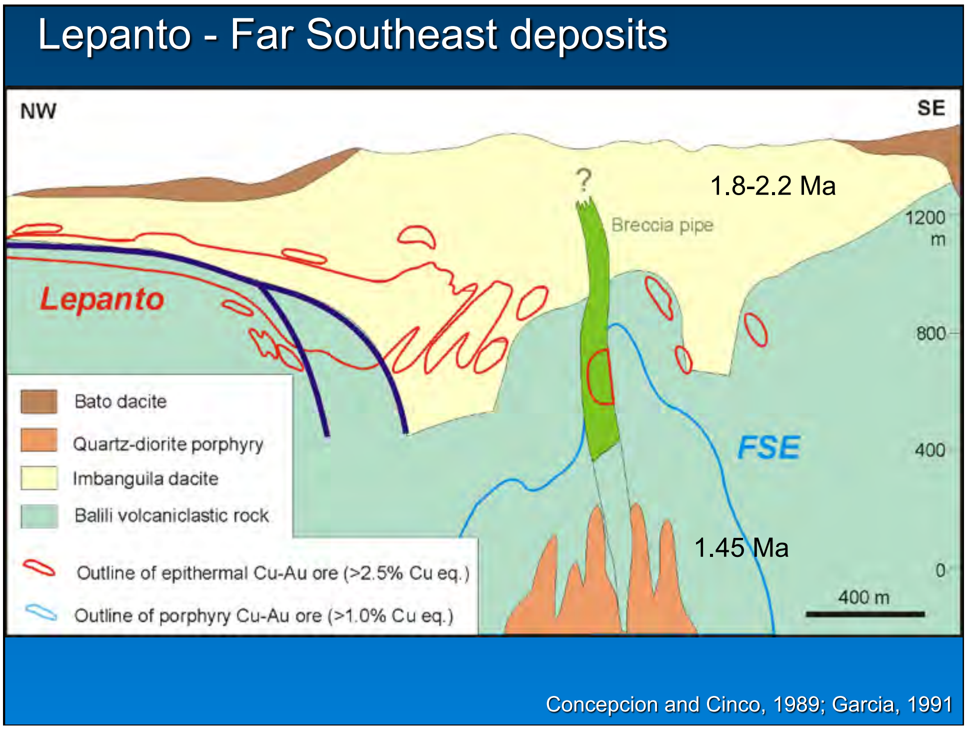

Pliocene volcanism
3.3 - 1.8 Ma, multiple eruptions
Late Oligocene to mid-Miocene Apaoan volcaniclastics
Slightly younger Balili volcaniclastics
Imbanguila dacite porphyry (3.3-1.8 Ma)
Cretaceous-Paleogene Lepanto metavolcanics
12-13 Ma Bagon intrusive complex
Imbanguila pyroclastics (3.3-1.8 Ma)
Qtz diorite porphyry
1 km
Mankayan
Baguio
Luzon
100 km
Lapangan Tuff
Bato dacite pyroclastic
Bato dacite porphyry
Imbanguila dacite pyroclastic rocks
Imbanguila dacite porphyry
Quartz diorite porphyry
Balili Volcaniclastic
Bagon intrusive complex
Apaoan volcaniclastic
Lepanto metavolcanics
Chang et al., 2011

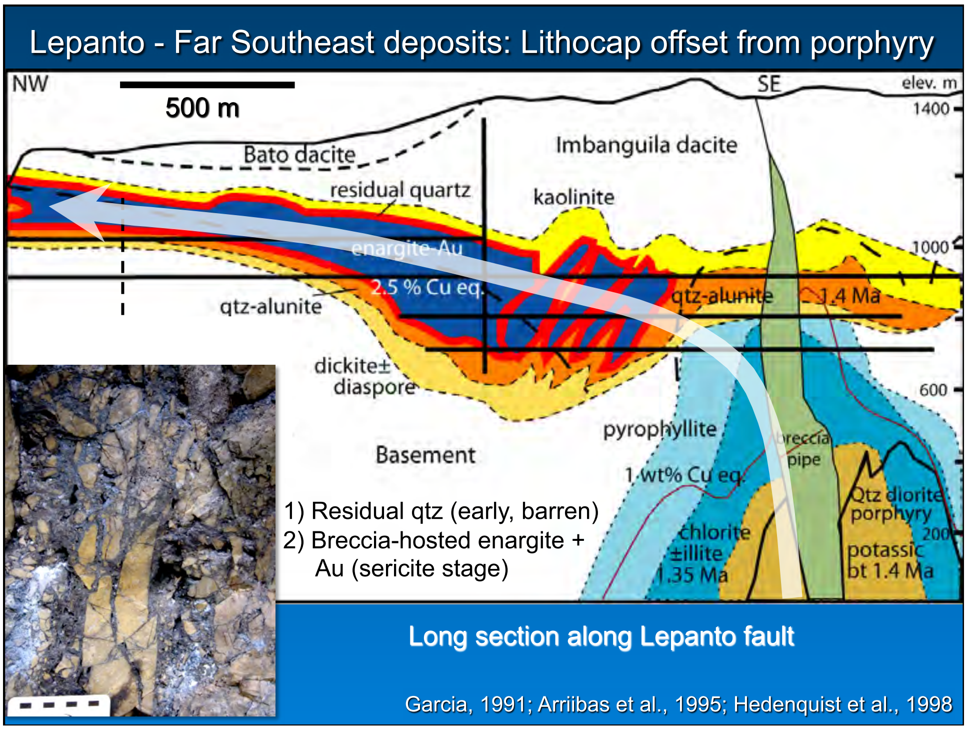

Young cover:
<1.2 Ma
Late Oligocene to mid-Miocene Apaoan volcaniclastics
Slightly younger Balili volcaniclastics
Imbanguila dacite porphyry (3.3-1.8 Ma)
Cretaceous-Paleogene Lepanto metavolcanics
12-13 Ma Bagon intrusive complex
Bato pyroclastics (1.2 Ma)
Bato dacite porphyry (1.2 Ma)
Imbanguila pyroclastics (3.3-1.8 Ma)
Qtz diorite porphyry
1 km
Lapangan Tuff (0.19 Ma)
Mankayan
Baguio
Luzon
100 km
Lapangan Tuff
Bato dacite pyroclastic
Bato dacite porphyry
Imbanguila dacite pyroclastic rocks
Imbanguila dacite porphyry
Quartz diorite porphyry
Balili Volcaniclastic
Bagon intrusive complex
Apaoan volcaniclastic
Lepanto metavolcanics
Chang et al., 2011

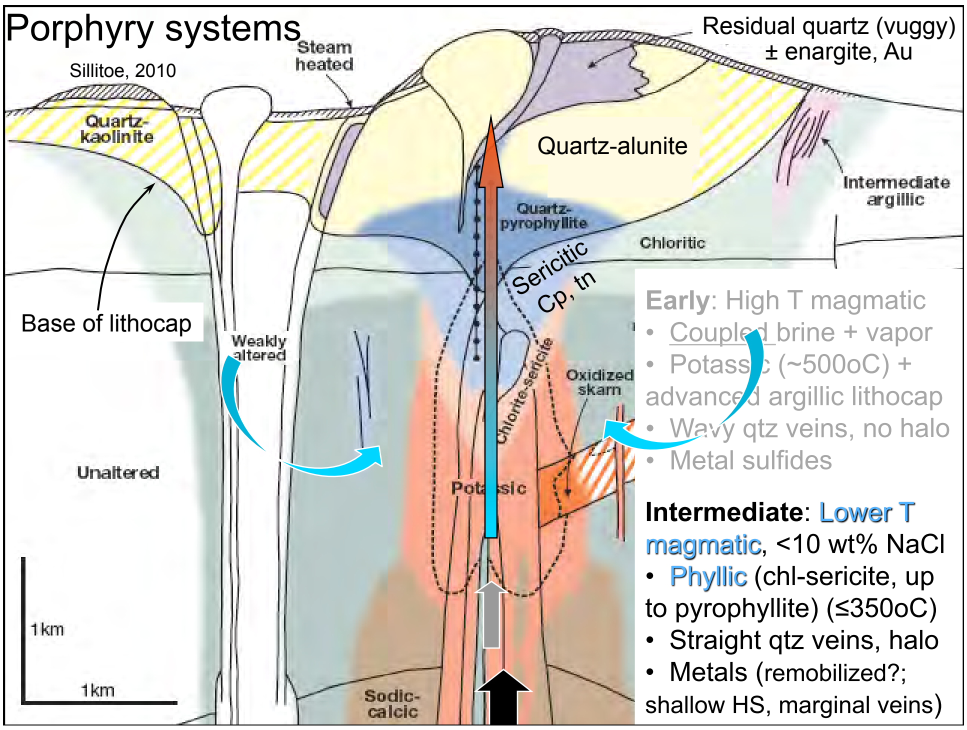

Silicic ± quartz-alunite ± pyrite
Dickite ± kaolinite ± pyrite
White mica + pyrite ± stockworks
Illite and/or smectite + pyrite
Buaki
Nayak
Palidan
1 km
NW end of lithocap: qtz-alunite cliffs at unconformity, with kaolinite halo
Chang et al., 2011


Silicic ± quartz-alunite ± pyrite
Dickite ± kaolinite ± pyrite
White mica + pyrite ± stockworks
Illite and/or smectite + pyrite
X Small workings, 1-4 g/t Au
▲ Breccias
Manila
< 50 ppb Au
Nayak
Palidan
1 km
Chang et al., 2011

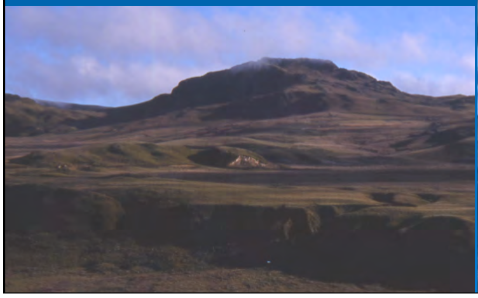

Silicic ± quartz-alunite ± pyrite
Dickite ± kaolinite ± pyrite
White mica + pyrite ± stockworks
Illite and/or smectite + pyrite
Alteration and Mineralization
Lepanto HS: 1 Mt Cu & 120 t Au
Lepanto HS
Buaki porphyry
FSE porphyry: >650 Mt @ 0.65% Cu & 1.2 g/t Au
Far Southeast porphyry
Victoria veins, 11 Mt @ 7.3 g/t Au + Ag-Cu-Pb-Zn
Victoria veins
Teresa veins
Teresa veins, 0.8 Mt @ 5.74 g/t Au
Nayak
Nayak veins
Guinaoang porphyry, 500 Mt @ 0.4% Cu & 0.4 g/t Au
Guinaoang Porphyry
1 km
Palidan
Mohong Hill porphyry + HS
Chang et al., 2011


Lepanto - Far Southeast deposits
NW
SE
?
1.8-2.2 Ma
Breccia pipe
1200 m
800
400
0
Lepanto
FSE
1.45 Ma
400 m
Bato dacite
Quartz-diorite porphyry
Imbanguila dacite
Balili volcaniclastic 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

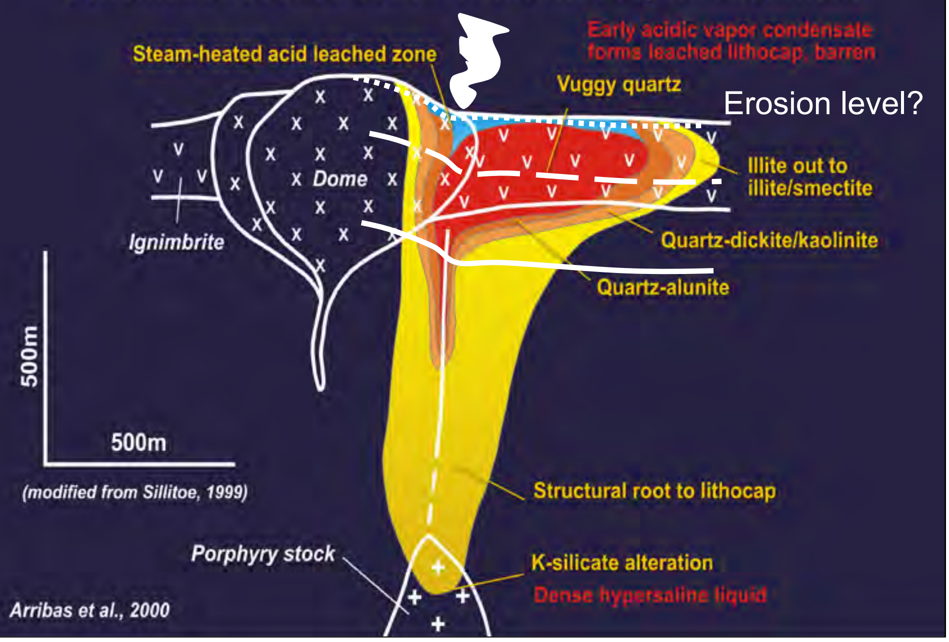

Lepanto - Far Southeast deposits: Lithocap offset from porphyry
NW
500 m
SE
elev. m
1400
Bato dacite
Imbanguila dacite
residual quartz
kaolinite
enargite-Au
2.5 % Cu eq.
1000
qtz-alunite
qtz-alunite
1.4 Ma
dickite± diaspore
600
pyrophyllite
Basement
breccia pipe
1 wt% Cu eq.
Qtz diorite porphyry
1) Residual qtz (early, barren)
2) Breccia-hosted enargite + Au (sericite stage)
chlorite ±illite 1.35 Ma
200
potassic bt 1.4 Ma
Long section along Lepanto fault
Garcia, 1991; Arriibas et al., 1995; Hedenquist et al., 1998

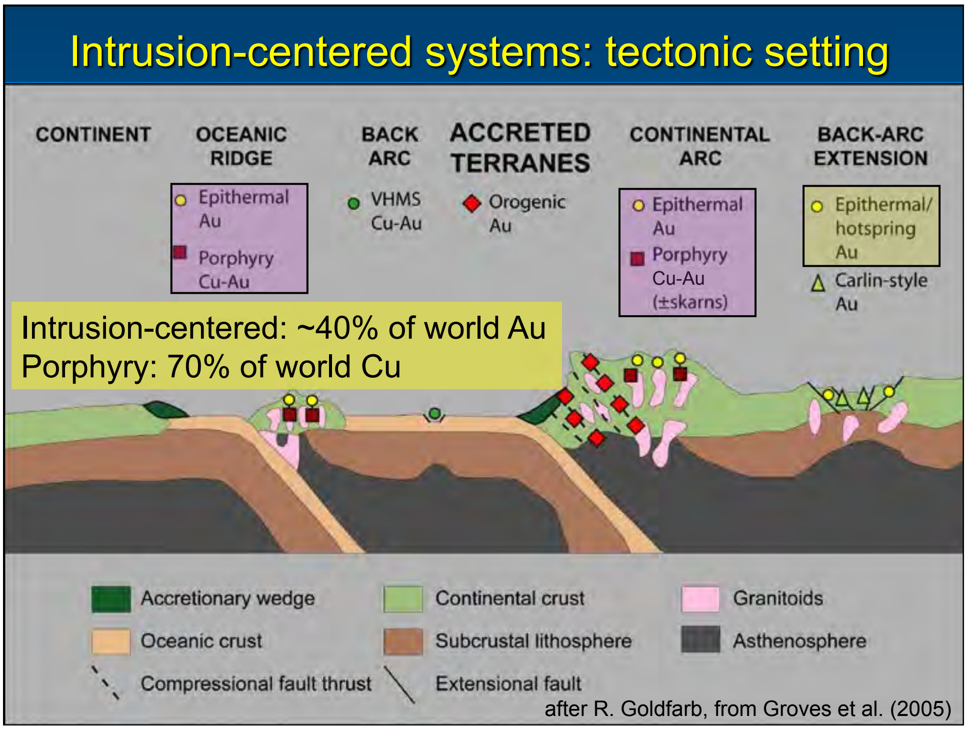

Porphyry systems
Sillitoe, 2010
Steam heated
Residual quartz (vuggy) ± enargite, Au
Quartz-kaolinite
Quartz-alunite
Intermediate argillic
Quartz-pyrophyllite
Chloritic
Sericitic
Cp, tn
Base of lithocap
Weakly altered
Chlorite-sericite
Oxidized skarn
Unaltered
Potassic
1 km
1km
Sodic-calcic
Early: High T magmatic
• Coupled brine + vapor
• Potassic (~500oC) + advanced argillic lithocap
• Wavy qtz veins, no halo
• Metal sulfides
Intermediate: Lower T magmatic, <10 wt% NaCl
• Phyllic (chl-sericite, up to pyrophyllite) (≤350oC)
• Straight qtz veins, halo
• Metals (remobilized?; shallow HS, marginal veins)

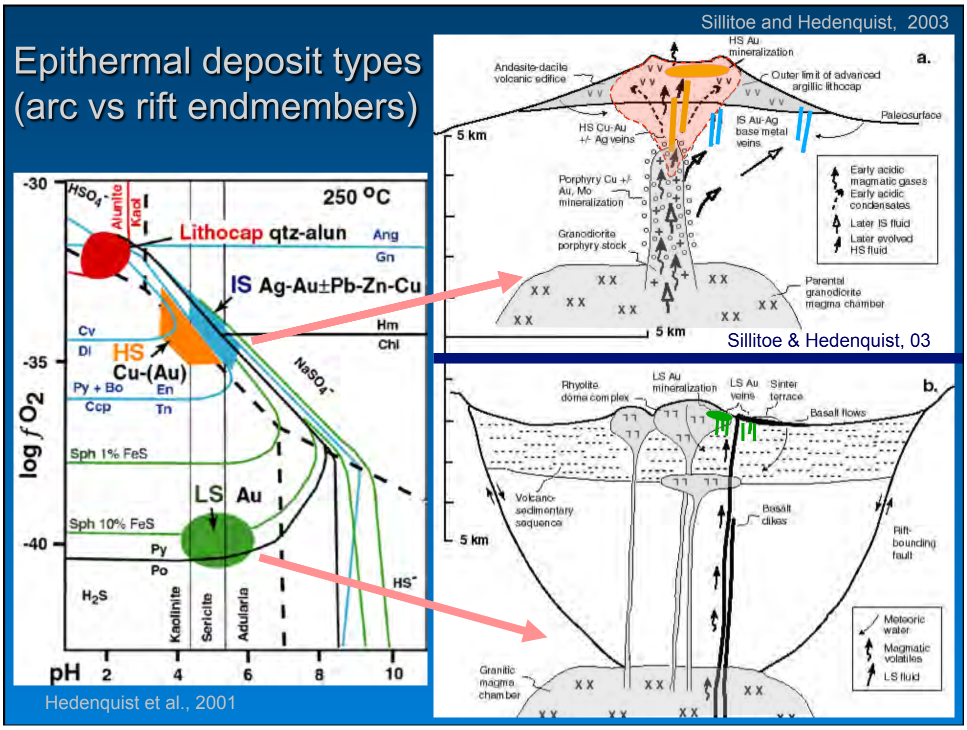
- Minas Conga: Perol porphyry (15.8 Ma), east of Yanacocha (5-12 Ma)
- Co. Cocañez: Barren quartz-alunite lithocap (16.1 Ma); related to Perol porphyry?
- **Multiple porphyry vein generations (parallel to silicic ribs in lithocap)**

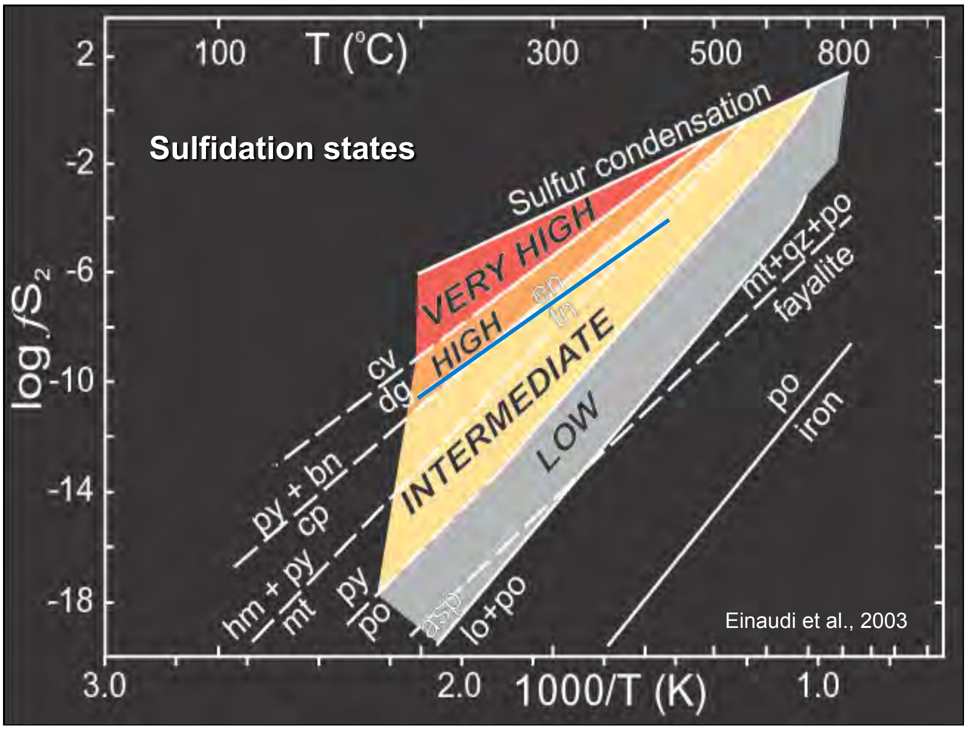


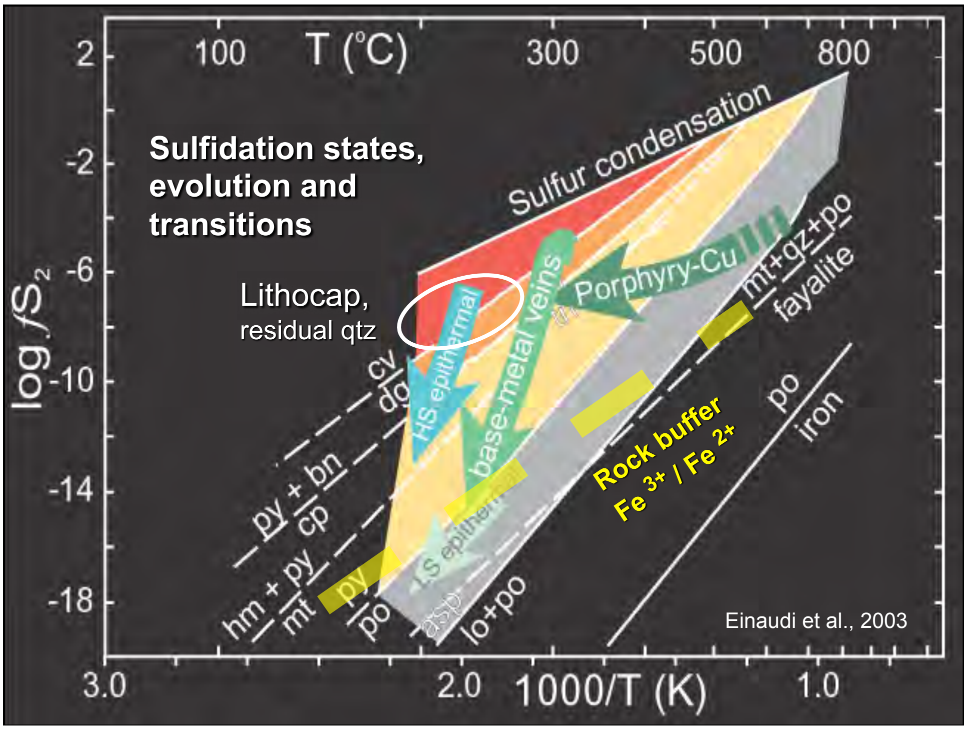
Schematic reconstruction of the lithocap environment




Intrusion-centered systems: tectonic setting
CONTINENT
OCEANIC RIDGE
BACK ARC
ACCRETED TERRANES
CONTINENTAL ARC
BACK-ARC EXTENSION
Epithermal Au
Porphyry Cu-Au
VHMS Cu-Au
Orogenic Au
Epithermal Au
Porphyry Cu-Au (±skarns)
Epithermal/ hotspring Au
Carlin-style Au
Intrusion-centered: ~40% of world Au
Porphyry: 70% of world Cu
Accretionary wedge
Continental crust
Granitoids
Oceanic crust
Subcrustal lithosphere
Asthenosphere
Compressional fault thrust
Extensional fault
after R. Goldfarb, from Groves et al. (2005)


Epithermal deposit types (arc vs rift endmembers)
Sillitoe and Hedenquist, 2003
250 °C
Lithocap qtz-alun
IS Ag-Au±Pb-Zn-Cu
HS Cu-(Au)
LS Au
Alunite
Kaol
Ang
Gn
Hm
Chl
Cv
Dl
Py + Bo
Ccp
En
Tn
Sph 1% FeS
Sph 10% FeS
Py
Po
H₂S
HS⁻
NaSO₄⁻
Kaolinite
Sericite
Adularia
log fO2
pH 2 4 6 8 10
-30
-35
-40
Hedenquist et al., 2001
HS Au mineralization
Andesite-dacite volcanic edifice
Outer limit of advanced argillic lithocap
Paleosurface
HS Cu-Au +/- Ag veins
IS Au-Ag base metal veins
Porphyry Cu +/- Au, Mo mineralization
Granodiorite porphyry stock
Early acidic magmatic gases
Early acidic condensates
Later IS fluid
Later evolved HS fluid
Parental granodiorite magma chamber
5 km
a.
Sillitoe & Hedenquist, 03
Rhyolite dome complex
LS Au mineralization
LS Au veins
Sinter terrace
Basalt flows
Volcano-sedimentary sequence
Basalt dikes
Rift-bounding fault
Meteoric water
Magmatic volatiles
LS fluid
Granitic magma chamber
b.


Sulfidation states
T (°C)
100
300
500
800
log fS_2
2
-2
-6
-10
-14
-18
3.0
2.0
1000/T (K)
1.0
Sulfur condensation
VERY HIGH
HIGH
INTERMEDIATE
LOW
cv
dg
py + bn
cp
hm + py
mt
py
po
lo+po
mt+qz+po
fayalite
po
iron
Einaudi et al., 2003


Sulfidation states, evolution and transitions
T (°C)
100
300
500
800
log fS_2
2
-2
-6
-10
-14
-18
3.0
2.0
1000/T (K)
1.0
Sulfur condensation
Lithocap,
residual qtz
HS epithermal
base-metal veins
Porphyry-Cu
LS epithermal
Rock buffer
Fe^{3+} / Fe^{2+}
cv
dg
py + bn
cp
hm + py
mt
py
po
lo+po
mt+qz+po
fayalite
po
iron
Einaudi et al., 2003

Exploration for epithermal Au-Ag vein deposits

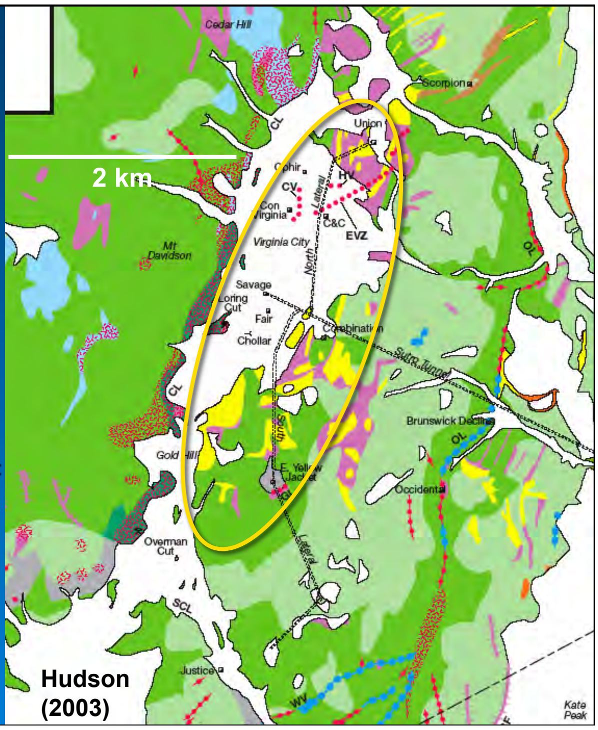
- **Large variations between deposit types and districts**
- **Model the prospect, do not fit prospect to the model**
- **Beware generalizations**
- **Paleosurface estimation, hydrology, erosion level**
  - **Lithology: volcanic (alteration) history, effect on permeability**
  - **Structure: relation 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

- Cristobolite + kaolinite + alunite
- Illitic
- Kaolinitic, alsic, alunitic → Al to pyrop ± diasp to kaol ± dick to illite
- Silica + kaolinite
- Propylitic-c (epidote absent)
- Propylitic-e (with epidote)
- Propylitic-a (chlorite + illite + K-spar + albite)
- Sericitic 2M mica
- Metamorphic rocks
- Unaltered units
- Illitic along faults
- Quartz + adularia vein
- Calcite + quartz vein
- Concealed vein
- Stockwork veins



Hudson (2003)