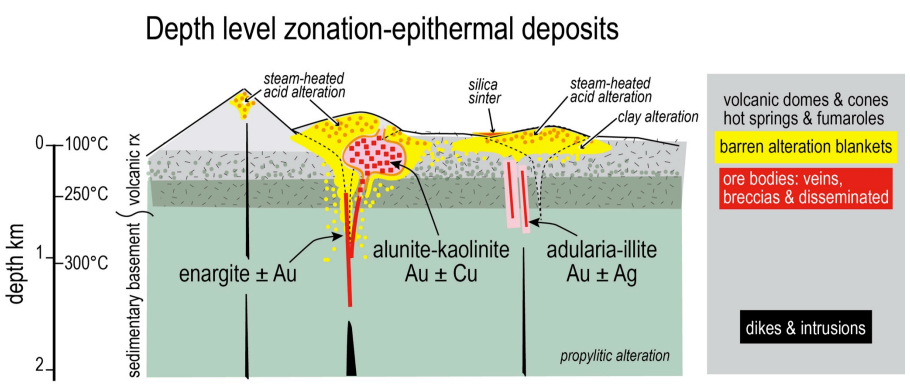
Exploration Considerations

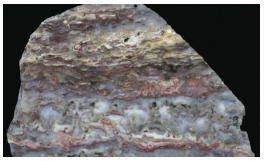
- Depth level of exposure
- Mineralogical-chemical signature of ore
- Lithological-structural controls that localize ores
- Potential footprint of ore mineralization
- Telescoped ore zones (blind mineralization)
- Ore vs sub-economic mineralization

Answers found in mineralogy, mineral textures, mineral zonation, alteration extents, structure-stratigraphy, and rock geochemistry.

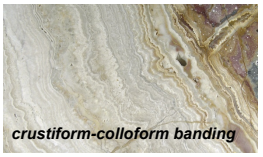


Depth Indicators

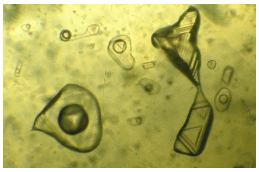
Sinter



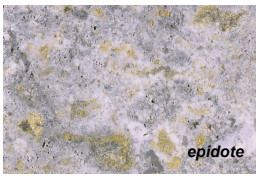
Vein textures



Fluid Inclusions



Temperature-sensitive alteration minerals



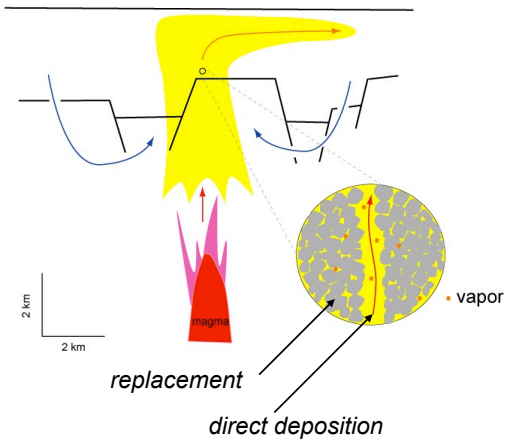
Simmons et al, 2005

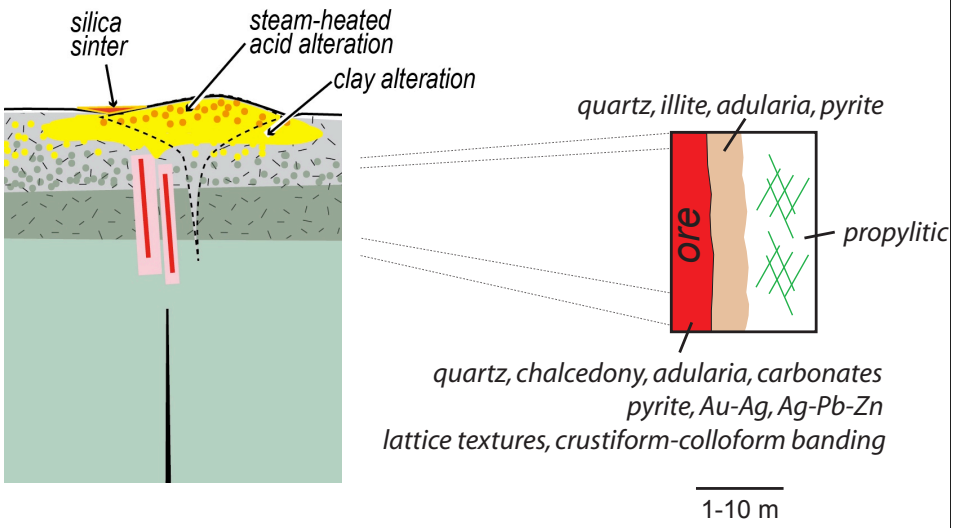
Replacement vs Direct Deposition

Direct Deposition involves precipitation of phases in open spaces (cavities, fractures) such as is the case for a rock veined with quartz and calcite.

Replacement involves the conversion of one phase to another by water-rock interaction. This usually involves dissolution-precipitation reactions at microscopic-submicroscopic scale.

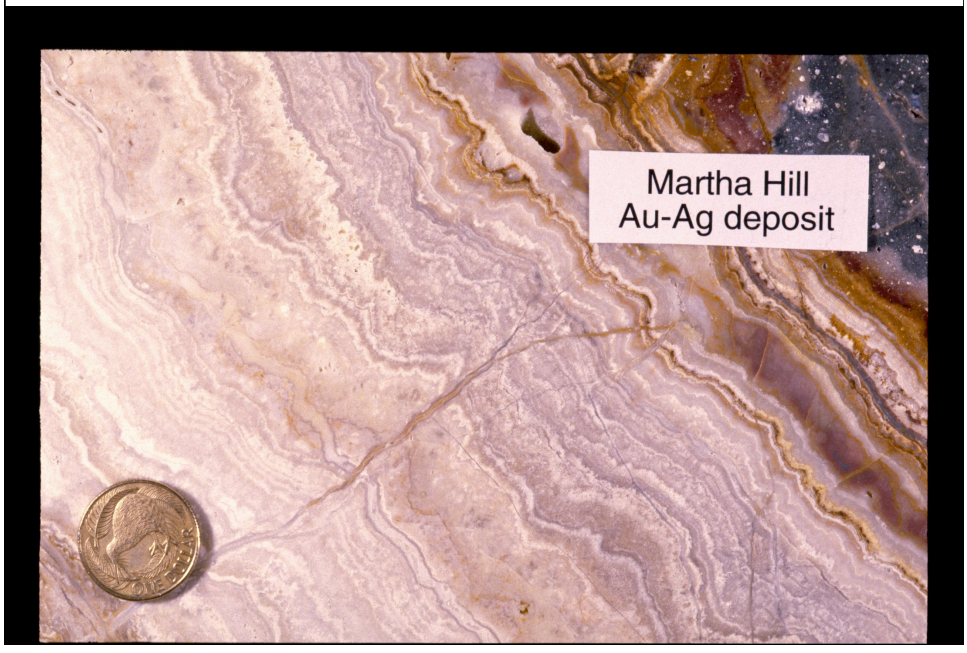
Leaching and rock dissolution are another form of hydrothermal alteration that can also occur in the presence of acid solutions



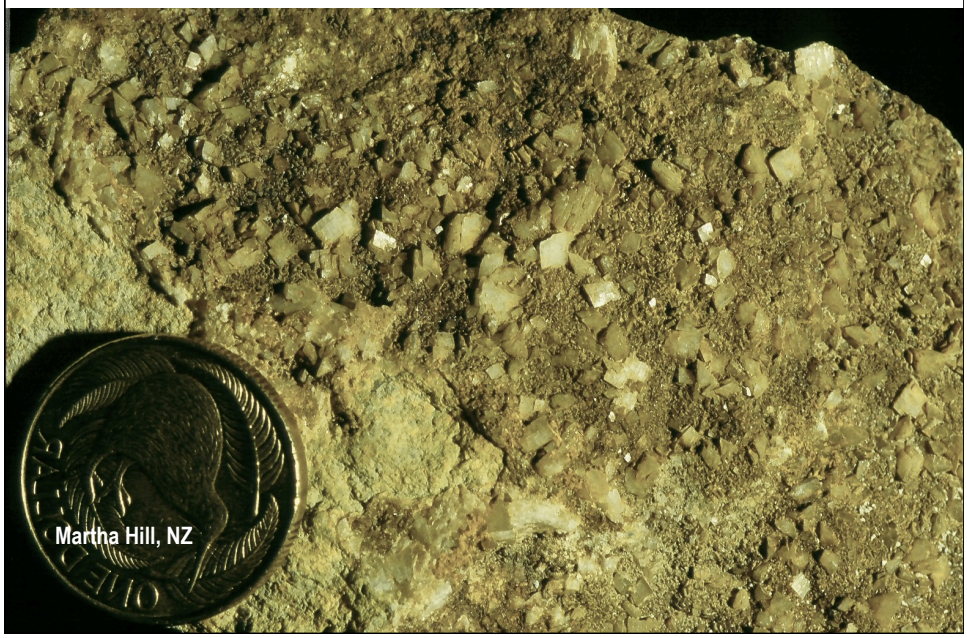


Quartz-calcite-adularia-illite epithermal ores: silica sinter

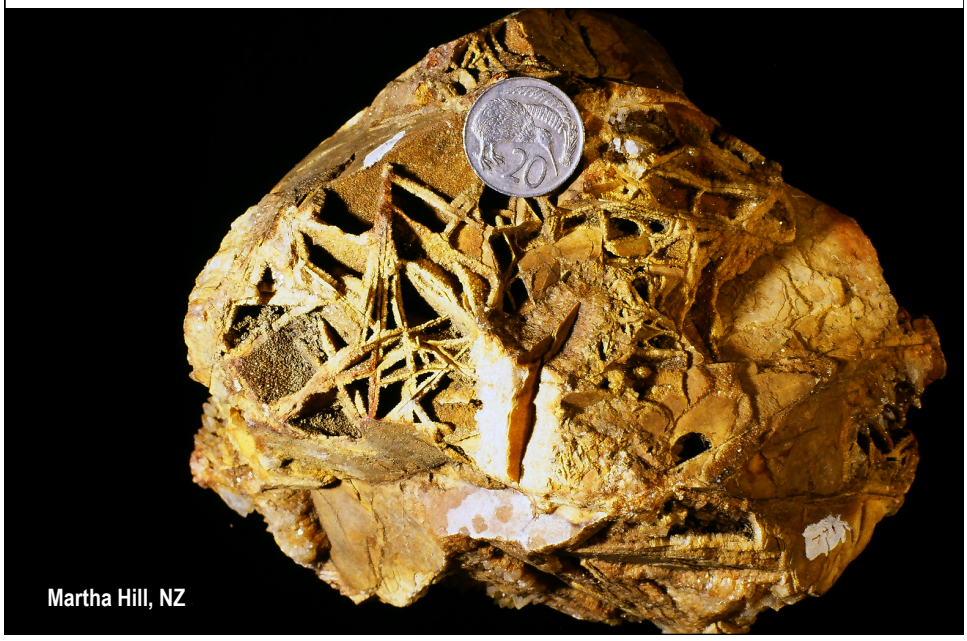
Quartz-calcite-adularia-illite epithermal ores: Colloform-crustiform banded quartz



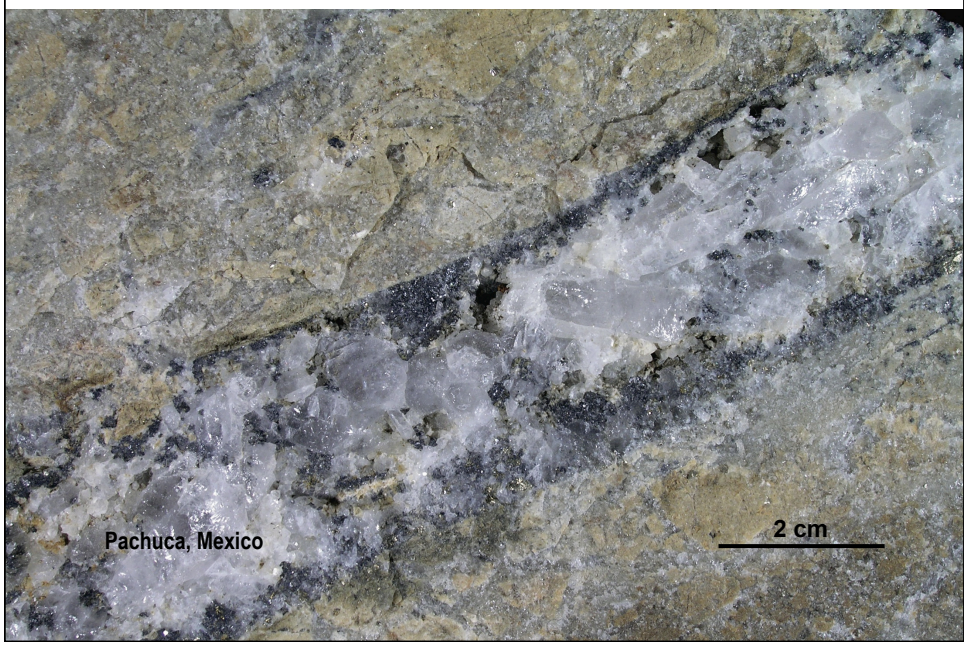
Quartz-calcite-adularia-illite epithermal ores: Adularia



Quartz-calcite-adularia-illite epithermal ores:
Lattice texture-qtz pseudomorph of platy calcite



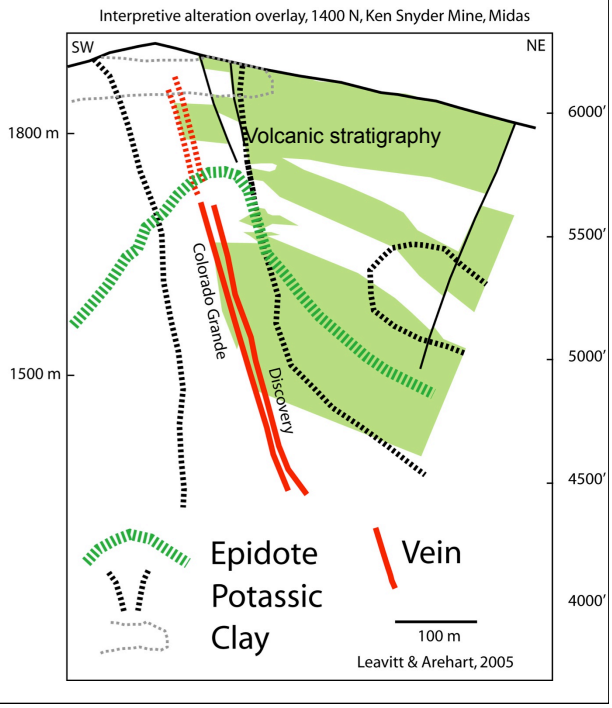
Quartz-calcite-adularia-illite epithermal ores: quartz with base-metal sulfides



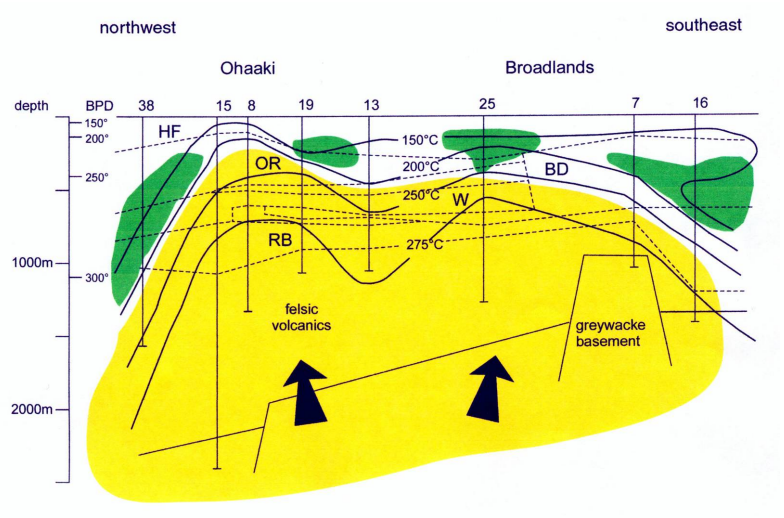
Epithermal veins enveloped by adularia

Epidote boundary indicates >230°C

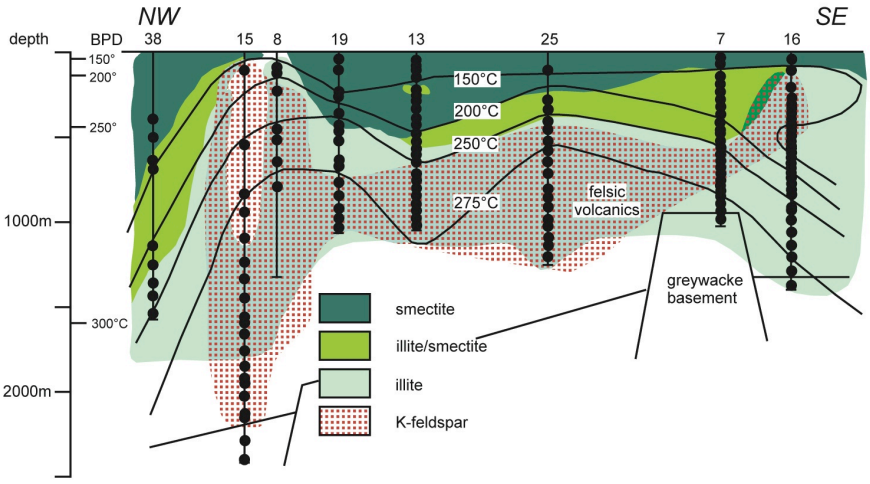
Midas, Nevada
Au-Ag ores: 15.2 Ma
(Leavitt et al., 2004)



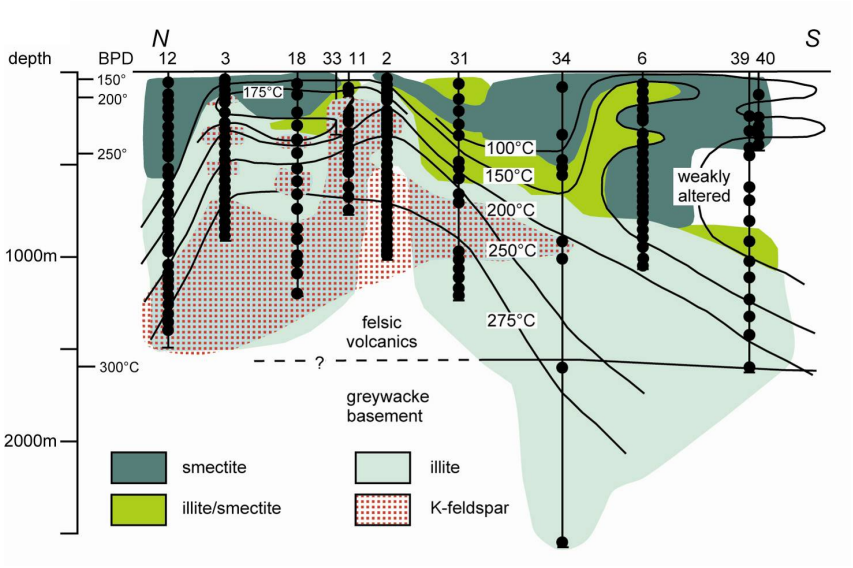
Broadlands-Ohaaki



Broadlands-Ohaaki



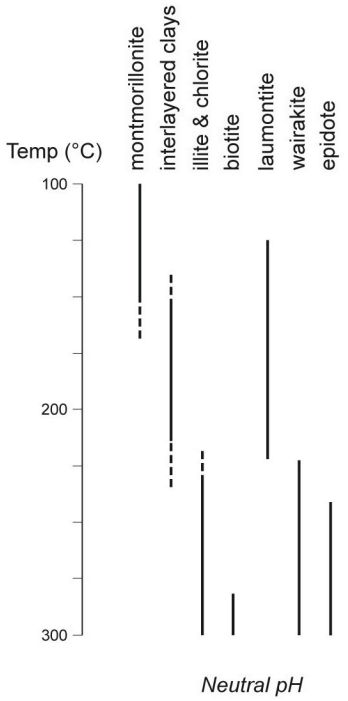
Broadlands-Ohaaki



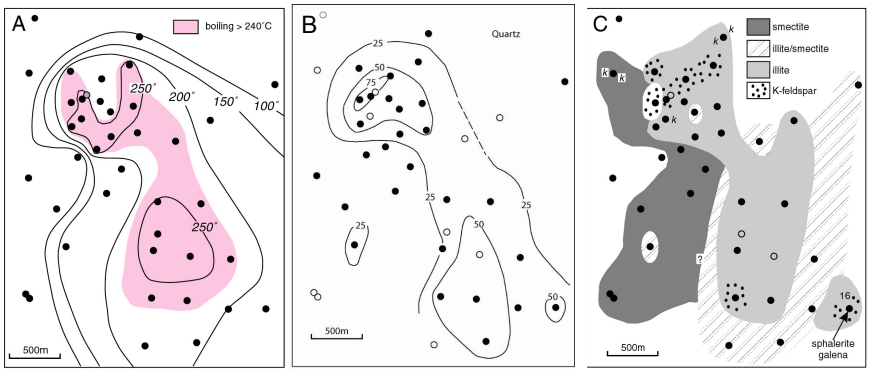
Mineral Geothermometers

H_2O and OH^- bearing minerals tend to be temperature sensitive.

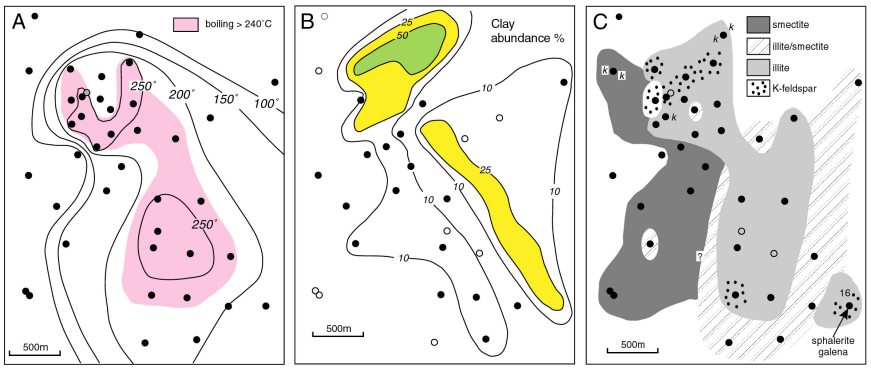
Clays best identified with XRD; others identified in thin section.



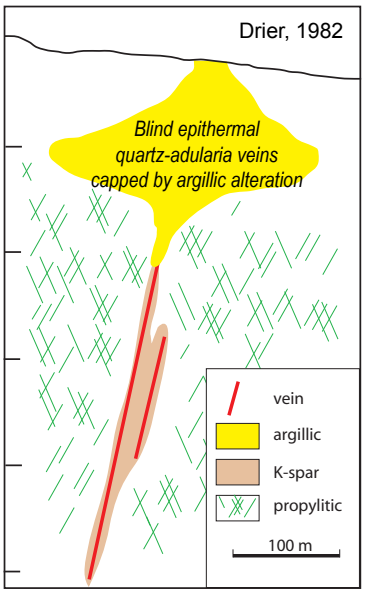
Broadlands-Ohaaki Plan views: 400 m depth



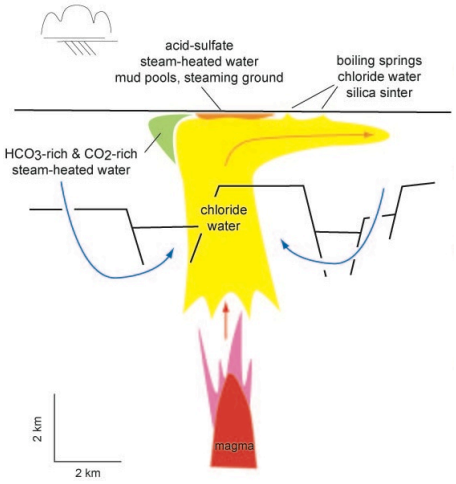
Broadlands-Ohaaki Plan views: 400 m depth



Pachuca-Real del Monte: Clay-Carbonate Alteration



Water Types-Hydrothermal Minerals



neutral pH chloride waters
silica (qtz), adularia, albite, illite, chlorite, epidote, pyrite, calcite

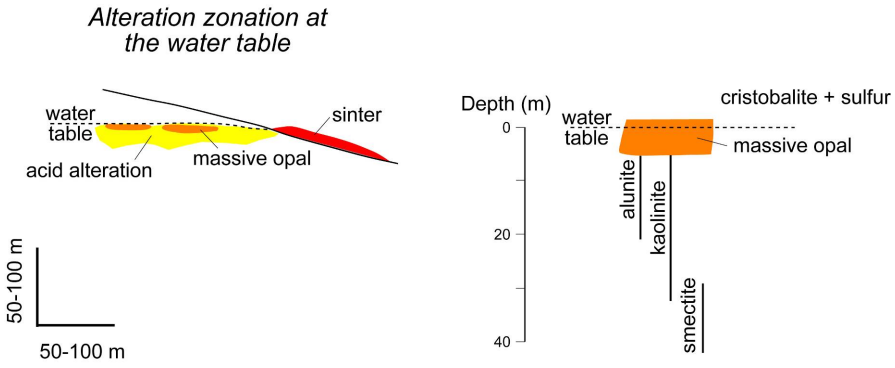
bicarbonate waters
calcite, illite, smectite, chalcedony, pyrite

acid sulfate waters
alunite, kaolinite, opal
pyrite, sulfur


silica sinter
geyserite
10 cm
columnar textures

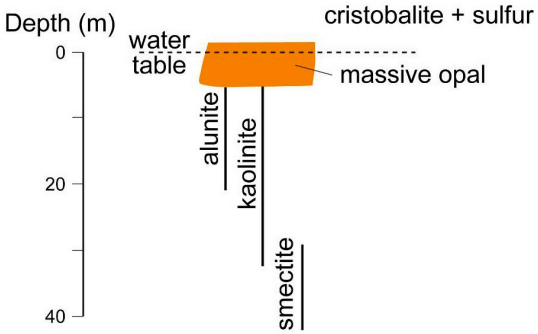

vent fissure
silica sinter

Surficial alteration (acid)



Chloride waters discharge at the water table where intersected by topography causing siica sinter to precipitate

Surficial alteration (acid)



Tabular bodies of massive opal (opalite) form at the water table. They are a feature of the paleosurface in epithermal deposits. Breccia textures are common probably a result of acid dissolution.

Surficial alteration (acid)

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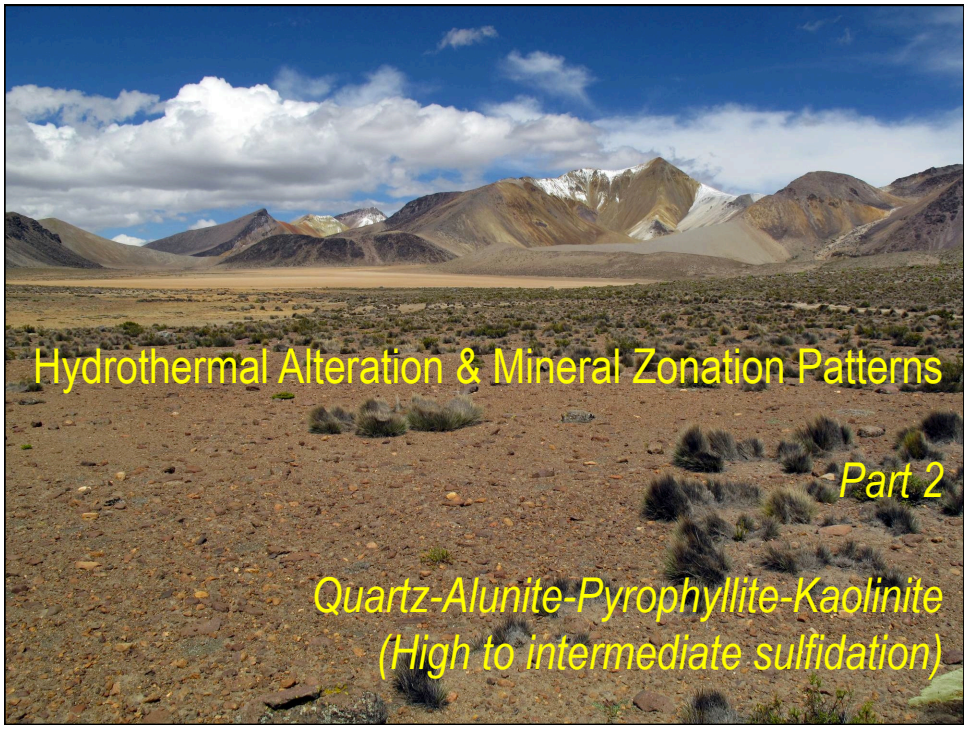
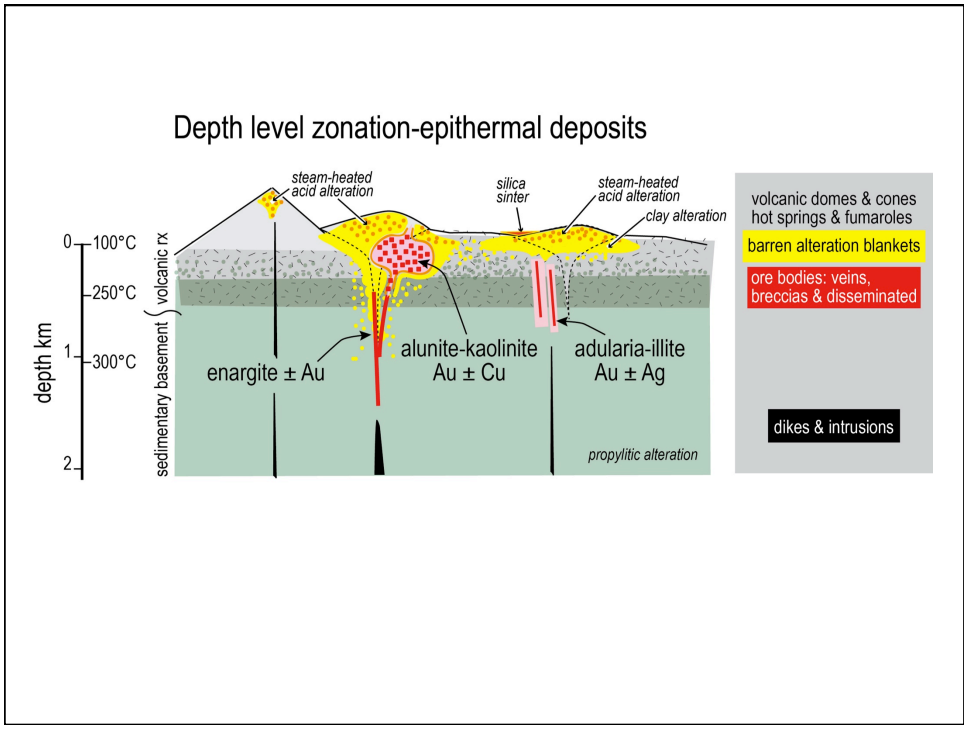
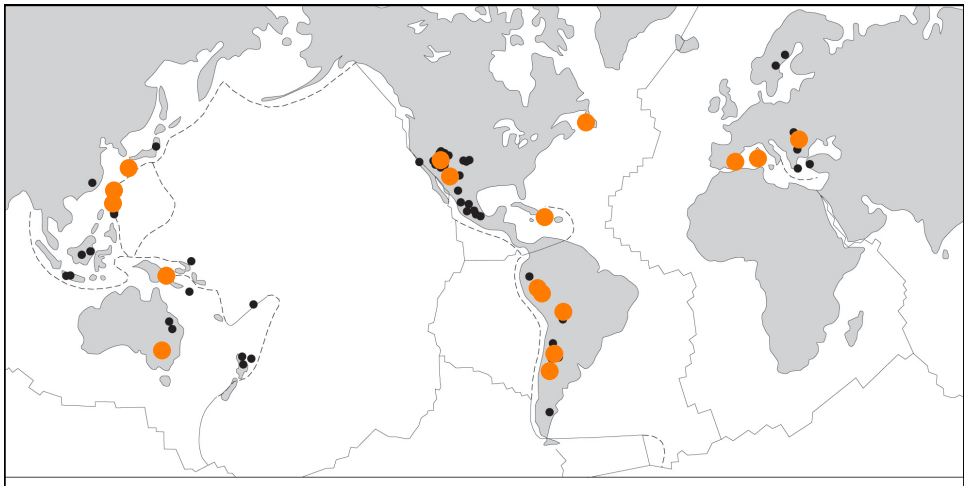
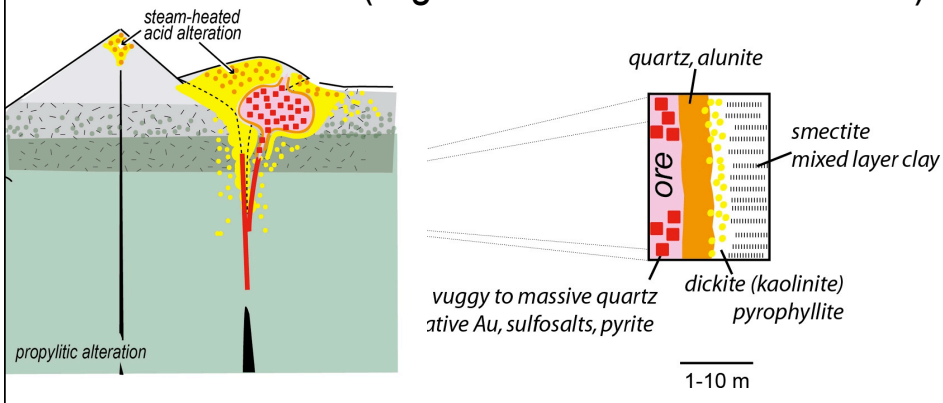

Hydrothermal Alteration & Mineral Zonation Patterns
Part 2
Quartz-Alunite-Pyrophyllite-Kaolinite
(High to intermediate sulfidation)


Depth level zonation-epithermal deposits
steam-heated acid alteration
silica sinter
steam-heated acid alteration
clay alteration
volcanic domes & cones
hot springs & fumaroles
barren alteration blankets
ore bodies: veins, breccias & disseminated
dikes & intrusions
depth km
0
1
2
100°C
250°C
300°C
volcanic rx
sedimentary basement
enargite ± Au
alunite-kaolinite
Au ± Cu
adularia-illite
Au ± Ag
propylitic alteration



- Quartz-Alunite-Pyrophyllite-Kaolinite epithermal deposits

Quartz-Alunite-Pyrophyllite-Kaolinite (High to intermediate sulfidation)



Associated with andesitic-dacitic (rhyolite) magmas

Acid Alteration Minerals

Muscovite (K-mica)	$KAl_3Si_3O_{10}(OH)_2$
Andalusite	Al_2SiO_5
Corundum	Al_2O_3
Pyrophyllite	$AlSi_2O_5(OH)$
Diaspore	$AlO(OH)$
Zunyite	$Al_{13}Si_5O_{20}(OH)_{18}Cl$
Kaolinite (Dickite)	$Al_2Si_2O_5(OH)_4$
Dumortierite	$Al_7BO_3(SiO_4)_3(OH)_3$
Alunite	$KAl_3(SO_4)_2(OH)_6$
Natroalunite	$NaAl_3(SO_4)_2(OH)_6$
Crandallite (AP)	$CaAl_3(PO_4)(PO_3OH)(OH)_6$
Woodhouseite (APS)	$CaAl_3(PO_4)(SO_4)(OH)_6$
	REE, Ca, Sr, Ba, Pb substitution

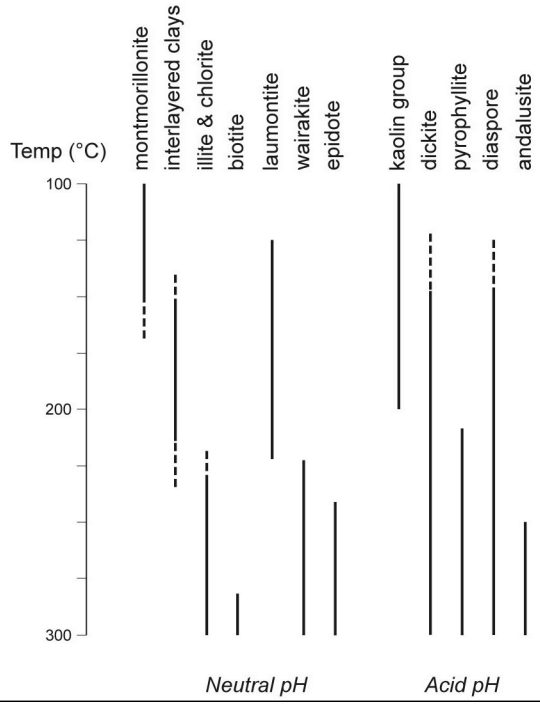
Temperature

Compare neutral pH & acid pH related minerals.

Acid pH minerals have mineral compositions that contain alumina (Al_2O_3) and silica (SiO_2). Na, K, Ca & Mg are absent.

Note the minerals that form under hot acid conditions.

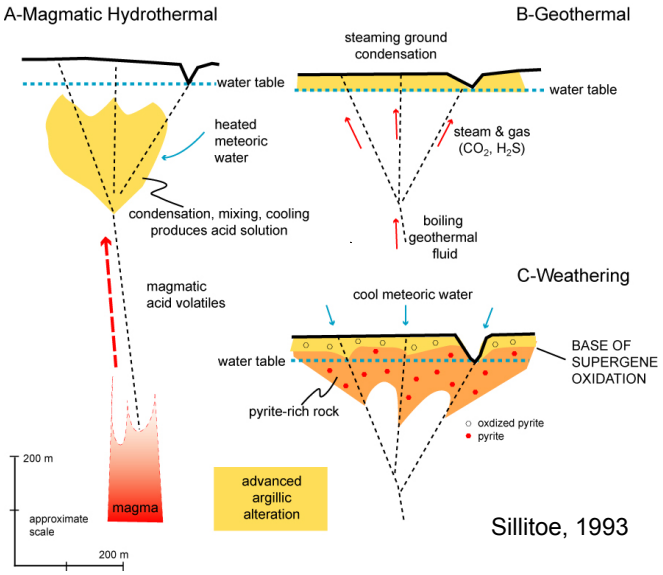
Alunite is the other diagnostic acid mineral-not shown because its occurrence is not temperature-sensitive.



Advanced Argillic Alteration

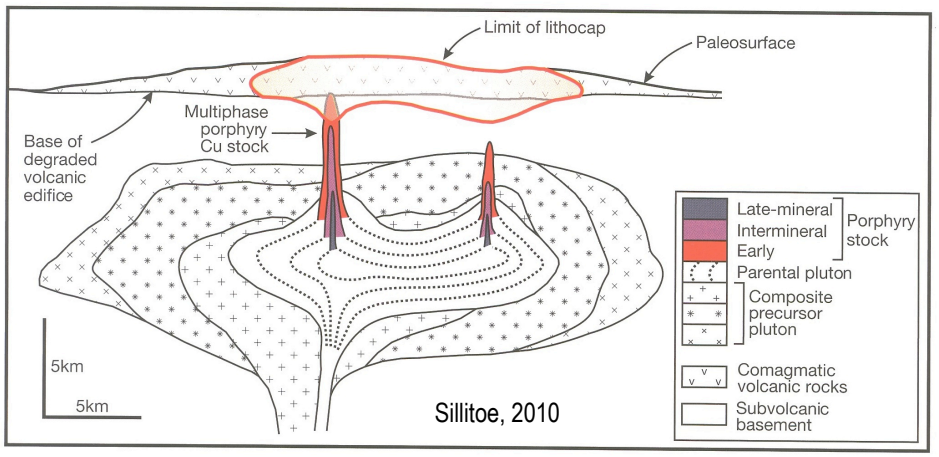
Steam-heated	Opal, alunite (white, powdery, fine-grained, pseudo-cubic), kaolinite, pyrite, marcasite	Develops at <120° C near the water table and in the shallowest epithermal environment through alteration by steam-heated acid-sulfate waters; locally associated with silica sinter but only in geothermal systems
Magmatic hydrothermal	Quartz, alunite (tabular), dickite, pyrophyllite, (diaspore, zunyite)	Develops at >200° C within the epithermal environment through alteration by magmatic derived acidic waters
Supergene	Alunite, kaolinite, halloysite, jarosite, Fe-oxides	Develops at <40° C through weathering and oxidation of sulfide-bearing rocks

Environments in which advanced argillic alteration forms



Schematic alteration zonation-Intrusion centered mineralization

Note the extent of the lithocap (acid alteration)



Alunite (steam-heated advanced argillic alteration)

Puren (La Coipa), Chile

Alunite (hypogene advanced argillic alteration)

Tambo, Chile

Mineralogical features (Deyell et al. 2005. Econ. Geol.)

alunite & APS

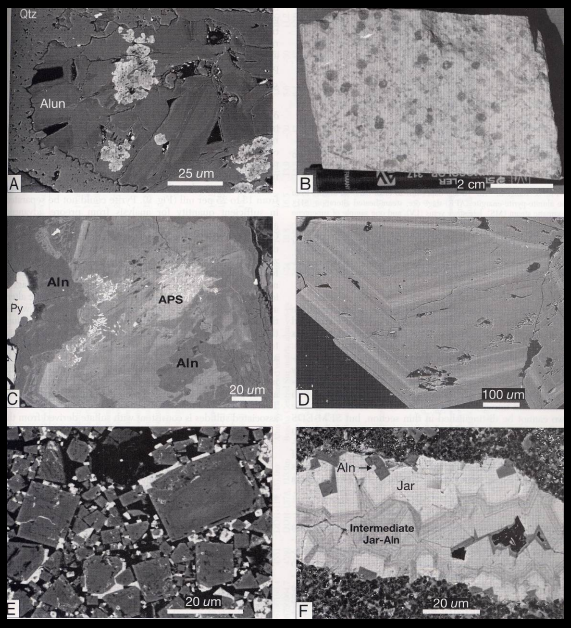
steam-heated alteration

alunite & APS

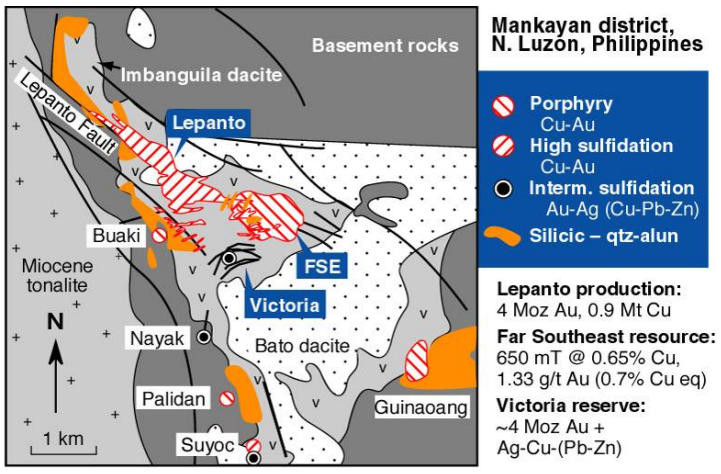
oscillatory zoning in magmatic alunite

steam-heated alunite (pseudo-cubic)

steam-heated alunite (pseudo-cubic)



Lepanto-Philippines



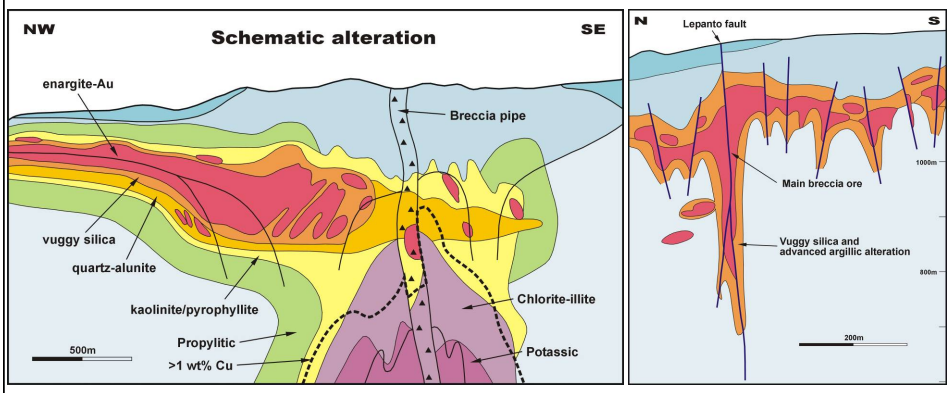
Hedenquist et al. 1998

Co-temporal (1.4 to 1.1 Ma)

Lepanto-Philippines

- enargite ore centered on Lepanto fault
- ore extends ~3km (bx, massive, vuggy residual qtz w/ alunite halo)
- upward from FSE, pervasive ser+clay+chl grades into pyrophyllite (w/ qtz+anhy+dick)
- crosscut & overlain by advanced argillic alteration (qtz+alun+anhy+dia+dick+pyroph)
- leached silica developed at unconformity & overlying dacitic rocks

Lepanto, Philippines

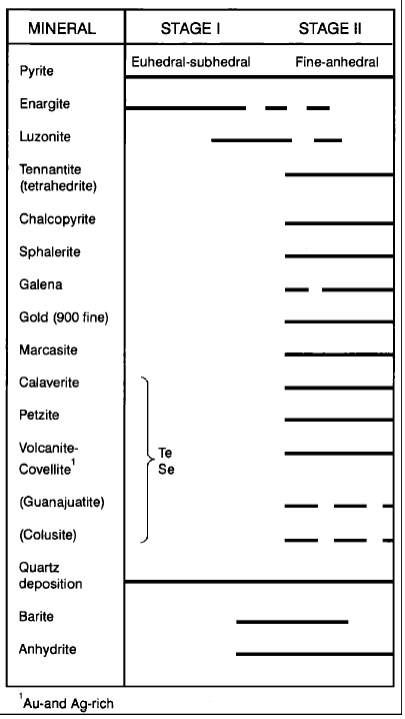


Hedenquist et al., 1998

Lepanto-Philippines

enargite ores

- Th 150-250°C
- 1-4.5 wt % NaCl
- mixing-cooling
- magmatic fluids
- <1-60 ppm Au in enargite



Hedenquist et al., 1998
Deyell & Hedenquist, 2011

White Island-andesitic volcano
aerosols from 850°C discharge (1988)

100 tonnes Cu/yr
.037 tonnes Au/yr

<1000 yrs to flux 1 million oz Au at White Island
>6000 yrs to flux 1 million oz Au at Broadlands-Ohaaki

(Hedenquist et al., 1993)

Acid sulphate chloride water

T°C	79
pH	1.4
Na	5910 ppm
K	635 ppm
Cl	38700 ppm
SO4	4870 ppm
HCO3	0 ppm

Hydrothermal minerals:
- alunite
- kaolinite
- quartz
- pyrite
- sulfur
- anhydrite

Quartz-Alunite-Pyrophyllite-Kaolinite (High to intermediate sulfidation)

- Associated with intermediate composition volcanic rocks
- Cu-Au ores assoc w/ massive to vuggy qtz (polymetalic ores)
- Secondary oxidation liberates refractory Au
- sharp lateral changes in alteration
- vertical zonation-vuggy qtz →pyrophyllite→ sericite w/ depth
- alteration sequence associated with neutralization of acidic fluids
- shallow steam-heated advanced argillic alteration
- cause of gold deposition: cooling, mixing, boiling?

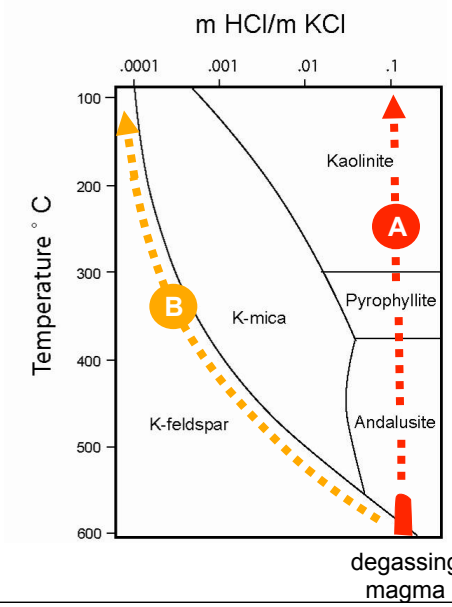
Summary Gangue Mineralogy

frequency of occurrence (abundance)

	qtz-calc-adularia-illite	qtz-alun-pyroph-kaol
Quartz	ubiquitous (abundant)	ubiquitous (abundant)
Chalcedony	common (variable)	uncommon (minor)
Calcite	common (variable)	absent (except overprint)
Adularia	common (variable)	absent
Illite	common (abundant)	uncommon (minor)
Kaolinite	rare (except overprint)	common (minor)
Pyrophyllite-diaspore	absent	common (variable)
Alunite	absent (except overprint)	common (minor)
Barite	common (very minor)	common (minor)

White and Hedenquist, 1995

Effect of water-rock interaction on fluid composition upon cooling & ascent (Giggenbach, 1992, 1997)

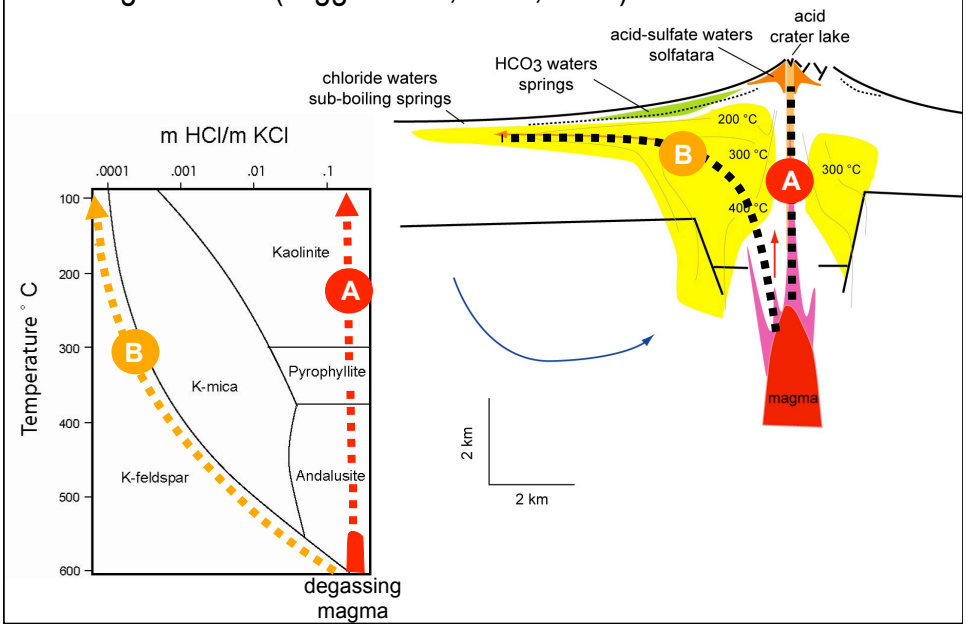


Path A: Rising volatiles condense into groundwater forming acidic-oxidized waters & intense hydrolytic clay alteration

Path B: Rising fluid remains in contact with rock & pH is buffered by K-feldspar-K-mica equilibrium, producing neutral pH-reduced chloride waters

Map paths A & B on the previous slide.

Effect of water-rock interaction on fluid composition upon cooling & ascent (Giggenbach, 1992, 1997)

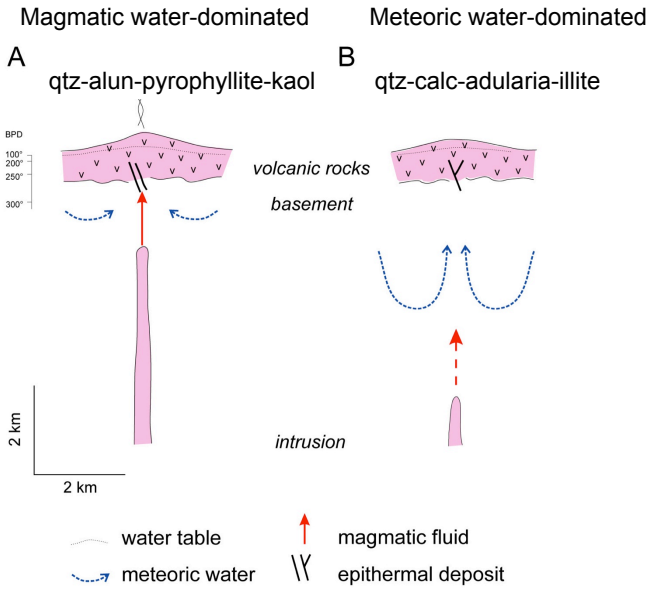


Summary: Genetic Controls for Epithermal Mineralization

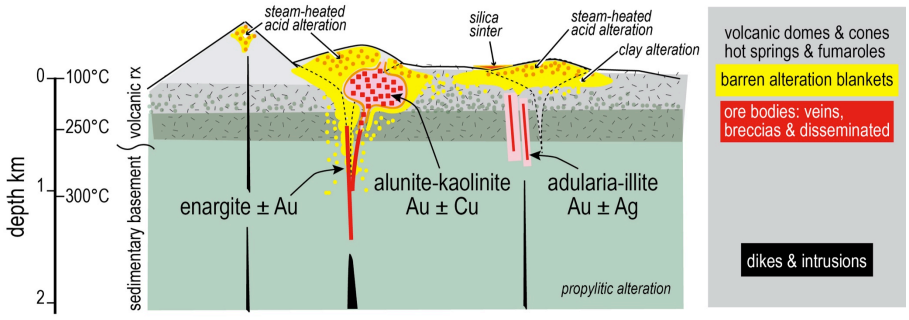
Genetic Factors

- Water table
- Mineralizing Processes
  -boiling, mixing, cooling

- Depth of Intrusion, path length to epithermal environment



Depth level zonation-epithermal deposits



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