Porphyry Cu-Mo-Au and Related Epithermal Au Systems:

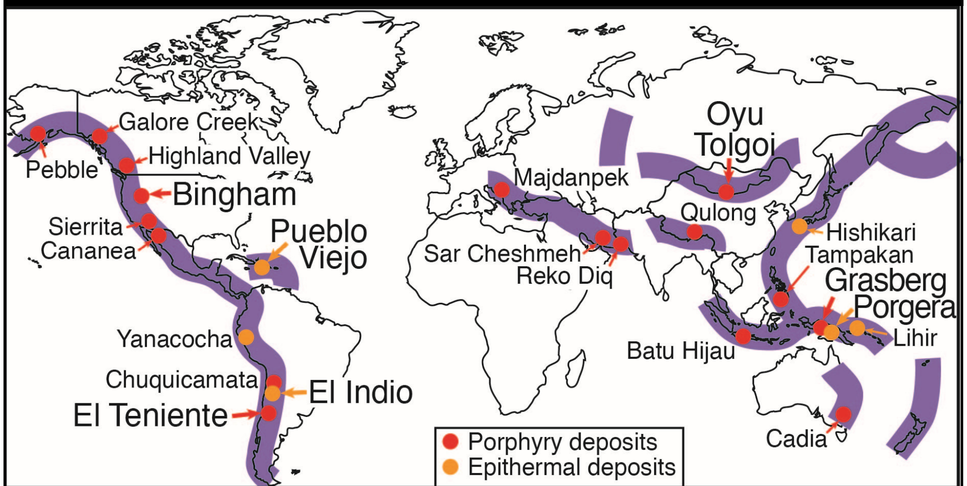
Controls on Ore Formation from Plate to Vein Scales

Bingham Canyon, Utah

Jeremy P. Richards
Harquail School of Earth Sciences, Laurentian University
Sudbury, ON, P3E 2C6
JRichards2@laurentian.ca

LaurentianUniversity UniversitéLaurentienne
HARQUAIL SCHOOL OF EARTH SCIENCES ÉCOLE DES SCIENCES DE LA TERRE

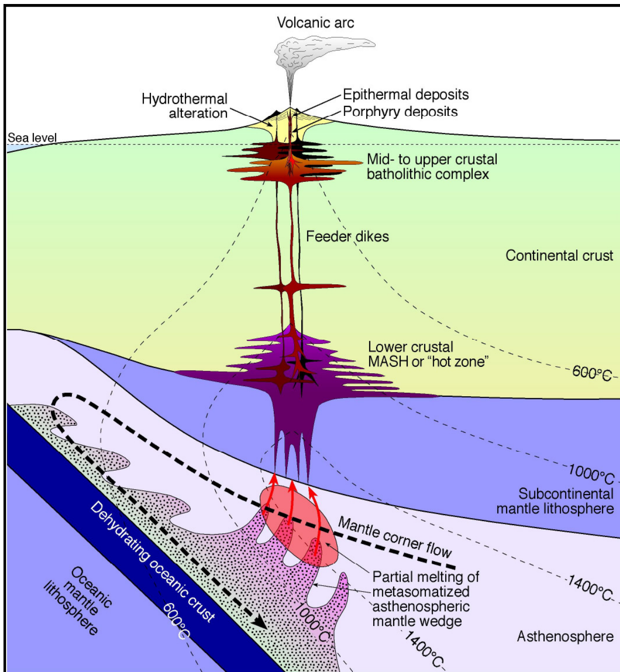
Global distribution of major porphyry Cu±Mo±Au and related epithermal Au-Ag-Cu deposits: Porphyry systems are common in arcs, but large economic deposits are rare, by definition



Richards, J.P., 2013, Giant ore deposits form by optimal alignments and combinations of geological processes: Nature Geoscience, v. 6, p. 911–916.

Porphyry deposits

- Porphyry Cu deposits come in all sizes, from small subeconomic systems displaying weak alteration and a few small veins, to giant deposits with alteration zones covering 100s of km^2, with intensely veined and mineralized centres.
- While small deposits may be economic (e.g., if grades are high), most exploration is focused on the discovery of large deposits (hundreds to billions of tonnes of ore) due to economies of scale and long mine life.
- By definition, the largest deposits in this spectrum are rare, although porphyries are a relatively common deposit type, reflecting a relatively simple, reproducible ore-forming process. The size of the deposit formed depends on the efficiency and scale of that process.



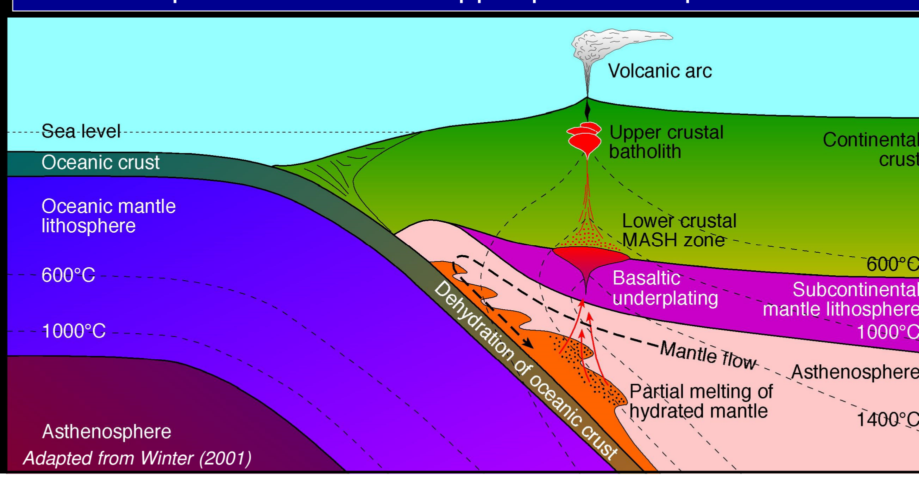
Richards (2011: Ore Geol. Reviews, v. 40, p. 1–26)

Porphyry-epithermal deposits are late stage parts of plate-scale tectonomagmatic systems.

Many steps must operate efficiently and additatively for an ore deposit to ultimately form.

Subduction of hydrated oceanic lithosphere recycles volatiles (H_2O, S, Cl) and alkalis into the asthenospheric mantle wedge, and progressively increases mantle oxidation state.

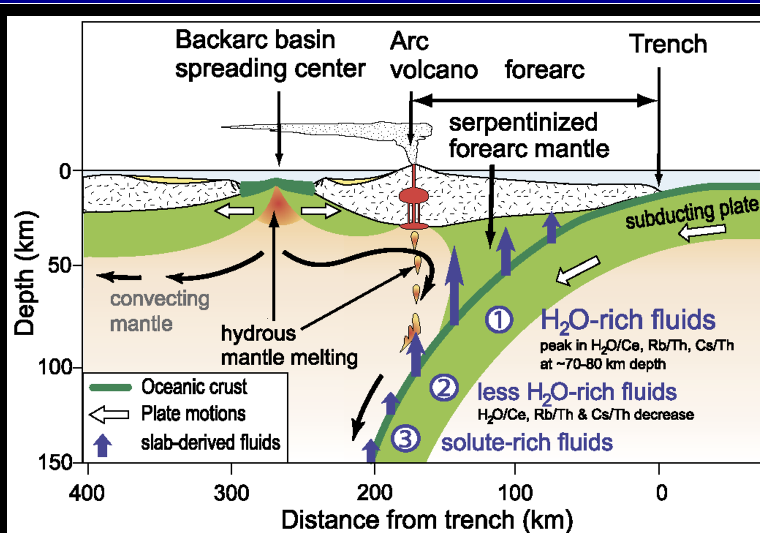
Partial melting of the hydrated mantle wedge transfers this metasomatic signature, including mantle-derived chalcophile and siderophile metals to the upper plate lithosphere.



Adapted from Winter (2001)

Slab dehydration:

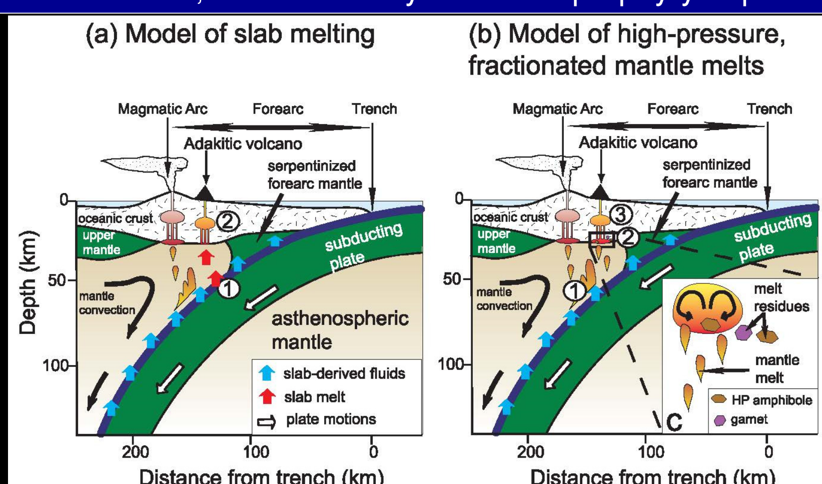
Initial fluids released from cool slabs at shallow depths are water rich, but become more solute-rich at sub-arc depths.



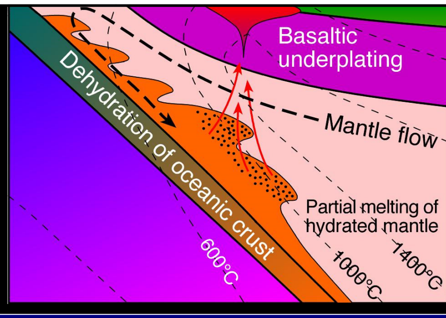
Ribeiro, J.M., et al., 2015, Composition of the slab-derived fluids released beneath the Mariana forearc: Evidence for shallow dehydration of the subducting plate: Earth and Planetary Science Letters, v. 418, p. 136–148.

Slab melting:

Melting of basaltic oceanic crust may give rise to intermediate-composition magmas named “adakites”, but these are rare in the Phanerozoic, and not clearly related to porphyry deposits.



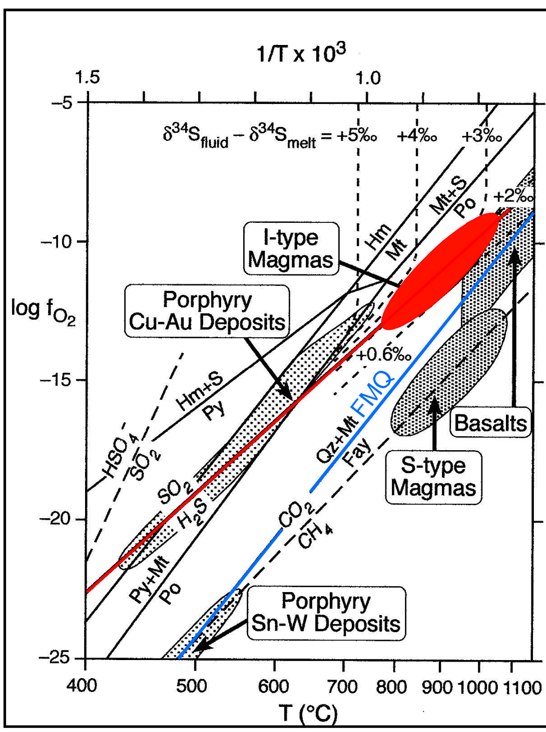
Ribeiro, J.M., et al., 2015, Composition of the slab-derived fluids released beneath the Mariana forearc: Evidence for shallow dehydration of the subducting plate: Earth and Planetary Science Letters, v. 418, p. 136–148.



Phanerozoic subduction involves the release of oxidizing volatiles from the slab, which cause metasomatism and partial melting of the asthenospheric mantle wedge.

Primary arc magmas:

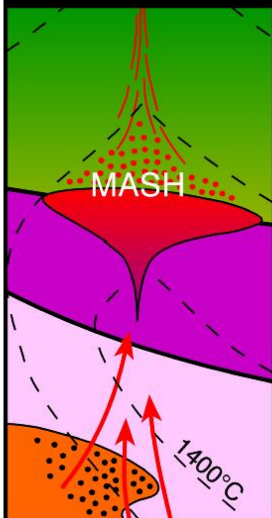
- High-Mg basalts (Arculus, 1994; Thirlwall et al., 1996).
- 1–4 wt.% H_2O (Sobolev & Chaussidon, 1996; Kimura & Ariskin, 2014; up to 8 wt.%: Wallace, 2005).
- Cl-rich (500–2000 ppm Cl) (Wallace, 2005).
- S-rich (900–2500 ppm S) (de Hoog et al., 2001; Wallace, 2005).
- Oxidized (up to FMQ+2) (Brandon & Draper, 1996).
- Metalliferous (undepleted; 50–100 ppm Cu, 1–5 ppb Au).



Relatively high oxidation state of arc magmas is critical for the retention of metals in the melt until late stages, when they can be partitioned into an exsolving hydrothermal fluid phase.

Hedenquist, J.W., and Richards, J.P., 1998, Reviews in Economic Geology, v. 10, p. 235–256.

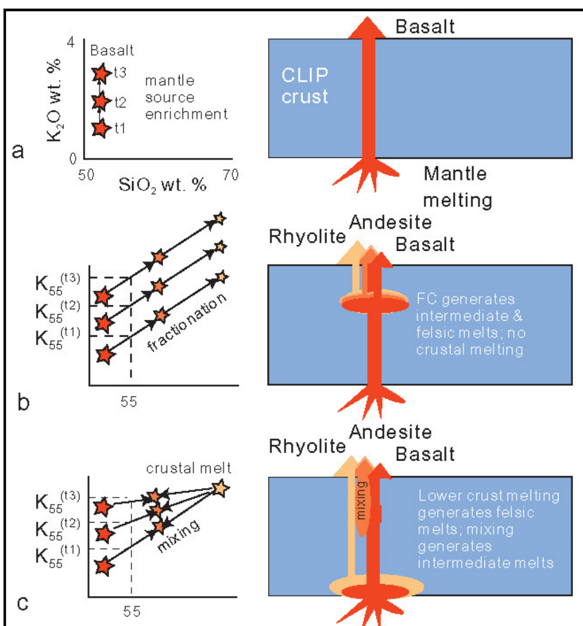
Primary arc magmas ascend from the mantle but pool at the base of the crust due to density contrasts: here they evolve to lower density, intermediate composition magmas through the MASH process



- Melting of crustal rocks;
- Assimilation of crustal rocks;
- Storage of magma in lower crustal dike/sill complexes;
- Homogenization to form hybrid calc-alkaline magmas.

This stage may enhance the volatile content and oxidation state of arc magmas, but probably is most important in terms of assembling large volumes of fertile magma prior to upper crustal emplacement.

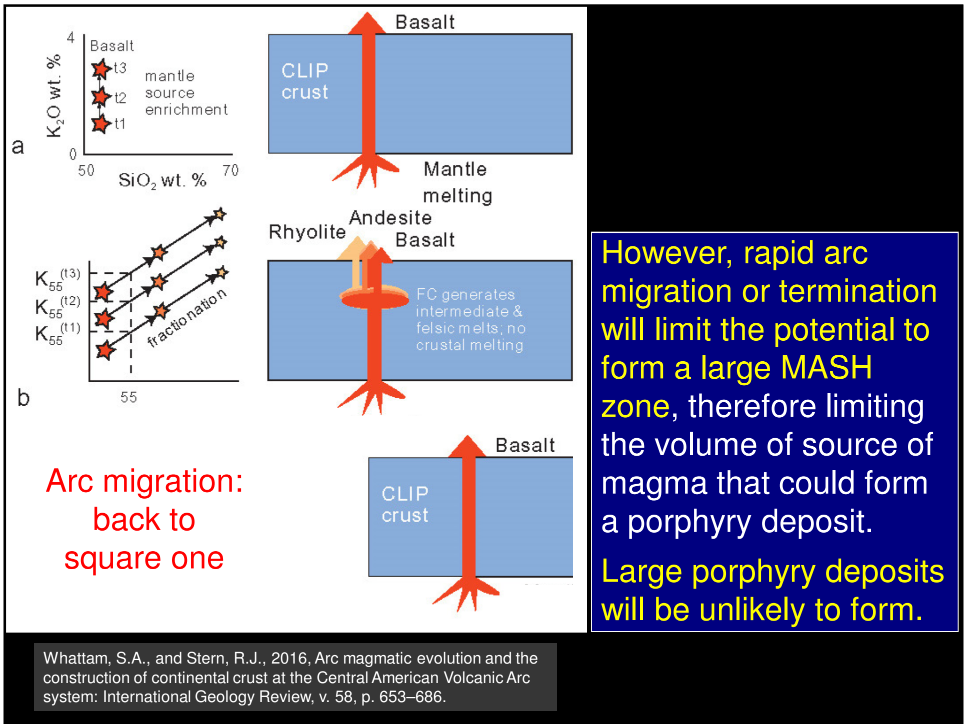
Large porphyry deposits *require* large volumes of source magma.

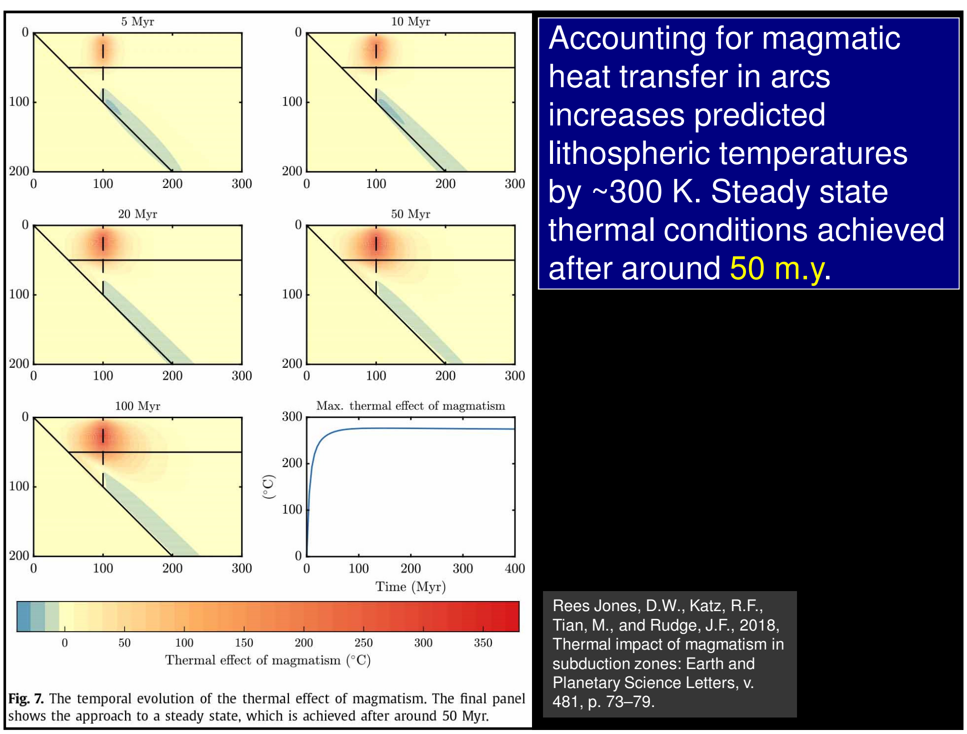


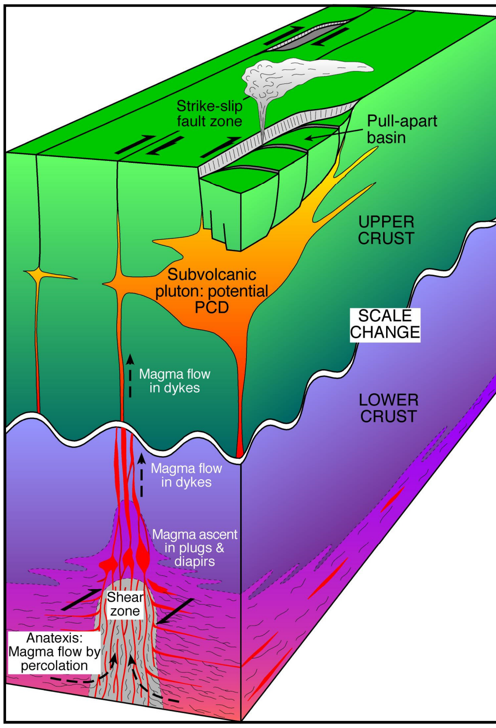
Whattam, S.A., and Stern, R.J., 2016, Arc magmatic evolution and the construction of continental crust at the Central American Volcanic Arc system: International Geology Review, v. 58, p. 653–686.

Time scale for evolution of MASH zone to produce evolved magmas:

≥ 10 m.y. of steady state arc magmatism.


Basalt
CLIP crust
Mantle melting
K$_2$O wt. %
SiO$_2$ wt. %
mantle source enrichment
Rhyolite
Andesite
Basalt
FC generates intermediate & felsic melts; no crustal melting
fractionation
Basalt
CLIP crust
Arc migration: back to square one
However, rapid arc migration or termination will limit the potential to form a large MASH zone, therefore limiting the volume of source of magma that could form a porphyry deposit.
Large porphyry deposits will be unlikely to form.
Whattam, S.A., and Stern, R.J., 2016, Arc magmatic evolution and the construction of continental crust at the Central American Volcanic Arc system: International Geology Review, v. 58, p. 653–686.

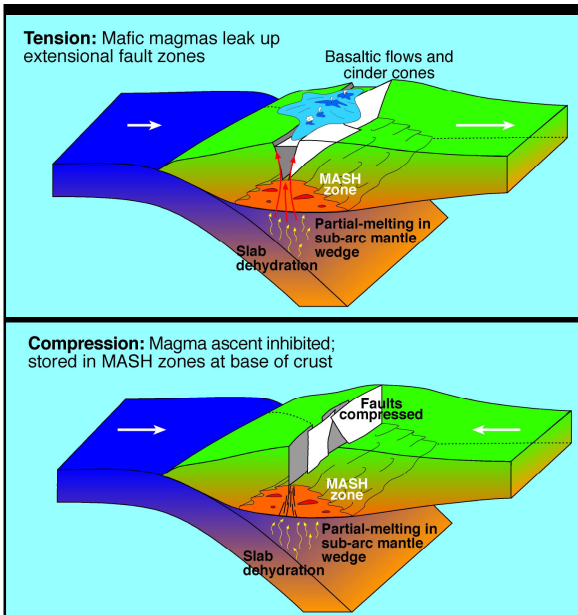

5 Myr
10 Myr
20 Myr
50 Myr
100 Myr
Max. thermal effect of magmatism
Time (Myr)
Thermal effect of magmatism (°C)
Fig. 7. The temporal evolution of the thermal effect of magmatism. The final panel shows the approach to a steady state, which is achieved after around 50 Myr.
Accounting for magmatic heat transfer in arcs increases predicted lithospheric temperatures by ~300 K. Steady state thermal conditions achieved after around 50 m.y.
Rees Jones, D.W., Katz, R.F., Tian, M., and Rudge, J.F., 2018, Thermal impact of magmatism in subduction zones: Earth and Planetary Science Letters, v. 481, p. 73–79.



For porphyry deposits to form in the upper crust, a large volume (>100 km^3) of fertile magma needs to be emplaced rapidly in a mid–upper crustal batholith. This is the source magma from which fluids and metals will be derived by exsolution.

Failure to rapidly amass this large volume of magma is a key reason for the failure to form porphyry deposits.

Richards, J.P., 2003, Tectono-magmatic precursors for porphyry Cu-(Mo-Au) deposit formation: Economic Geology, v. 98, p. 1515–1533.

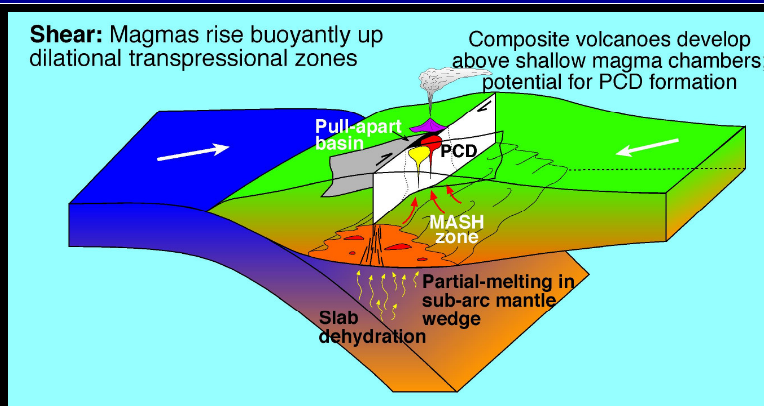


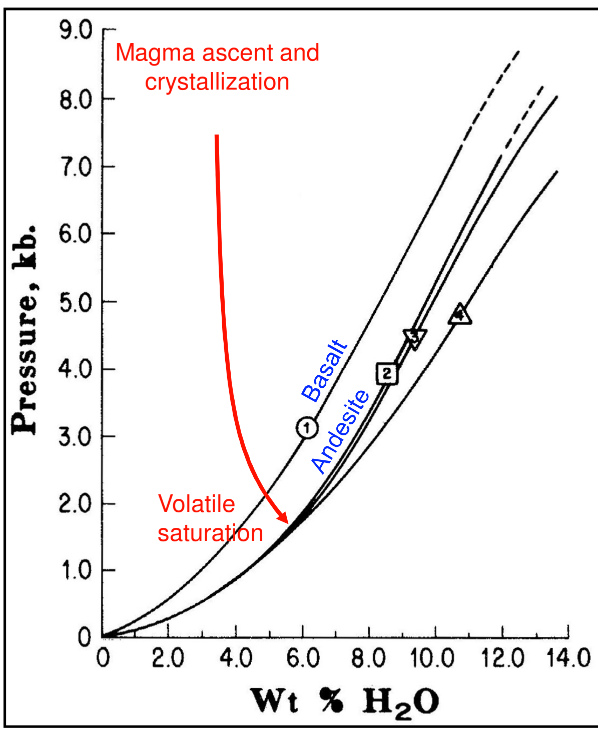
Tosdal, R.M., and Richards, J.P., 2001, Magmatic and structural controls on the development of porphyry Cu±Mo±Au deposits: Reviews in Economic Geology, v. 14, 157–181.

Periods of tensional or compressional stress in the upper plate are unfavourable for upper crustal plutonism, leading either to excessive volcanism or pooling of magma in the deep crust.

However, compressional stress may be an important precursor, leading to the build up of large volumes of magma in the MASH zone, prior to ascent following stress relaxation.

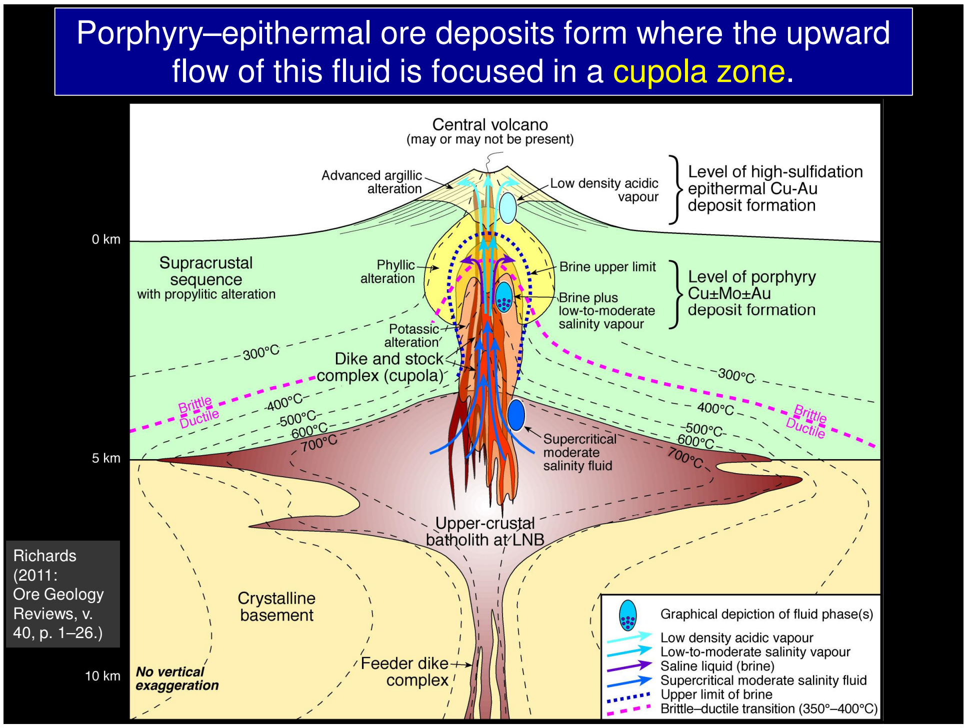
Transpressional (or transtensional) tectonic settings are optimal for upper crustal plutonism, because magma ascent can be channelled and focused along vertical low pressure pathways (jogs and step-overs) in strike-slip fault systems. Large batholiths and porphyry deposits therefore tend to form at the end of protracted compressional episodes, when stresses relax or change to shear.

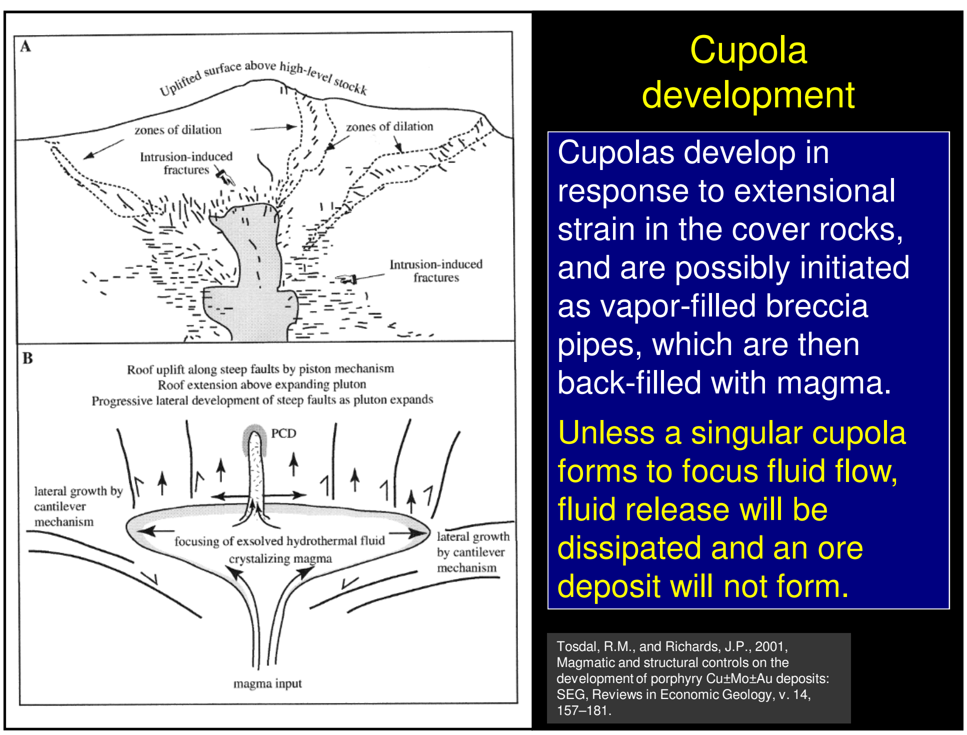


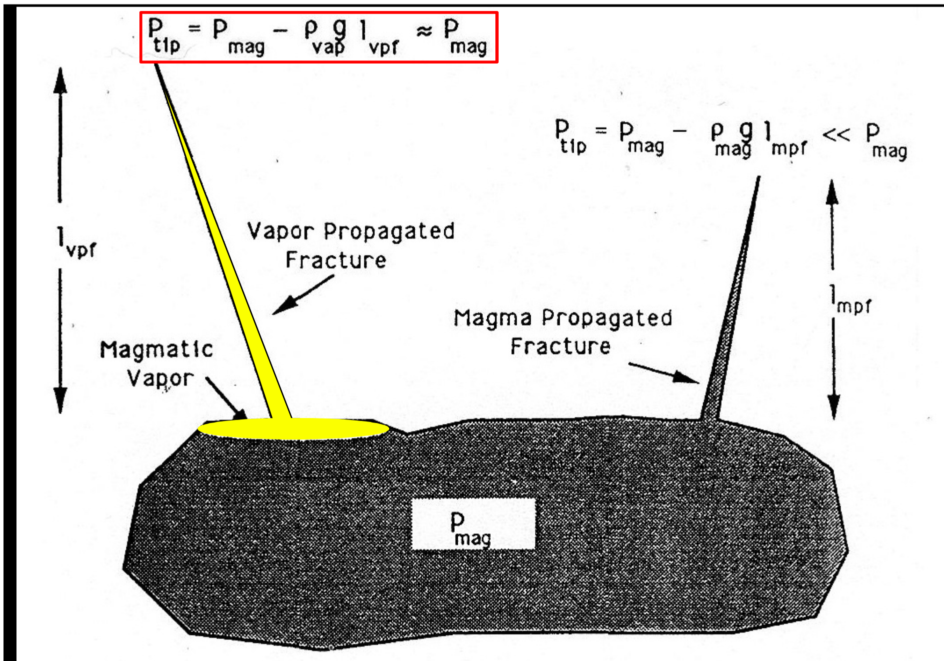


Emplacement of large volumes of hydrous calc-alkaline magma in the upper crust will inevitably lead to fluid exsolution.

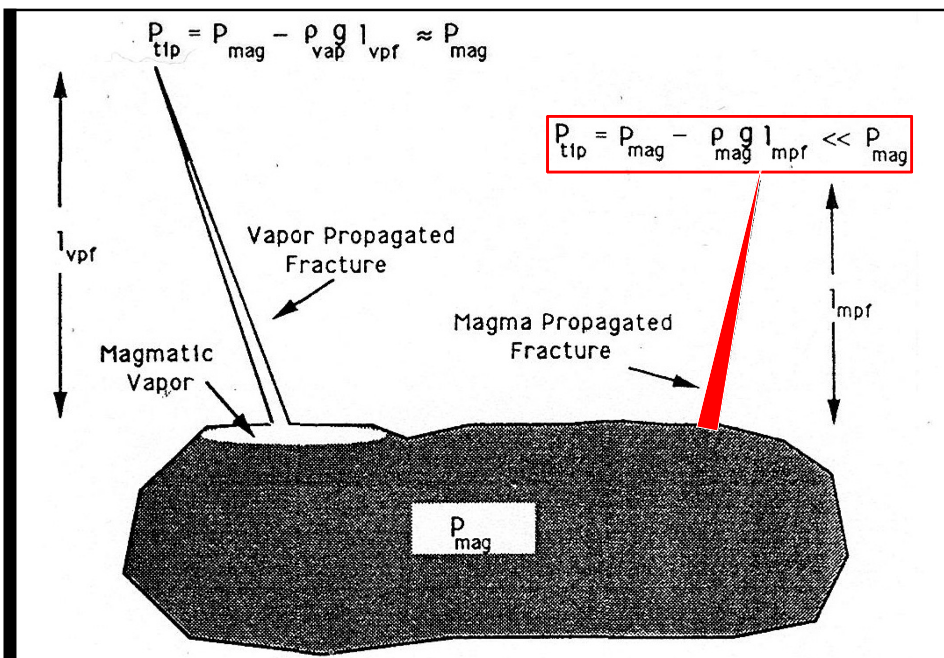
Fig. 3.1 in Burnham, C.W., 1979, Magmas and hydrothermal fluids, *in* Barnes, H.L., ed., Geochemistry of hydrothermal ore deposits, 2nd edition: New York, John Wiley and Sons, p. 71–136.


Porphyry–epithermal ore deposits form where the upward flow of this fluid is focused in a cupola zone.
Central volcano
(may or may not be present)
Advanced argillic alteration
Low density acidic vapour
Level of high-sulfidation epithermal Cu-Au deposit formation
0 km
Supracrustal sequence
with propylitic alteration
Phyllic alteration
Brine upper limit
Brine plus low-to-moderate salinity vapour
Level of porphyry Cu±Mo±Au deposit formation
Potassic alteration
300°C
Dike and stock complex (cupola)
Brittle
Ductile
400°C
500°C
600°C
700°C
Supercritical moderate salinity fluid
5 km
Upper-crustal batholith at LNB
Richards (2011: Ore Geology Reviews, v. 40, p. 1–26.)
Crystalline basement
10 km
No vertical exaggeration
Feeder dike complex
Graphical depiction of fluid phase(s)
Low density acidic vapour
Low-to-moderate salinity vapour
Saline liquid (brine)
Supercritical moderate salinity fluid
Upper limit of brine
Brittle–ductile transition (350°–400°C)

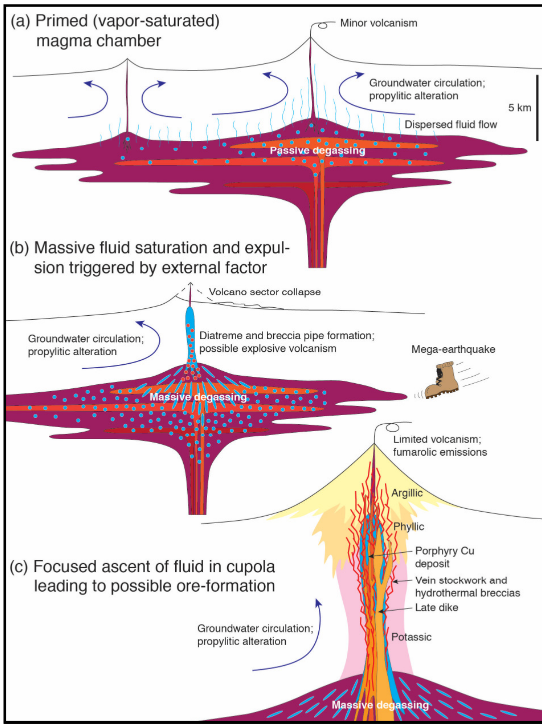

A
Uplifted surface above high-level stockk
zones of dilation
zones of dilation
Intrusion-induced fractures
Intrusion-induced fractures
B
Roof uplift along steep faults by piston mechanism
Roof extension above expanding pluton
Progressive lateral development of steep faults as pluton expands
PCD
lateral growth by cantilever mechanism
focusing of exsolved hydrothermal fluid
crystalizing magma
lateral growth by cantilever mechanism
magma input
Cupola development
Cupolas develop in response to extensional strain in the cover rocks, and are possibly initiated as vapor-filled breccia pipes, which are then back-filled with magma.
Unless a singular cupola forms to focus fluid flow, fluid release will be dissipated and an ore deposit will not form.
Tosdal, R.M., and Richards, J.P., 2001, Magmatic and structural controls on the development of porphyry Cu±Mo±Au deposits: SEG, Reviews in Economic Geology, v. 14, 157–181.



Carrigan, C.R., Schubert, G., and Eichelberger, J.C., 1992, Thermal and dynamical regimes of single- and two-phase magmatic flow in dikes: Journal of Geophysical Research, v. 97, p. 17,377–17,392.



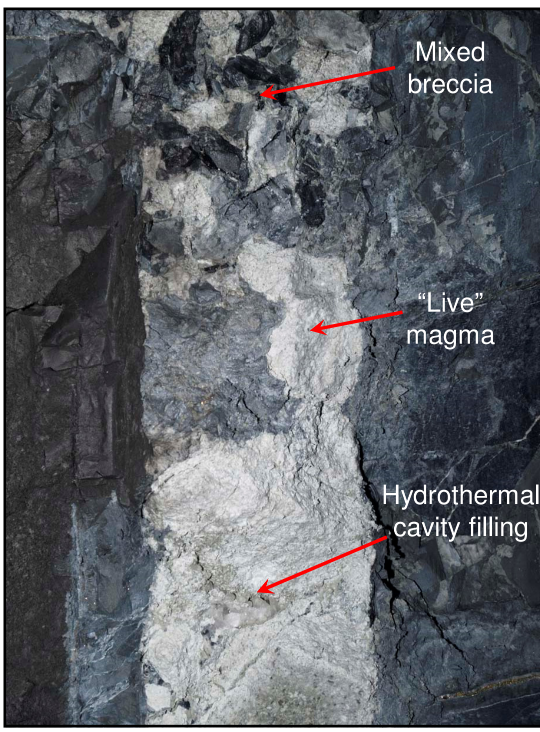
Carrigan, C.R., Schubert, G., and Eichelberger, J.C., 1992, Thermal and dynamical regimes of single- and two-phase magmatic flow in dikes: Journal of Geophysical Research, v. 97, p. 17,377–17,392.



Steady state degassing from a batholith will not normally result in ore-formation.

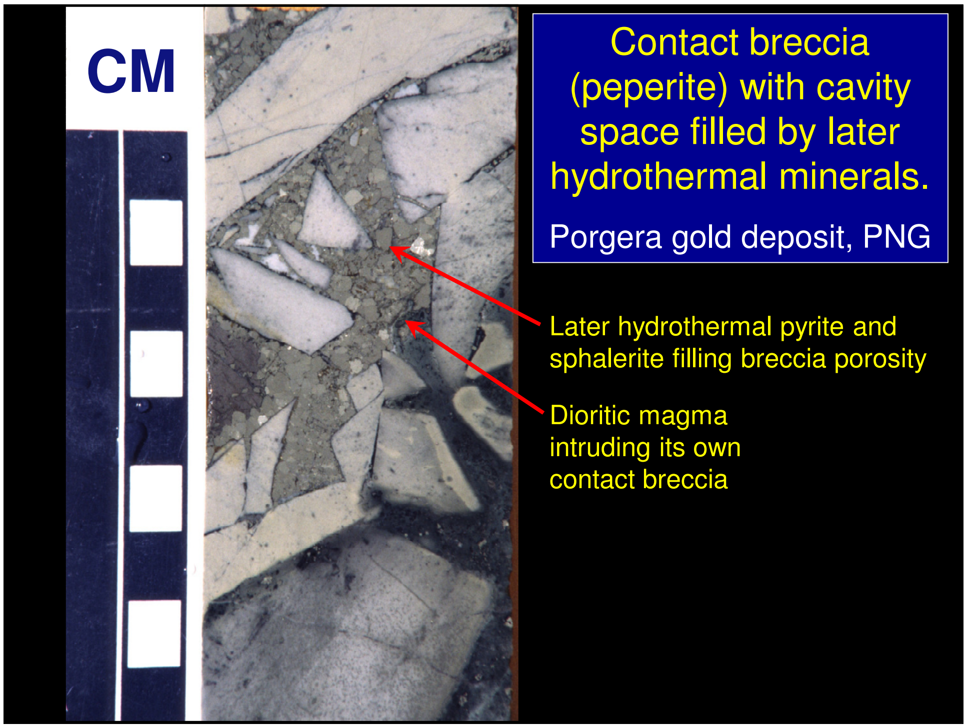
Focussing of fluid flow and a possible tectonic trigger for sudden, massive fluid release seem to be required by the short duration (<0.1 m.y.) and singularity of ore-formation in batholiths.

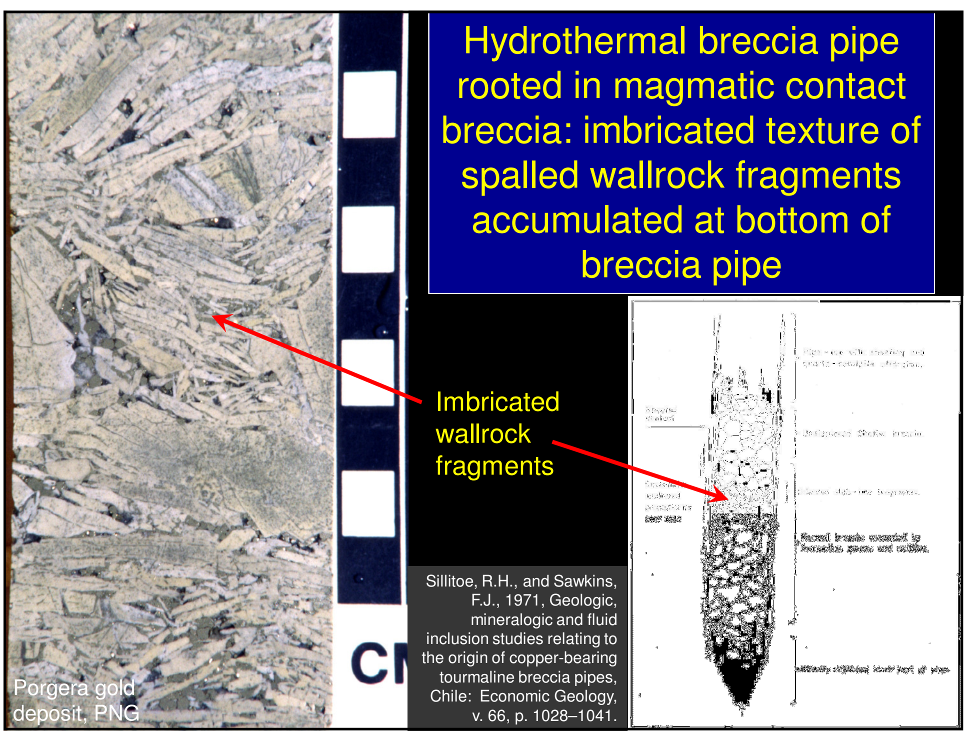
Richards, J.P., 2018, A shake-up in the porphyry world? Economic Geology, v. 113, p. 1225–1233.



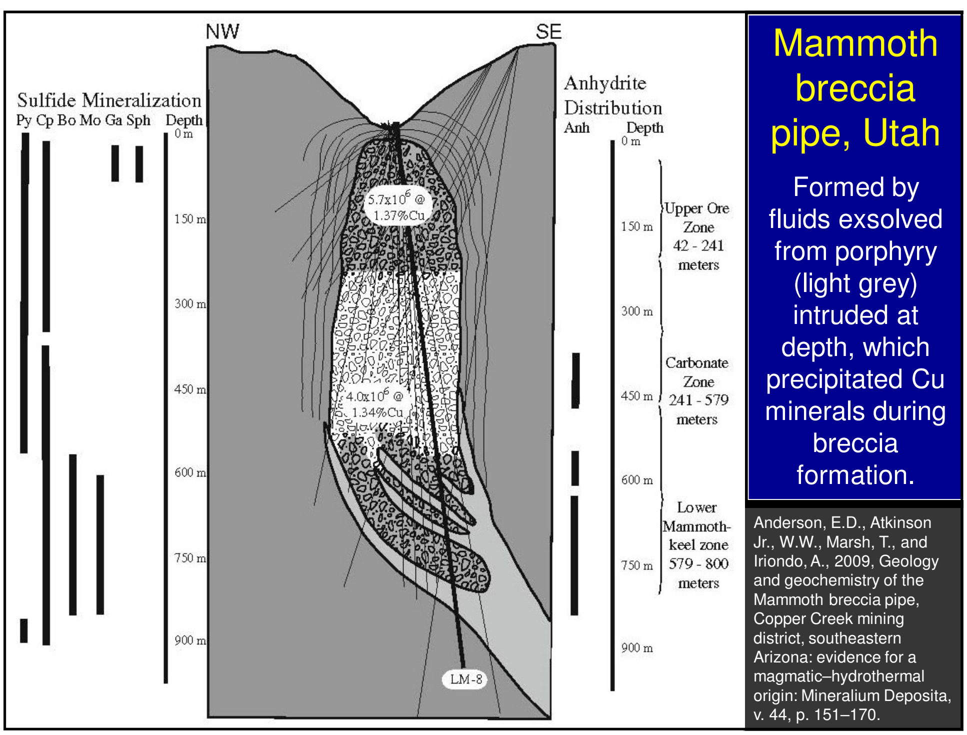
Magmatic–hydrothermal breccia dike

Pachapaqui Pb-Zn-Ag deposit, Péru


CM
Contact breccia (peperite) with cavity space filled by later hydrothermal minerals.
Porgera gold deposit, PNG
Later hydrothermal pyrite and sphalerite filling breccia porosity
Dioritic magma intruding its own contact breccia

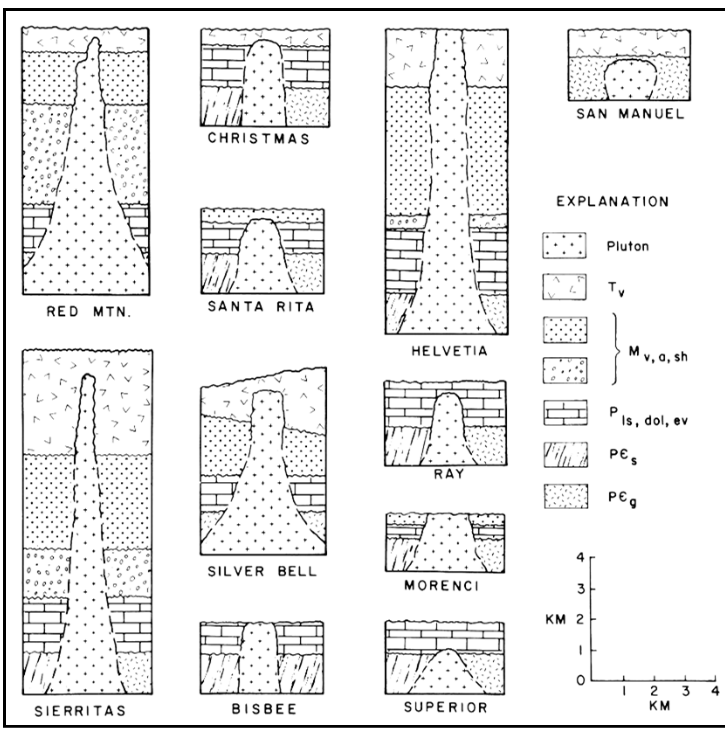

Hydrothermal breccia pipe rooted in magmatic contact breccia: imbricated texture of spalled wallrock fragments accumulated at bottom of breccia pipe
Imbricated wallrock fragments
Porgera gold deposit, PNG
CM
Sillitoe, R.H., and Sawkins, F.J., 1971, Geologic, mineralogic and fluid inclusion studies relating to the origin of copper-bearing tourmaline breccia pipes, Chile: Economic Geology, v. 66, p. 1028–1041.


Intrusive breccias and breccia pipes: commonly barren when emplaced but later mineralized due to permeability
Pachapaqui Pb-Zn-Ag deposit, Péru
“Amoeboid” texture of “live” magma clasts, indicating magmatic-breccia origin
CENTIMETRES


NW
SE
Sulfide Mineralization
Py Cp Bo Mo Ga Sph
Depth
0 m
150 m
300 m
450 m
600 m
750 m
900 m
5.7x10^6 @ 1.37%Cu
4.0x10^6 @ 1.34%Cu
LM-8
Anhydrite Distribution
Anh
Depth
0 m
150 m
300 m
450 m
600 m
750 m
900 m
Upper Ore Zone 42 - 241 meters
Carbonate Zone 241 - 579 meters
Lower Mammoth-keel zone 579 - 800 meters
Mammoth breccia pipe, Utah
Formed by fluids exsolved from porphyry (light grey) intruded at depth, which precipitated Cu minerals during breccia formation.
Anderson, E.D., Atkinson Jr., W.W., Marsh, T., and Iriondo, A., 2009, Geology and geochemistry of the Mammoth breccia pipe, Copper Creek mining district, southeastern Arizona: evidence for a magmatic–hydrothermal origin: Mineralium Deposita, v. 44, p. 151–170.

Japonesa tourmaline breccia pipe, Copiapó, Chile

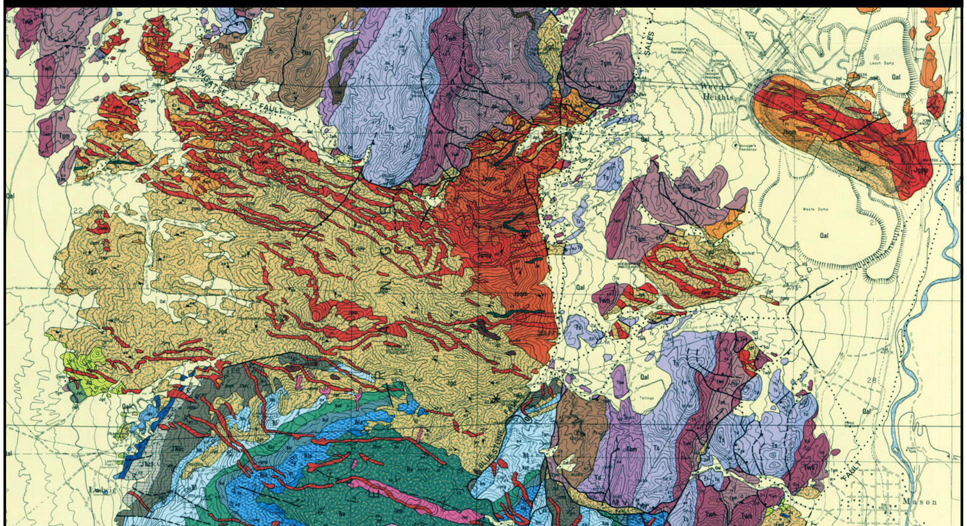
Photo: N. Reardon, 23 Feb, 2013

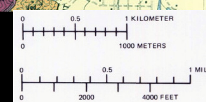


Porphyry pluton shapes: cupolas

Norton, D.L., 1982, Fluid and heat transport phenomena typical of copper-bearing pluton environments, *in* Titley, S.R., ed., Advances in geology of porphyry copper deposits of southwestern North America: Tucson, Univ. Arizona Press, p. 59–72.

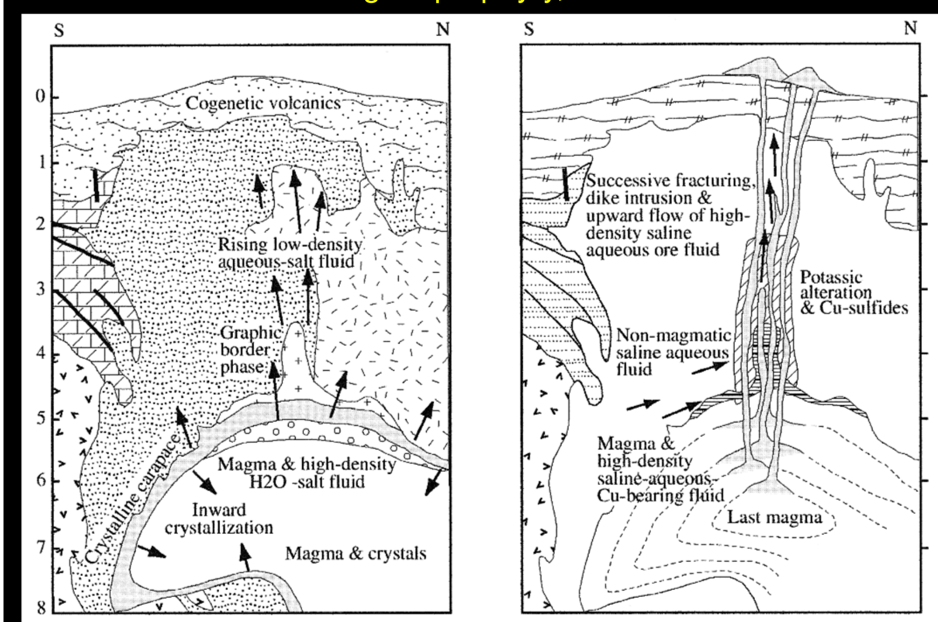
Yerington porphyry, Nevada





Proffett, J.M., Jr., and Dilles, J.H., 1984, Geologic map of the Yerington district, Nevada: Nevada Bureau of Mines and Geology, Map 77, 1:24,000.

Yerington porphyry, Nevada



Tosdal & Richards (2001) modified from Dilles (1987)

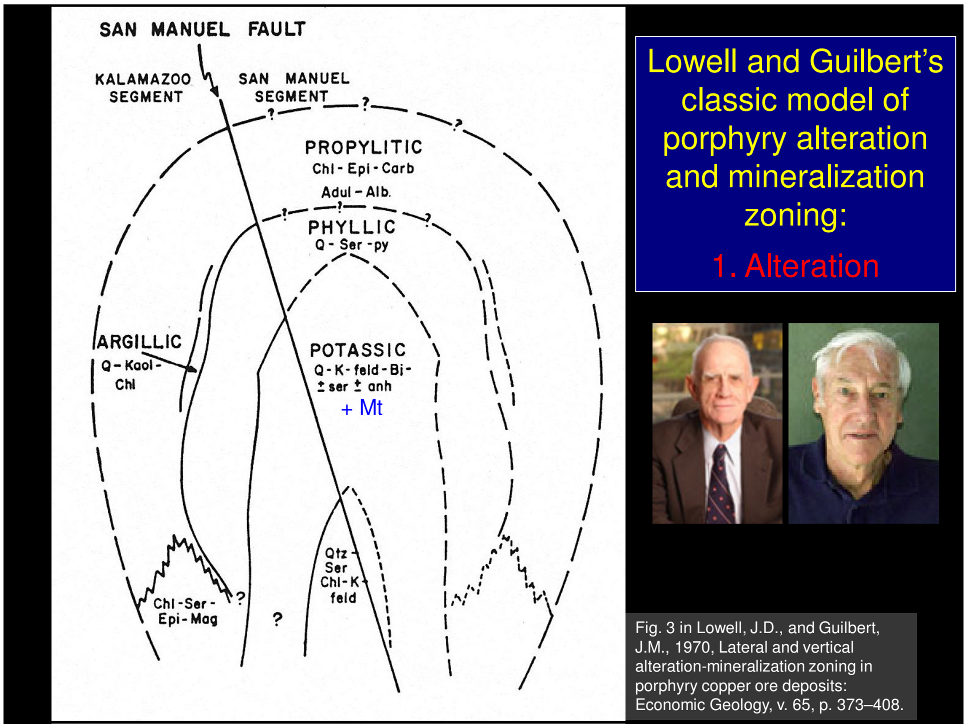
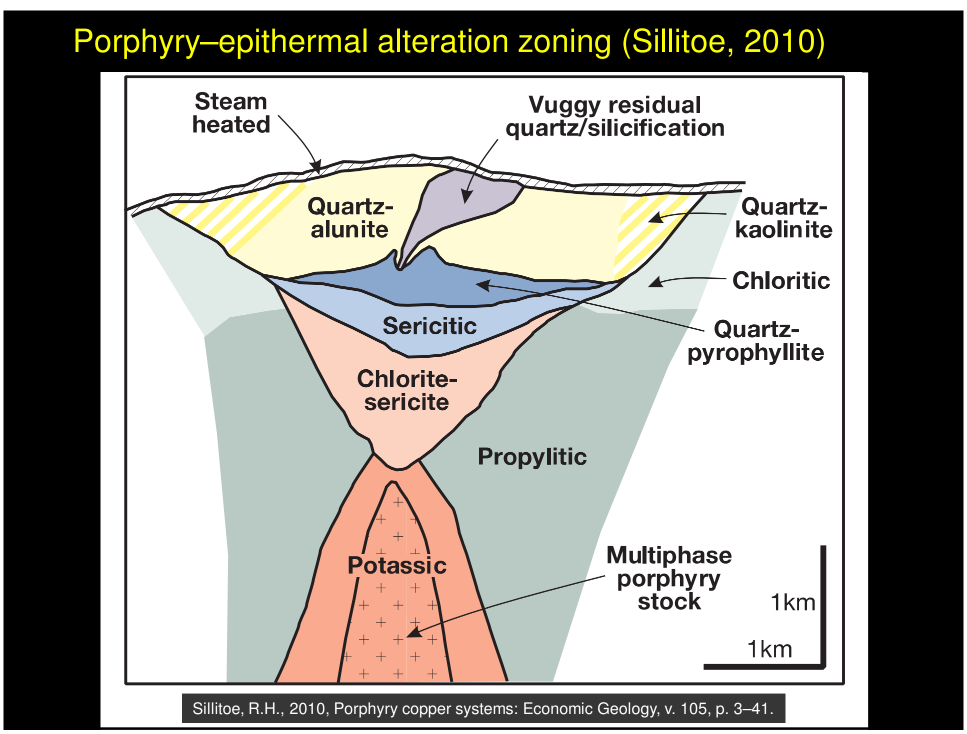


Fig. 3 in Lowell, J.D., and Guilbert, J.M., 1970, Lateral and vertical alteration-mineralization zoning in porphyry copper ore deposits: Economic Geology, v. 65, p. 373–408.



Sillitoe, R.H., 2010, Porphyry copper systems: Economic Geology, v. 105, p. 3–41.

Alteration zonation, Reko Diq porphyry Cu deposit, Pakistan

Views from potassic core, out over phyllic low ground, to propyliticallyaltered volcanic hills in middle distance

Alteration Styles

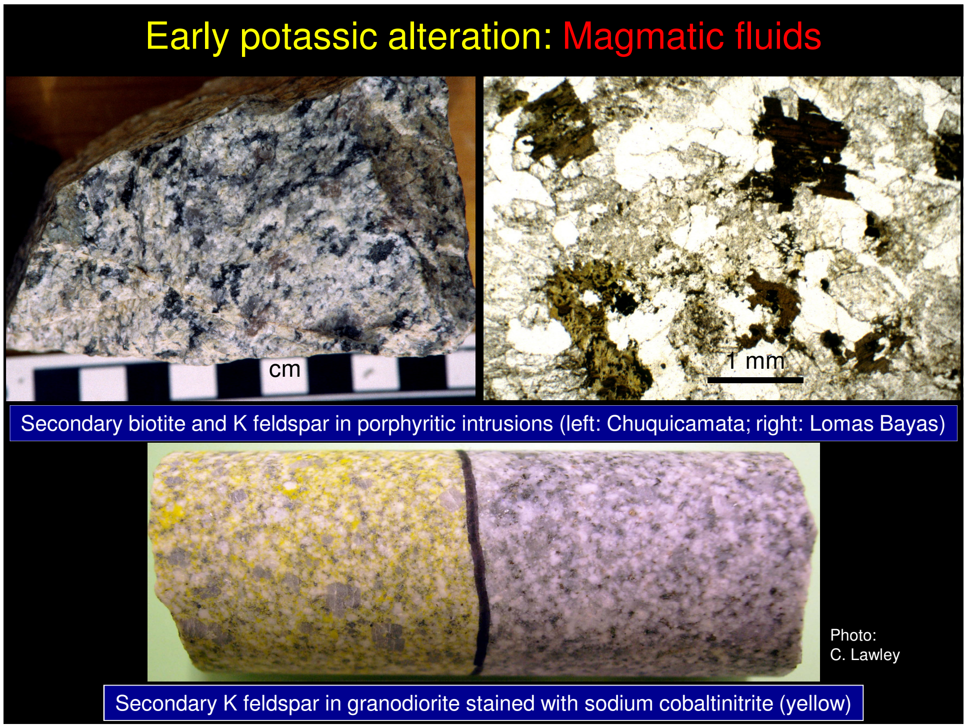
Potassic zone: Roughly coincides with main ore zone; consists of secondary orthoclase-biotite/chlorite, magnetite, anhydrite. An inner low-grade (Cp, Py, Mo) core may exist, surrounded by a stockwork ore shell of > 0.5 % Cu (Py, Cp, Bn, Mo, Mt). T ≤ 725°C.

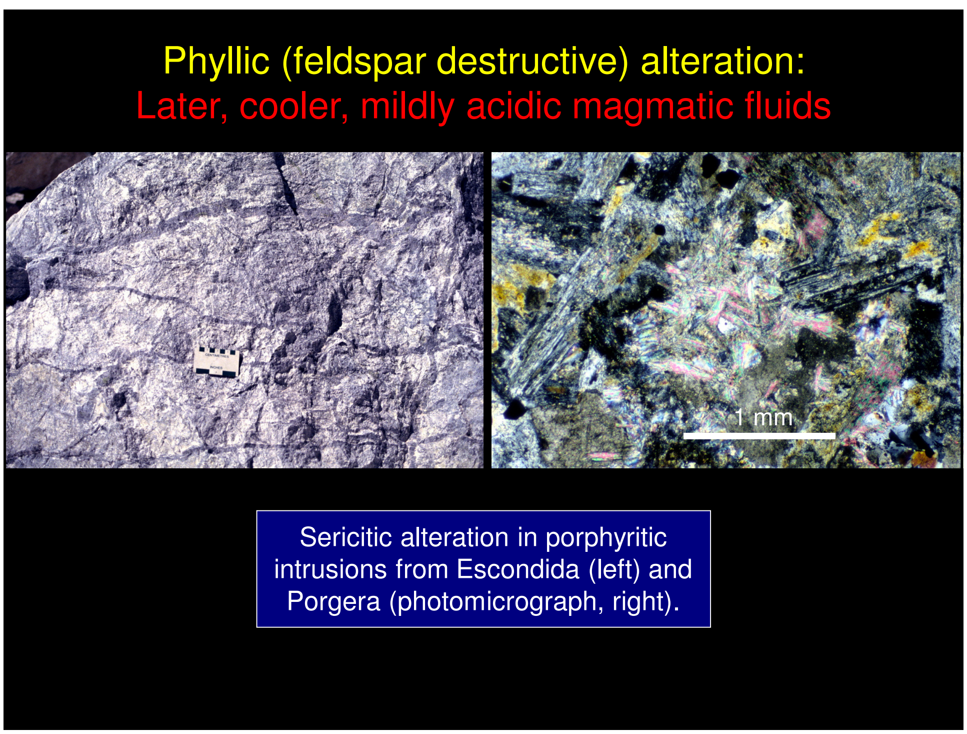
Phyllic zone: Coincides with outer part of ore shell and the Py-shell; consists of quartz-sericite-Py alteration, often with minor chlorite, illite, rutile; carbonates and sulfates are rare. Sericite grades to clay minerals towards edge of zone. Coarse Qz-Py veins and dissem Py (up to 25 vol. %) occur. T ~250–350°C.

Argillic zone: Not always present; consists of clay minerals (kaolinite, montmorillonite). Py is less abundant.

Advanced argillic zone: Intense acidic alteration in near-surface environment; consists of clay minerals (kaolinite+quartz below ~300°C; pyrophyllite/andalusite+quartz above ~300°C), alunite, diaspore, residual vuggy silica.

Propylitic zone: Outer ore zone, always present; consists of chlorite, with Py, calcite, epidote. Fades into background over several 100m. Veins may carry base-metal sulfides.


Early potassic alteration: Magmatic fluids
cm
1 mm
Secondary biotite and K feldspar in porphyritic intrusions (left: Chuquicamata; right: Lomas Bayas)
Photo:
C. Lawley
Secondary K feldspar in granodiorite stained with sodium cobaltinitrite (yellow)


Phyllic (feldspar destructive) alteration:
Later, cooler, mildly acidic magmatic fluids
1 mm
Sericitic alteration in porphyritic intrusions from Escondida (left) and Porgera (photomicrograph, right).

Argillic and advanced argillic alteration

Argillic alteration is the product of cooler, acidic (lower a_{K+}/a_{H+}) fluids, and is characterized by the breakdown of aluminosilicate minerals to clays. When magmatic fluids cool, the sulfur that they carry disproportionates from SO_2 (S^{4+}), which is the dominant dissolved species at high temperature, to a mixture of H_2S (S^{2-}) and sulfuric acid (S^{6+}):

$$4\,SO_2 + 4\,H_2O \rightarrow H_2S + 3\,HSO_4^- + 3\,H^+$$

K-feldspar + acid → clay (kaolinite) + Qz + K+

$$2\,KAlSi_3O_8 + 2\,H^+ + H_2O \rightarrow Al_2Si_2O_5(OH)_4 + 4\,SiO_2 + 2\,K^+$$

Thus, as high temperature solute-laden or gaseous hydrothermal fluids cool, they become increasingly acidic, and argillic to advanced argillic alteration results.

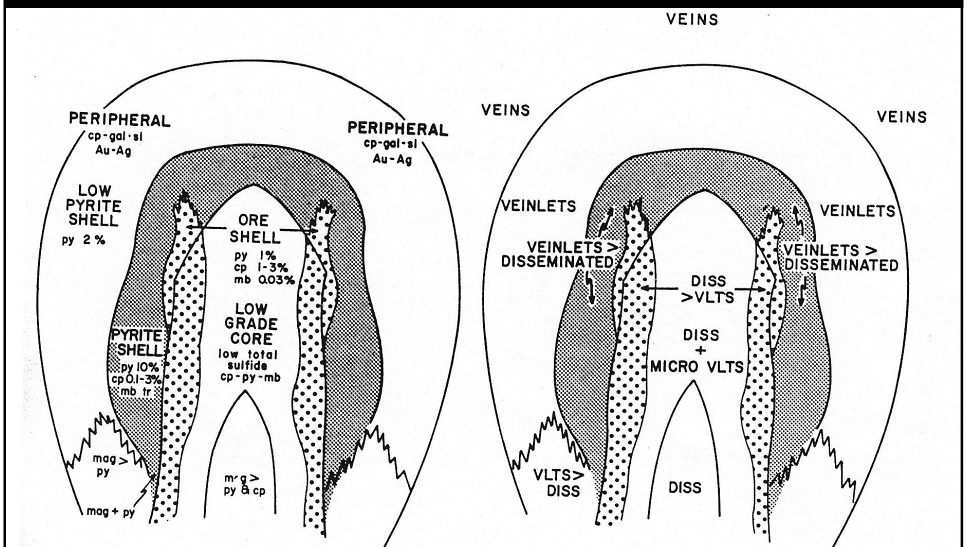
Argillic alteration in volcanic rocks around an epithermal system
(Saheb Divan, Iran)

Advanced argillic alteration: alunite-silica body surrounded by quartz-kaolinite
(Aras, Iran)

Late propylitic (chloritic) overprint on potassic alteration:
It is important to be able to distinguish chlorite overprinting of biotite in potassic alteration vs. barren propylitic alteration
(Montoso porphyry Cu prospect, Mexico)

Porphyry ore formation

Lowell and Guilbert's porphyry model: Mineralization



Lowell, J.D., and Guilbert, J.M., 1970, Lateral and vertical alteration-mineralization zoning in porphyry copper ore deposits: Economic Geology, v. 65, p. 373–408.

Ore deposition

Key processes that control deposition of sulfides from magmatic-hydrothermal fluids between 400°–300°C:

1. High initial base metal solubility in hot, saline fluids.
2. Cooling from 600° to 300°C greatly reduces solubility, with greatest changes occurring between ~425–320°C (Landtwing et al., 2005; Klemm et al., 2007).
3. SO_2 disproportionates to H_2S and SO_4^{2-} below ~400°C (Holland, 1965).

Holland, H.D., 1965, Some applications of thermochemical data to problems of ore deposits II. Mineral assemblages and the composition of ore forming fluids: Economic Geology, v. 60, p. 1101–1166.

Klemm, L.M., Pettke, T., Heinrich, C.A., and Campos, E., 2007, Hydrothermal evolution of the El Teniente deposit, Chile: Porphyry Cu-Mo ore deposit from low-salinity magmatic fluids: Economic Geology, v. 102, p. 1021–1045.

Landtwing, M.R., Pettke, T., Halter, W.E., Heinrich, C.A., Redmond, P.B., Einaudi, M.T., and Kunze, K., 2005, Copper deposition during quartz dissolution by cooling magmatic-hydrothermal fluids: The Bingham porphyry: Earth and Planetary Science Letters, v. 235, p. 229–243.

- Disproportionation of SO_2 <400°C generates H_2S and acid. H_2S reacts with dissolved metals to precipitate sulfide minerals:

  $4S^{IV}O_2 + 4H_2O \Leftrightarrow H_2S^{-II} + 3H_2S^{VI}O_4$

  Magnetite precipitation:

  $9Fe^{II}Cl_2 + SO_2 + 10H_2O \Leftrightarrow 3Fe^{II}Fe^{III}{}_2O_4 + H_2S + 18HCl$

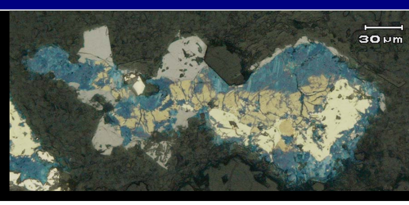
  Cu-Fe-sulfide precipitation:

  $CuCl_{(aq)} + H_2S \Leftrightarrow Cu_2S + 2HCl$

  $8CuCl_{(aq)} + 8Fe^{II}Cl_{2(aq)} + 15H_2S + H_2SO_4 \Leftrightarrow$

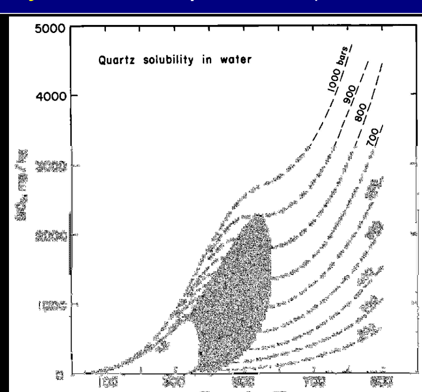
  $8CuFe^{III}S_2 + 24HCl + 4H_2O$

- Hydrolytic wallrock reactions forming sericite (phyllic alteration) and clay (argillic alteration) absorb acids and promote further sulfide precipitation.



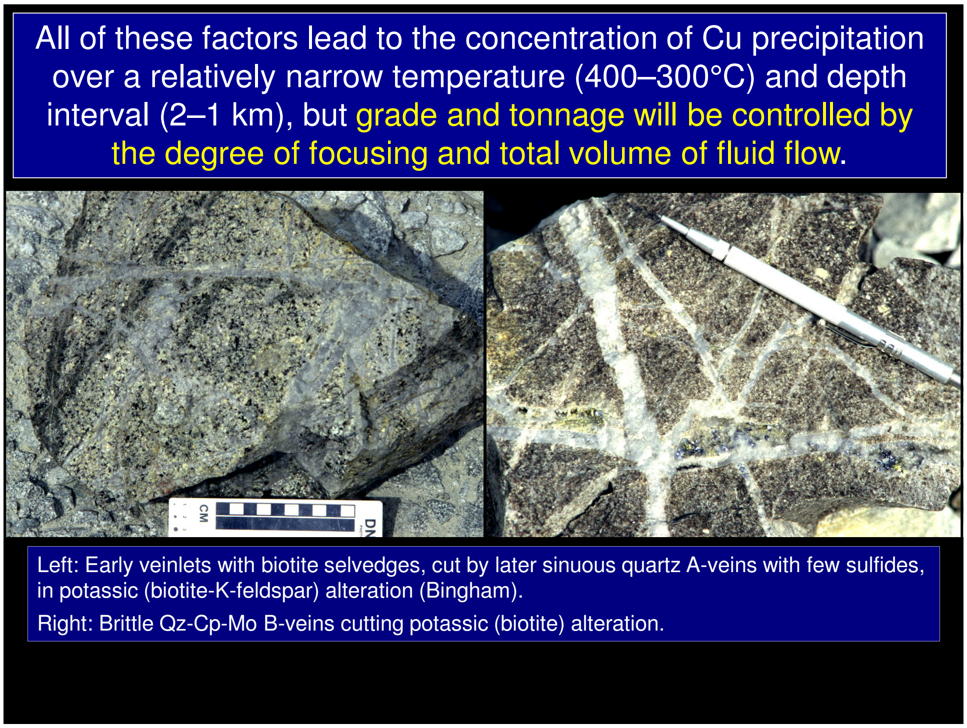
Mt-Cp-Py-(covellite)

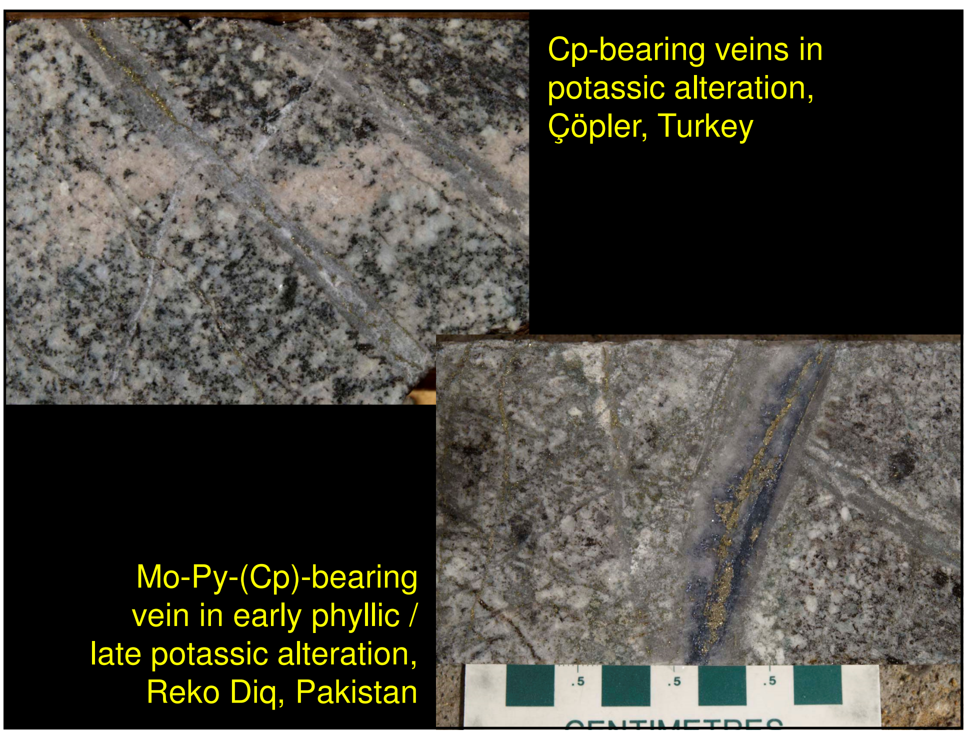
4. Steep pressure gradients across the ductile–brittle transition (400–350°C) promote phase separation, brecciation, and stockwork formation (permeability) (Fournier, 1999).
5. Silica shows retrograde solubility between ~550°–350°C, creating porosity for ore deposition (Fournier, 1985).

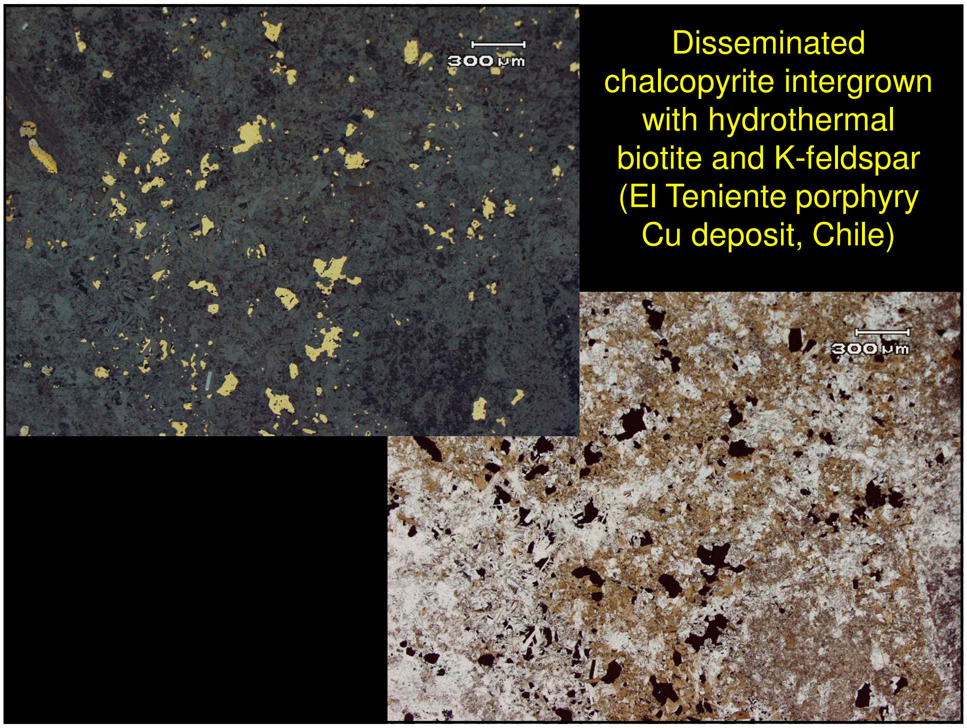


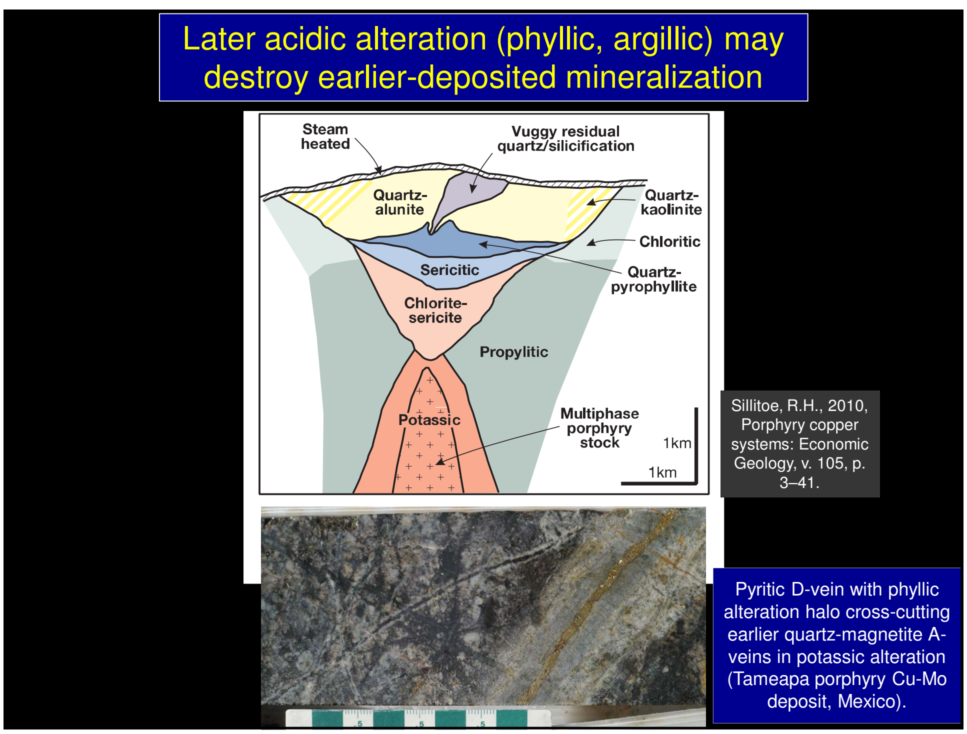
Fournier, R.O., 1985, The behavior of silica in hydrothermal solutions, *in* Berger, B.R., and Bethke, P.M., eds., Geology and Geochemistry of Epithermal Systems: Soc. Econ. Geol., Reviews in Economic Geology, v. 2, p. 45–61.

Fournier, R.O., 1999, Hydrothermal processes related to movement of fluid from plastic into brittle rock in the magmatic-epithermal environment: Economic Geology, v. 94, p. 1193–1212.


All of these factors lead to the concentration of Cu precipitation over a relatively narrow temperature (400–300°C) and depth interval (2–1 km), but grade and tonnage will be controlled by the degree of focusing and total volume of fluid flow.
Left: Early veinlets with biotite selvedges, cut by later sinuous quartz A-veins with few sulfides, in potassic (biotite-K-feldspar) alteration (Bingham).
Right: Brittle Qz-Cp-Mo B-veins cutting potassic (biotite) alteration.


Cp-bearing veins in potassic alteration, Çöpler, Turkey
Mo-Py-(Cp)-bearing vein in early phyllic / late potassic alteration, Reko Diq, Pakistan


300 μm
Disseminated chalcopyrite intergrown with hydrothermal biotite and K-feldspar (El Teniente porphyry Cu deposit, Chile)
300 μm


Later acidic alteration (phyllic, argillic) may destroy earlier-deposited mineralization
Steam heated
Vuggy residual quartz/silicification
Quartz-alunite
Quartz-kaolinite
Chloritic
Sericitic
Quartz-pyrophyllite
Chlorite-sericite
Propylitic
Potassic
Multiphase porphyry stock
1km
1km
Sillitoe, R.H., 2010, Porphyry copper systems: Economic Geology, v. 105, p. 3–41.
Pyritic D-vein with phyllic alteration halo cross-cutting earlier quartz-magnetite A-veins in potassic alteration (Tameapa porphyry Cu-Mo deposit, Mexico).

The Porphyry–Epithermal Transition

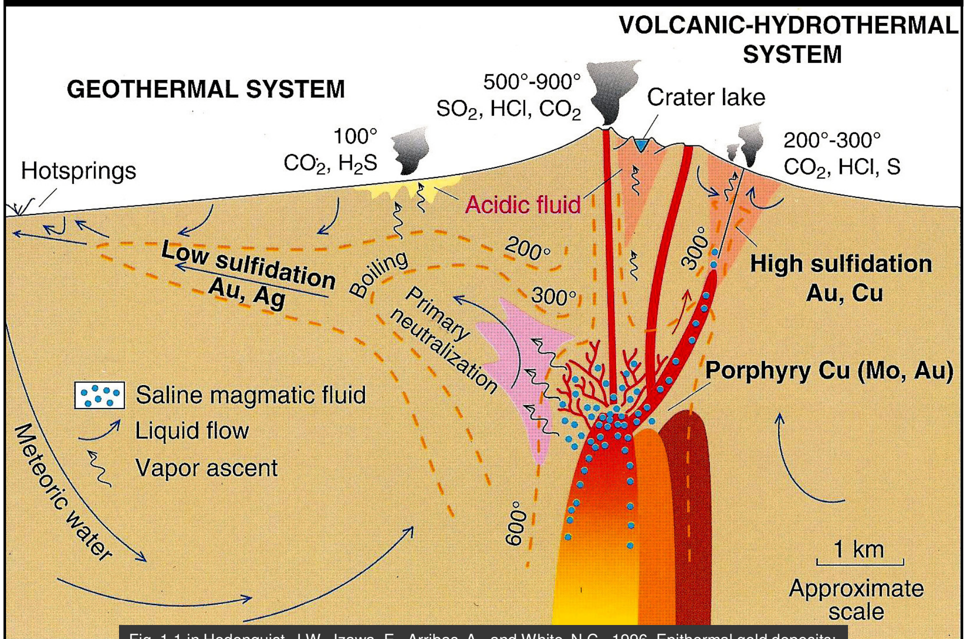


Fig. 1.1 in Hedenquist, J.W., Izawa, E., Arribas, A., and White, N.C., 1996, Epithermal gold deposits: Styles, characteristics, and exploration: Resource Geology Special Publication No. 1, 16 p.

Relationship between epithermal systems and volcanism; the 1970s view (Sillitoe, 1973)

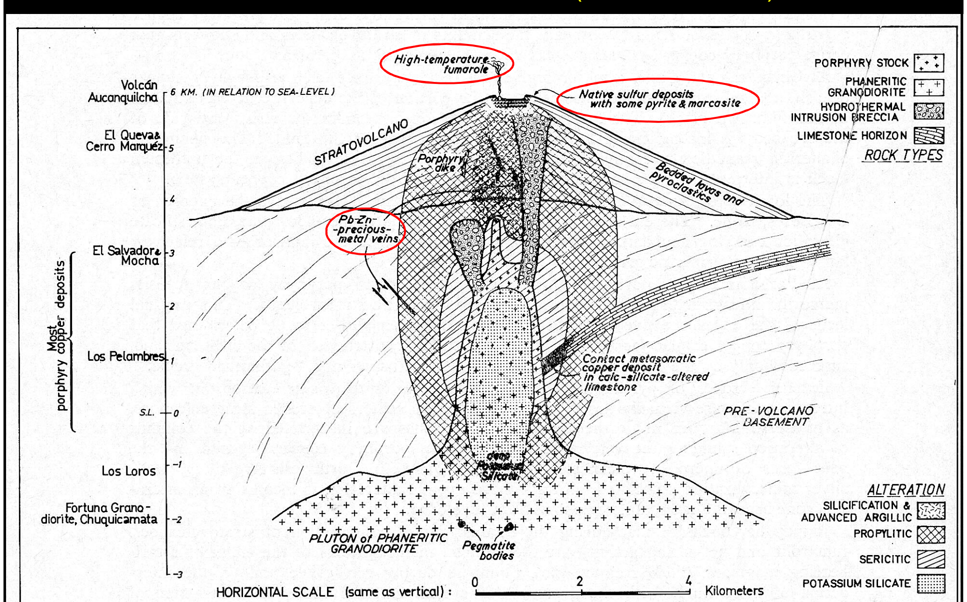
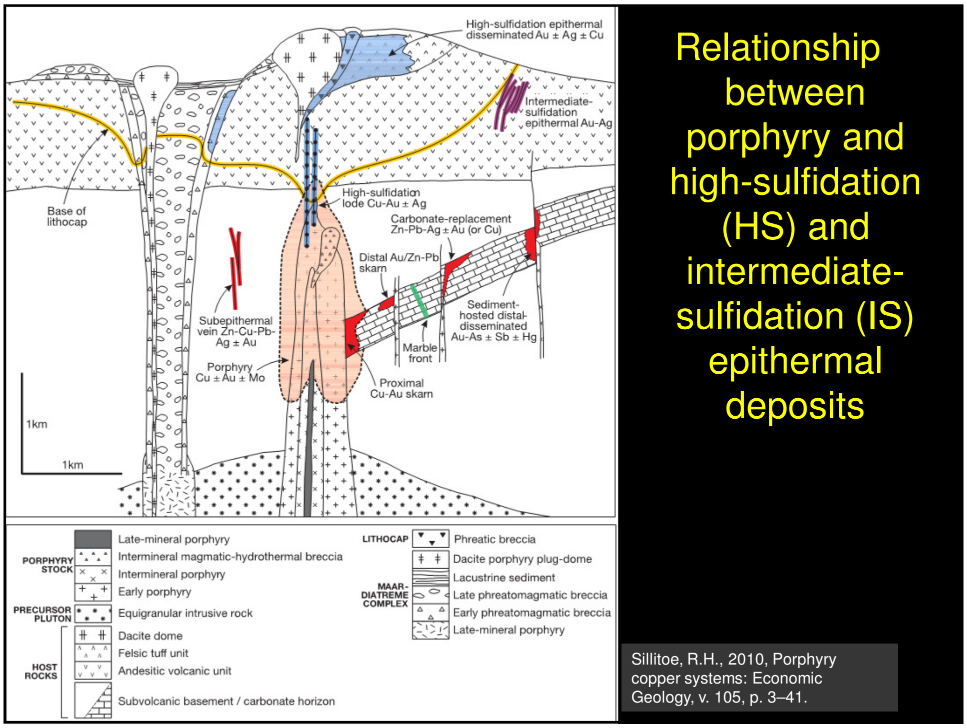
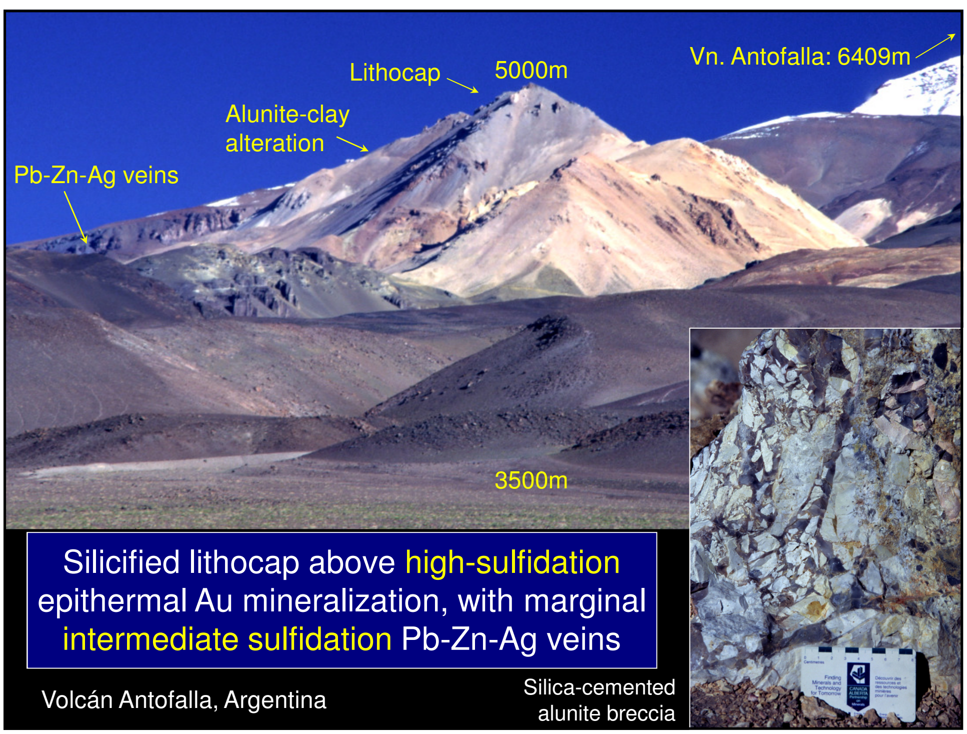
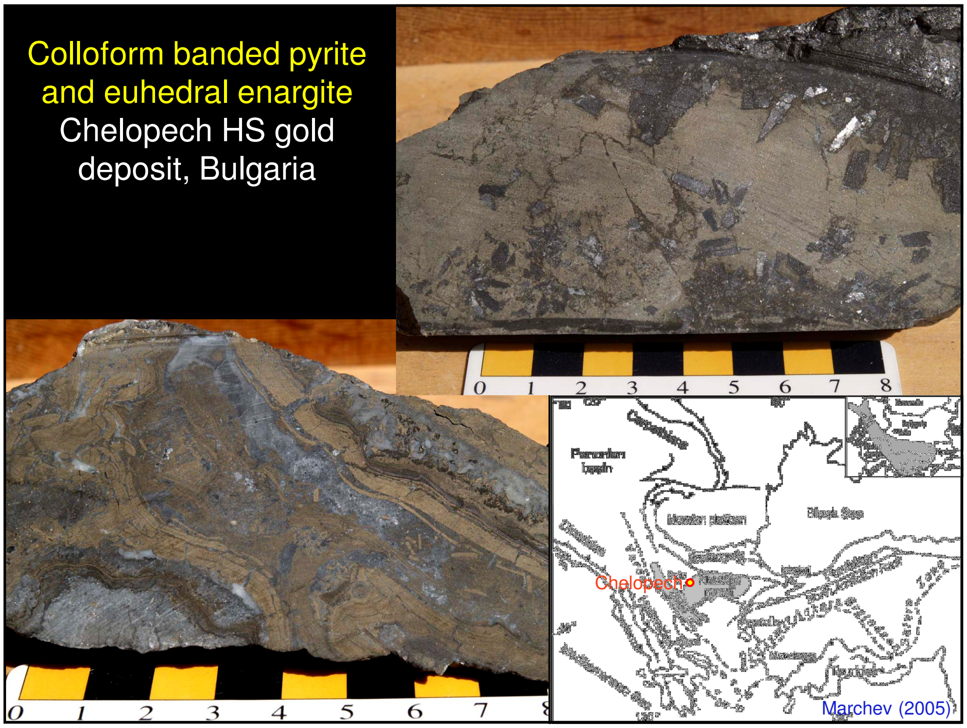
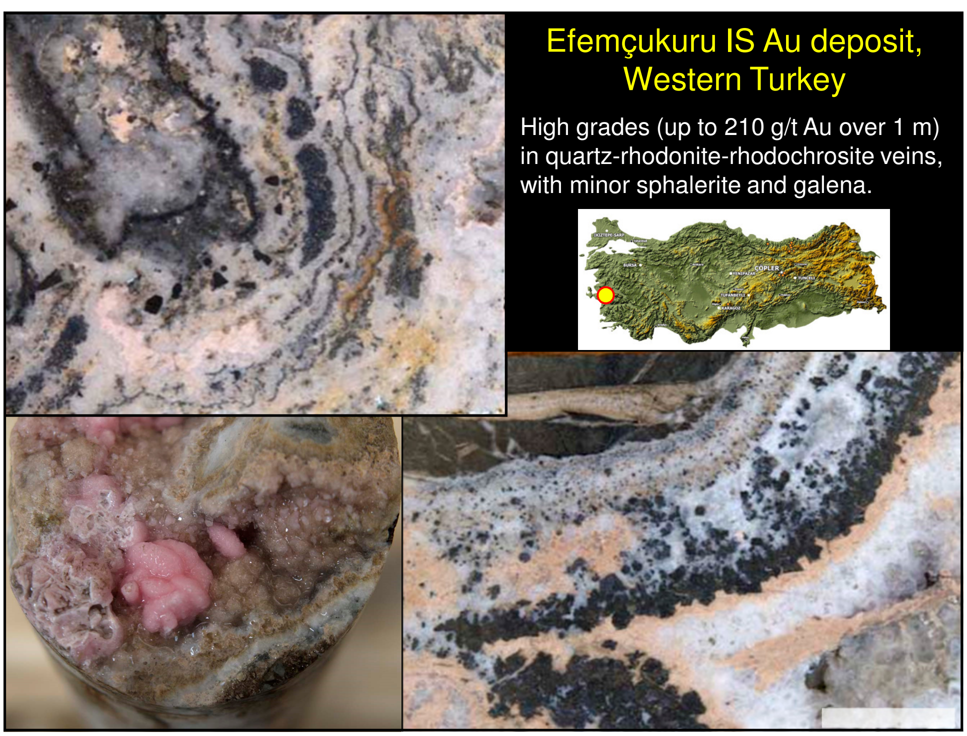


Fig. 1 in Sillitoe, R.H., 1973, The tops and bottoms of porphyry copper deposits: Economic Geology, v. 68, p. 799–815.


Relationship between porphyry and high-sulfidation (HS) and intermediate-sulfidation (IS) epithermal deposits
High-sulfidation epithermal disseminated Au ± Ag ± Cu
Intermediate-sulfidation epithermal Au-Ag
Base of lithocap
High-sulfidation lode Cu-Au ± Ag
Carbonate-replacement Zn-Pb-Ag ± Au (or Cu)
Distal Au/Zn-Pb skarn
Subepithermal vein Zn-Cu-Pb-Ag ± Au
Sediment-hosted distal-disseminated Au-As ± Sb ± Hg
Marble front
Porphyry Cu ± Au ± Mo
Proximal Cu-Au skarn
1km
1km
PORPHYRY STOCK
Late-mineral porphyry
Intermineral magmatic-hydrothermal breccia
Intermineral porphyry
Early porphyry
PRECURSOR PLUTON
Equigranular intrusive rock
HOST ROCKS
Dacite dome
Felsic tuff unit
Andesitic volcanic unit
Subvolcanic basement / carbonate horizon
LITHOCAP
Phreatic breccia
Dacite porphyry plug-dome
MAAR-DIATREME COMPLEX
Lacustrine sediment
Late phreatomagmatic breccia
Early phreatomagmatic breccia
Late-mineral porphyry
Sillitoe, R.H., 2010, Porphyry copper systems: Economic Geology, v. 105, p. 3–41.

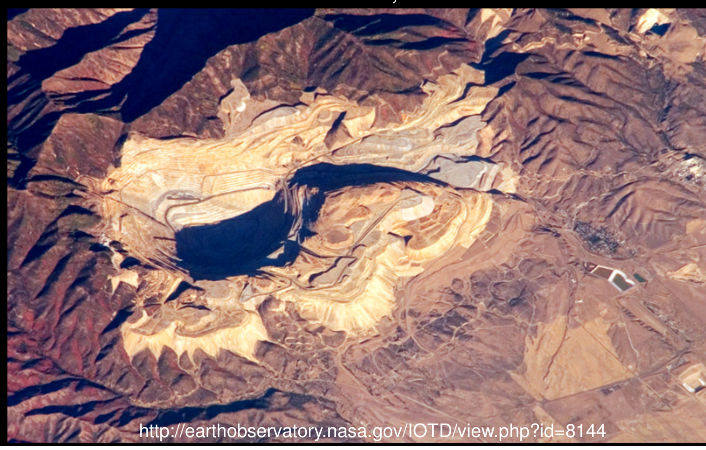

Vn. Antofalla: 6409m
Lithocap
5000m
Alunite-clay alteration
Pb-Zn-Ag veins
3500m
Silicified lithocap above high-sulfidation epithermal Au mineralization, with marginal intermediate sulfidation Pb-Zn-Ag veins
Volcán Antofalla, Argentina
Silica-cemented alunite breccia


Colloform banded pyrite
and euhedral enargite
Chelopech HS gold
deposit, Bulgaria
Chelopech
Marchev (2005)

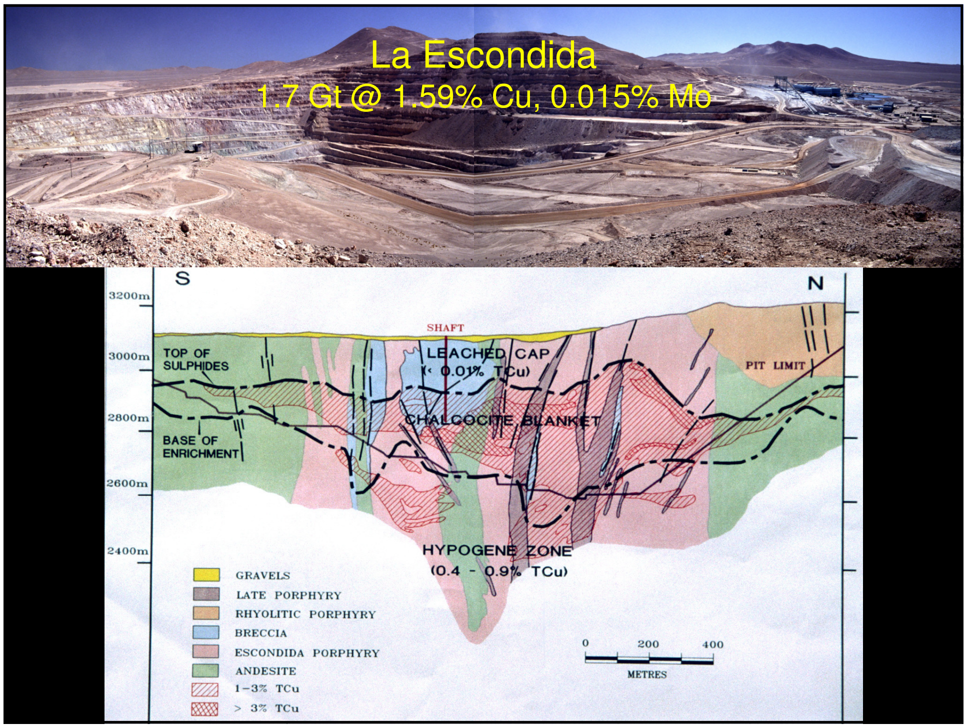

Efemçukuru IS Au deposit,
Western Turkey
High grades (up to 210 g/t Au over 1 m)
in quartz-rhodonite-rhodochrosite veins,
with minor sphalerite and galena.

If all the above processes operate optimally, maximally, and non-destructively, then a giant ore deposit *might* form.
But if not, it definitely won't.

The giant Bingham Canyon porphyry Cu deposit, Utah
~3 Gt @ 0.70% Cu, 0.04% Mo, 0.3 g/t Au
Σ 21 Mt Cu metal, 30 Moz Au



A final word:
Supergene enrichment may transform a subeconomic deposit into a world-class ore deposit.


La Escondida
1.7 Gt @ 1.59% Cu, 0.015% Mo
S
N
3200m
3000m
2800m
2600m
2400m
SHAFT
TOP OF SULPHIDES
LEACHED CAP
(< 0.01% TCu)
PIT LIMIT
CHALCOCITE BLANKET
BASE OF ENRICHMENT
HYPOGENE ZONE
(0.4 - 0.9% TCu)
GRAVELS
LATE PORPHYRY
RHYOLITIC PORPHYRY
BRECCIA
ESCONDIDA PORPHYRY
ANDESITE
1-3% TCu
> 3% TCu
0
200
400
METRES