Porphyry Cu-Mo-Au and Related Epithermal Au Systems:
Controls on Ore Formation from Plate to Vein Scales

Jeremy P. Richards
Harquail School of Earth Sciences, Laurentian University
Sudbury, ON, P3E 2C6
JR Richards2@laurentian.ca

Please note:
These slides contain copyrighted images; please do not further copy, distribute, or post to the web without the author’s or publisher’s permission.
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.

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 km², 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.
Porphyry-epithermal deposits are late stage parts of plate-scale tectonomagmatic systems. Many steps must operate efficiently and additively for an ore deposit to ultimately form.

Subduction of hydrated oceanic lithosphere recycles volatiles (H₂O, 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.
Slab dehydration:
Initial fluids released from cool slabs at shallow depths are water rich, but become more solute-rich at sub-arc depths.

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.
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$_2$O (Sobolev & Chaussidon, 1996; Kimura & Ariskin, 2014; up to 8 wt.%; 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.
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.

Time scale for evolution of MASH zone to produce evolved magmas:
$\geq 10 \text{ m.y.}$ of steady state arc magmatism.

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.


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 m.y.
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.


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.

Magma ascent and crystallization

Emplacement of large volumes of hydrous calc-alkaline magma in the upper crust will inevitably lead to fluid exsolution.
Porphyry–epithermal ore deposits form where the upward flow of this fluid is focused in a **cupola** zone.

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.
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.


Magmatic–hydrothermal breccia dike
Pachapaqui Pb-Zn-Ag deposit, Péru
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

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.

Mammoth breccia pipe, Utah

Formed by fluids exsolved from porphyry (light grey) intruded at depth, which precipitated Cu minerals during breccia formation.

Japonesa tourmaline breccia pipe, Copiapó, Chile

Porphyry pluton shapes: cupolas

Lowell and Guilbert’s classic model of porphyry alteration and mineralization zoning:

1. Alteration

Porphyry–epithermal alteration zoning (Sillitoe, 2010)

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

Secondary biotite and K feldspar in porphyritic intrusions (left: Chuquicamata; right: Lomas Bayas)

Secondary K feldspar in granodiorite stained with sodium cobaltinitrite (yellow)

Phyllitic (feldspar destructive) alteration:
Later, cooler, mildly acidic magmatic fluids

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 $a_{K+/H^+}$) fluids, and is characterized by the breakdown of aluminosilicate minerals to clays. When magmatic fluids cool, the sulfur that they carry disproportionates from $\text{SO}_2$ ($S^{4+}$), which is the dominant dissolved species at high temperature, to a mixture of $\text{H}_2\text{S}$ ($S^{2-}$) and sulfuric acid ($S^{6+}$):

$$4 \text{SO}_2 + 4 \text{H}_2\text{O} \rightarrow \text{H}_2\text{S} + 3 \text{HSO}_4^- + 3 \text{H}^+$$

K-feldspar + acid $\rightarrow$ clay (kaolinite) + Qz + K+

$$2 \text{KAlSi}_3\text{O}_8 + 2 \text{H}^+ + \text{H}_2\text{O} \rightarrow \text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4 + 4 \text{SiO}_2 + 2 \text{K}^+$$

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

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. $\text{SO}_2$ disproportionates to $\text{H}_2\text{S}$ and $\text{SO}_4^{2-}$ below ~400°C (Holland, 1965).

Disproportionation of $\text{SO}_2 <400^\circ\text{C}$ generates $\text{H}_2\text{S}$ and acid. $\text{H}_2\text{S}$ reacts with dissolved metals to precipitate sulfide minerals:

$$4\text{S}^{\text{IV}}\text{O}_2 + 4\text{H}_2\text{O} \Leftrightarrow \text{H}_2\text{S}^{\text{II}} + 3\text{H}_2\text{S}^{\text{VI}}\text{O}_4$$

Magnetite precipitation:

$$9\text{Fe}^{\text{II}}\text{Cl}_2 + \text{SO}_2 + 10\text{H}_2\text{O} \Leftrightarrow 3\text{Fe}^{\text{II}}\text{Fe}^{\text{III}}_2\text{O}_4 + \text{H}_2\text{S} + 18\text{HCl}$$

Cu-Fe-sulfide precipitation:

$$\text{CuCl}_{(aq)} + \text{H}_2\text{S} \Leftrightarrow \text{Cu}_2\text{S} + 2\text{HCl}$$

$$8\text{CuCl}_{(aq)} + 8\text{Fe}^{\text{II}}\text{Cl}_2_{(aq)} + 15\text{H}_2\text{S} + \text{H}_2\text{SO}_4 \Leftrightarrow 8\text{CuFe}^{\text{III}}\text{S}_2 + 24\text{HCl} + 4\text{H}_2\text{O}$$

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

4. Steep pressure gradients across the ductile–brittle transition ($400–350^\circ\text{C}$) promote phase separation, brecciation, and stockwork formation (permeability) (Fournier, 1999).

5. Silica shows retrograde solubility between $550^\circ–350^\circ\text{C}$, creating porosity for ore deposition (Fournier, 1985).
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
Disseminated chalcopyrite intergrown with hydrothermal biotite and K-feldspar (El Teniente porphyry Cu deposit, Chile)

Later acidic alteration (phylllic, argillic) may destroy earlier-deposited mineralization

Pyritic D-vein with phylllic alteration halo cross-cutting earlier quartz-magnetite A-veins in potassic alteration (Tameapa porphyry Cu-Mo deposit, Mexico).
The Porphyry–Epithermal Transition

VOLCANIC-HYDROTHERMAL SYSTEM

GEOTHERMAL SYSTEM

Hotsprings
100°
CO₂, H₂S
500°-900°
SO₂, HCl, CO₂
Crater lake
200°-300°
CO₂, HCl, S
Acidic fluid
Boiling
Primary neutralization
300°
300°
Saline magmatic fluid
Liquid flow
Vapor ascent
Low sulfidation
Au, Ag
High sulfidation
Au, Cu
Porphyry Cu (Mo, Au)

Relationship between epithermal systems and volcanism; the 1970s view (Sillitoe, 1973)
Relationship between porphyry and high-sulfidation (HS) and intermediate-sulfidation (IS) epithermal deposits

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
Chelopecch HS gold deposit, Bulgaria

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

Geology, genesis, and exploration for magmatic and magmatic-hydrothermal ore deposits