Economic Geology: Lecture Notes

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Cu porphyry and Hydrothermal Veins

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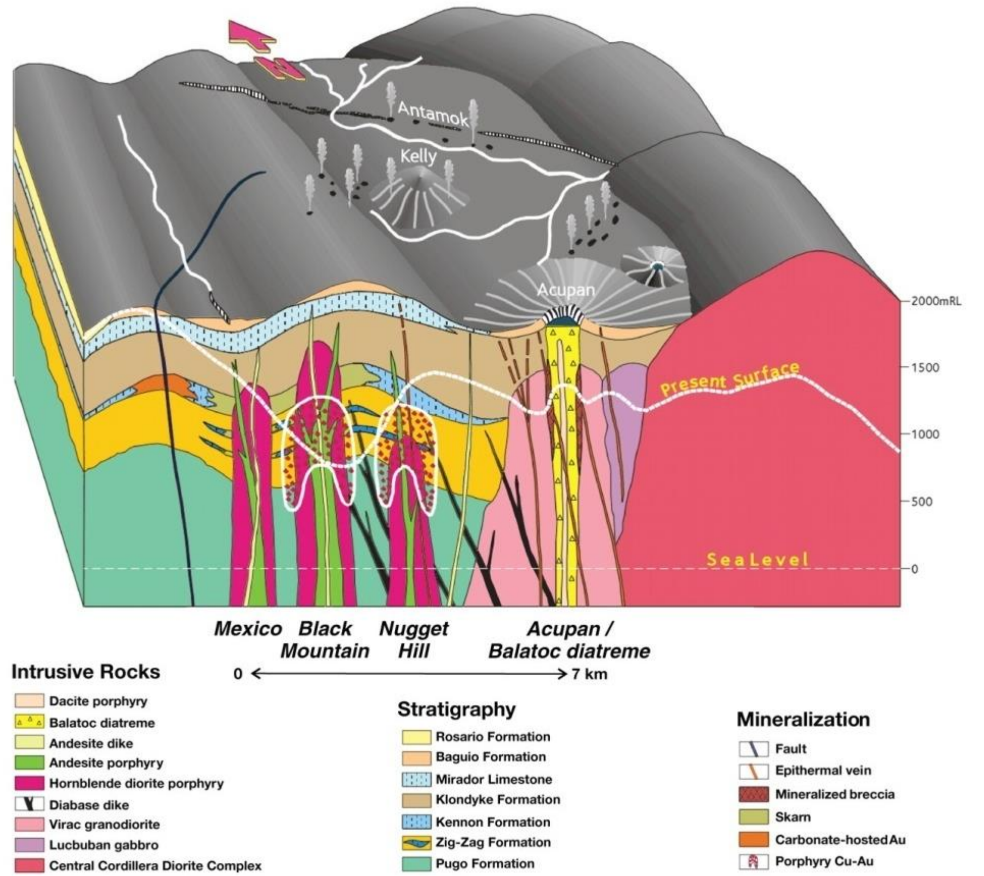
8. Porphyry copper (Mo-Au-Sn-W) deposits

I. What are Porphyry copper deposits (PCDs)?

Porphyry ore deposits are products of magmatic-hydrothermal activity at shallow crustal levels. Primarily copper, but also molybdenum, tin, tungsten and gold occur closely related to epizonal intrusions of porphyric magmatic rocks.

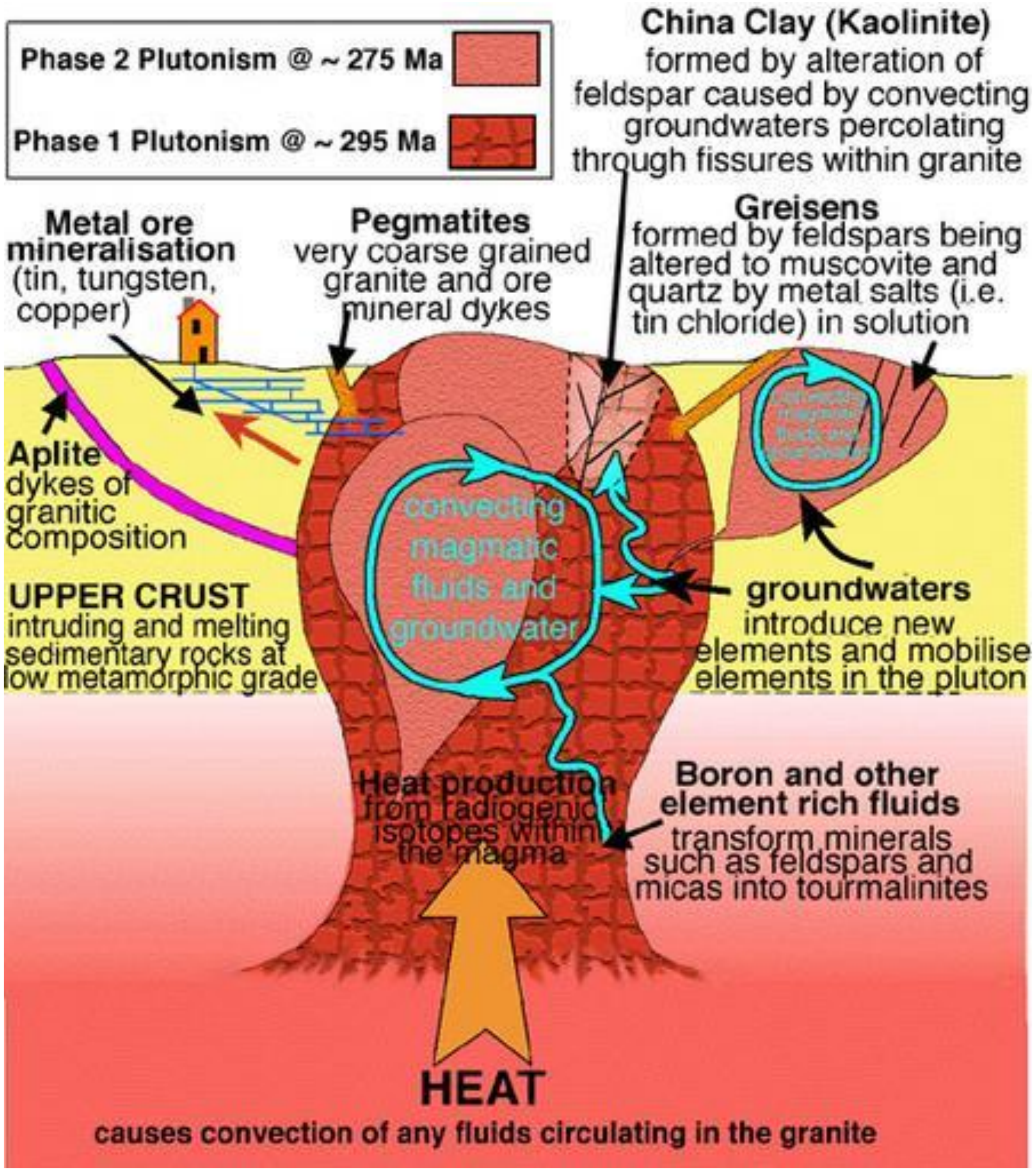
Porphyries contain phenocrysts of hornblende, biotite, feldspar or quartz in aplitic (fine grained) groundmass. The phenocrysts crystallize when a fertile magma exists on deeper depths. Due to tectonic movements (subduction zones), the pressure is suddenly released and the magma is promoted to move to shallower depths and lose their volatile content. The fertile magma freezing during rapid ascent interprets the aplitic groundmass.

Cu-Au-Mo porphyry ore deposits supply 75% of the world's Cu, 50% of Mo, nearly all of Re and 20% of gold.



The most significant characteristics of copper porphyries include:

1. plug-like multiple porphyric intrusions below co-magmatic volcanoes, formed before mineralization;
2. an extraordinary tonnage of magmatic hydrothermal ore;
3. the ore occurs mainly in stockwork vein systems within the intrusion;
4. metal contents in ore are low to moderate, and supergene enrichment is often the key to exploitability;
5. extensive hydrothermal alteration and metals are vertically and cylindrically zoned in relation to the axis of the intrusion.



The major products from porphyry copper deposits are copper and molybdenum or copper and gold. The term porphyry copper refers to large, relatively low grade, intrusion-related deposits that can be mined using mass mining techniques.

Host rocks of Cu-Au-Mo porphyry deposits are shallow (<4000 m), sub-volcanic cylindric intrusions. The porphyry parent rocks are frequently:

1. calc-alkaline diorites (andesite-dacite),
2. monzonites (latite) or
3. granites (rhyolite) of I-type

Such parent rocks occur above subduction zones (convergent plate boundaries), either on active continental margins or in island arcs. Porphyries on active continental margins are marked by elevated Cu, Sn and Mo, those of island arcs are often Cu-Au.

There are usually multiple episodes of intrusive activity, so, are commonly associated with swarms of dykes and intrusive breccias.

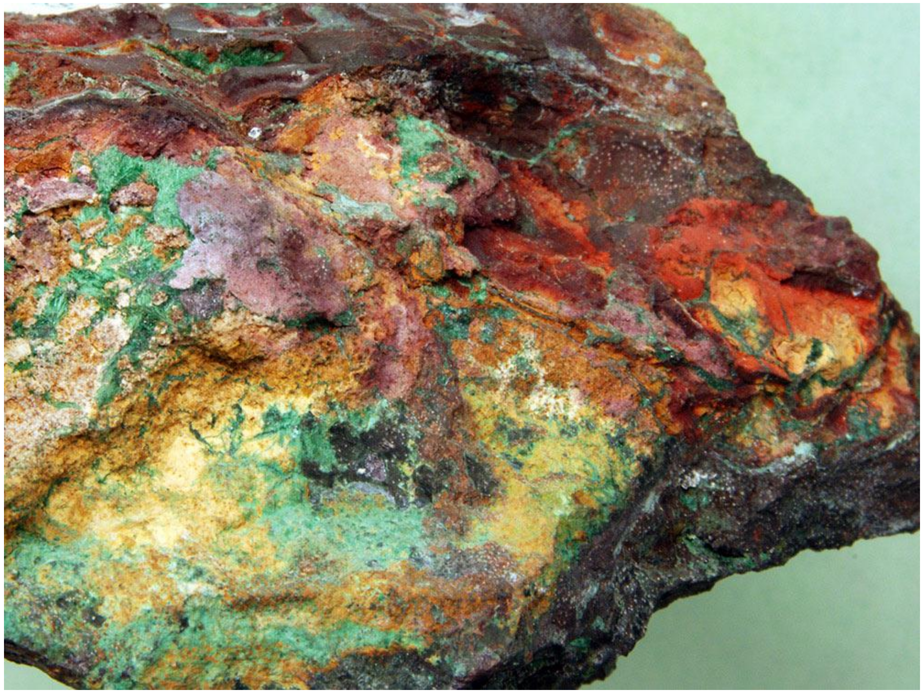
Esconida Copper mine in Chile

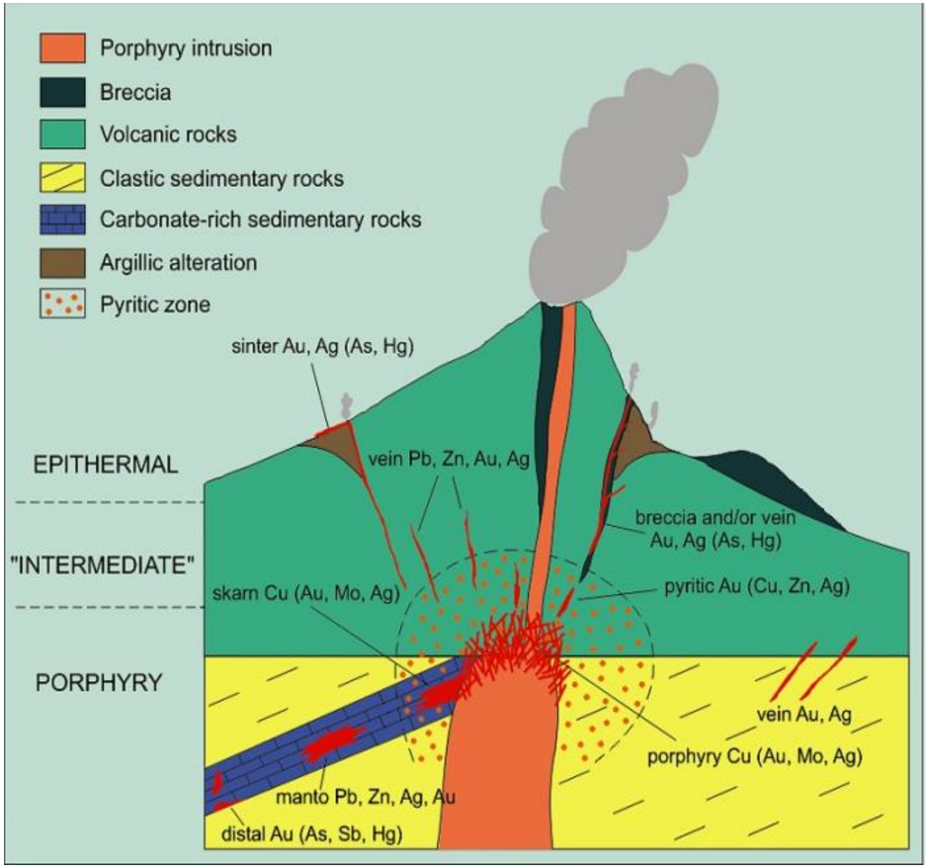
As stated before, the porphyry copper could be found in any country rocks, and often there are wide zones of closely fractured and altered rock surrounding the intrusions.

The country rock alteration is distinctive and changes as mineralization is approached. Where sulphide mineralization occurs, surface weathering – by solutions - often produces rusty-stained bleached zones from which the metals – (Cu-Mo-Au) - have been leached; then re-deposited near the water table to form an enriched zone of secondary mineralization.

II. Genesis of PCDs

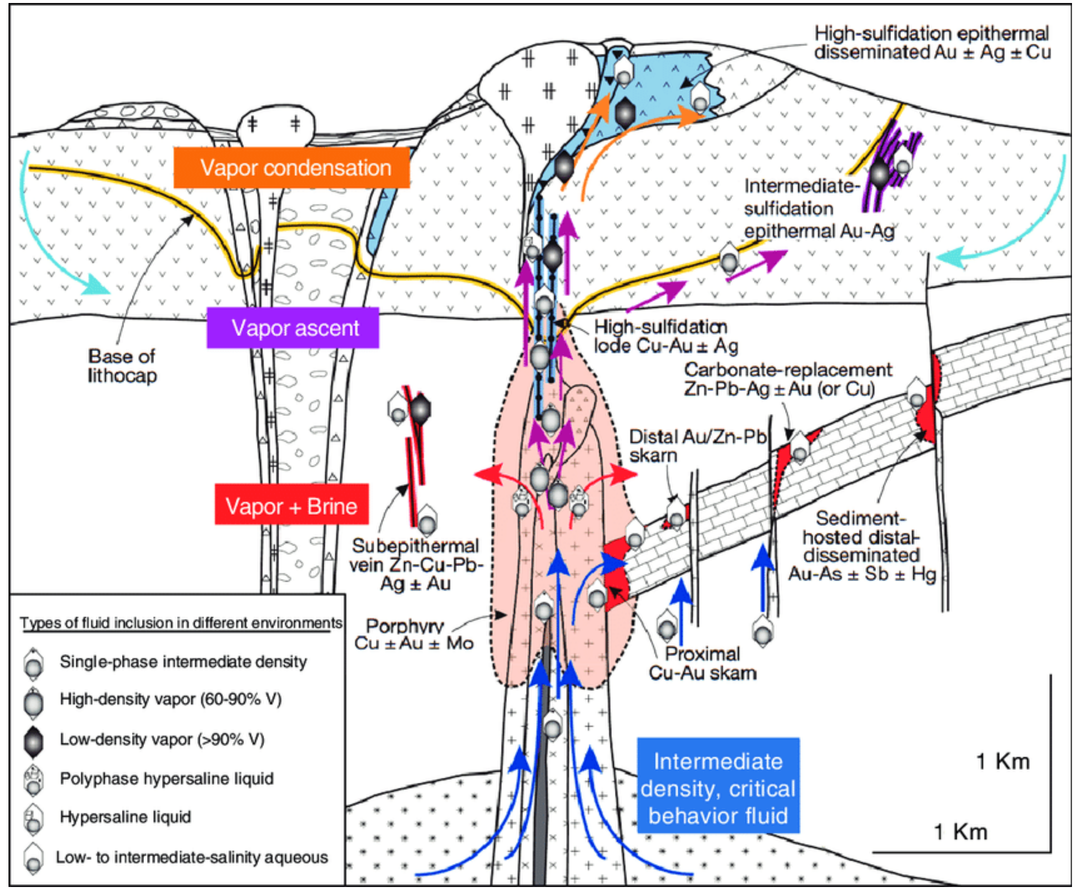
1. Various factors affect the porphyry copper formation, such as: magma type; volatile and oxygen content; the number, size, timing and depth of emplacement of mineralizing porphyry plutons; variations in country rock composition and fracturing; the rate of fluid mixing; density contrasts in the fluids; pressure and temperature gradients in the fluids, all combine to affect the porphyry copper genesis.





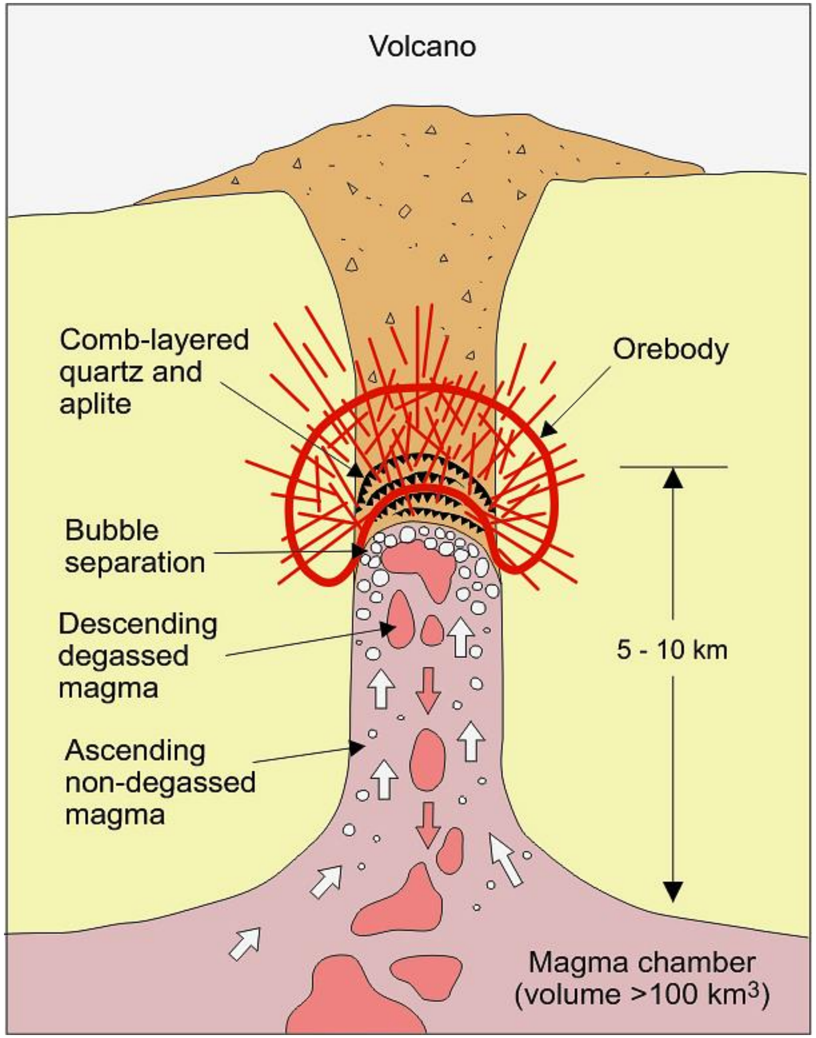
Schematic diagram of a porphyry Cu system in the root zone of an andesitic stratovolcano. Figure shows mineral zonation and possible relationship to skarn, manto, "mesothermal" or "intermediate" precious-metal and base-metal vein and replacement, and epithermal precious-metal deposits.

2. Fertile, volatile-enriched, highly oxidized magmas emplaced near highly permeable rock are the main sources of the ores. The ore could be crystalized/formed during the magma cooling and disseminated in the groundmass of the Porphyry intrusion. This could happen due to the absence of reduced sulphur in the parent magma otherwise sulphide melts would form and lag behind the rising silicate liquid. However; porphyry copper ore deposits display a strong epithermal signature overprinting an earlier hydrothermal alteration. Therefore, two hydrothermal regimes are the most probable modes for ore formation and concentration.



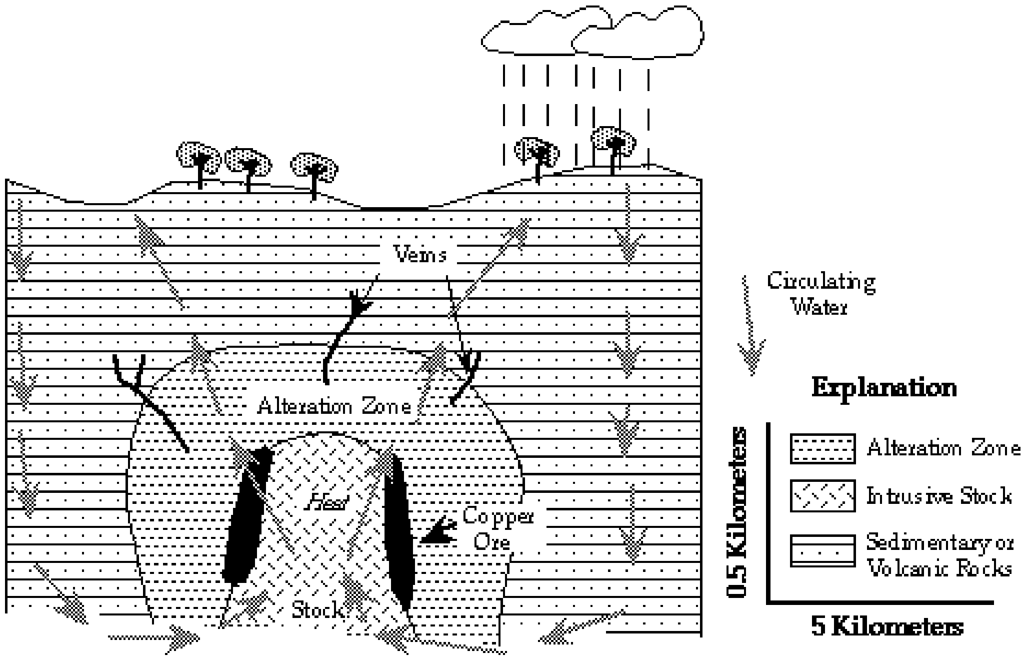
3. Two hydrothermal regimes including i) orthomagmatic systems dominated by magmatic hydrothermal fluids (derived from molten rock) and ii) convective systems, dominated by non-magmatic meteoric waters (usually groundwater) interpret and portray the alteration and mineralization processes that have produced the wide variety of porphyry copper deposits.

4. Orthomagmatic Model (regime/stage): Volatiles and metals are concentrated during crystallisation of the magma, then break through the crystallised carapace as metal-charged ore brines, i.e., magmatic hydrothermal fluids. The initial wave of the escaping hydrothermal fluids fractures the country rock and creates a crackle zone and plumbing system that controls the travel paths of subsequent hydrothermal fluids and localizes alteration and mineralisation. Further cracking results from magmatic pressures, boiling and hydrofracturing.

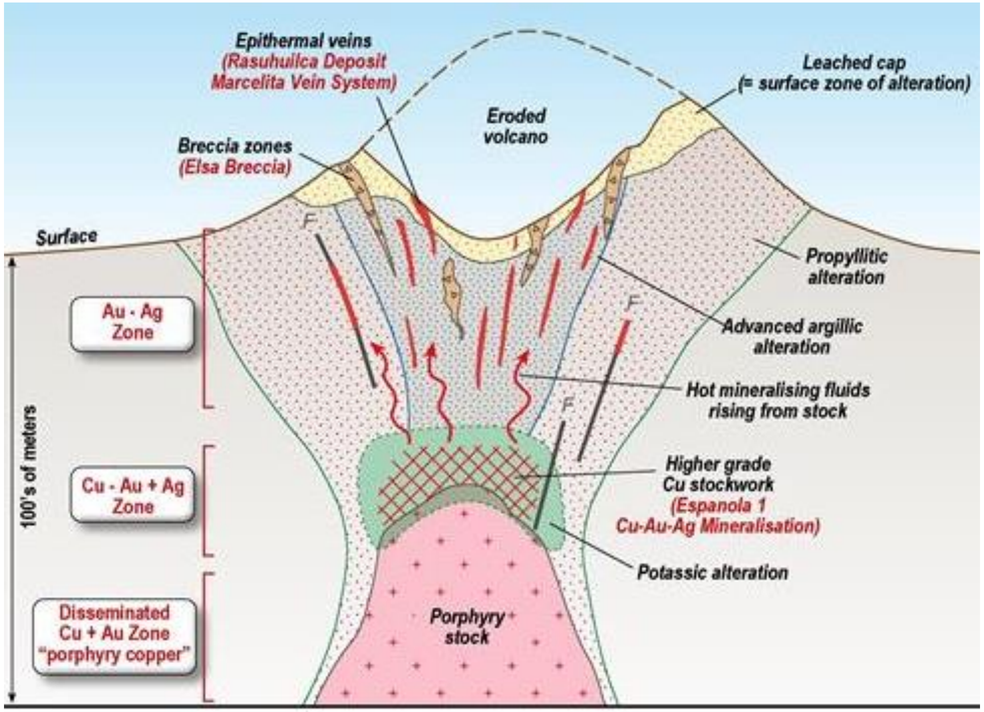


Magma that is feeding a small sub volcanic intrusion below a porphyry deposit.

5. **Convective Model (regime/stage): The convecting fluids (meteoric/groundwater-non-magmatic) transfer metals and heat from the magma into the country rock and re-distribute elements in the convective system. Here the hydrothermal fluid is originated from meteoric or seawater, i.e., non-magmatic.**



6. **The two models are continuum. The fundamental difference between the two models is the source and flowpath of the hydrothermal fluids. The permeability of the country rock is increased by the intrusive events to allow convective circulation. The convective hydrothermal fluids concentrate ore and gangue minerals near the intrusion.**



Orthomagmatic	Convective
Magmatic intrusion generates an ascending hydrothermal plume. Magmatic component constitutes up to 95% of the hydrothermal fluid	Permeable country rocks are the primary source of fluids. Magmatic fluids may be only 5% of the hydrothermal fluids.
Salinity is high, ranging from 15 wt % to 60 wt %.	Salinity is low, generally less than 15 wt %.
Multiple episodes of boiling, caused by repeated self-sealing and re-fracturing of the rocks.	Boiling is localised and of limited duration.
Fluid temperatures 400°C - 650°C, persisting over long periods of time.	Fluid temperatures may briefly reach 450°C, but quickly drop to around 250°C. The lower temperatures are then maintained for a long time.
Pervasive alteration and mineralisation form a series of shells around the core of the intrusion.	Alteration and mineralisation are both pervasive and fracture controlled.
Metals and sulphur are derived from the magma and are concentrated in residual fluids.	Metals and sulphur are scavenged from the enclosing rocks by convective ground waters.

Porphyry deposits occur in two main settings within the orogenic belts; in island arcs and at continental margins.

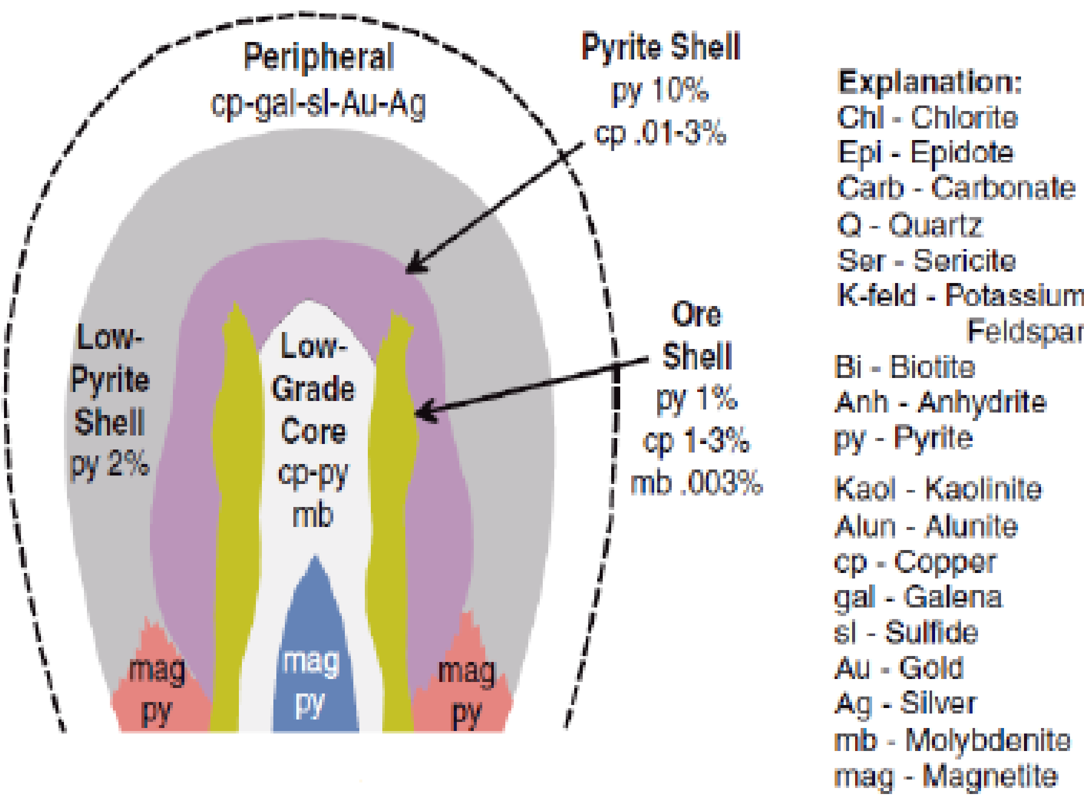
III. Mineralization of PCDs

Original sulphide minerals in these deposits are pyrite, chalcopyrite, bornite and molybdenite. Gold is often in native found as tiny blobs along borders of sulphide crystals.

Most of the sulphides occur in veins or fractures; most are intergrown with quartz or sericite.

In many cases, the porphry deposits have a central very low grade zone enclosed by 'shells' dominated by bornite, then chalcopyrite, and finally pyrite, which may be up to 15wt.% of the rock.

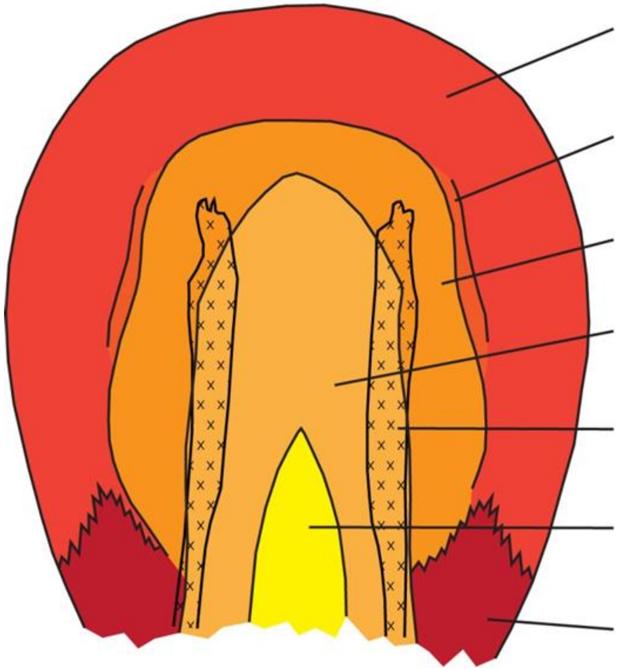
Molybdenite distribution is variable. Radial fracture zones outside the pyrite halo may contain lead-zinc veins with gold and silver values.



Schematic cross section of ores associated with each alteration zone.

IV. Alteration zones related to porphyry deposits

Alteration zones develop in/around granitic rocks with related porphyry deposits. If the alkali to hydrogen ratio is low, (i.e.; high K from the high volatile magma) feldspars, micas and other silicates become unstable and hydrolysis occurs when affected by hydrothermal solutions.



Four alteration types are common:

i. **Propylitic:** Weak hydrolysis. Quartz and alkali feldspar are stable, but plagioclase and mafic minerals react with the fluid to form albitised (Na) plagioclase, chlorite, epidote, carbonate and montmorillonite.

ii. **Argillic:** More intense hydrolysis. Characterized by quartz, kaolinite and chlorite.

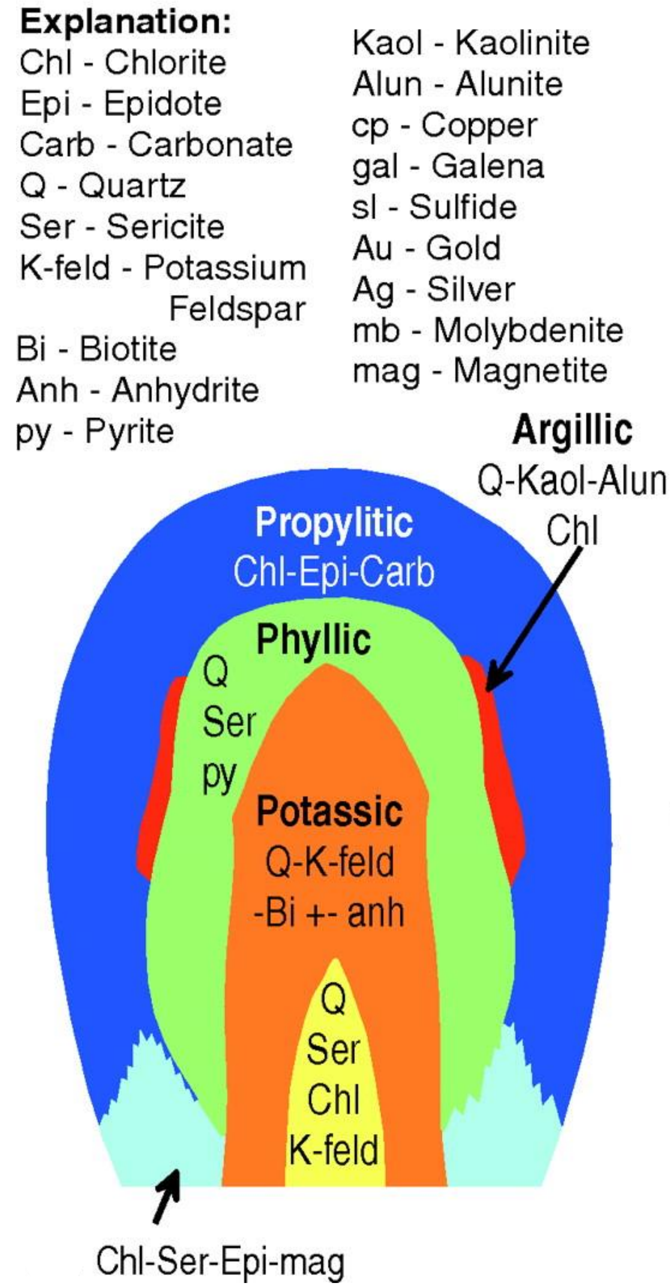
iii. **Phyllic:** Quartz and sericite (fine muscovite), commonly accompanied by pyrite.

iv. **Potassic:** High temperature alteration by concentrated hydrothermal fluids. All rock constituents are unstable. Alteration assemblages of quartz (commonly resorbed), K-feldspar, biotite and intermediate plagioclase.

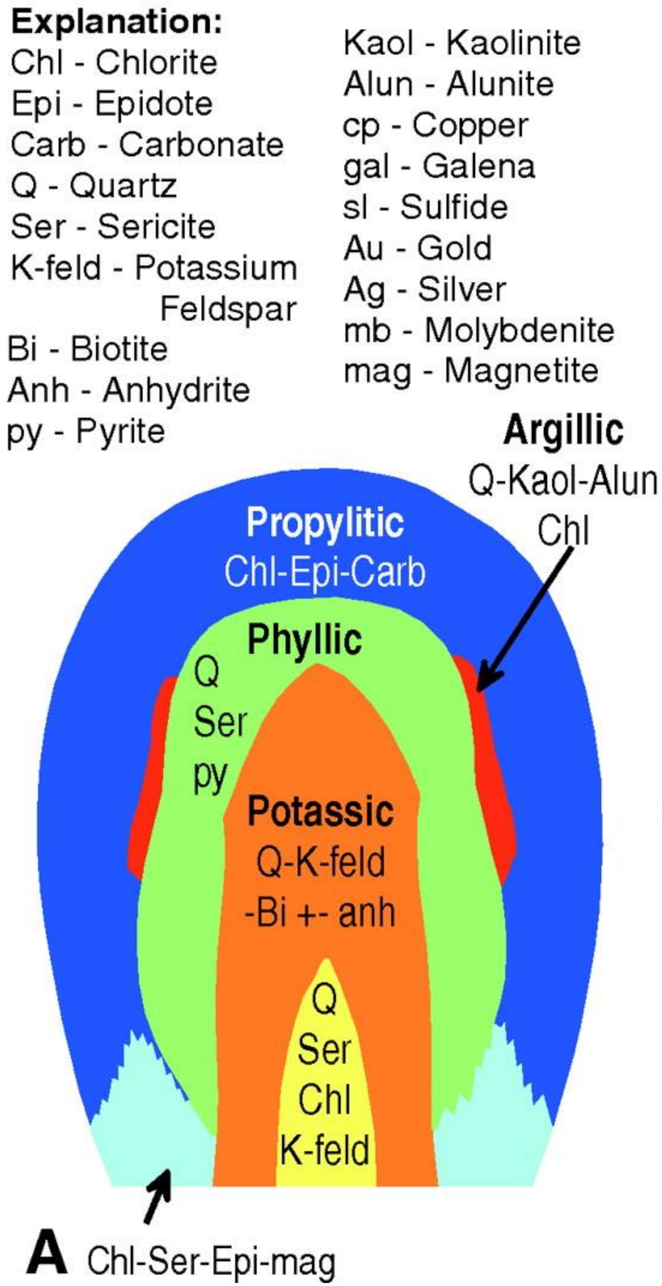
As a generalized model, these alteration assemblages form distinct zones around the intrusion, with a shell of potassic alteration grading outward through a shell of cream or green quartz and sericite (phyllic), white, chalky clay (argillic) and then greenish chlorite, epidote, sodic plagioclase and carbonate (propylitic) alteration zones into unaltered country rock.

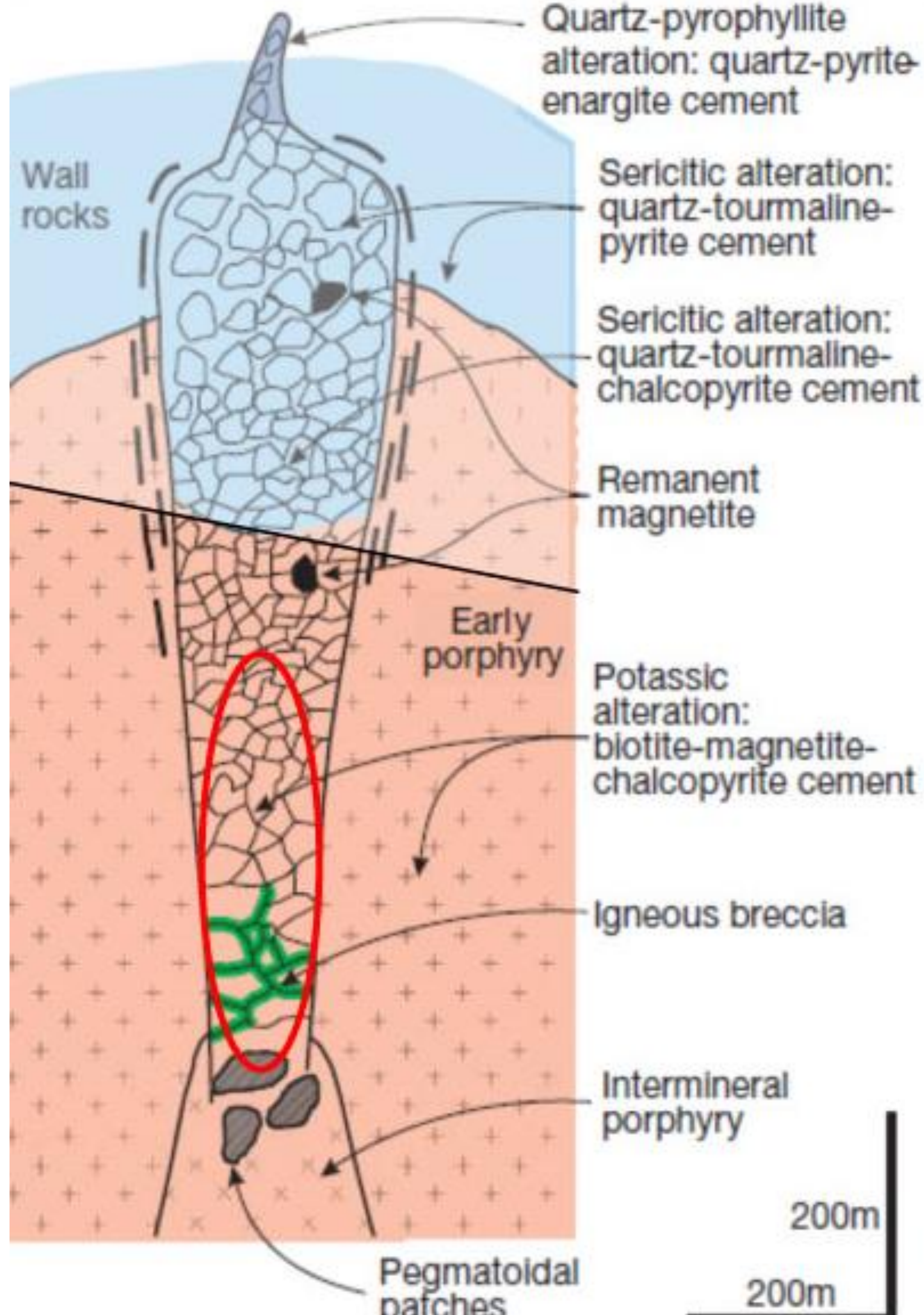
In reality, the complete sequence is rarely developed or preserved, and assemblages are strongly influenced by the composition of the host rocks.

Often there is early development of a wide area of secondary biotite that gives the rock a distinctive brownish colour.

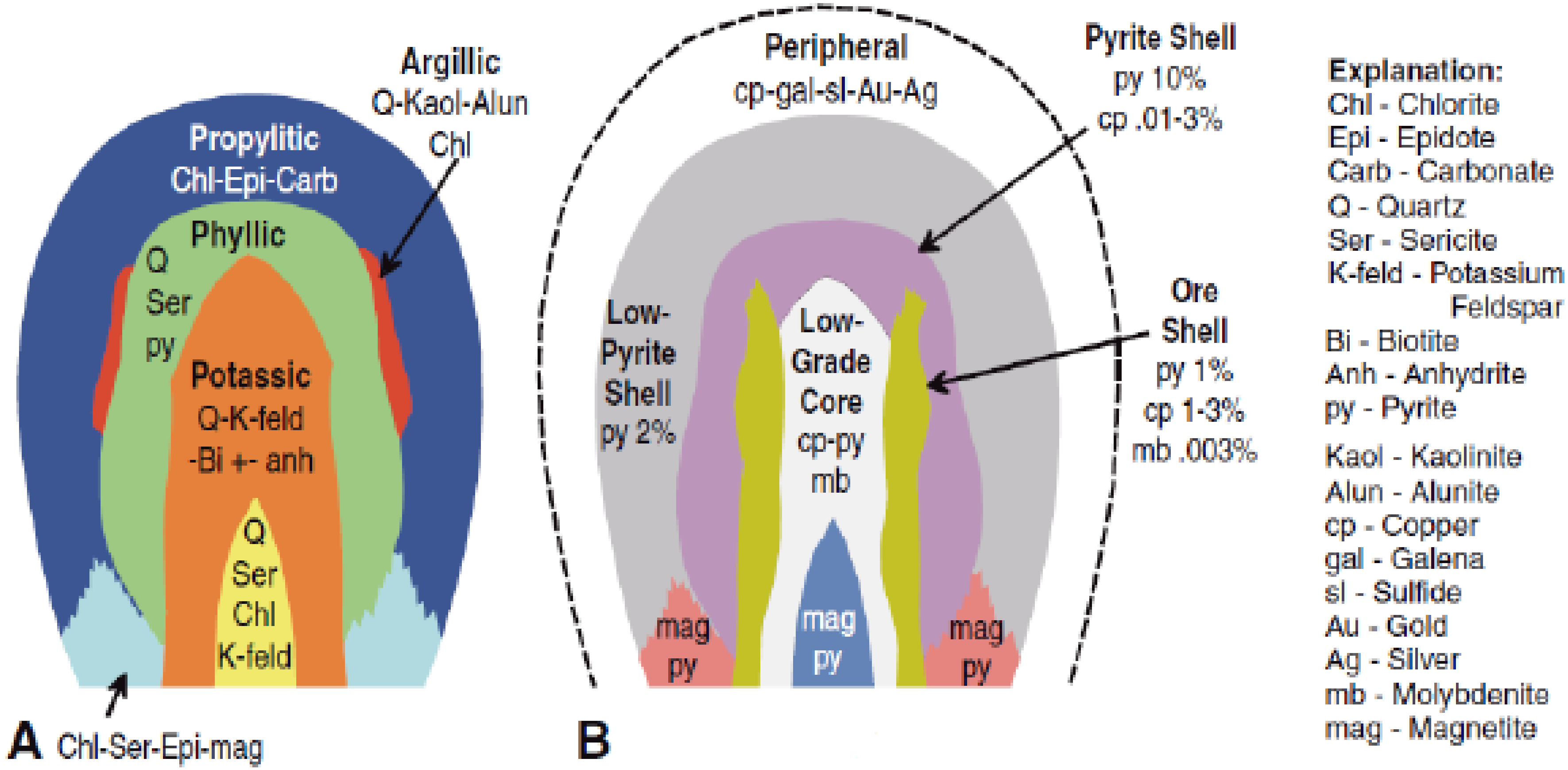


Schematic cross section of hydrothermal alteration mineral zones, which consist of propylitic, phyllic, argillic, and potassic alteration zones.





Schematic cross section of hydrothermal alteration mineral zones, which consist of propylitic, phyllic, argillic, and potassic alteration zones.

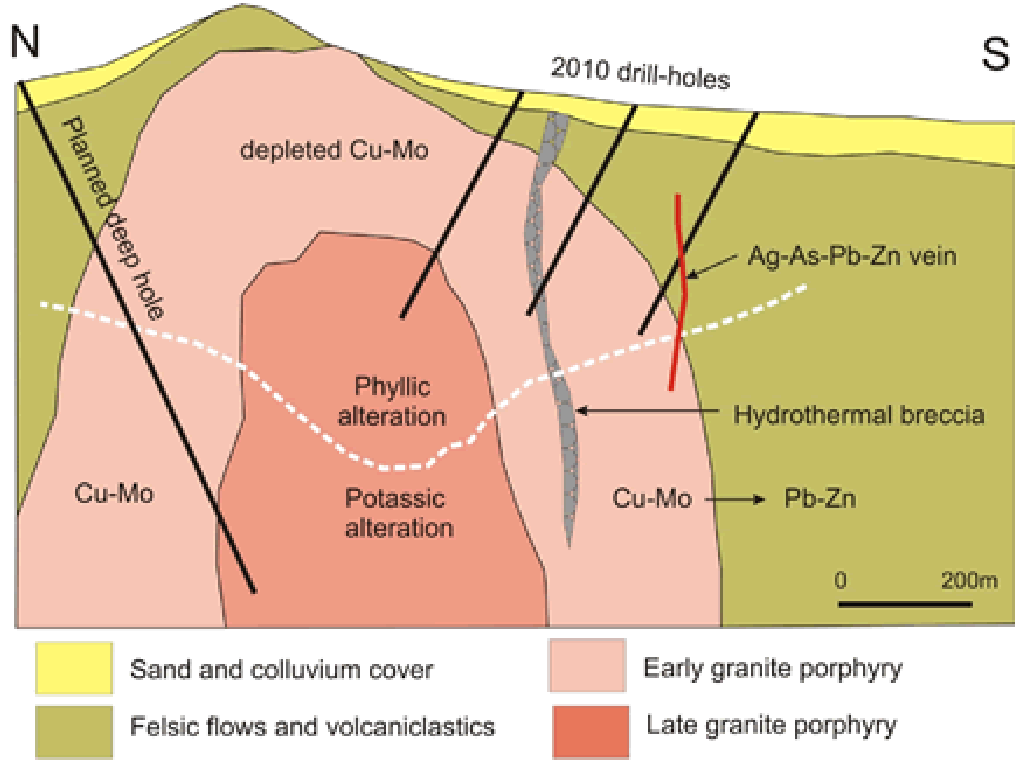


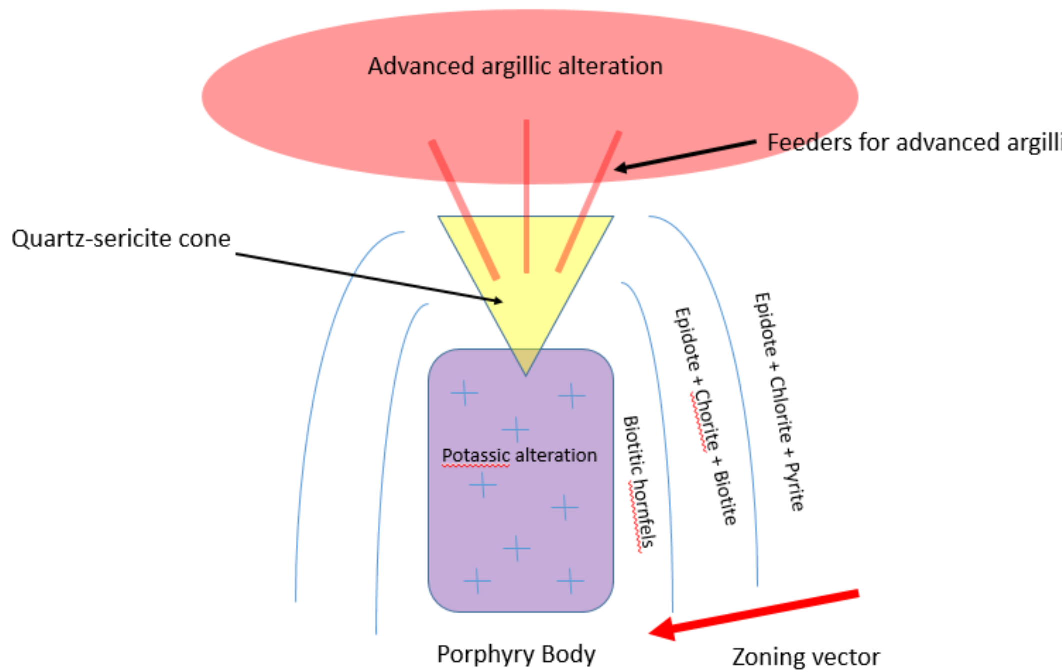
Hydrothermal alteration zones associated with porphyry copper deposit (A) Schematic cross section of hydrothermal alteration mineral zones, which consist of propylitic, phyllic, argillic, and potassic alteration zones. (B) Schematic cross section of ores associated with each alteration zone.

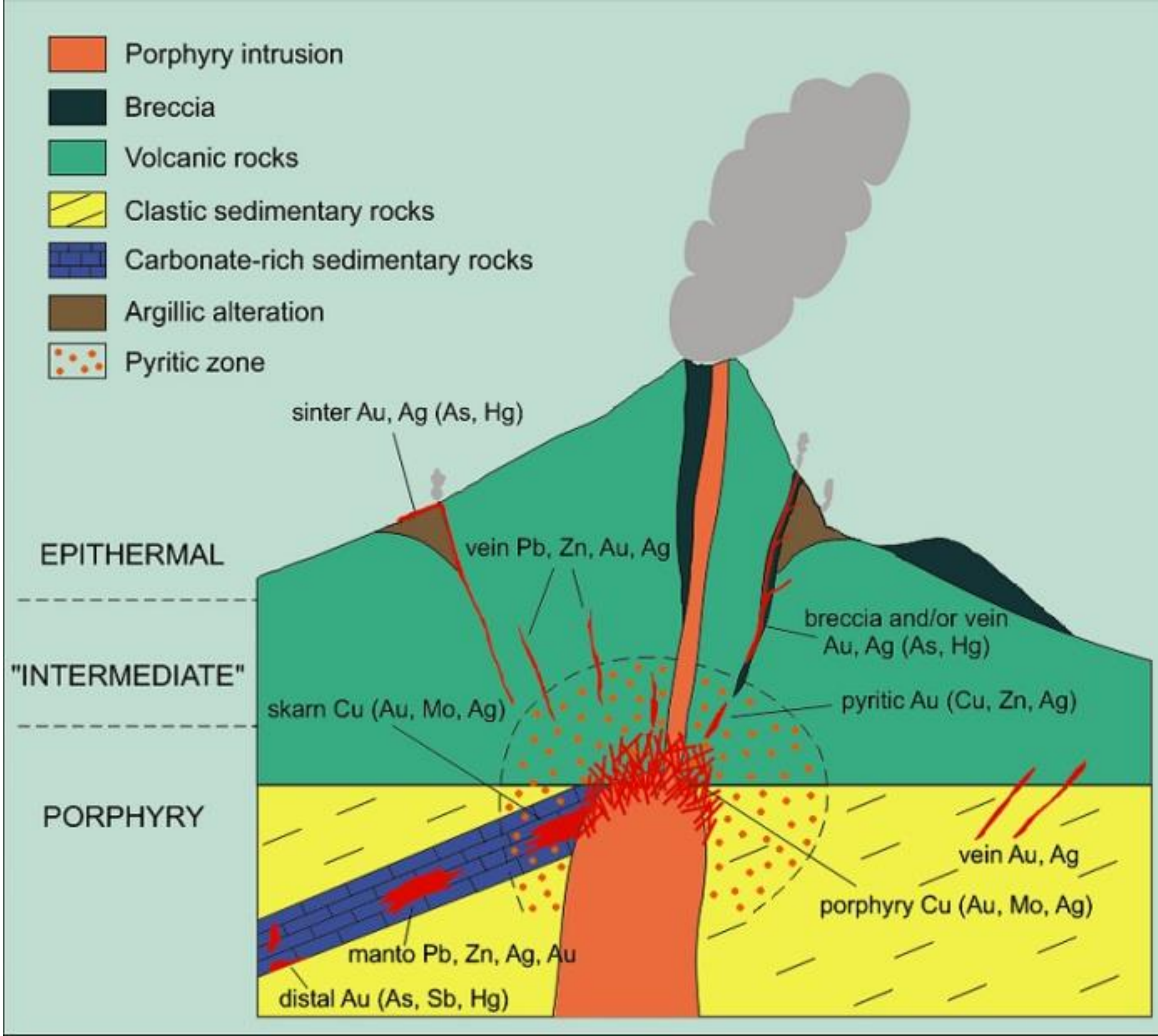
V. Structural features associated with PCDs.

Mineralization in porphyry deposits is mostly on fractures, so ground preparation or development of a 'plumbing system' is vitally important and grades are best where the rocks are closely fractured. Porphyry-type mineral deposits result when large amounts of hot water that carry small amounts of metals pass through permeable rocks and deposit the metals.

Intrusions associated with, porphyry copper deposits are porphyritic, reflecting rapid chilling. Porphyry dykes are very common and many breccia bodies reflect an explosive escape of volatiles. Several periods of brecciation occur.






Porphyry intrusion
Breccia
Volcanic rocks
Clastic sedimentary rocks
Carbonate-rich sedimentary rocks
Argillic alteration
Pyritic zone
sinter Au, Ag (As, Hg)
EPITHERMAL
vein Pb, Zn, Au, Ag
breccia and/or vein
Au, Ag (As, Hg)
"INTERMEDIATE"
skarn Cu (Au, Mo, Ag)
pyritic Au (Cu, Zn, Ag)
PORPHYRY
vein Au, Ag
porphyry Cu (Au, Mo, Ag)
manto Pb, Zn, Ag, Au
distal Au (As, Sb, Hg)

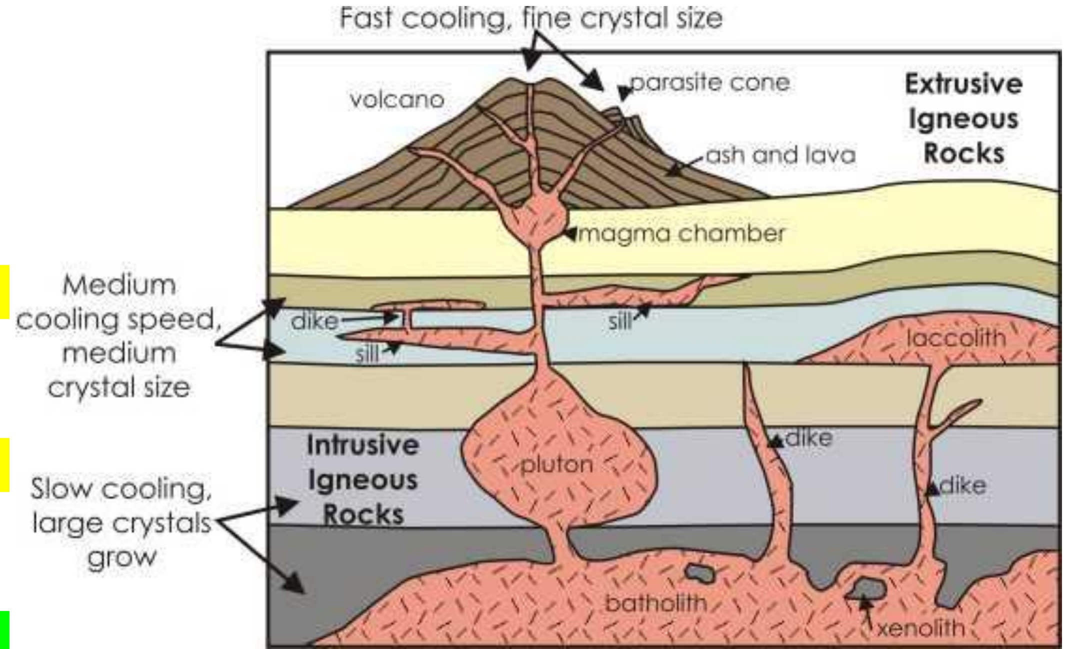
VI. Classification of PCDs

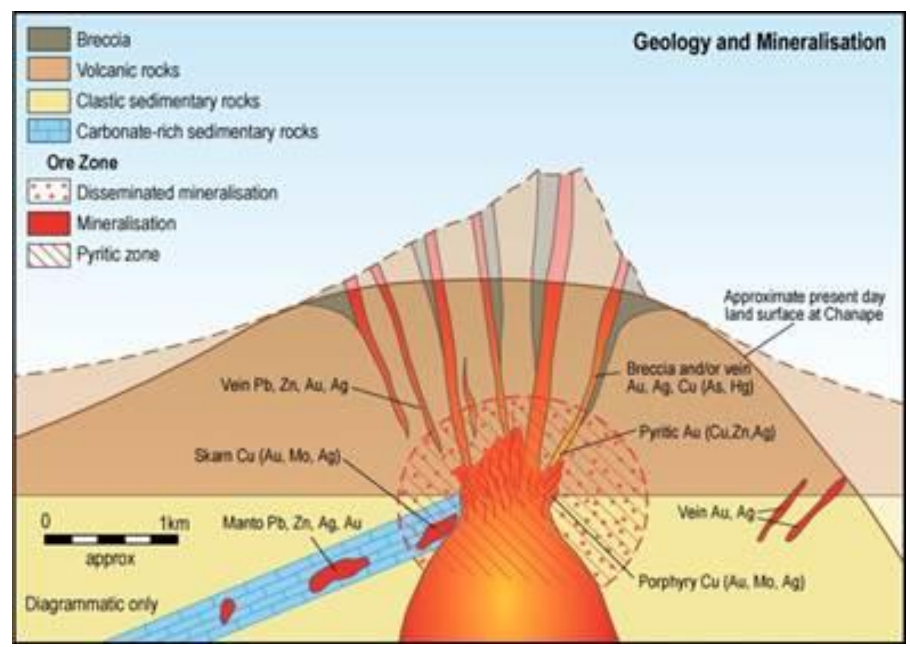
Porphyry copper deposits comprise three broad types:

1. **Plutonic: porphyry copper deposits occur in batholithic settings with mineralization principally occurring in one or more phases of plutonic host rock.**

2. **Volcanic: occur in the roots of volcanoes, with mineralisation both in the volcanic rocks and in associated co-magmatic plutons.**

3. **Classic: occur with high-level, post-orogenic stocks that intrude unrelated host rocks; mineralization may occur within the stock, the country rock, or in both.**



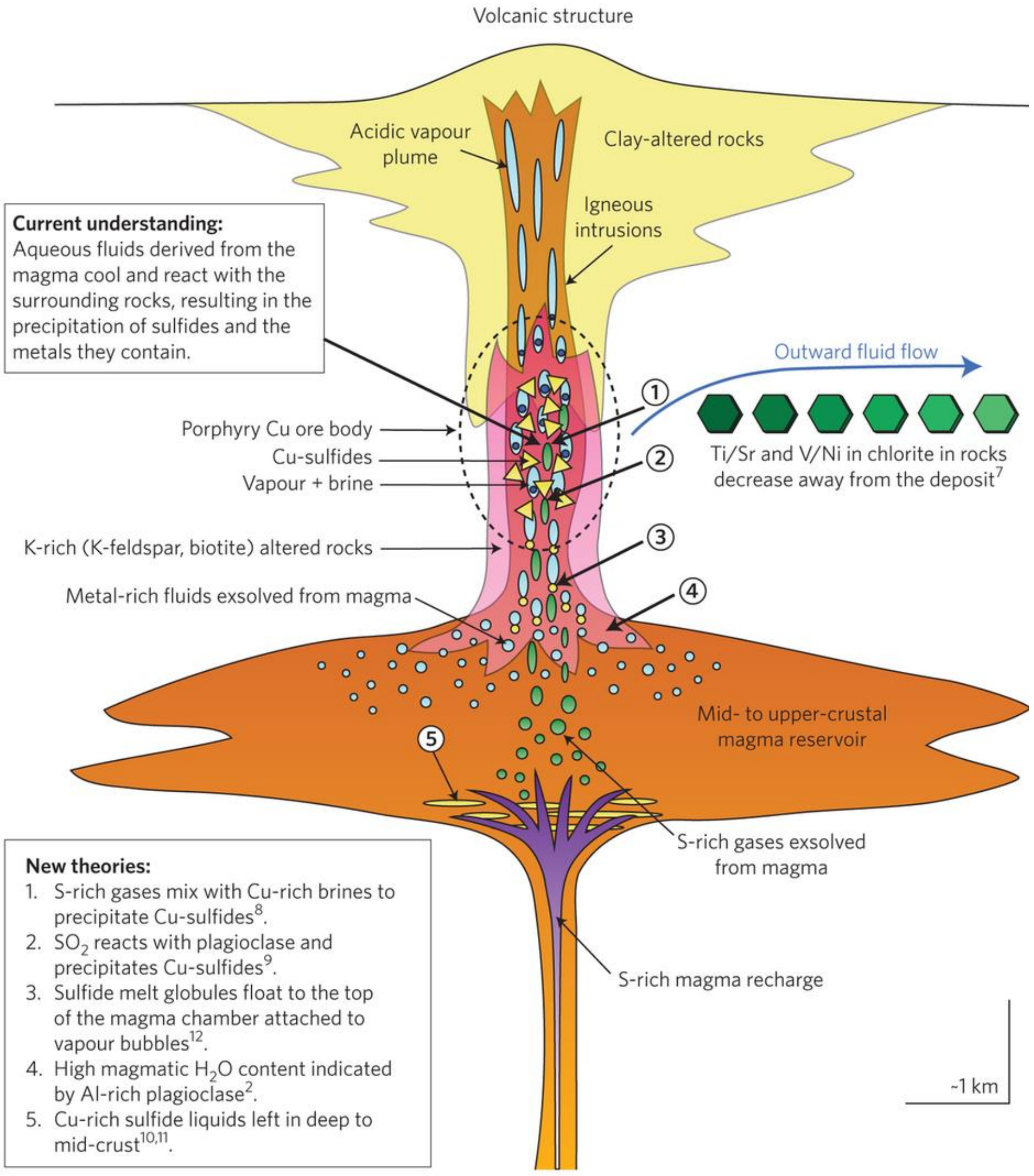


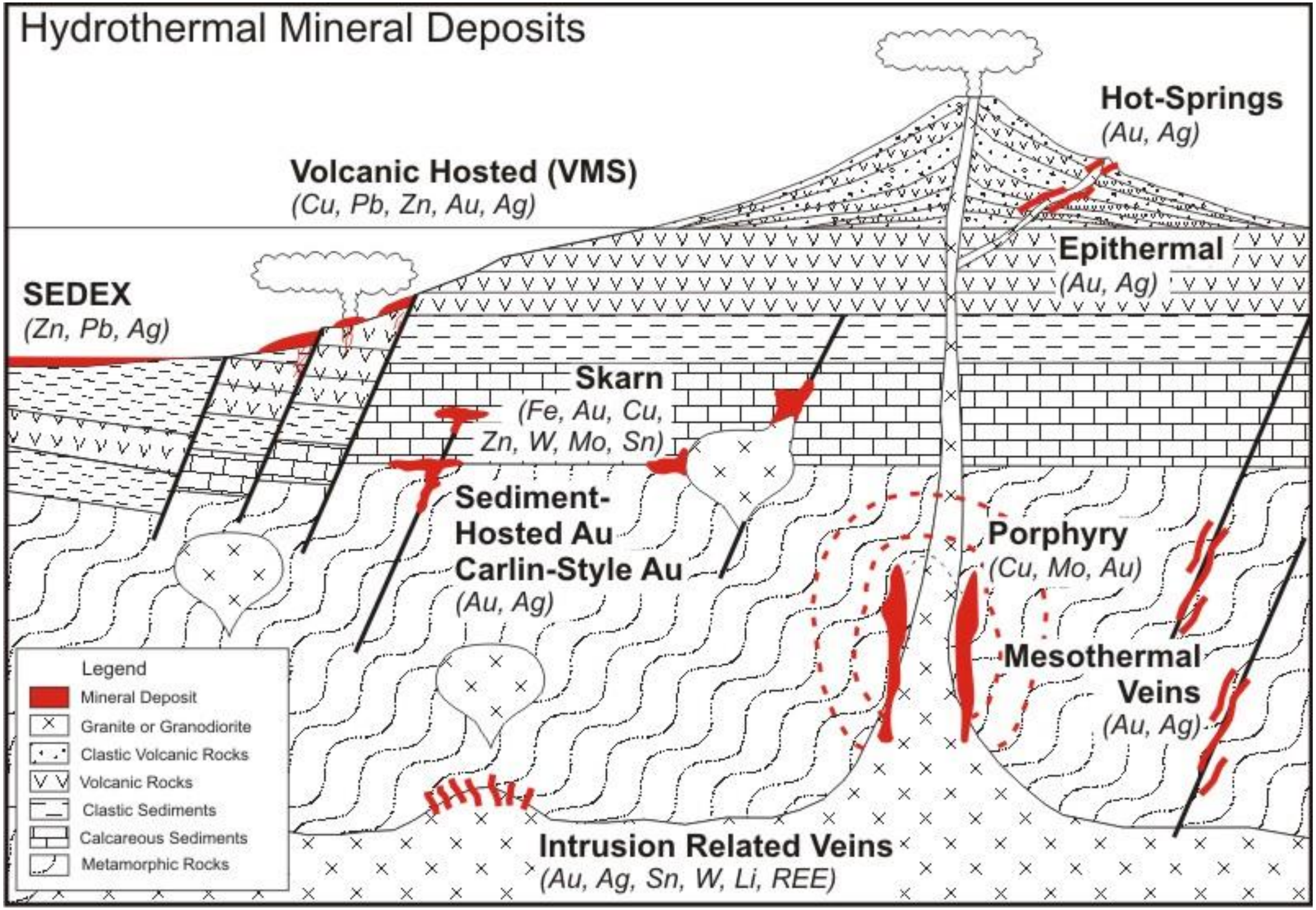
VII. Current understanding of PCDs.

Porphyry copper ore deposits mostly form beneath volcanoes, where magmas derived from a mid- to upper-crustal magma-reservoir intrude into the shallower crust.

Hydrothermal fluids transporting copper and sulfur (as well as other metals) are released from the magma and migrate into the surrounding and shallower crust. As the fluids cool and react with the surrounding rocks, metal-sulfide minerals are deposited and become concentrated in the crust.

Recent research suggests that ore bodies may form during specific fluid-release events and by a combination of different processes (1–5).





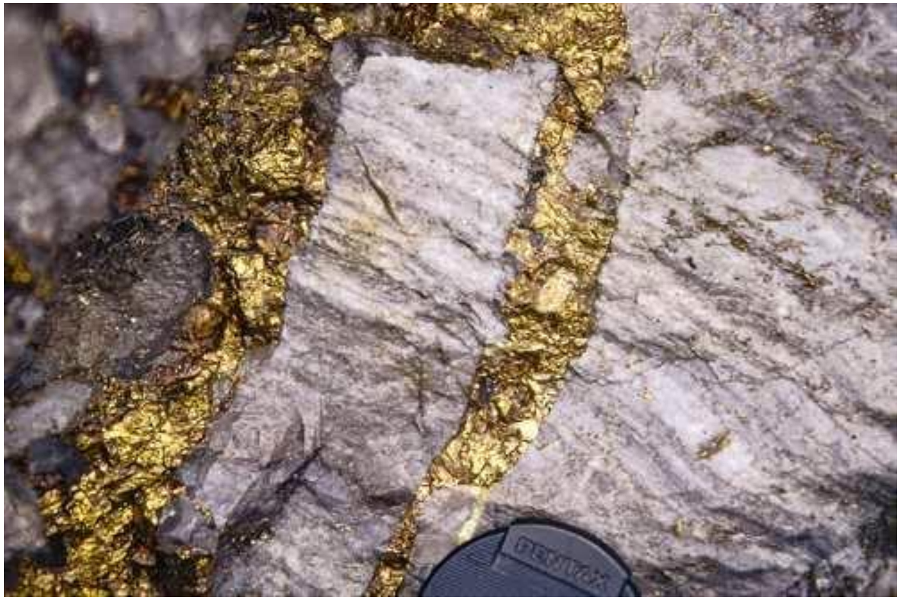
Hydrothermal mineral deposits, are formed by a process involving the dissolution, transportation, and precipitation of metals in "hot" hydrothermal fluids. These deposits can form at or near the earth's surface or they can form deep in the crust and show distinct characteristics based on the depth of formation. Each mineral deposit shows distinct characteristics which are controlled by the characteristics of the mineralizing fluids, the characteristics of the host rocks and the solubility of the elements of interest.

9. Hydrothermal vein deposits

IX. Ore veins were the most important deposit type. More recently, the economic relevance of vein mining decreased compared to large-tonnage low grade operations such as those based on copper porphyries.

Veins are tabular bodies of hydrothermal precipitates that typically occupy fissures. Less often, veins originate by metasomatic replacement of rock (replacement veins). Many veins develop upwards into a fan of thinner veins and veinlets which resemble a branching tree.

Less than 0.5m thickness may allow profitable mining of high-grade gold and silver ore veins, whereas tin and tungsten require a width of 1m, barite and fluorite a minimum of 2m. The world's longest veins may be those of the Mother Lode system of California, with 120km strike length. Most veins, however, have lengths between a few tens to several thousand meters.



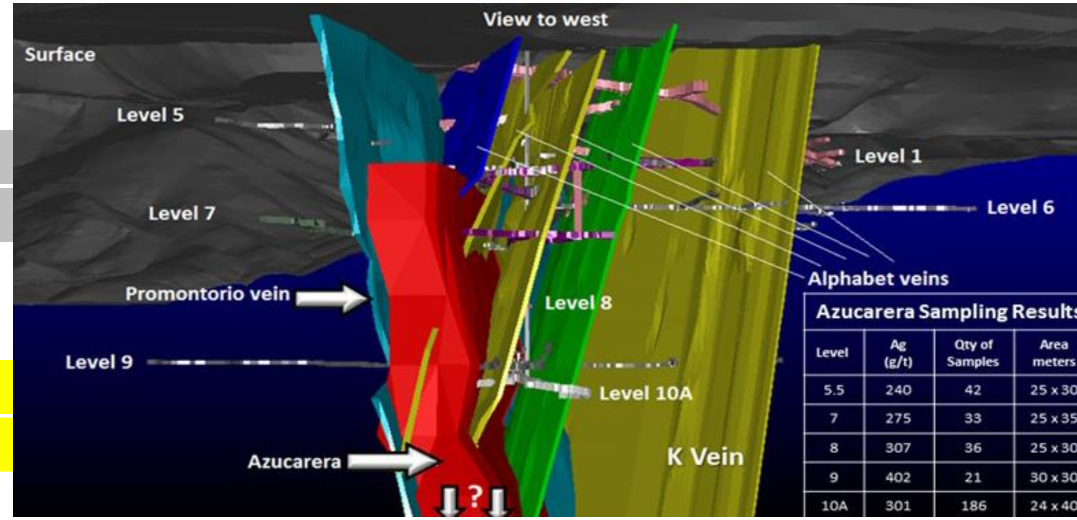
Epidote vein in a granite (unakite). Epidote is a hydrothermal mineral. There is a crack in the middle which allowed the fluids to flow and alter the rock.

Hydrothermal water which is a solvent and a transporter of dissolved metals deposit the minerals in the veins. The source of hydrothermal water is expelled from crystallizing magma, rain water that became ground water, seawater that intruded hot magmatic rocks near the mid-ocean ridges or could be water that was part of hydrous minerals that were metamorphosed to anhydrous phases which liberated the water into the pore space of rocks.

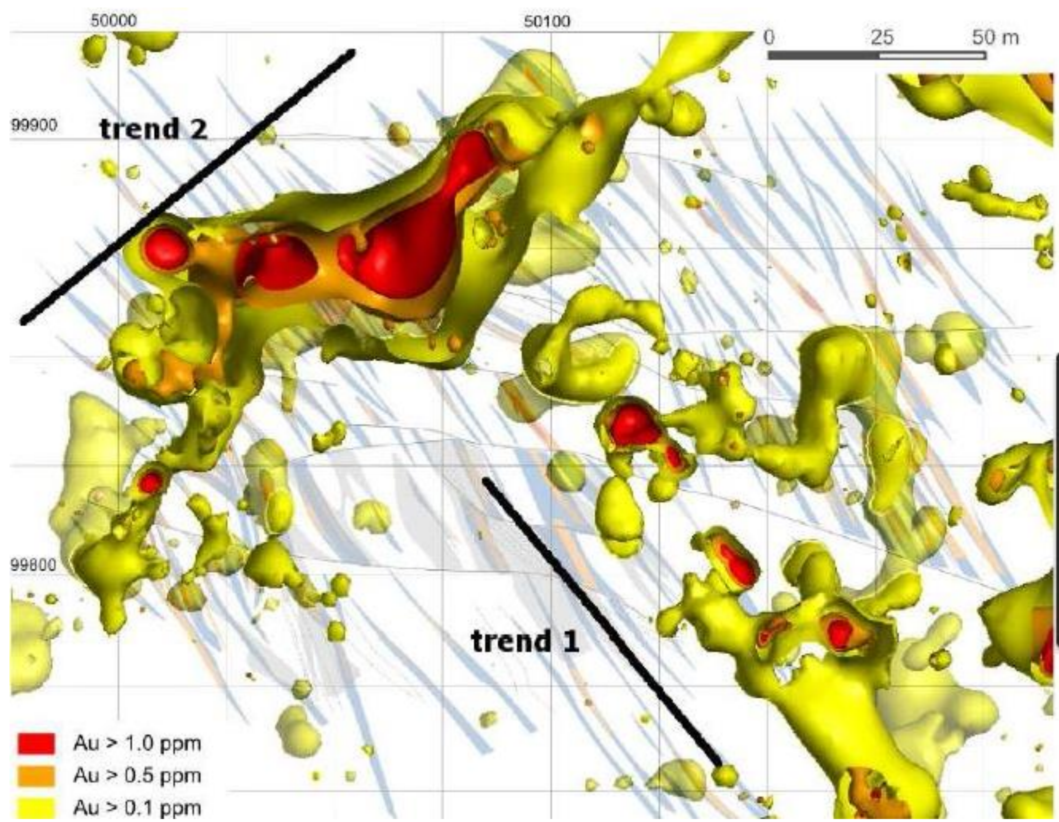
Mechanical properties of host rocks are the most important controls of vein formation, in contrast to metasomatic ore deposits that depend first on chemical properties. Fractures form more readily in competent rocks than in ductile material. Therefore, the cassiterite–quartz (muscovite, arsenopyrite, tourmaline) veins at Rutongo, Rwanda occur preferentially in vitreous quartzites and few cut across low-grade metamorphic schists.

Very brittle rocks such as dolomite, rhyolite and quartzite are prone to form a network of short fractures instead of spatially separated longer ones. In that case, hydrothermal activity may result in stockwork ore. **"Stockwork ore bodies"** consist of numerous short veins of three-dimensional orientation, which are so closely spaced (e.g. 10–30m vein) in the tin deposit of Tongkeng-Changpo, South China) that the whole rock mass can be mined.

Many **vein deposits** are associated with **brecciated rock** bodies that may host rich ore. As a rule, fissures and breccias have **a much higher permeability than most consolidated rocks.**



Perspective View of a Vein



Vein-hosted gold ore body

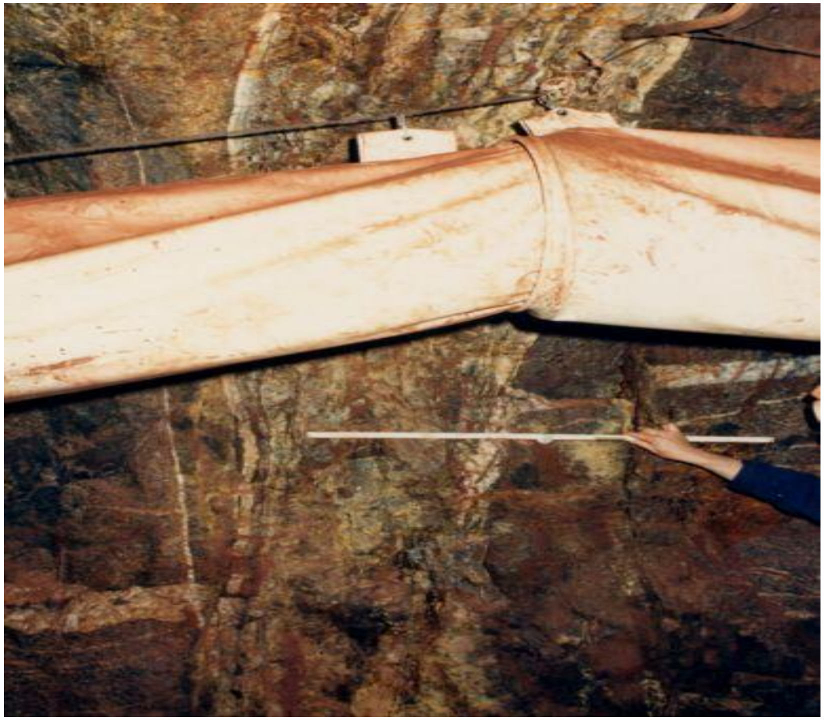
Veins are channels of former fluid flow. Flow in a single fissure is controlled by the fissure aperture and secondary properties such as morphology and roughness of the walls. Many veins display pronounced banding that indicates a correlation between pressure increase of the fluids and precipitation of hydrothermal fill. This is called "seismic pumping" or "fault valve cycling".

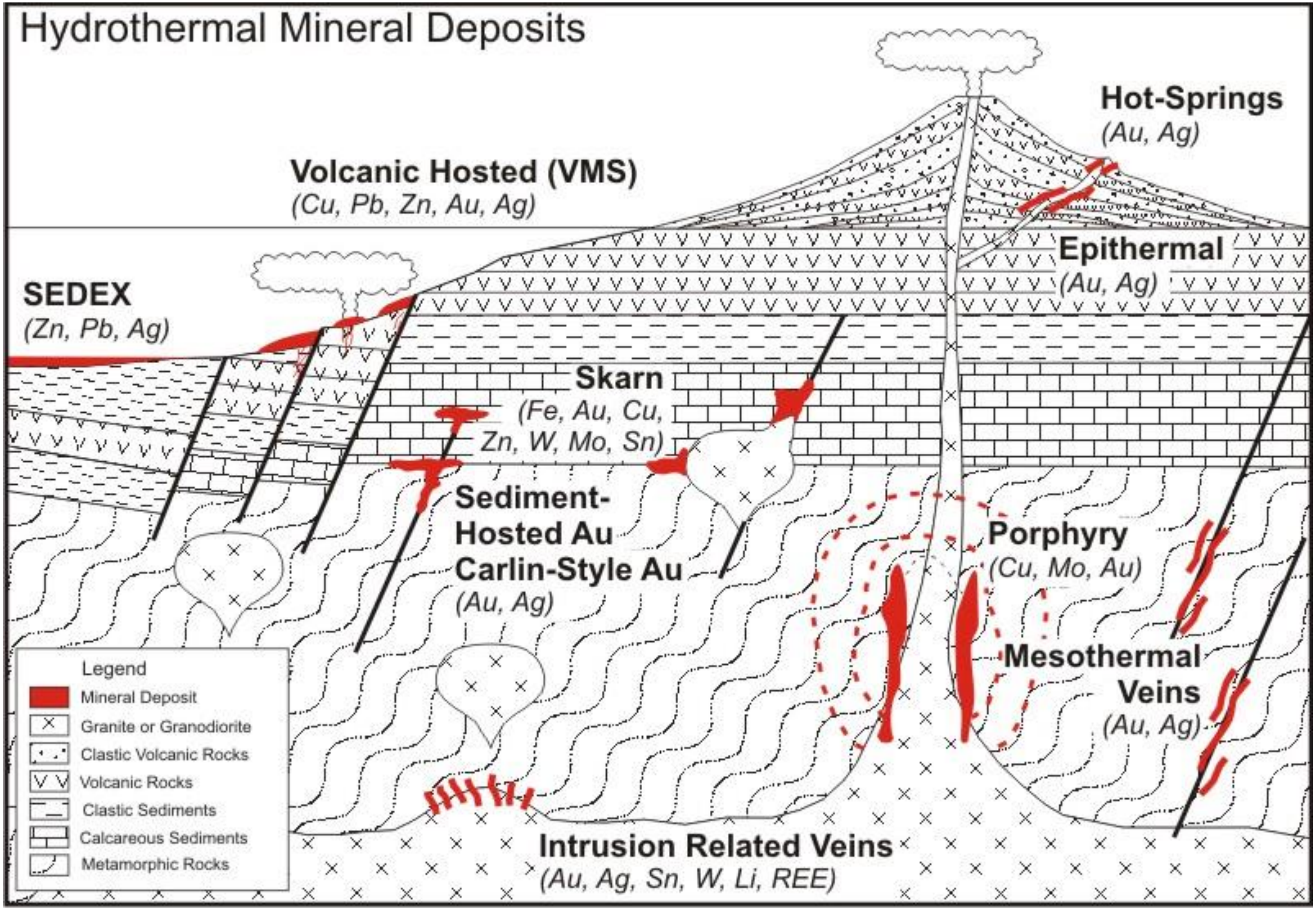
Many veins are associated with large-scale tensional tectonics including rifting (e.g. silver-lead-barite ore veins near the Rhine Rift) and late-orogenic relaxation of orogens (e.g. silver veins near Freiberg, Germany). Veins may also originate during convergent tectonics and folding thrusting (gold quartz veins in Western Australia).

Fissure fill in Carboniferous Limestone, rock armour, east of Watch House, Lepe Beach Hampshire. Red siltstone occupies an extensional brittle fracture system. *Ian West & Tonya West (c) 2006.*

During ore deposit formation, ore shoots (High-grade ore zones) were preferential channels of fluid flow and ore precipitation. Intersections of veins are often enriched, as are vein contacts with agents of metal precipitation in fissures, such as sulphides, organic matter and carbonates. The distribution of ore in veins is inhomogeneous and only a small part of the total vein fill may be exploitable. Related to either surface or volume, the ratio of economic to uneconomic parts of a vein is called the “coefficient of workability” (frequent values are 0.2–0.3).

Hydrothermal ore veins of Cornwall are located in granites. The mineralization is not monophase but the product of several activity periods. Tin, tungsten and much tourmaline are the main ore minerals. Highly saline aqueous fluid inclusions with tin, and cogenetic gaseous inclusions with CO_2 and W, Sn, suggest an origin by unmixing from high-temperature magmatic fluids.





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End of Lecture