

# Porphyry copper systems, zones of oxidation and secondary enrichment

Summary

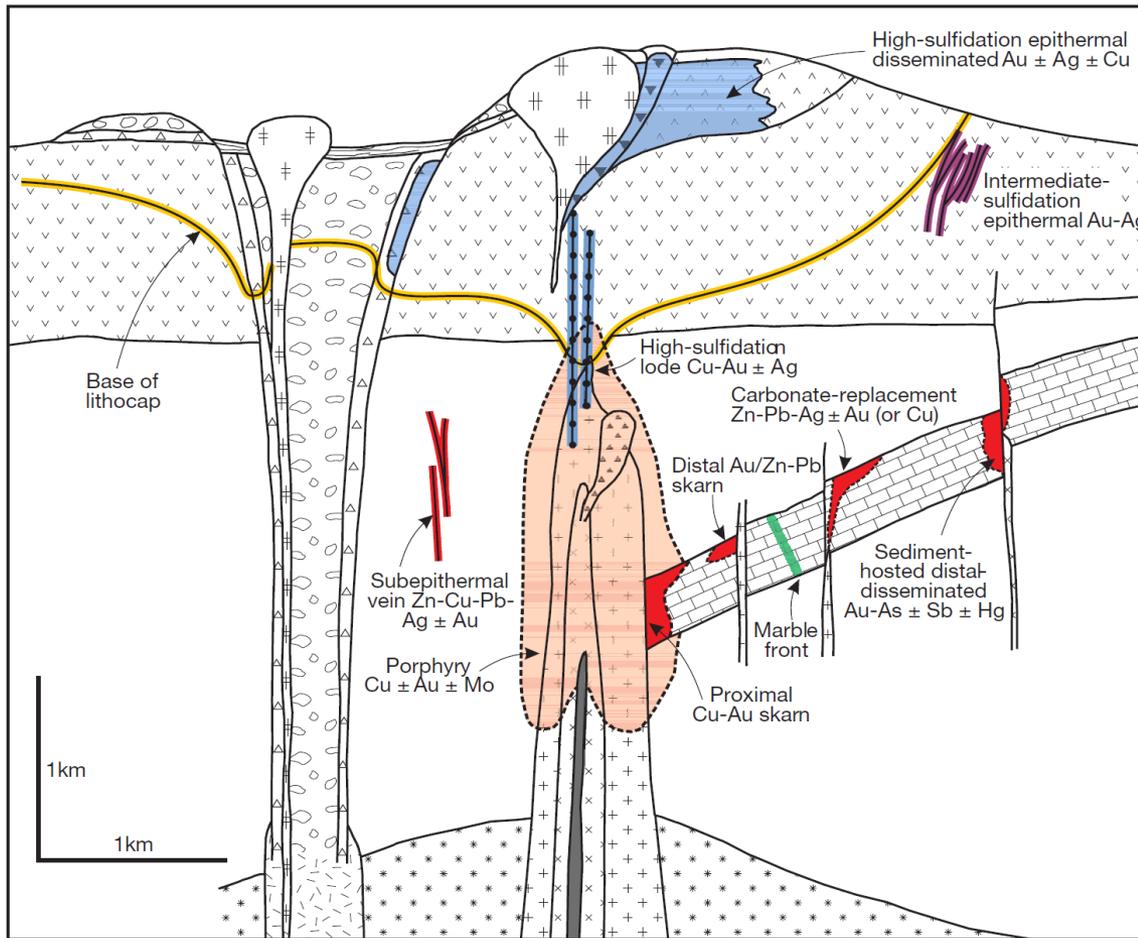
after D. Briggs, D. Sillitoe, M. Barton, et al.

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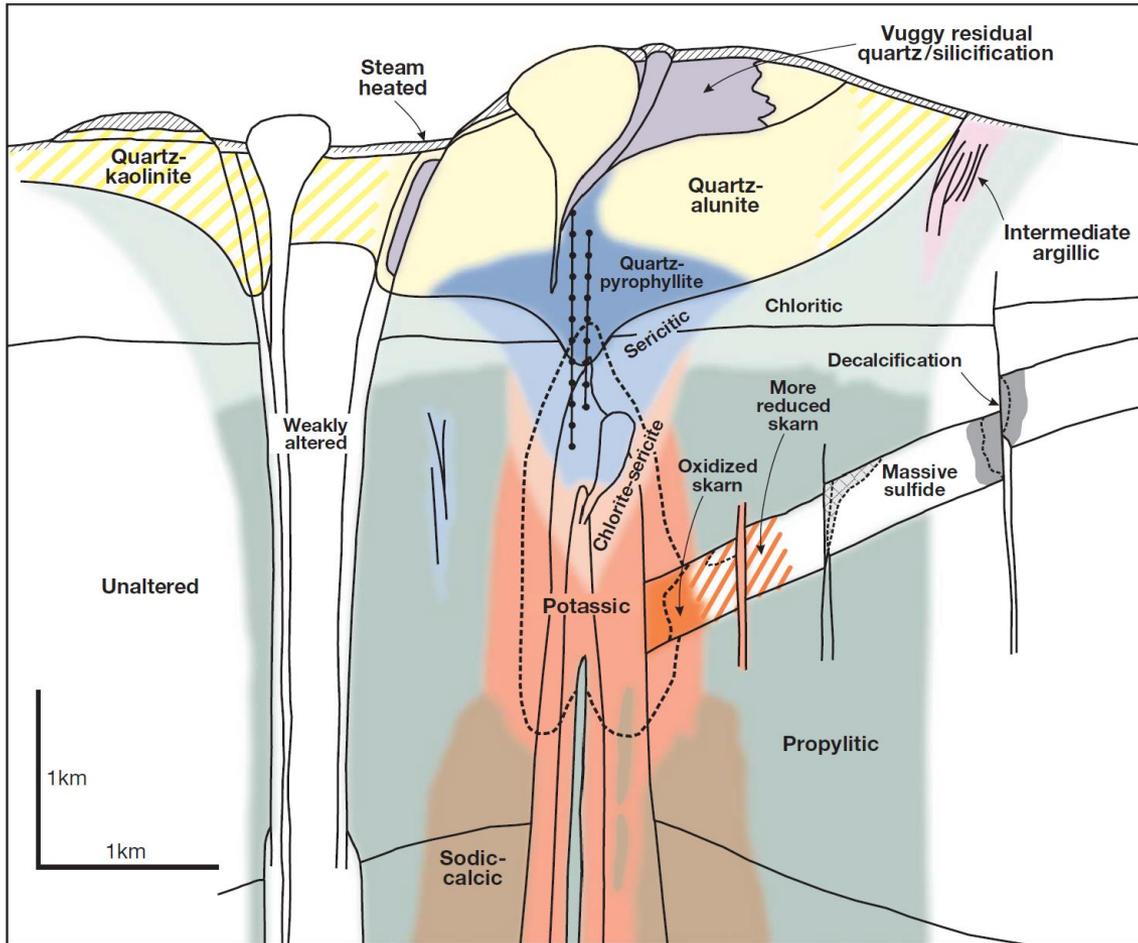
# Introduction

- Mineralization in porphyry systems is usually produced by hydrothermal solutions ascending from cooling subvolcanic intrusives (generalized model in slide 3, after R. Sillitoe, 2010)
- While cooling intrusive rocks crackle creating numerous fractures and joints through which hydrothermal solutions migrate as the system cools off
- These hot hydrothermal solutions traveling through the cracked channels deposit a quartz-sulfide “hypogene” mineralization and cause hydrothermal alteration (slide 4, after R. Sillitoe, 2010) of the host rocks as a porphyry copper deposit is formed
- Once the hypogene cycle is finished the block with the porphyry deposit may be tectonically elevated and exhumed by erosion subjecting the hypogene mineralization to weathering and ground water oxidation
- This triggers a process of “supergene” alteration and formation of mineral assemblages, which are formed during the weathering process (slide 7, after J. Guilbert and C. Park, 1985)

# Generalized model of telescoped porphyry system after R. Sillitoe, 2010



<b>PORPHYRY STOCK</b>		Late-mineral porphyry	<b>LITHOCAP</b>		Phreatic breccia
		Intermineral magmatic-hydrothermal breccia			Dacite porphyry plug-dome
		Intermineral porphyry			Lacustrine sediment
<b>PRECURSOR PLUTON</b>		Early porphyry	<b>MAAR-DIATREME COMPLEX</b>		Late phreatomagmatic breccia
		Equigranular intrusive rock			Early phreatomagmatic breccia
<b>HOST ROCKS</b>		Dacite dome			Late-mineral porphyry
		Felsic tuff unit			
		Andesitic volcanic unit			
		Subvolcanic basement / carbonate horizon			



Generalized model of hydrothermal alterations in porphyry system after R. Sillitoe, 2010

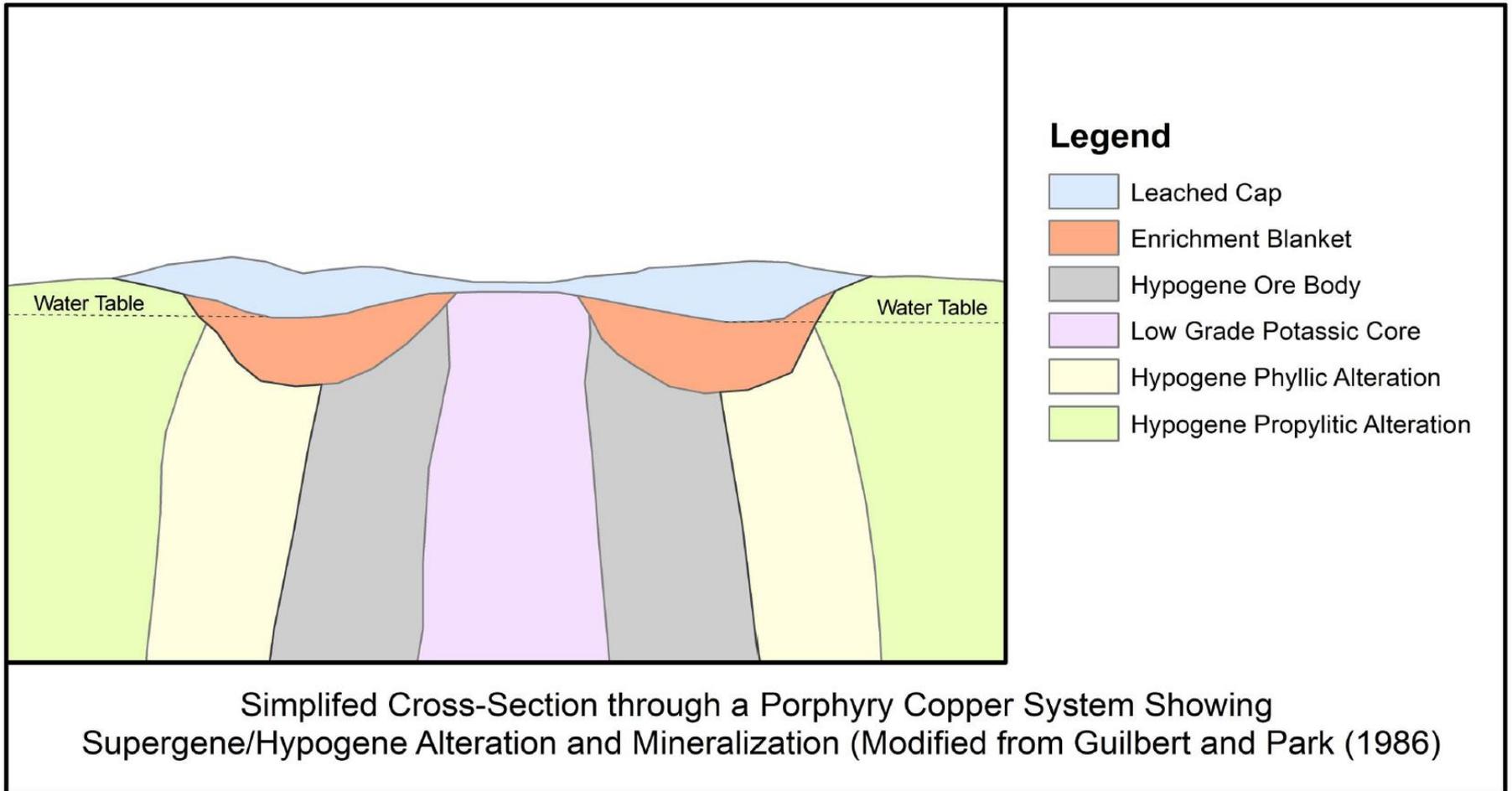
# Porphyry hypogene mineralization and alterations features

- Porphyry deposits occur in clusters forming ore districts with individual intrusives emplaced along major structures
- Metallogenically porphyry deposits are subdivided into Cu-Mo, Cu-Au-Mo, Mo
- Porphyry Cu ± Au ± Mo deposits are centered on the intrusions formed as a result of injection of oxidized magma saturated with S- and metal-rich, aqueous fluids from cupolas on the tops of subjacent parental plutons
- Mineralization and alteration in porphyry systems are zoned outward from the intrusive stocks comprising several generations of intermediate to felsic porphyry intrusions with progressive rock and fluid cooling from above 700° to below 250°C temperatures
- Typical primary (hypogene) alterations and mineralization in porphyry copper systems include low grade potassic core in the center of the system characterized by quartz, potassium feldspar, biotite and anhydrite with minor amounts of sulfide-bearing minerals
- Phyllic alteration assemblages contain quartz and sericite with abundant pyrite and lesser amounts of copper-bearing sulfides
- Chlorite, epidote and calcite with minor amounts of pyrite are typically found in the outer propylitic zone
- Straddling the boundary between the low grade potassic core and the phyllic zone, the primary (hypogene) ore body contains chalcopyrite, bornite, and molybdenite (minor) with minor to moderate amounts of pyrite

# Porphyry supergene features

- Exposed on daylight surface primary sulfide minerals within the rocks of the porphyry system (i.e., pyrite, chalcopyrite, bornite) are oxidized
- During the oxidation process, iron contained in these minerals is transformed into red, reddish brown, orange and yellow colored iron oxides, while the sulfur is combined with groundwater to produce a weak sulfuric acid solution
- These sulfuric acid solutions facilitate the process of destruction of primary sulfide minerals
- Products of oxidation and weathering of sulfide-bearing minerals contained within a porphyry copper system form leached caps and secondary enrichment blankets
- Any copper contained within the rock is dissolved by these acidic solutions, which percolate downward to the water table, where they encounter reducing conditions that allow the copper to precipitate out as chalcocite
- Over time this action forms thick, copper rich, blanket-shaped zone, known as a supergene enrichment blanket (slides 7, 8, 12 and 13)

# Simplified cross-section of eroded porphyry system



# Strongly Oxidized Leached Cap at Bisbee, Arizona



Photo by J. Rasmussen, April 2005

# Porphyry supergene features

- Leached cap and underlying enrichment blanket primarily occur above the primary ore body and phyllic zone due to presence of copper sulfides and the relatively abundant amounts of pyrite (slides 11, 12 and 13)
- Ideally, enrichment requires a sulfide assemblage that contains more pyrite than copper sulfides since pyrite is primary source for acid required for their development
- Moderately to strongly fractured nature of these zones permit movement of supergene solutions downward through these zones
- Leached cap and enrichment blanket are generally thin or absent above the low grade potassic core and propylitic zone due to their low pyrite content and low fracture density
- Presence of abundant calcite (limestone or skarn) is not conducive for development of enrichment blankets due to calcite neutralizing effect on acids forming by oxidation of pyrite contained within these rocks, e.g., absence of well-defined enrichment blanket at the Rosemont deposit in Arizona due to low total sulfide content of ore and presence of abundant calcite in the host rocks

# Porphyry supergene features

- In rocks where the formation of acidic solutions does not occur due to the absence of pyrite or presence of neutralizing agents (i.e., calcite), the copper-bearing sulfides are oxidized in place to form ores containing green and blue copper oxides, like chrysocolla, malachite, azurite, atacamite and brochantite
- Leached cap is typically characterized by strongly oxidized, clay-altered rock, which ranges from 0 to 1,600 feet in thickness
- Iron oxides are common, including hematite (red), goethite (brownish red), limonite (orange) and jarosite (yellow). Little copper remains within the leached cap
- Leached caps overlying many porphyry copper deposits form large, conspicuous color anomalies observed at Red Mountain near Patagonia, Arizona (slide 11)
- This association makes them attractive exploration targets for drilling programs
- Tectonic elevation of copper porphyry systems with oxidation and erosion could result in the several stages of ground water dropping and movement of chalcocite blankets. Each new process results in dissolution of previous blanket and formation of the new one. The more cycles of tectonic uplifts – the richer and thicker chalcocite blankets could form

# Strongly oxidized leach cap in volcanics overlying porphyry copper deposit at Red Mountain, Arizona



Photo by D. Briggs, October 2009

# Chalcocite mineralization from secondary enrichment blanket at Oyu Tolgoi

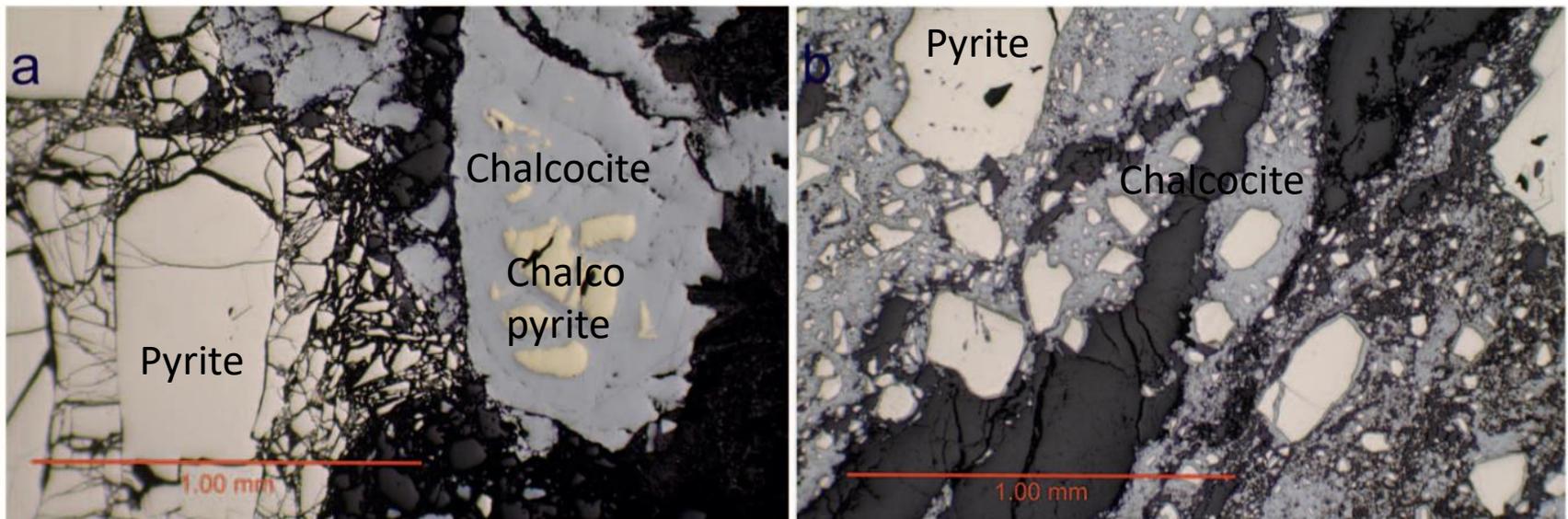


Drillhole OT3

Grey-blue - disseminated chalcocite mineralization, red - hematite

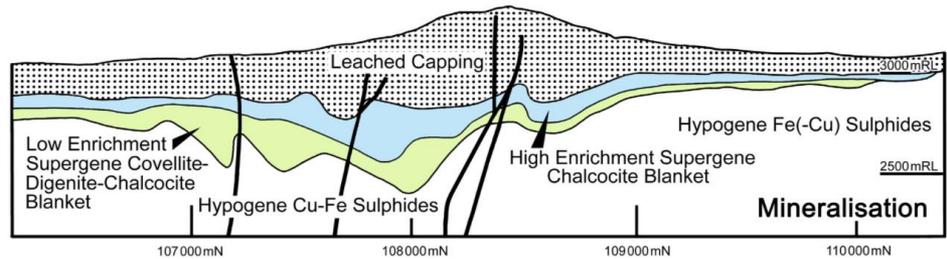
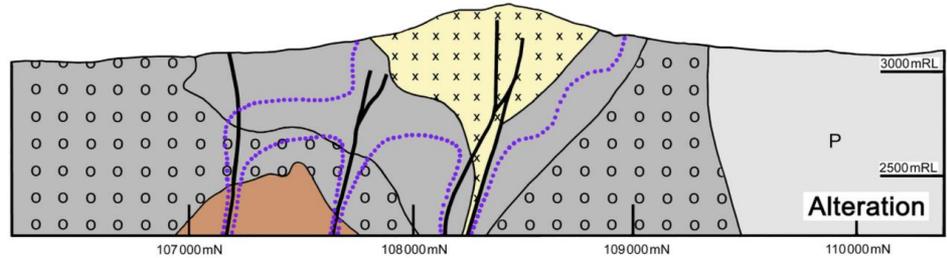
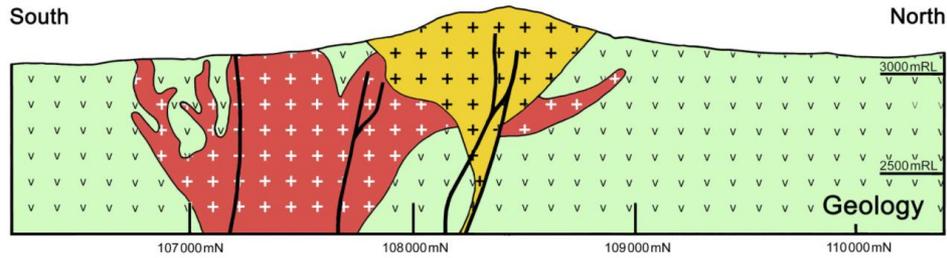
S. Diakov et al, 2018

# Photomicrographs of supergene enrichment over pyrite-chalcopyrite and pyrite assemblages at Morenci, Arizona



# Supergene enrichment blankets

- Enrichment blankets at many porphyry copper deposits form large laterally extensive zones ranging from 200 to 1,000 feet in thickness (up to 2,500 feet at Chuquicamata), generally thin 10 to 100 feet
- Copper content of enrichment blankets generally ranges from two to eight times greater than non-enriched primary sulfide mineralization (0.1 to 0.4% copper)
- Small very high-grade enriched zones, averaging 20% Cu, were mined at Morenci during 1880s
- Enriched sulfide ores are mainly composed of sooty to fine-grained chalcocite that coats and/or replaces pyrite and copper-bearing sulfides
- Much of copper production from the world's major copper provinces in southwestern North America (i.e., Morenci, Ray, Cananea and La Caridad) and northern Chile (i.e., Chuquicamata, Escondida, El Teniente and Los Pelambres) has been derived from the products of oxidation and enrichment



**Geology**

LATE EOCENE - EARLY OLIGOCENE

- + + Colorado Chico rhyolite dome
- + + Escondida Stock - granodiorite porphyry

PALEOCENE - EARLY EOCENE

- v v Augusta Victoria Formation - andesite

Main fault zone



**Alteration**

STAGE - C HYDROTHERMAL ALTERATION

- Envelope surrounding advanced argillic overprint - occurring in veins and as pervasive pyrophyllite-alunite + pyrite-bornite-chalcocopyrite (enargite-chalcocite-covellite-sphalerite-galena).

x x x Rhyolite - only subjected to Stage C alteration

STAGE - B HYDROTHERMAL ALTERATION

  Quartz-Sericite - veins and veinlets + chalcocopyrite-pyrite-molybdenite

o o Sericite-Chlorite - veins and veinlets + chalcocopyrite-pyrite(-molybdenite)

STAGE - A HYDROTHERMAL ALTERATION

  Potassic Alteration - K feldspar - veins & pervasive K feldspar-biotite-anhydrite-chalcocopyrite-bornite

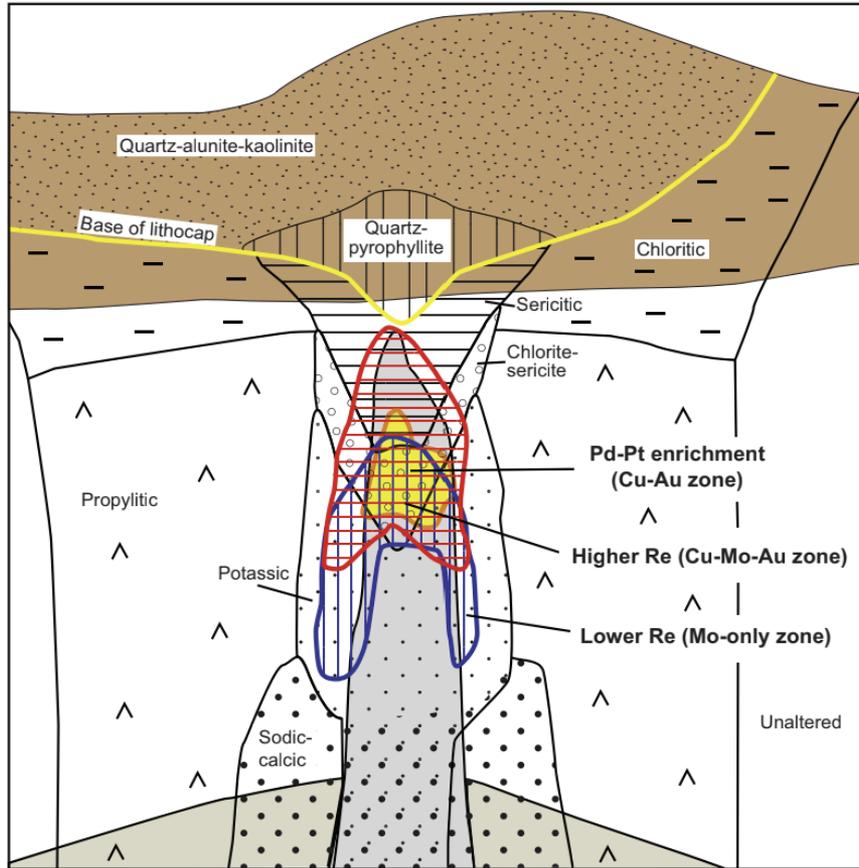
P Propylitic Alteration - pervasive and in veins with epidote-calcite-chlorite-grossularite

Cross-sections of Escondida after R. Padilla, 2001

# Porphyry deposits by-products

- Besides major source of copper, gold, silver and molybdenum metals porphyry deposits also an important source of several by-product elements, including Re, Se, and Te
- About 80% of the Re and nearly all Se and Te produced by mining come from porphyry Cu deposits
- Rhenium is concentrated in molybdenite with Re content varying from 100 to 3,000 ppm in porphyry Cu deposits (see slide 17, d. John, 2016)
- Potential causes of variation in Re content of molybdenites in porphyry deposits are numerous and complex, and this variation is likely the result of combination of processes that may change between and within deposits
- Pd and lesser Pt are recovered from some deposits, PGMs are not strongly enriched in porphyry Cu deposits and PGM resources contained in known porphyry deposits are small
- Other critical commodities, such as In and Nb, may eventually be recovered from porphyry Cu and Mo

Generalized model of alteration and metal zoning in porphyries after D. Sillitoe, 2010 and D. Jones, 2016



Alteration

-  Sodic-calcic
-  Potassic
-  Chlorite-sericite
-  Sericitic
-  Quartz-pyrophyllite
-  Quartz-alunite-kaolinite
-  Propylitic
-  Chloritic

Mineralization

-  Gold
-  Copper
-  Molybdenum

Lithology

-  Intermineral porphyry
-  Precursor pluton
-  Andesitic volcanic rocks
-  Subvolcanic basement

1 km



# List of publications

- D. Briggs, 2014. Supergene Enrichment - How Natural Processes have Transformed Low-Grade Copper Mineralization into Economic Ores, Tucson, 5 p.
- Diakov, S., S. Sanjdorj and G. Jamsrandorj, 2018. Discovery of Oyu Tolgoi. A Case Study of Mineral and Geological Exploration, Elsevier, 241 p.
- Guilbert, J. M., and Park, C. F., 1986. The Geology of Ore Deposits. W. H. Freeman and Company, New York, 985 p.
- John, D., and Taylor, R., 2016. By-Products of Porphyry Copper and Molybdenum Deposits. SEG, Reviews in Economic Geology, v. 18, pp. 137–164
- Padilla, R., Titley, S., Pimentel, F., 2001. Geology of the Escondida Porphyry Copper Deposit, Antofagasta Region, Chile. Economic Geology, v. 96, 2001, pp. 307–324
- Sillitoe, R., 2010. Porphyry Copper Systems. SGE, Economic Geology, v.105, pp. 3-41
- Schumer, P. Barton, M., et al, 2019. Mineralogical Profile of Supergene Sulfide Ore in the Wester Copper Area, Morenci Mine, Arizona. The Canadian Mineralogist, v. 57, pp. 391-401