EARTH 471
Mineral Deposits

Porphyry Deposits

Pophyritic

Igneous rocks that have two dominant grain sizes. Larger crystals are called **phenocrysts** and the finer crystals are called **groundmass**.

http://www.nr.gov.nl.ca/mines&en/geosurvey/education/features/intrusive/

http://pcwww.liv.ac.uk/geo-oer/index_htm_files/3332.png

Porphyry deposits – general points

- Most are genetically related to the intrusion of felsic to intermediate magmas
- Mineralization is structurally controlled (stockworks, veins, breccias)
- Ore may be in the intrusive rocks or in the country rock
- Igneous rocks (usually granites *sensu lato*) are commonly porphyritic but not always!
- Are Earth's major resource of Cu and Mo and a significant resource of Au, Ag and other metals

Porphyry References

Porphyry Deposits

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Abstract

Porphyry deposits are the world's most important source of Cu and Mo, and are major sources of Au, Ag, and Sn; significant byproduct metals include Re, W, In, Pt, Pd, and Se. They account for about 50 to 60% of world Cu production and more than 95% of world Mo production. In Canada, they account for more than 40% of Cu production, virtually all Mo production, and about 10% of Au production. Porphyry deposits are large, low- to medium-grade deposits in which primary (hypogene) ore minerals are dominantly structurally controlled and which are spatially and genetically related to felsic to intermediate porphyritic intrusions. They are distinguished from other granite-related deposits such as skarns and mantos by their large size and structural control, mainly stockworks, veins, vein sets, fractures, and breccias. Porphyry deposits typically contain hundreds of millions of tonnes of ore, although they range in size from tens of millions to billions of tonnes; grades for the different metals vary considerably but generally average less than 1%. In porphyry Cu deposits, for example, Cu grades range from 0.2% to more than 1% Cu; in porphyry Mo deposits, Mo grades range from 0.07% to nearly 0.3% Mo. In porphyry Au and Cu-Au deposits, Au grades range from 0.2 to 2 g/t Au. Associated igneous rocks vary in composition from diorite-granodiorite to high-silica granite; they are typically porphyritic epizonal and mesozonal intrusions, commonly subvolcanic. A close temporal and genetic relationship between magmatic activity and hydrothermal mineralization in porphyry deposits is indicated by the presence of intermineral intrusions and breccias that were emplaced between or during periods of mineralization. Porphyry deposits range in age from Archean to Recent, although most economic deposits are Jurassic or younger.

Résumé

Les gîtes porphyriques constituent, à l'échelle mondiale, la plus importante source de cuivre et de molybdène, une grande source d'or, d'argent et d'étain, de même qu'une source considérable de métaux récupérés comme sous-produits, dont le rhénium, le tungstène, l'indium, le platine, le palladium et le sélénium. En outre, ils comptent pour 50 à 60 % environ de la production mondiale de cuivre et pour plus de 95 % de celle de molybdène. Au Canada, ces proportions atteignent plus de 40 %, dans le cas du cuivre, presque 100 %, dans celui du molybdène et quelque 10 %, dans celui de l'or. Les gisements porphyriques consistent en vastes accumulations de minerai à teneur faible ou moyenne où la répartition des minéraux métalliques primaires (hypogènes) est régie principalement par des contrôles structuraux et liée, tant sur le plan spatial que génétique, à des intrusions porphyriques de composition felsique à intermédiaire. Ils se distinguent des autres gisements apparentés à des granites, comme les skarns et les mantos, par leur grande taille et leurs contrôles structuraux, la minéralisation se présentant surtout dans des stockwerks, des filons, des réseaux de filons, des fractures et des brèches. Ils renferment généralement des centaines de millions de tonnes de minerai, quoique leur volume peut varier de quelques dizaines de millions de tonnes à des milliards de tonnes. Leurs teneurs en métaux varient considérablement mais se situent habituellement en moyenne à moins de 1 %. Par exemple, la teneur en Cu des gisements porphyriques de cuivre va de 0,2 % à plus de 1 %, celle en Mo des gisements porphyriques de molybdène, de 0,07 % à presque 0,3 % et celle en Au des gisements porphyriques d'or et de cuivre-or, de 0,2 à 2 g/t. Les roches ignées qui leur sont associés montrent une composition variant de la diorite-granodiorite au granite fortement siliceux et se présentent en général sous forme d'intrusions à texture porphyrique épizonales et mésozonales, habituellement subvolcaniques. Dans les gîtes porphyriques, la présence de brèches et d'intrusions mises en place entre les zones minéralisées pendant ou entre les périodes de minéralisation témoigne d'un étroit lien temporel et génétique entre le magmatisme et la minéralisation hydrothermale. L'âge des gîtes porphyriques s'étend de l'Archéen à l'Holocène, quoique la plupart des gisements rentables datent du Jurassique ou d'une époque plus récente.

Definition

Porphyry deposits are large, low- to medium-grade deposits in which primary (hypogene) ore minerals are dominantly structurally controlled and which are spatially and genetically related to felsic to intermediate porphyritic intrusions (Kirkham, 1972). The large size and structural control (e.g. veins, vein sets, stockworks, fractures, 'crackled zones', and breccias) serve to distinguish porphyry deposits from a variety of deposits that may be peripherally associated, including skarns, high-temperature mantos, peripheral mesothermal veins, and epithermal precious-metal deposits. Secondary minerals may be developed in supergene-enriched zones in porphyry Cu deposits by weathering of primary sulphides. Such zones typically have significantly higher Cu grades, thereby enhancing the potential for economic exploitation.

The metal content of porphyry deposits is diverse. The following subtypes of porphyry deposits were defined by Kirkham and Sinclair (1995) according to the metals that are essential to the economics of the deposit (metals that are byproducts or potential byproducts are listed in brackets):

Cu (±Au, Mo, Ag, Re, PGE)
Cu-Mo (±Au, Ag)
Cu-Mo-Au (±Ag)
Cu-Au (±Ag, PGE)
Au (±Ag, Cu, Mo)
Mo (±W, Sn)
W-Mo (±Bi, Sn)
Sn (±W, Mo, Ag, Bi, Cu, Zn, In)
Sn-Ag (±W, Cu, Zn, Mo, Bi)
Ag (±Au, Zn, Pb)

Sinclair, W.D., 2007, Porphyry deposits, *in* Goodfellow, W.D., ed., Mineral Deposits of Canada: A Synthesis of Major Deposit-Types, District Metallogeny, the Evolution of Geological Provinces, and Exploration Methods: Geological Association of Canada, Mineral Deposits Division, Special Publication No. 5, p. 223-243.

13.14 Geochemistry of Porphyry Deposits

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13.14.1 Introduction

Porphyry ore deposits are the Earth's major resources of copper, molybdenum, and rhenium (Sillitoe, 2010) and also provide significant amounts of gold, silver, and other metals. Mineralization styles include stockwork veins, hydrothermal breccias, and wall-rock replacements. Porphyry deposits form at depths of approximately 1–6 km below the paleosurface due to magmatic–hydrothermal phenomena associated with the emplacement of intermediate to felsic intrusive complexes (Seedorff et al., 2005). Most porphyry deposits have a spatial, temporal, and genetic association with geodynamic processes at convergent plate margins where hydrous melts are generated in the subarc mantle. These oxidized melts transport metals and volatiles to magma chambers located in the mid to upper crust, where fractional crystallization and volatile exsolution result in porphyry ore formation.

Porphyry deposits are typically classified on the basis of their economic metal endowment (Kesler, 1973). Subtypes include porphyry Cu, Au, Mo, Cu–Mo, Cu–Au, and Cu–Au–Mo. There are also examples of porphyry Sn and porphyry W deposits (Seedorff et al., 2005). Porphyry deposits can also be classified on the basis of the composition of magmatic rocks associated with mineralization. This scheme recognizes three subcategories of calc-alkaline porphyry deposits (low-K, medium-K, and high-K) and two subcategories of alkalic porphyry deposits (silica-saturated and silica-undersaturated; Lang et al., 1995). The alkalic porphyries are exclusively of Cu–Au character, whereas calc-alkaline deposits span the entire spectrum of Cu, Au, and Mo mineralization.

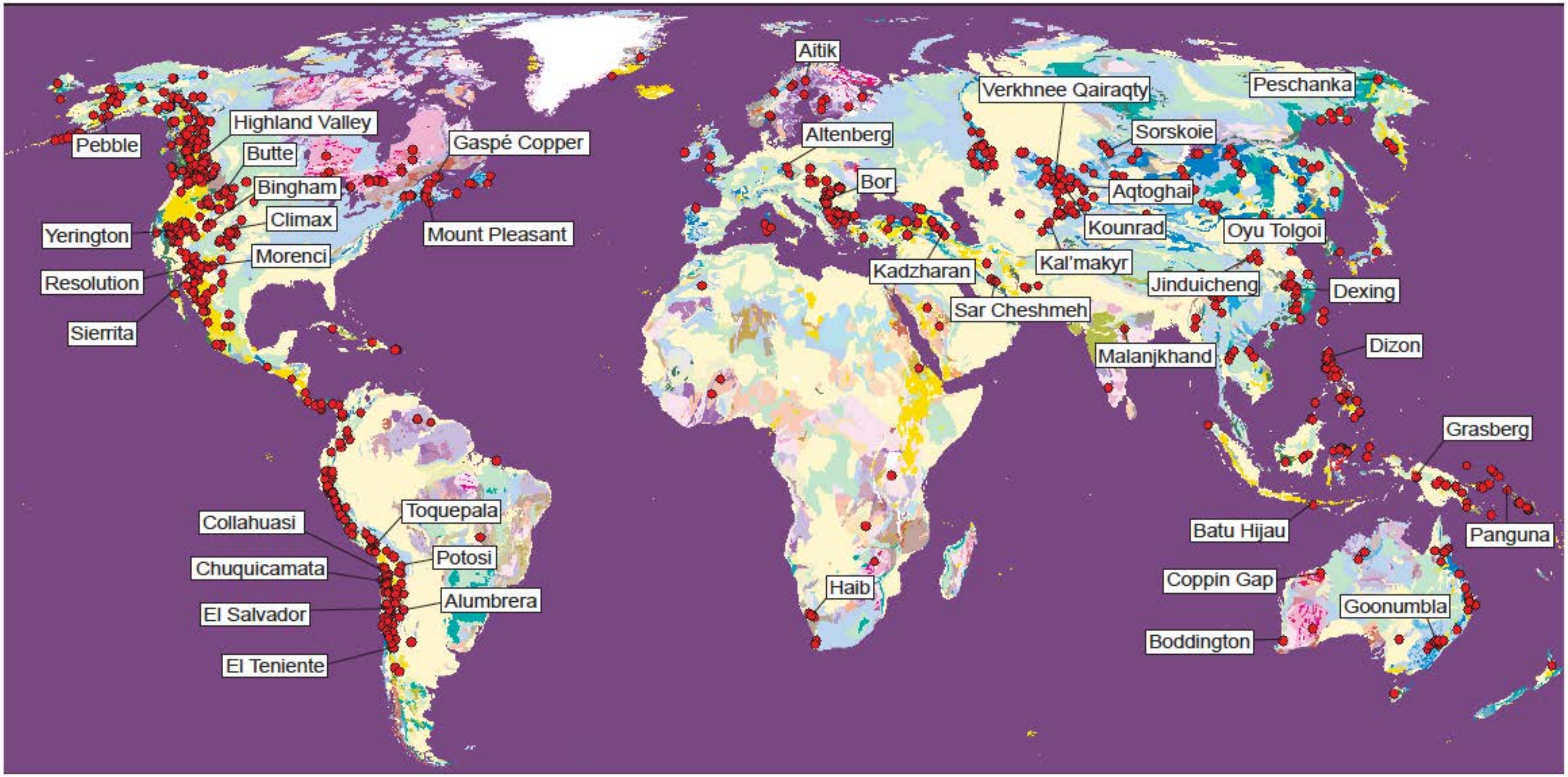
13.14.2 Geology, Alteration, and Mineralization

Porphyry deposits are centered on, or hosted within, multiphase intrusive complexes (Figures 1 and 2(a)). The geometries of individual intrusions vary from pipes ('pencil' porphyries) to dikes, stocks, and, in rare cases, plutons. In some cases, individual intrusive phases have distinctive phenocryst abundances, mineralogies, and grain sizes, making them easy to discriminate (e.g., Bingham Canyon; Redmond and Einaudi, 2010; Figure 2(a)). In other cases, intrusive contacts are more subtle due to similar compositions and textures of the porphyritic rocks (e.g., Lickfold et al., 2003). Sillitoe (2000) outlined field criteria that can be used to locate subtle intrusive contacts in porphyry complexes: (1) abrupt changes in metal assays; (2) veins in the older intrusion that are truncated at the contact with the younger intrusion; (3) xenoliths of older intrusive phases and/or xenoliths containing veins in the younger intrusive phase; (4) less abundant veins, less intense alteration, and greater textural preservation in the younger intrusion; and (5) narrow chilled margins and/or flow alignment of phenocrysts in the younger intrusion.

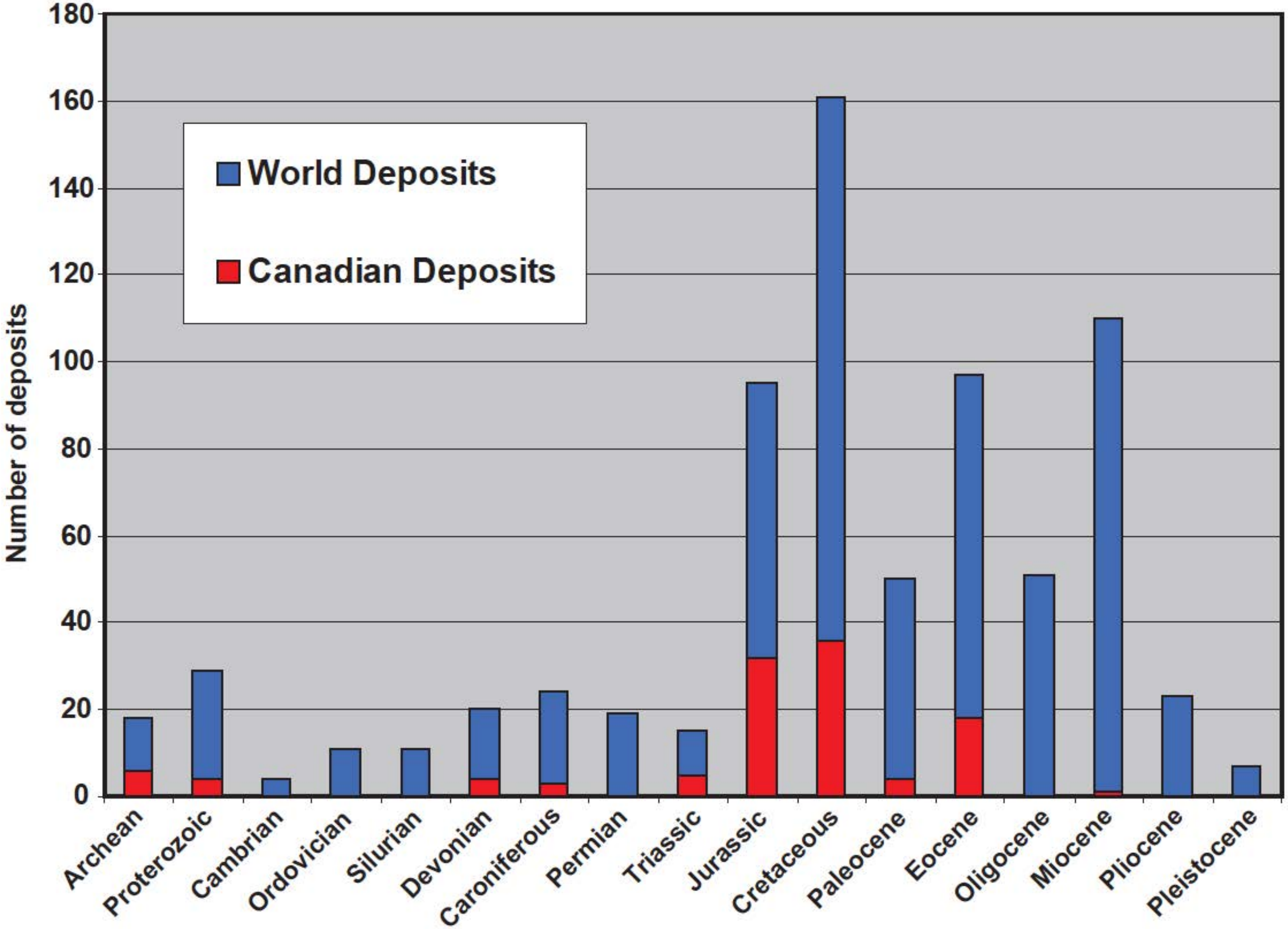
Treatise on Geochemistry 2nd Edition http://dx.doi.org/10.1016/B978-0-08-095975-7.01116-5 357

Worldwide distribution of porphyry deposits

(note their presence along active margins!!)

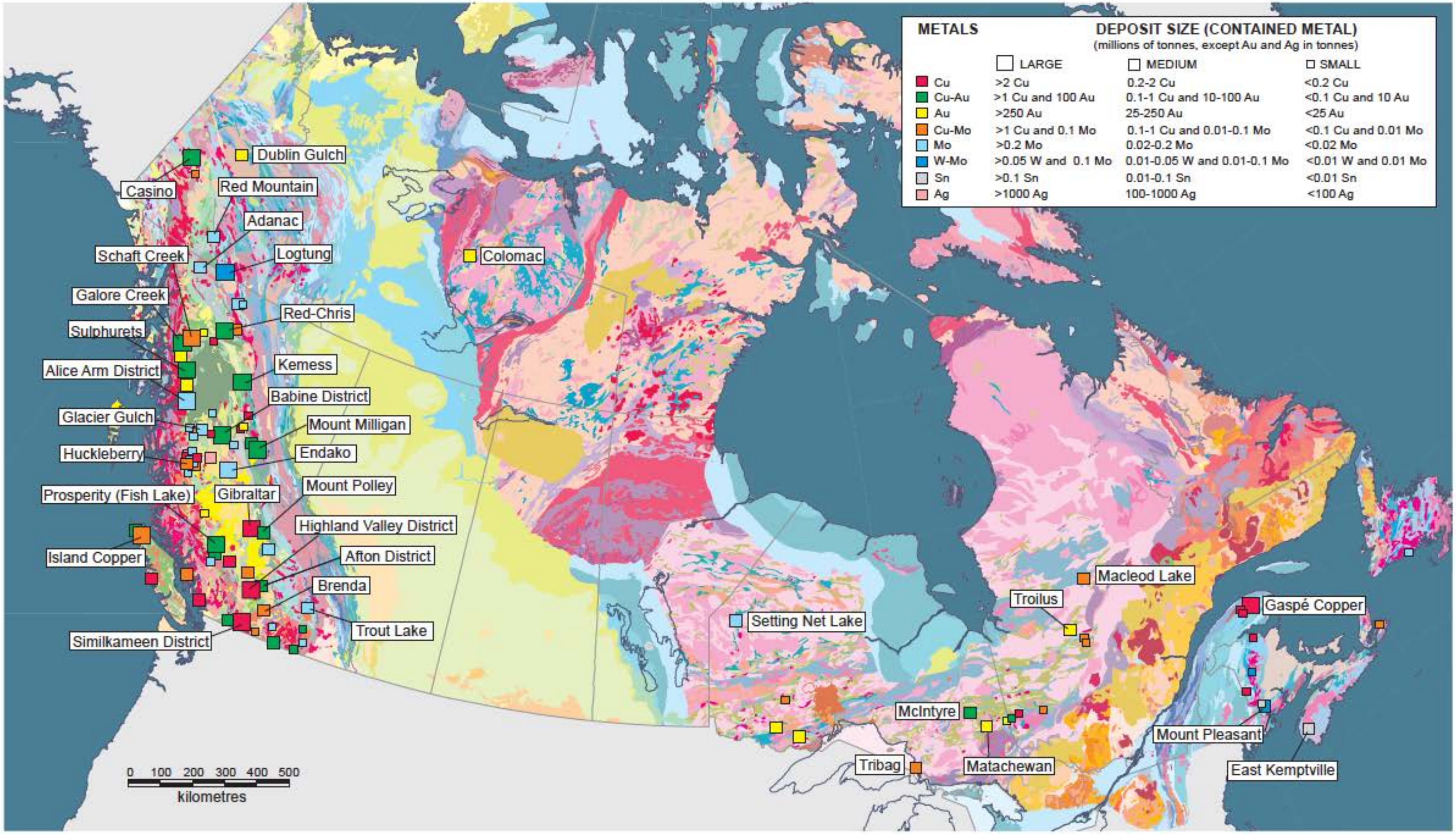


Most porphyry deposits are young – why?



Canadian distribution of porphyry deposits

(note where most are found: along an active margin!!)



Porphyry deposits

Worldwide
- 60–70% of Cu production
- >95% of Mo production

Canada
- 40% of Cu production
- 10% of Au production
- 100% of Mo production

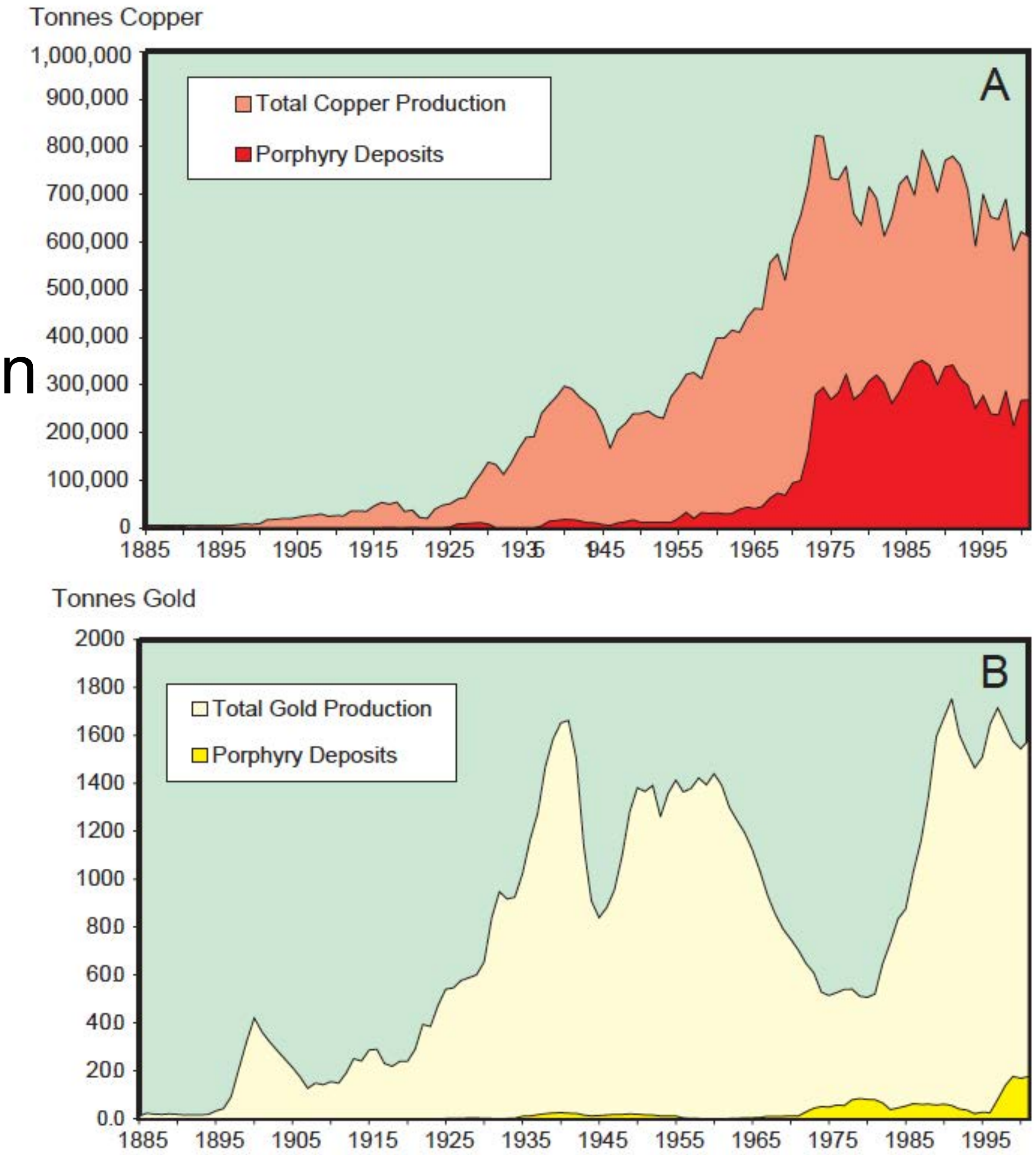


FIGURE 3. Canadian production of copper **(A)** and gold **(B)** between 1885 and 2000. Data are from Natural Resources Canada and Statistics Canada.

Porphyry classification

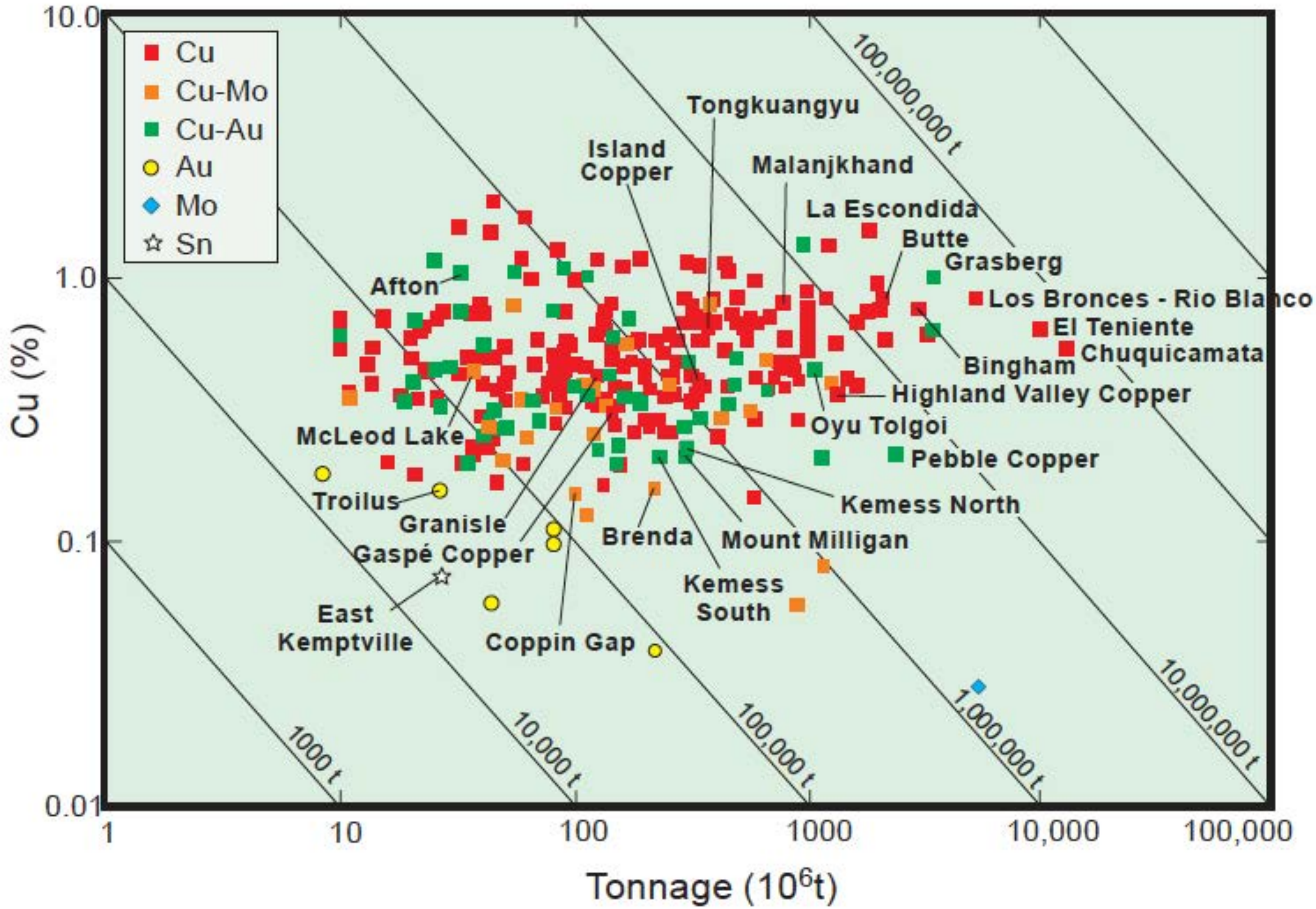
Subtypes defined according to metals that are essential to the economics of the deposit. (Byproducts in brackets).

Cu (±Au, Mo, Ag, Re, PGE)
Cu-Mo (±Au, Ag)
Cu-Mo-Au (±Ag)
Cu-Au (±Ag, PGE)
Au (±Ag, Cu, Mo)
Mo (±W, Sn)
W-Mo (±Bi, Sn)
Sn (±W, Mo, Ag, Bi, Cu, Zn, In)
Sn-Ag (±W, Cu, Zn, Mo, Bi)
Ag (±Au, Zn, Pb)

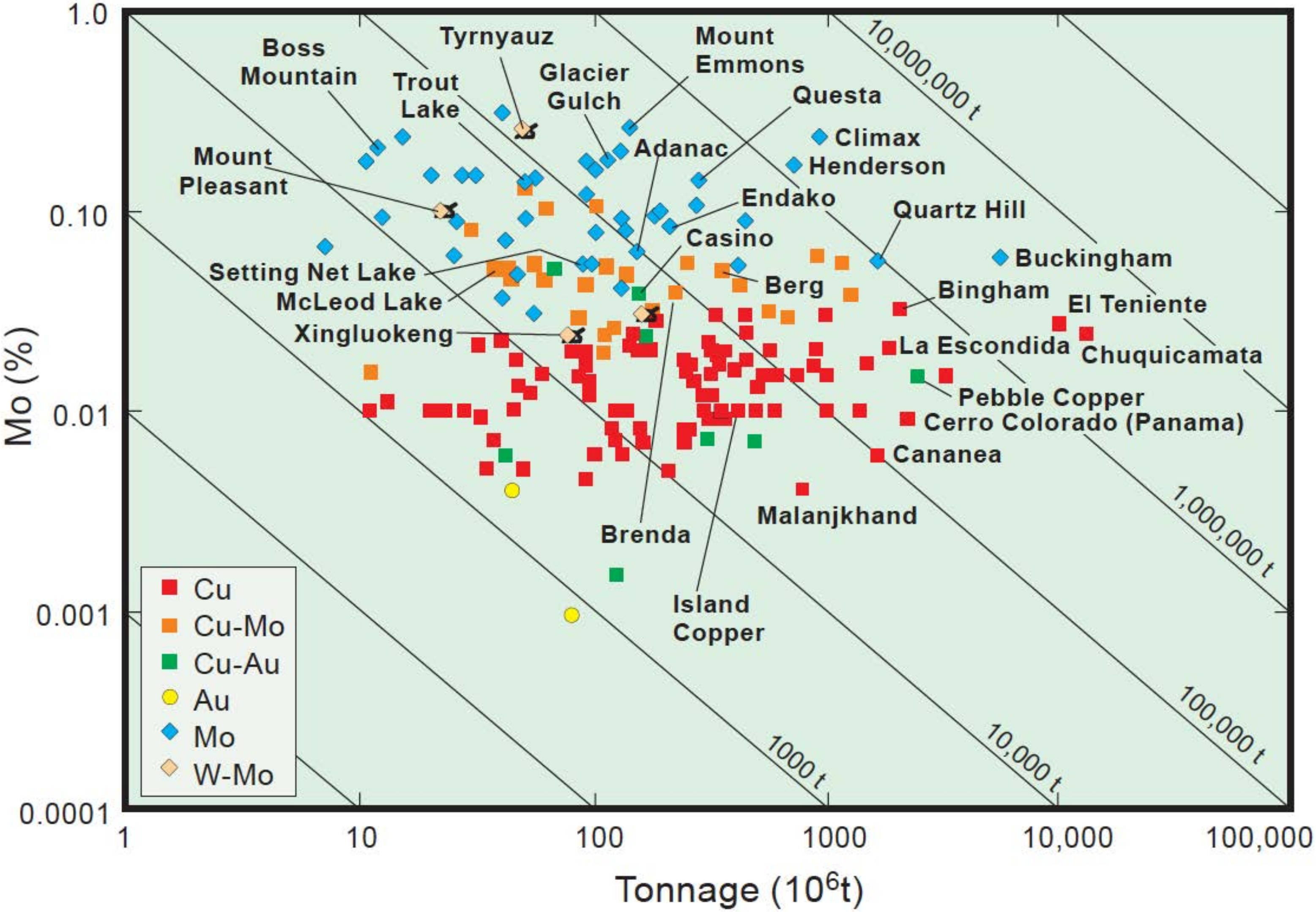
Porphyry grades and tonnage

- Large tonnage (up to 10 Gt) and low grade
- Typical grades:
  - <1% Cu
  - ~0.1% Mo
  - ~1 ppm Au
- Can be polymetallic
- Because of relatively low grade, must be amenable to bulk mining techniques (open pit)

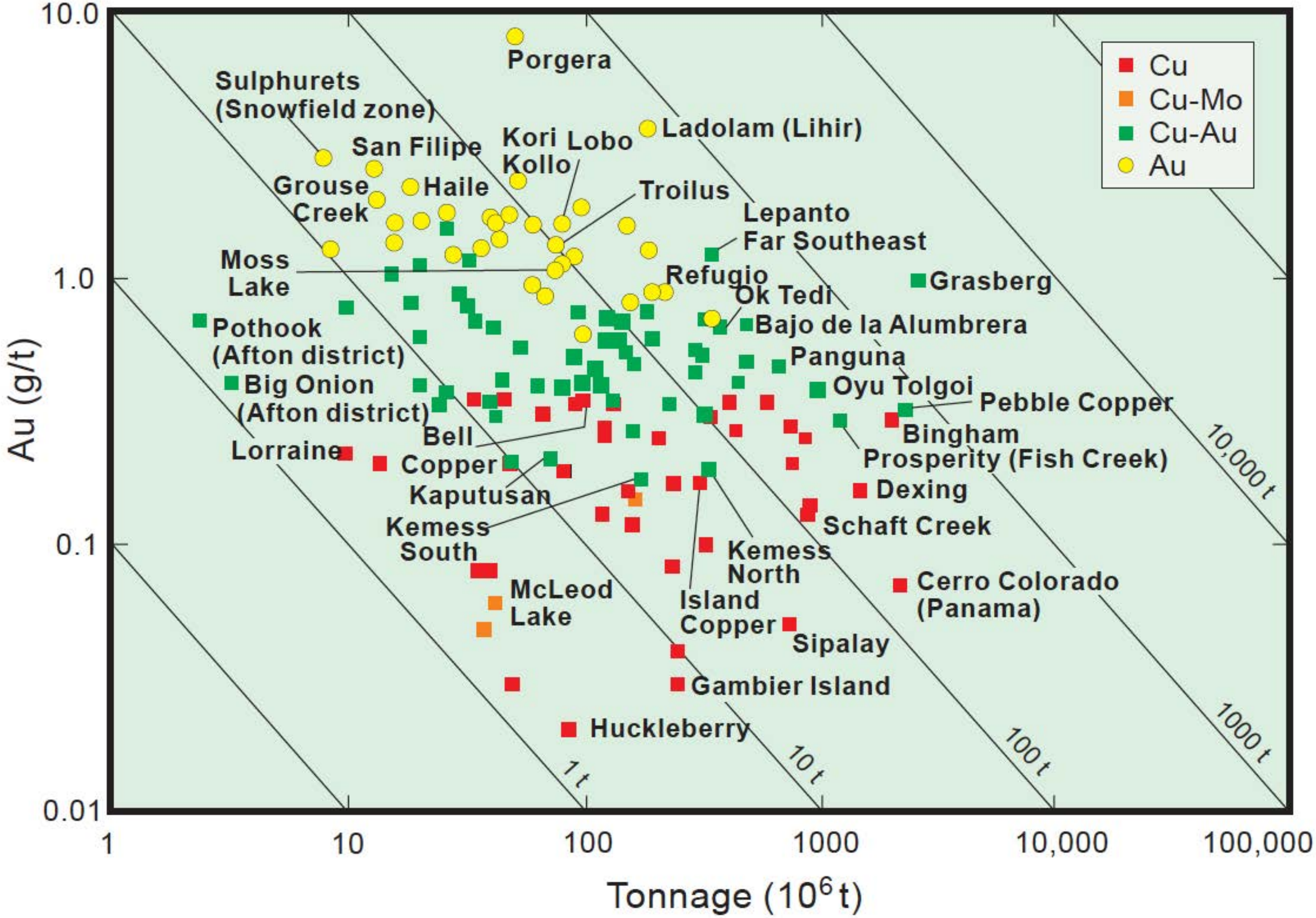
Cu grades


Cu
Cu-Mo
Cu-Au
Au
Mo
Sn
10.0
1.0
0.1
0.01
Cu (%)
1
10
100
1000
10,000
100,000
Tonnage (10^6t)
1000 t
10,000 t
100,000 t
1,000,000 t
10,000,000 t
100,000,000 t
Tongkuangyu
Island Copper
Malanjkhand
La Escondida
Butte
Grasberg
Los Bronces - Rio Blanco
El Teniente
Chuquicamata
Bingham
Highland Valley Copper
Oyu Tolgoi
Pebble Copper
Kemess North
Mount Milligan
Kemess South
Brenda
Coppin Gap
Gaspé Copper
Granisle
Troilus
McLeod Lake
Afton
East Kemptville

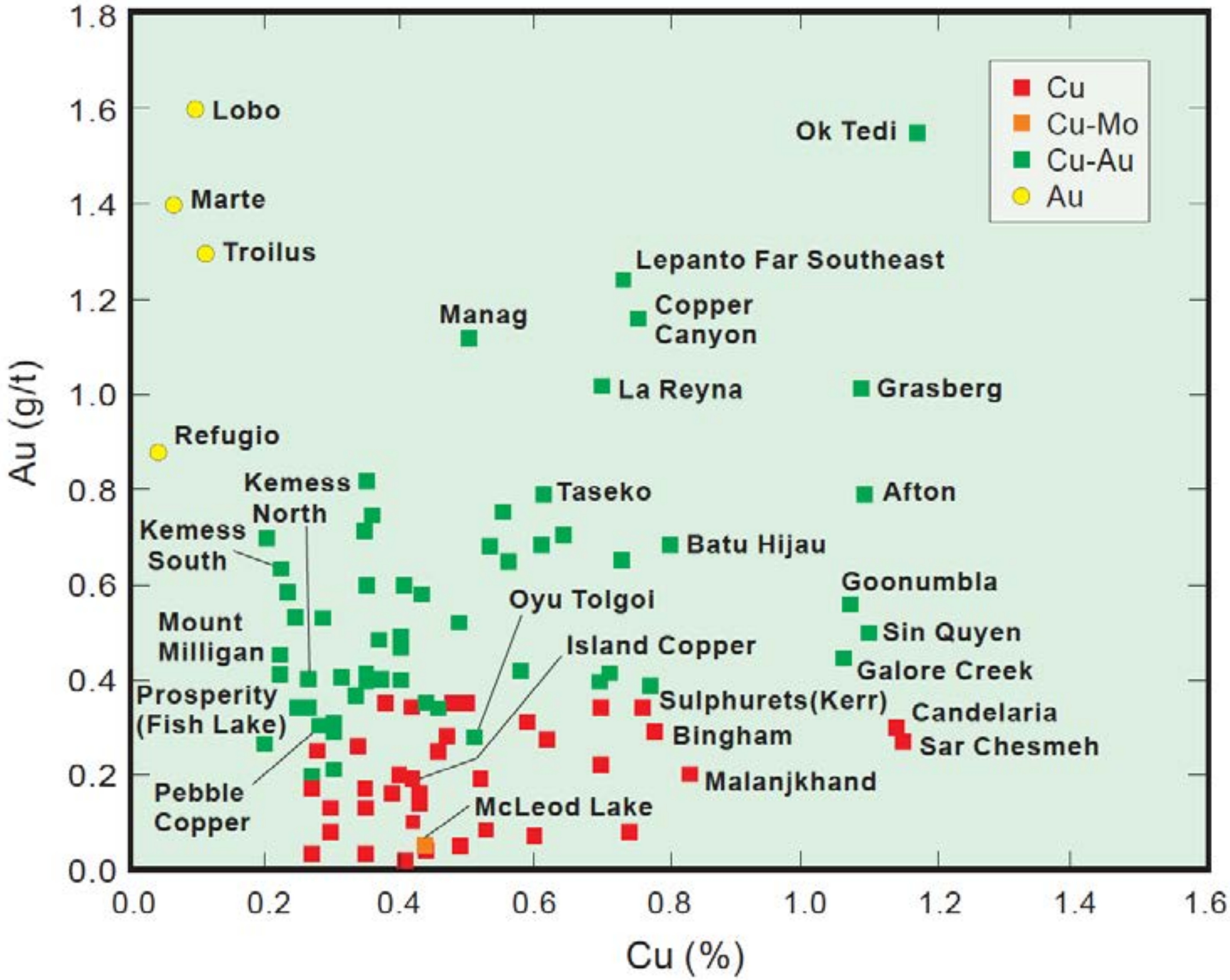
Mo grades


1.0
0.10
0.01
0.001
0.0001
Mo (%)
1
10
100
1000
10,000
100,000
Tonnage (10^6t)
10,000,000 t
1,000,000 t
100,000 t
10,000 t
1000 t
Boss Mountain
Tyrnyauz
Trout Lake
Glacier Gulch
Mount Emmons
Questa
Climax
Henderson
Mount Pleasant
Adanac
Endako
Quartz Hill
Casino
Buckingham
Setting Net Lake
McLeod Lake
Xingluokeng
Berg
Bingham
El Teniente
La Escondida
Chuquicamata
Pebble Copper
Cerro Colorado (Panama)
Cananea
Malanjkhand
Brenda
Island Copper
Cu
Cu-Mo
Cu-Au
Au
Mo
W-Mo

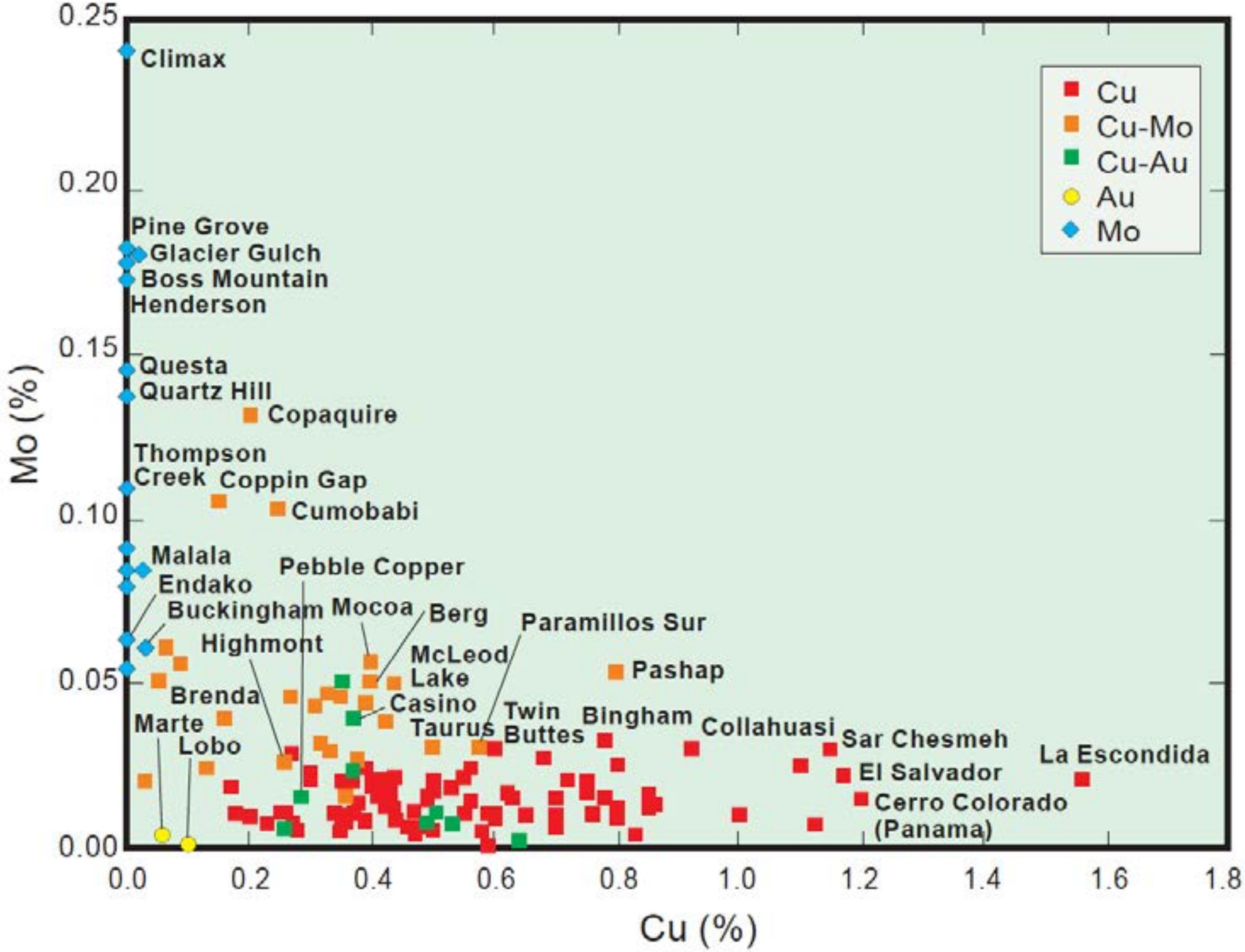
Au grades


10.0
1.0
0.1
0.01
Au (g/t)
1
10
100
1000
10,000
100,000
Tonnage (10^6 t)
Cu
Cu-Mo
Cu-Au
Au
1 t
10 t
100 t
1000 t
10,000 t
Porgera
Sulphurets (Snowfield zone)
San Filipe
Kori Lobo
Kollo
Ladolam (Lihir)
Grouse Creek
Haile
Troilus
Lepanto
Far Southeast
Moss Lake
Refugio
Ok Tedi
Grasberg
Pothook (Afton district)
Bajo de la Alumbrera
Panguna
Big Onion (Afton district)
Oyu Tolgoi
Pebble Copper
Bell
Bingham
Lorraine
Copper
Prosperity (Fish Creek)
Kaputusan
Dexing
Kemess South
Schaft Creek
Kemess North
McLeod Lake
Island Copper
Cerro Colorado (Panama)
Sipalay
Gambier Island
Huckleberry

Au vs Cu

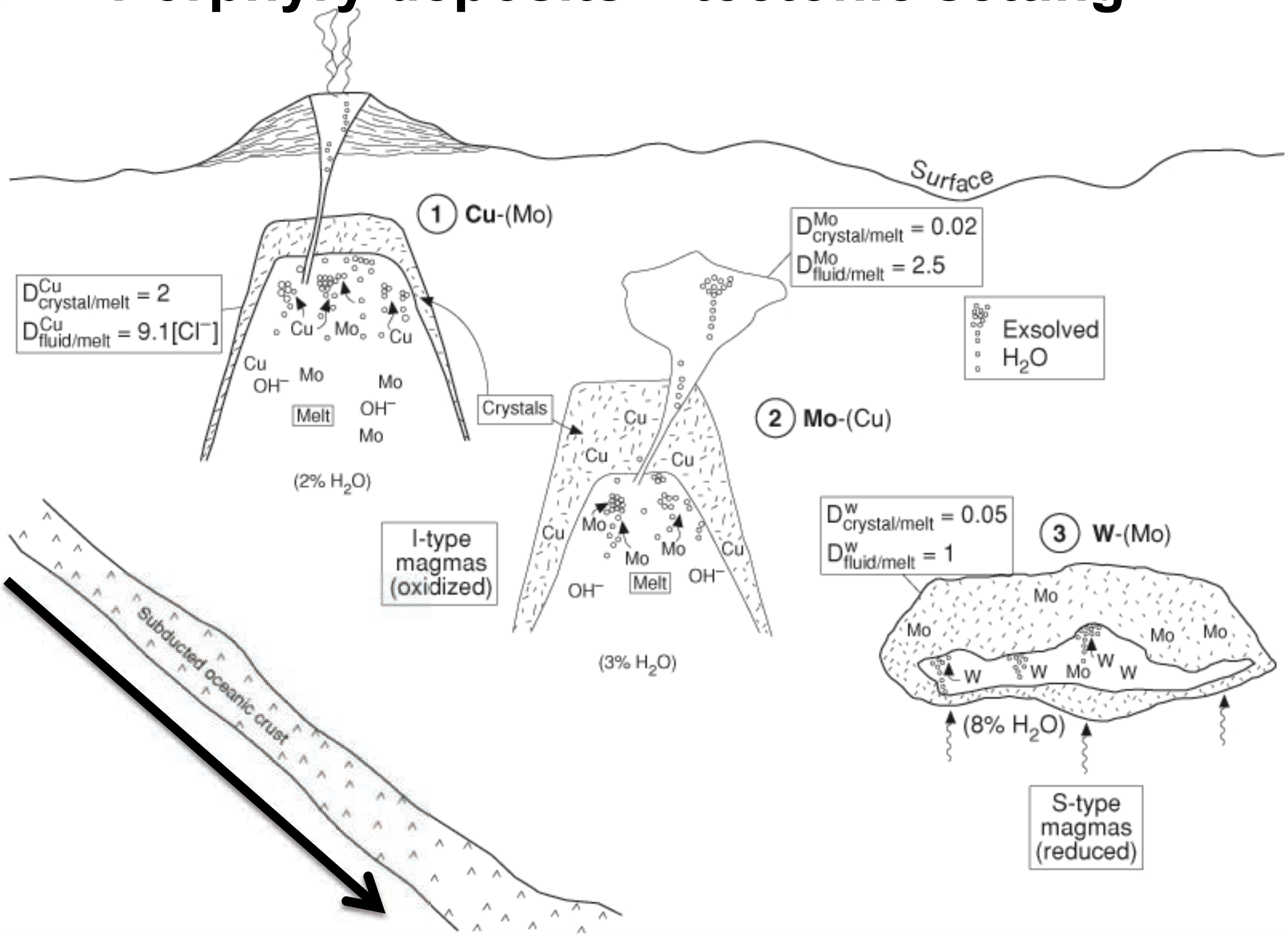

Au (g/t)
Cu (%)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
Cu
Cu-Mo
Cu-Au
Au
Lobo
Marte
Troilus
Refugio
Ok Tedi
Lepanto Far Southeast
Manag
Copper Canyon
La Reyna
Grasberg
Kemess North
Kemess South
Taseko
Afton
Batu Hijau
Goonumbla
Oyu Tolgoi
Mount Milligan
Island Copper
Sin Quyen
Galore Creek
Prosperity (Fish Lake)
Sulphurets(Kerr)
Candelaria
Bingham
Sar Chesmeh
Pebble Copper
Malanjkhand
McLeod Lake

Mo vs Cu



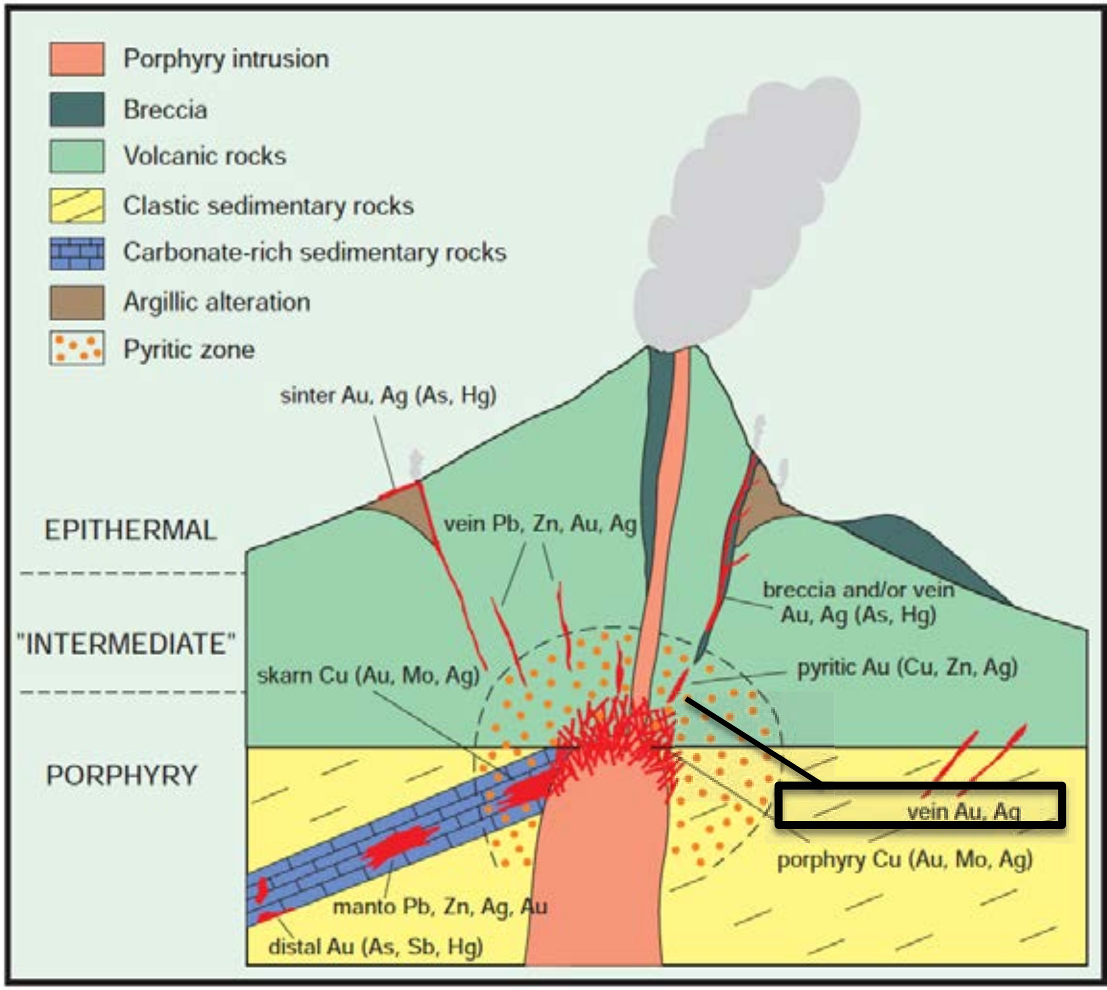
Mo (%)
Cu (%)
0.25
0.20
0.15
0.10
0.05
0.00
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
Cu
Cu-Mo
Cu-Au
Au
Mo
Climax
Pine Grove
Glacier Gulch
Boss Mountain
Henderson
Questa
Quartz Hill
Copaquire
Thompson Creek
Coppin Gap
Cumobabi
Malala
Endako
Pebble Copper
Buckingham
Mocoa
Berg
Paramillos Sur
Highmont
McLeod Lake
Pashap
Brenda
Casino
Marte
Lobo
Taurus
Twin Buttes
Bingham
Collahuasi
Sar Chesmeh
El Salvador
La Escondida
Cerro Colorado (Panama)

Porphyry deposits – tectonic setting



Porphyry deposits – major characteristics

- Associated with intermediate to felsic plutons (52–77 wt% SiO_2)
- Mineralization hosted by a variety of rock types <u>spatially associated with the intrusion</u>
- <u>Multiple intrusion events</u>
- Can often be linked to <u>epithermal</u> deposits at shallower crustal levels
- May be linked to <u>skarn</u> mineralization in surrounding carbonate rocks
- <u>Extensive hydrothermal alteration!</u>



Porphyry deposits – ore

- Ore occurs as: veins, stockwork, breccias and disseminated ore in wall rocks and also in intrusive body
- Important ore minerals: Cu (chalcopyrite, bornite, chalcocite), Mo (molybdenite), Au (native), W (scheelite, wolframite) and Sn (cassiterite)
- Multiple cross-cutting intrusions

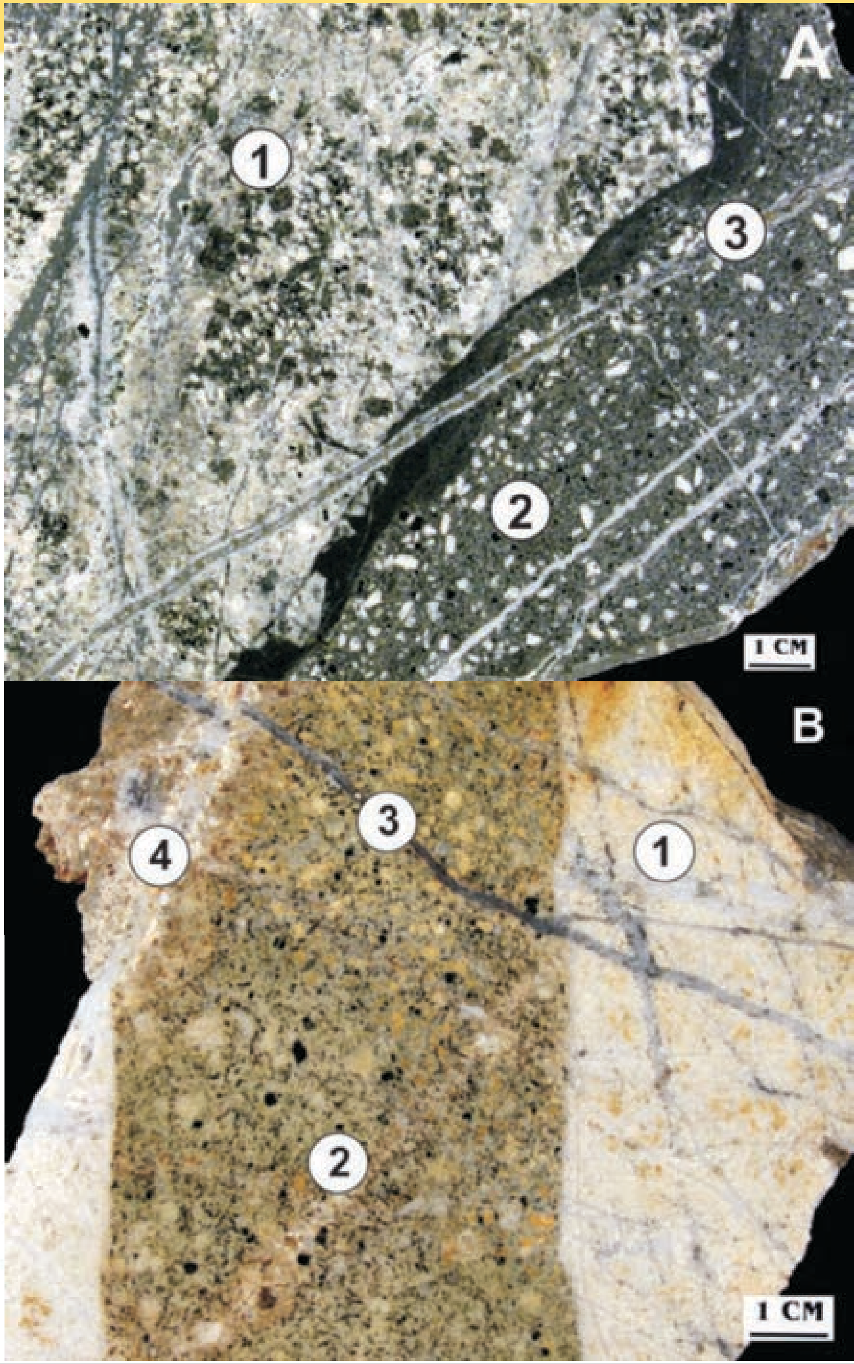
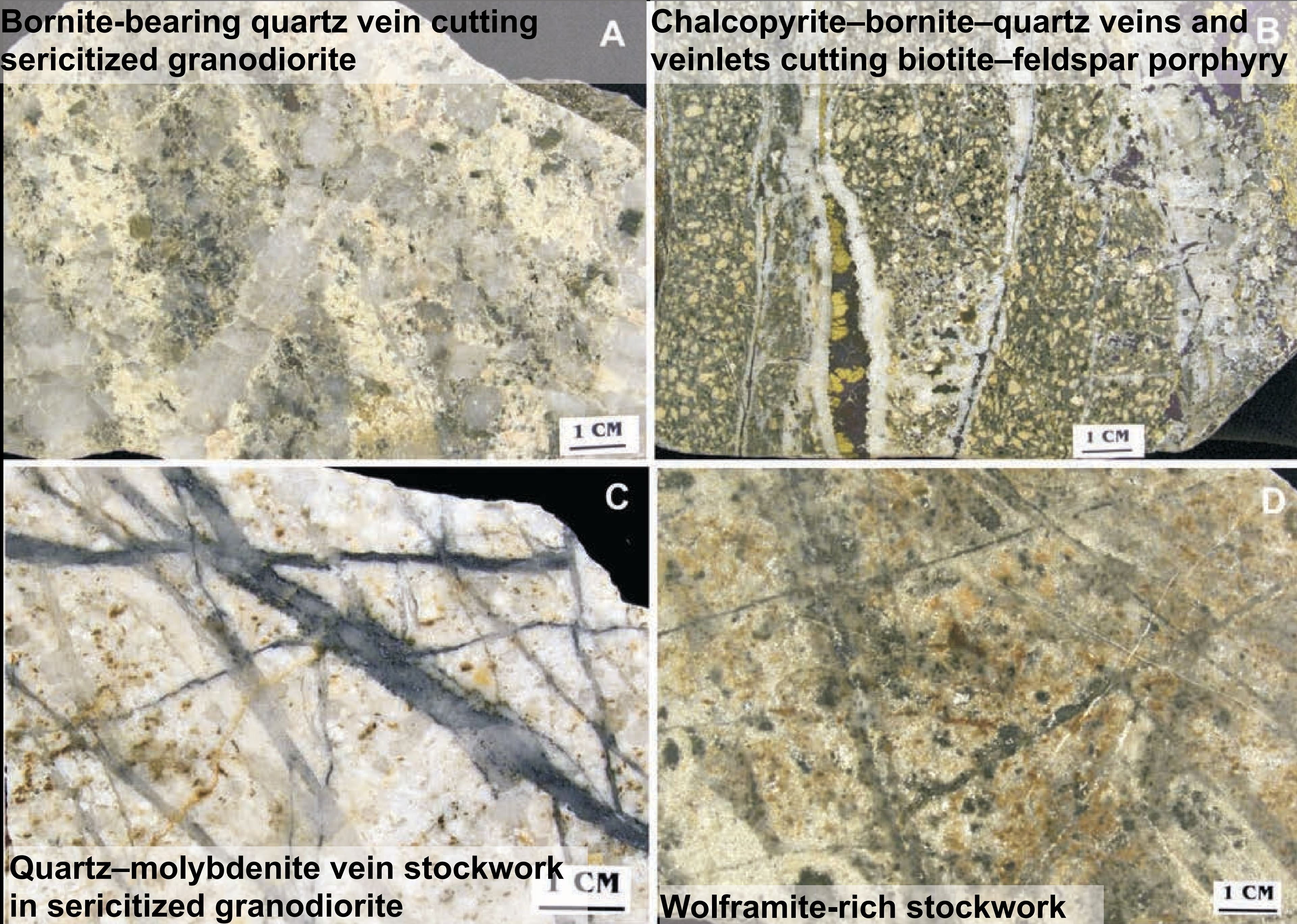
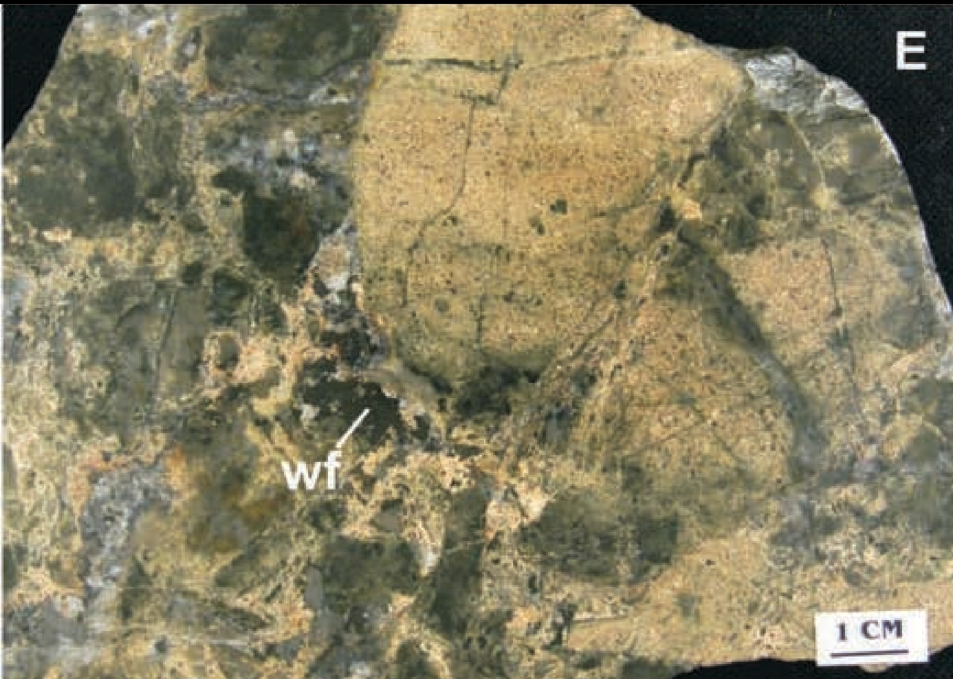
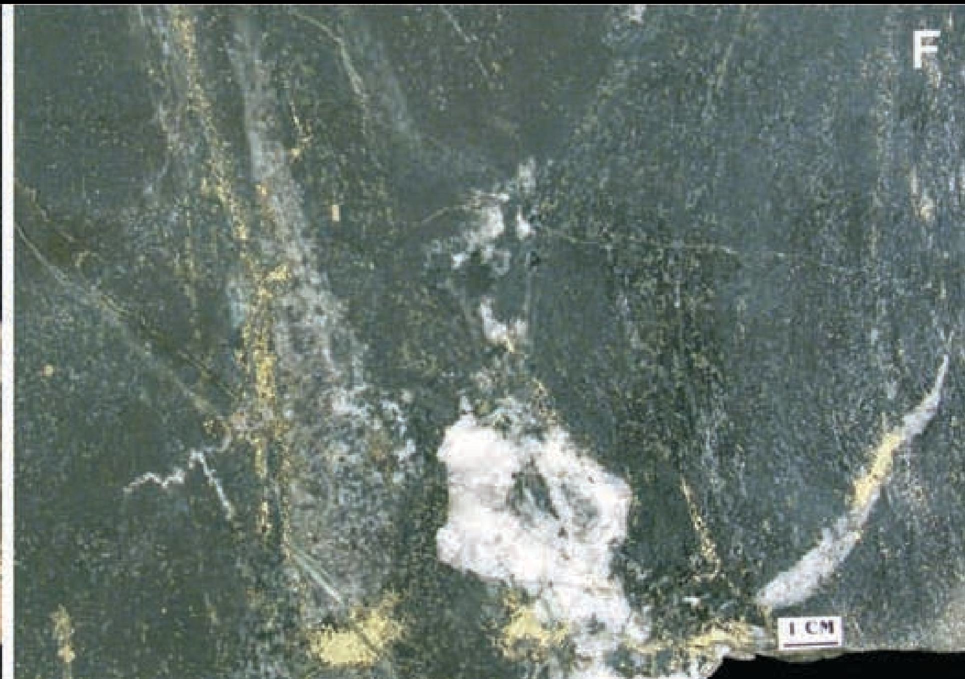


FIGURE 11. Examples of intermineral dykes and breccias associated with porphyry deposits. **(A)** Older porphyry with magnetite and quartz-magnetite veins and associated biotite and K-feldspar (potassic) alteration (1) truncated by an intermineral porphyry dyke with a chilled margin (2); both the older porphyry and the intermineral porphyry are cut by a bornite- and chalcopyrite-bearing quartz vein (3). Granisle Cu deposit, Babine district, British Columbia, GSC 2006-014. **(B)** Quartz-molybdenite veins in altered porphyry (1) terminate at contact of intermineral dyke (2); a younger quartz-molybdenite (3) vein cuts the altered porphyry, earlier veins and the intermineral dyke. A late quartz-base metal vein (4) cuts all other features. Kitsault Mo deposit, Alice Arm district, British Columbia, GSC 2006-013.


Bornite-bearing quartz vein cutting sericitized granodiorite
A
1 CM
Chalcopyrite–bornite–quartz veins and veinlets cutting biotite–feldspar porphyry
B
1 CM
C
Quartz–molybdenite vein stockwork in sericitized granodiorite
1 CM
D
Wolframite-rich stockwork
1 CM



Wolframite (wf)-bearing fractures in granite breccia



Chalcopyrite: disseminated and in quartz veins

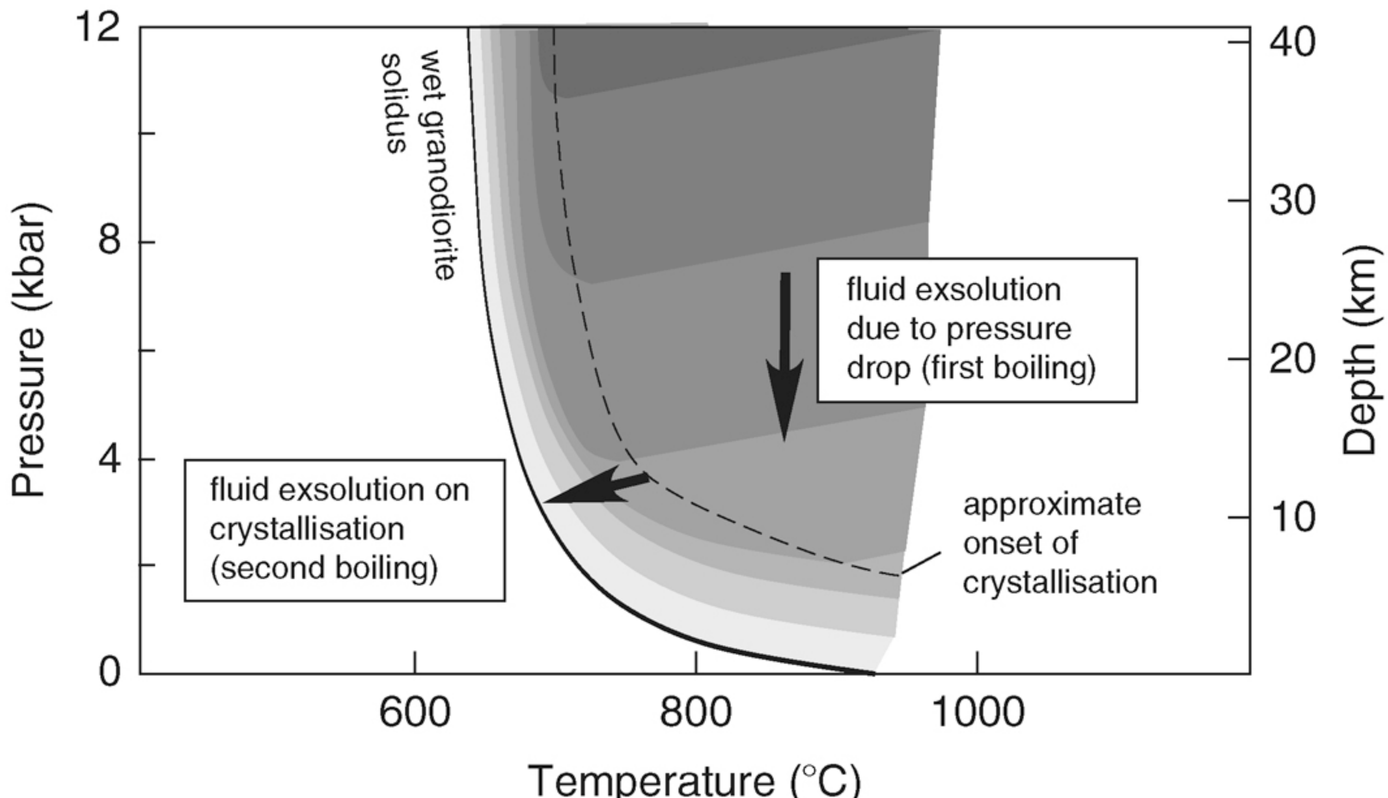
Boiling – a reminder

First boiling:

- Caused by a drop in pressure
- Generally associated with an ascending shallow magma

Second boiling:

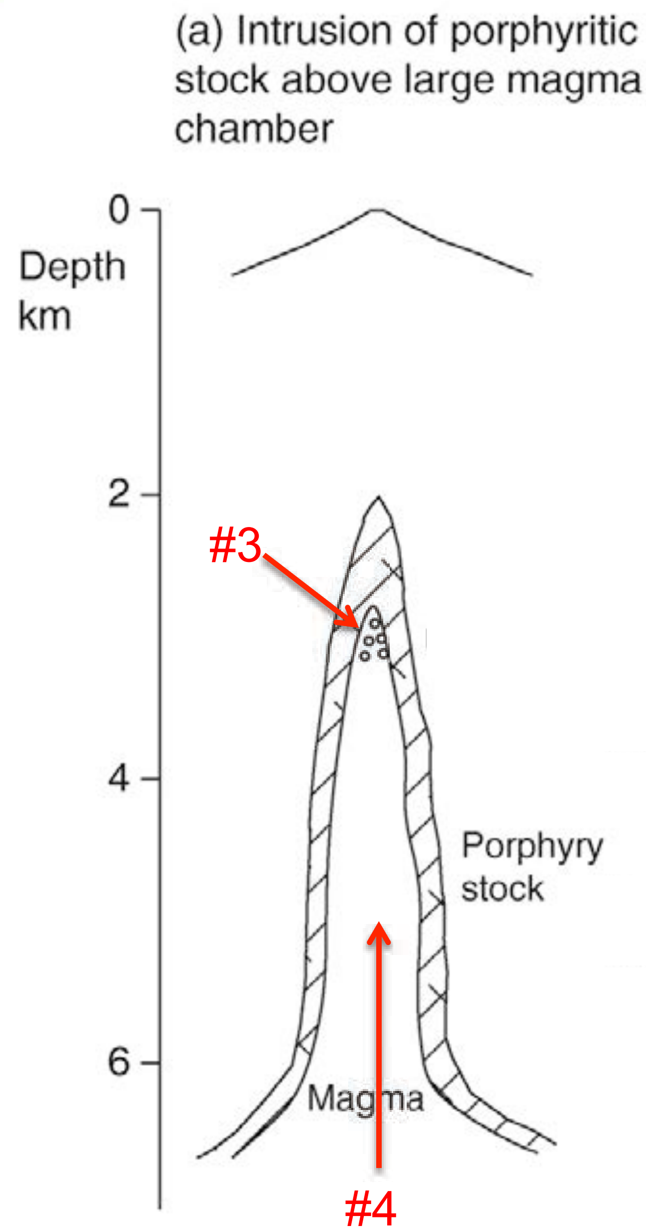
- Vapor saturation reached due to progressive crystallization of anhydrous minerals (deep magmas)
- Usually associated with a drop in *T* towards the end of a magmas history



Ridley (2013)

Genetic model (Stage A)

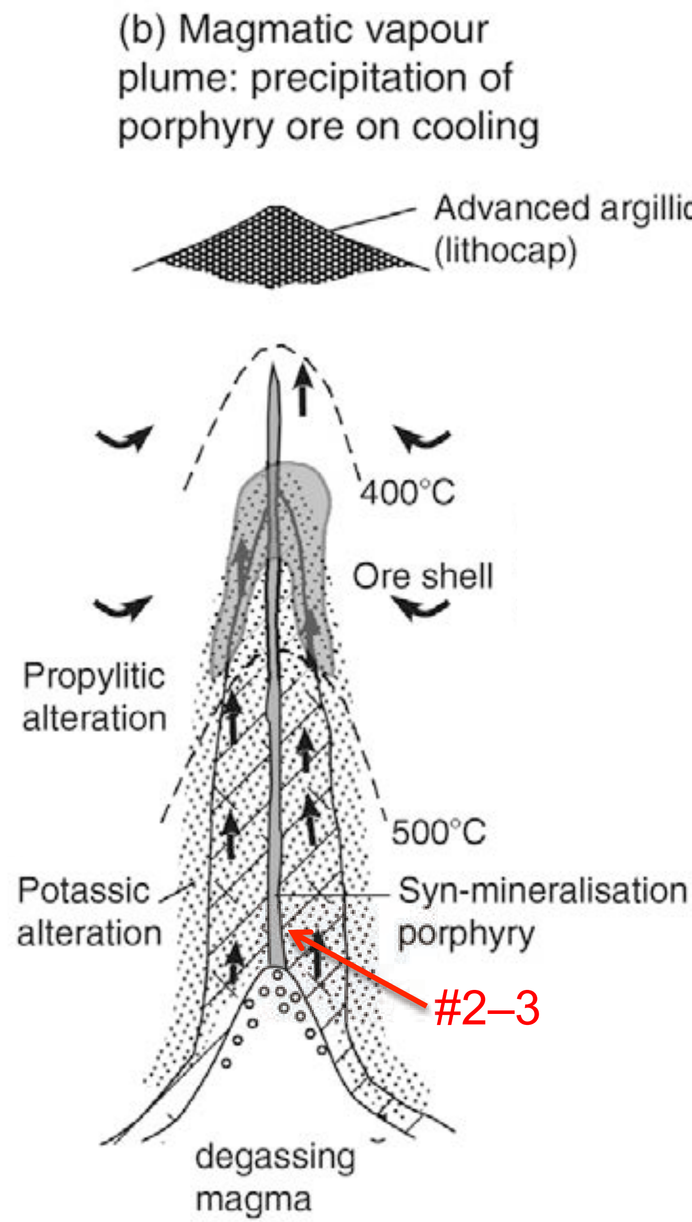
1. Pluton-sized body of magma is crystallizing (second boiling) or rising (first boiling)
2. Magma reaches saturation (with respect to an aqueous fluid)
3. Magma exsolves bubbles of the hydrothermal fluid at the pluton roof
4. Produces a volume of low-density and volatile rich magma that intrudes as a porphyry stock
5. Porphyry stock crystallizes. It is unmineralized but it will act as an exhaust valve.



Ridley (2013)

Genetic model (Stage B)

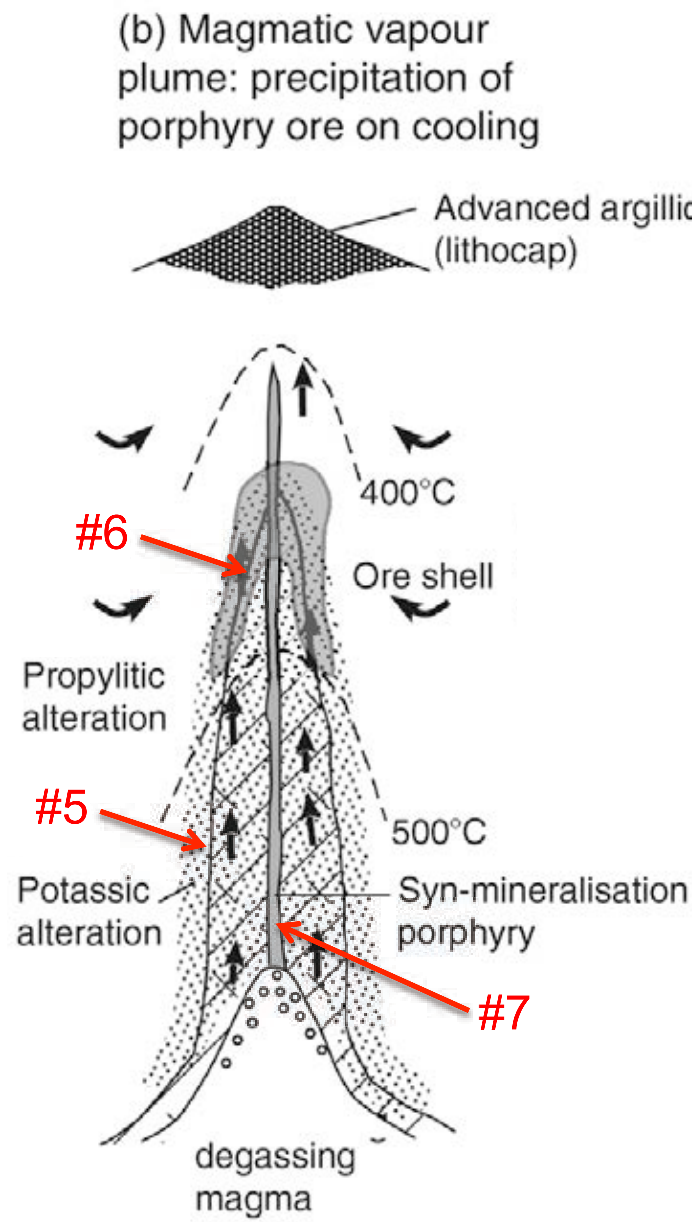
1. Continued <u>cooling</u> and crystallization of magma allows accumulation of fluid that scavenges ore metals
2. Increasing fluid pressure leads to **hydrofracturing** of overlying rock
3. High-temperature fluid escapes
4. Fluid is thought to represent a two-phase hypersaline liquid and vapor that leads to both mineralization and potassic alteration
5. Mineral precipitation from fluids produces stockwork quartz veins or a breccia pipe above the magma chamber that may contain ore minerals



Ridley (2013)

Genetic model (Stage B)

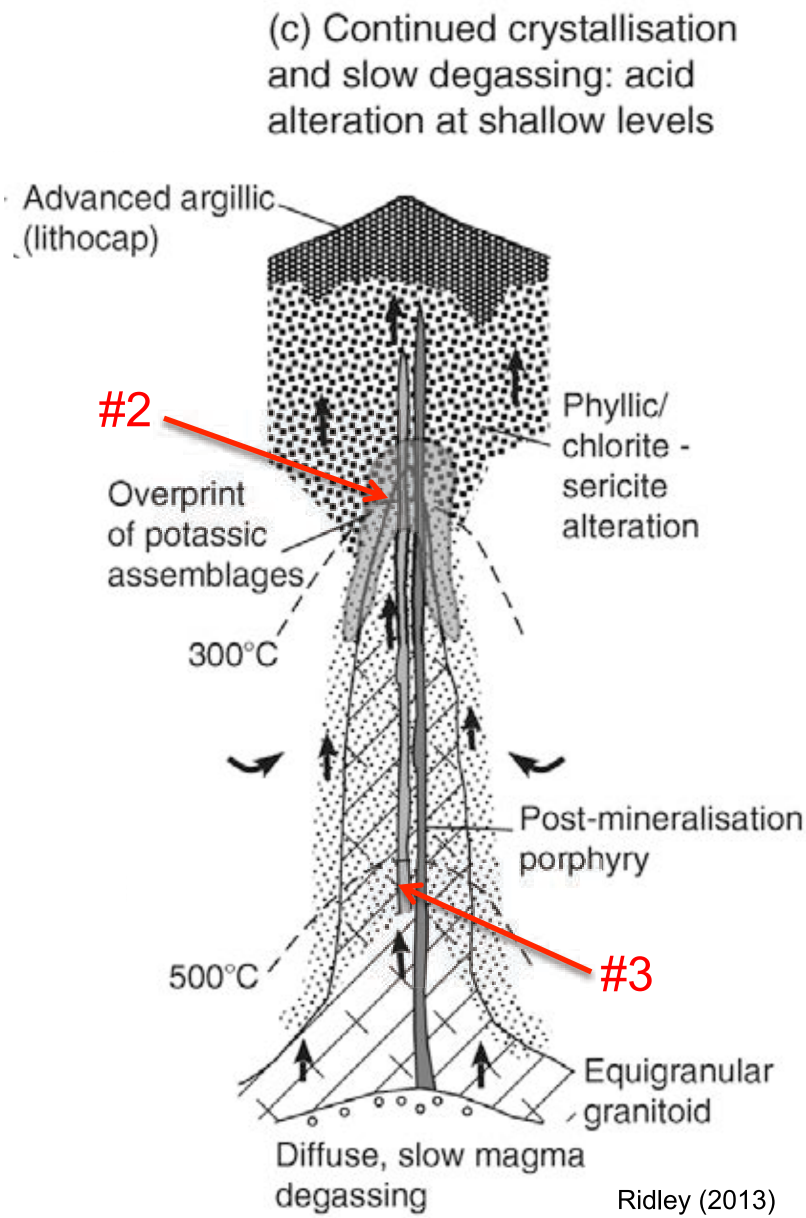
5. Ascending fluid becomes more acidic due to dissociation of dissolved acid volatile species (HCl -> H^+ + Cl^-) and produces potassic alteration at high temperatures (500–450°C)
6. Hydrothermal convection of meteoric fluids induce propylitic alteration at higher levels (450–400°C)
7. Intrusion of syn-mineralization porphyry (textures results from rapid quenching during ascent)
8. System continues to cool



Ridley (2013)

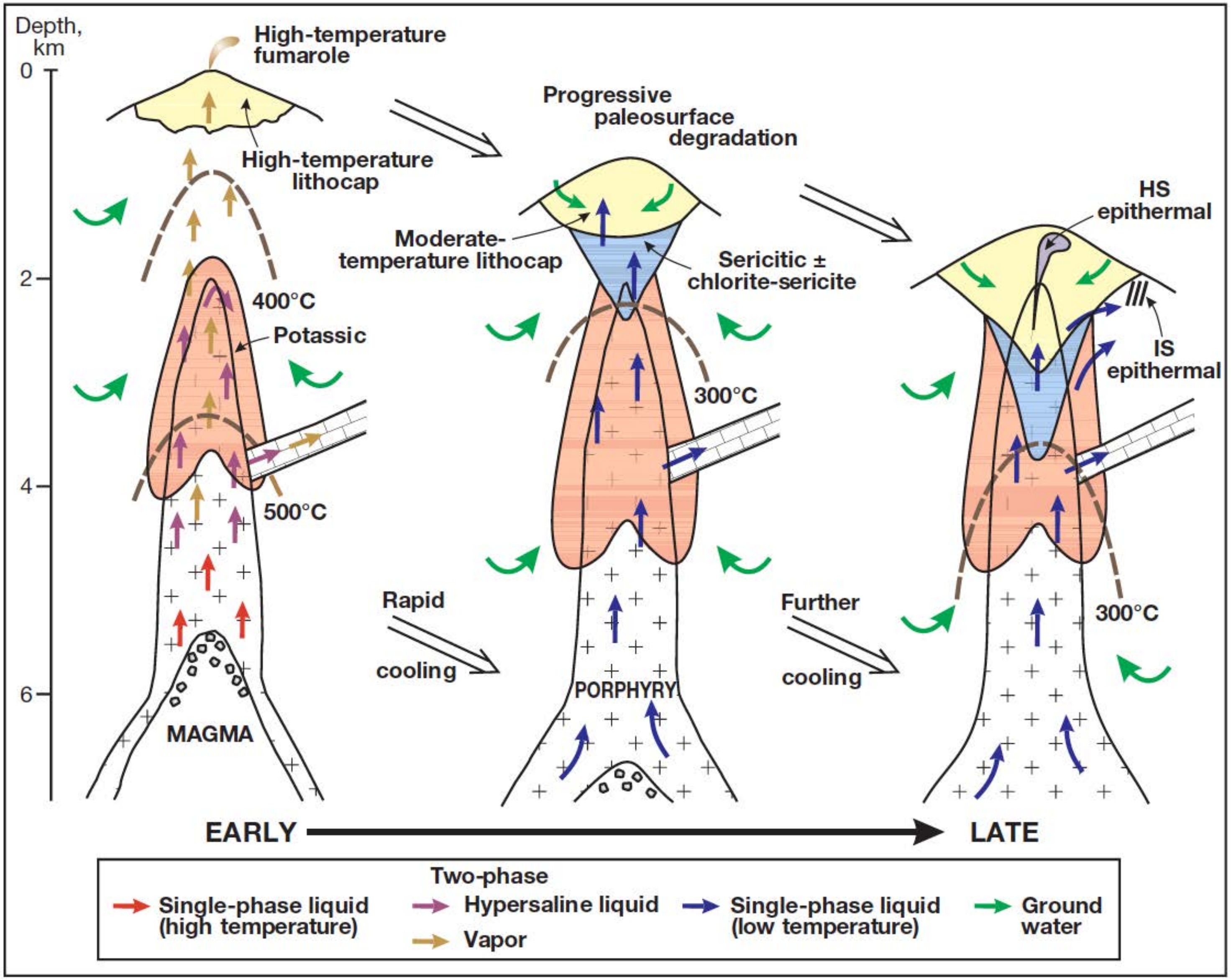
Genetic model (Stage C)

1. Pluton progressively cools and crystallizes and releases progressively cooler fluids <350°C)
2. These fluids induce phyllic, argillic and chlorite–sericite alteration that overprint earlier potassic alteration
3. Post-mineralization dykes may intrude (but barren of mineralization)



Ridley (2013)

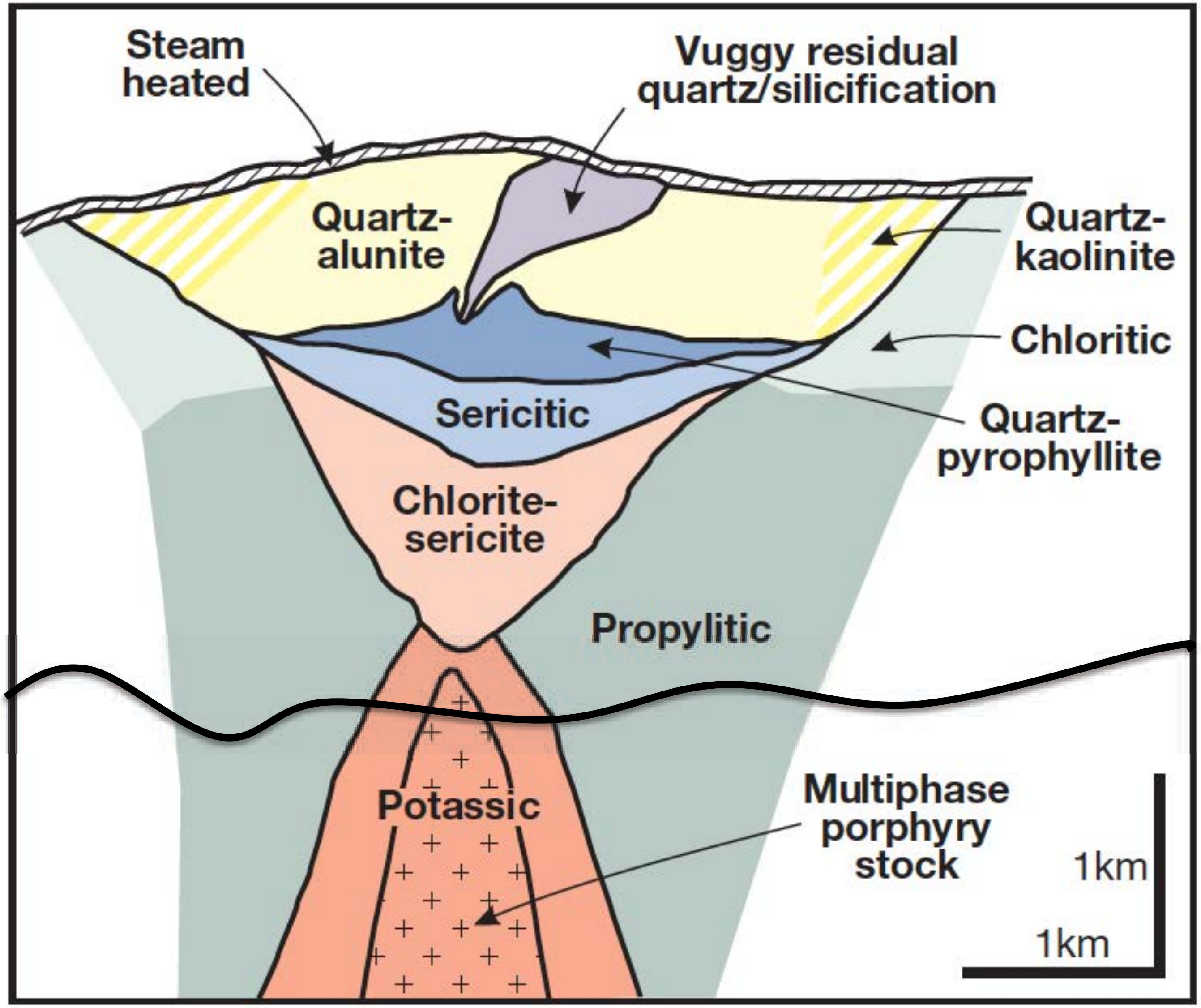
Overprinting hydrothermal alteration



Sillitoe (2010)

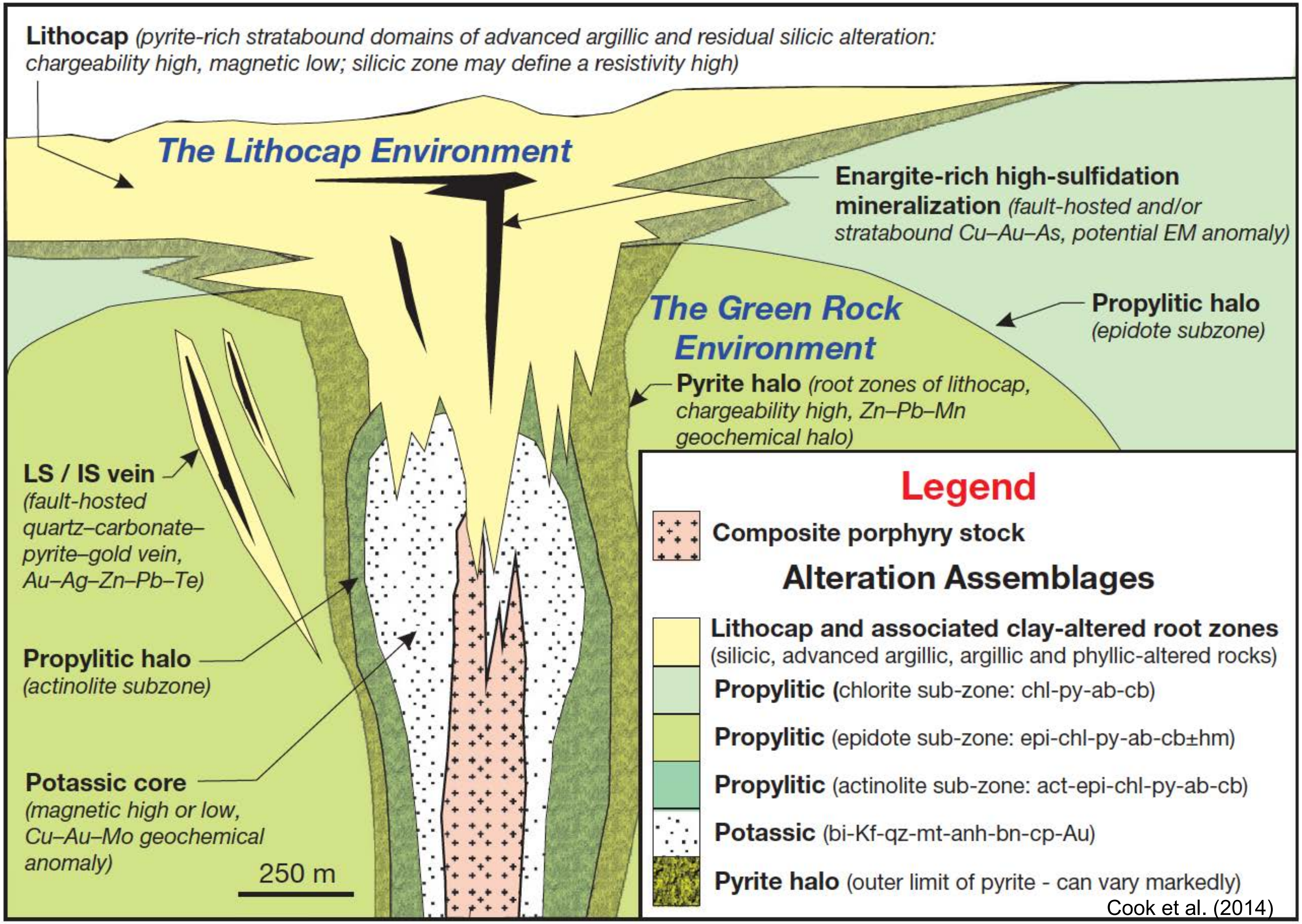
Hydrothermal alteration – vertical zoning

Erosion surface?



Sillitoe (2010)

Hydrothermal alteration – horizontal zoning



Cook et al. (2014)

Hydrothermal alteration – temporal zoning

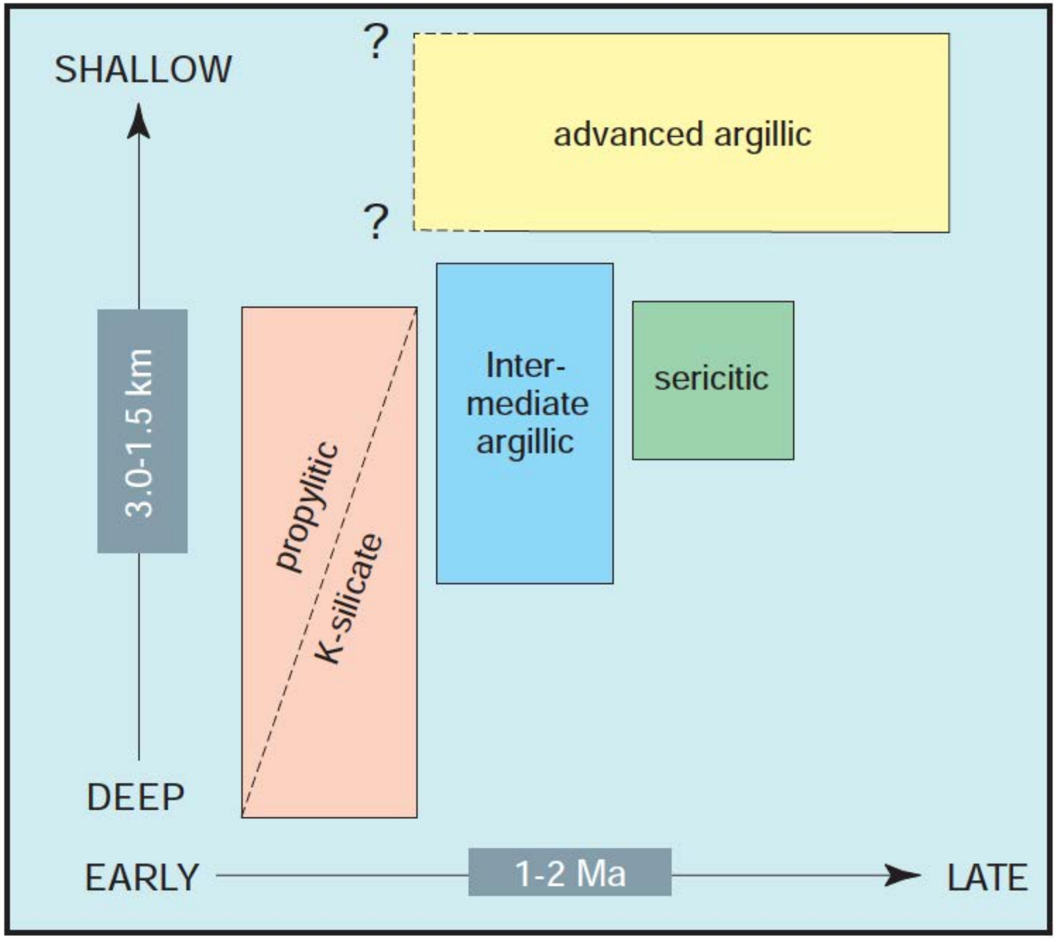
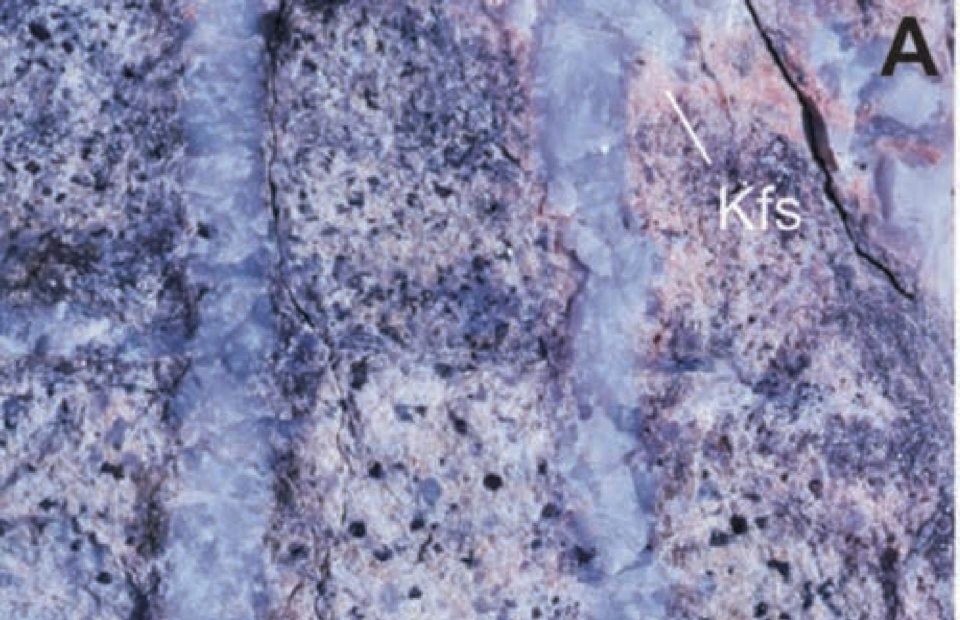
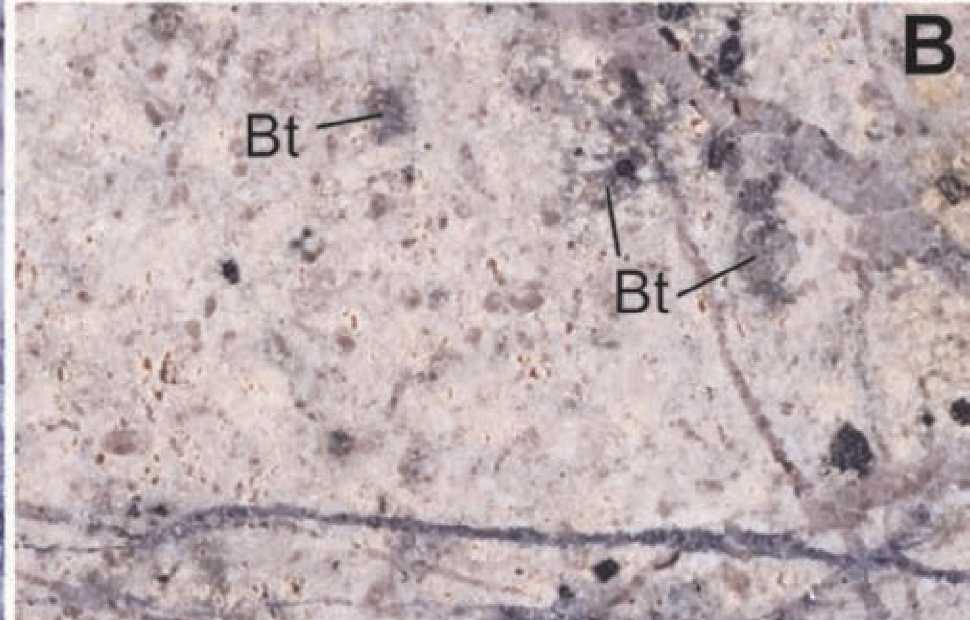


FIGURE 16. Schematic time-depth relations of principal alteration types in Au-rich porphyry Cu systems and other types of porphyry deposits (after Sillitoe, 1993b).

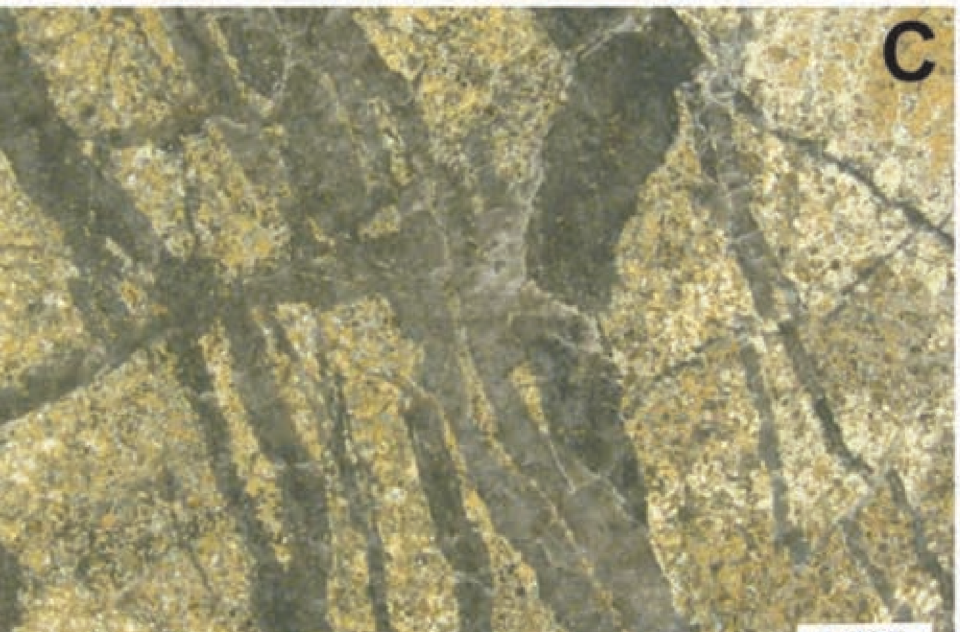
Sinclair (2007)



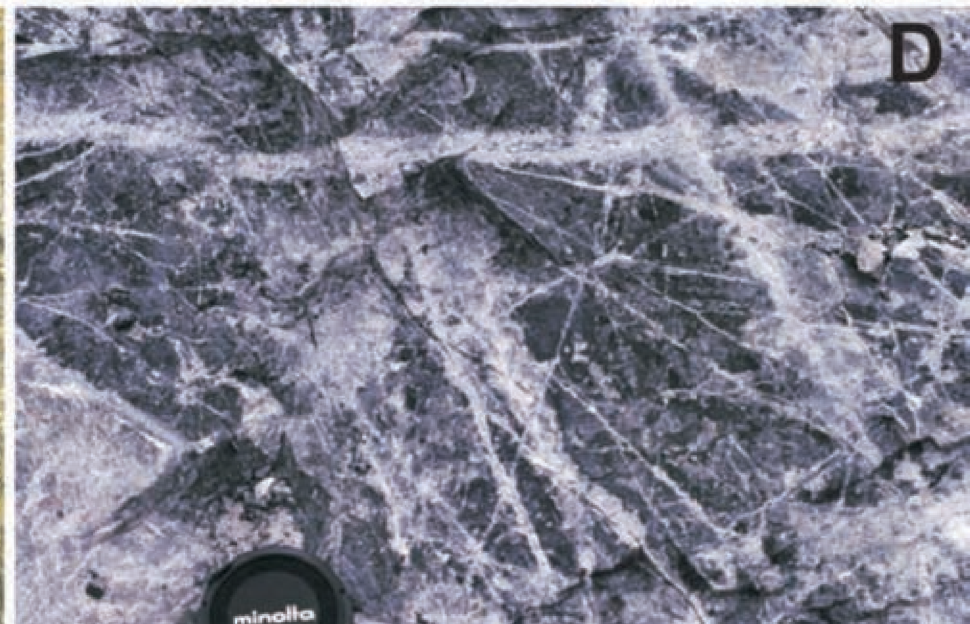
K-feldspar alteration around quartz



Potassic alteration (pink fsp and biotite)



Sericitic (phyllic) alteration with quartz stockwork



Choritized granite (with stockwork quartz)

Cu–(Mo), Mo–(Cu) and W–(Mo) porphyry deposit genetic models

Before we continue…

We need to learn about the different types of granites…

Yes, granites…

Yes, there are many types of granites…

Two contrasting granite types: 25 years later

B. W. CHAPPELL[1*] AND A. J. R. WHITE[2]

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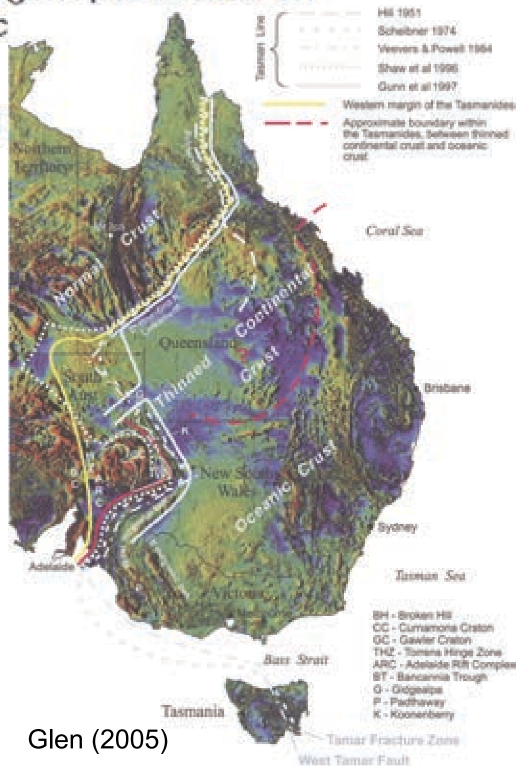
The concept of I- and S-type granites was introduced in 1974 to account for the observation that, apart from the most felsic rocks, the granites in the Lachlan Fold Belt have properties that generally fall into two distinct groups. This has been interpreted to result from derivation by partial melting of two kinds of source rocks, namely sedimentary and older igneous rocks. The original publication on these two granite types is reprinted and reviewed in the light of 25 years of c
these granites.

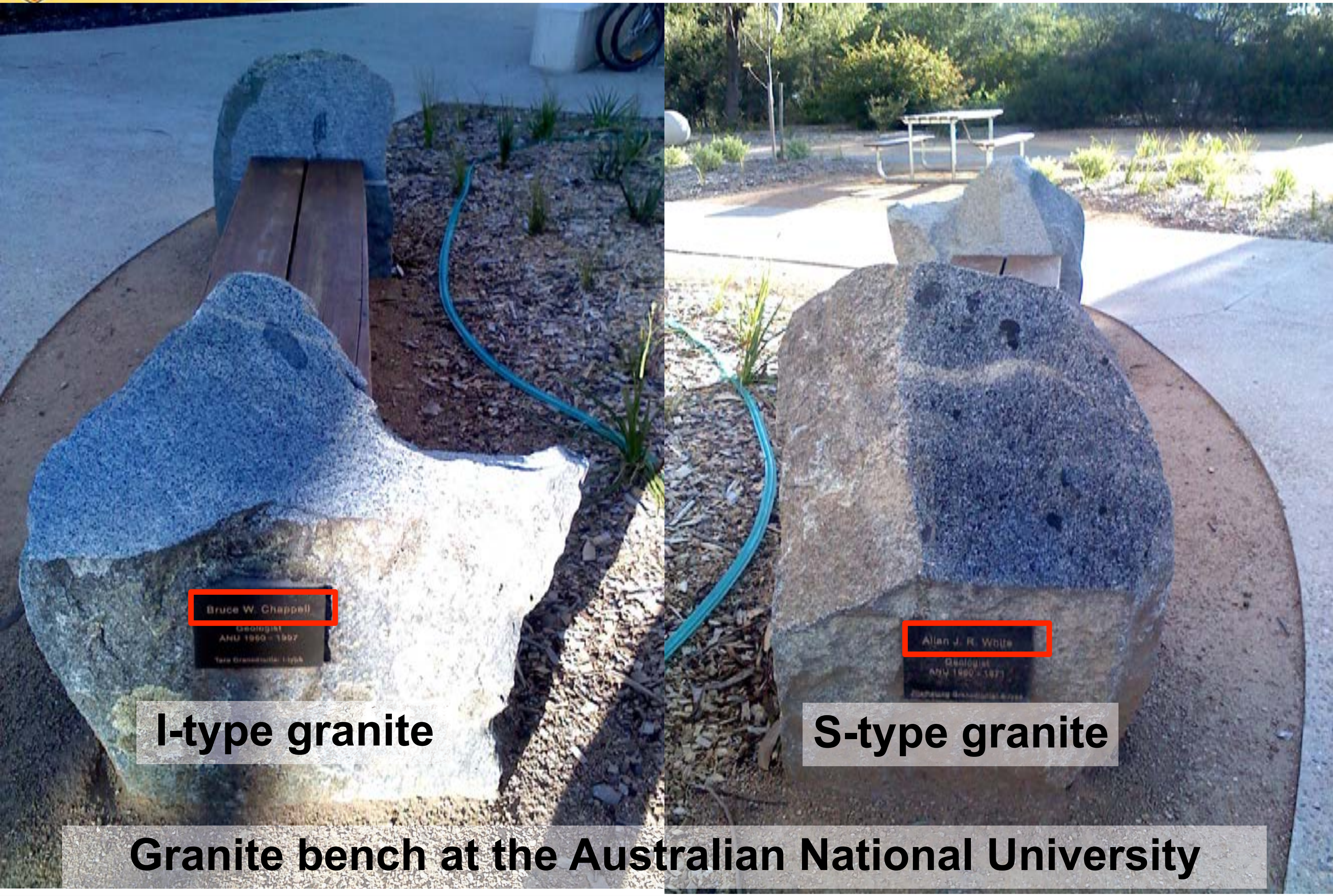
KEY WORDS: Berridale Batholith, I-type granite, Kosciuszko Batholith, Lachlan Fold

S-type granite: derived from partial melting of meta<u>sedimentary</u> rocks…'evolved' sources

I-type granite: derived from partial melting of <u>igneous</u> rocks (basalts, granodiorites) …'primitive' sources



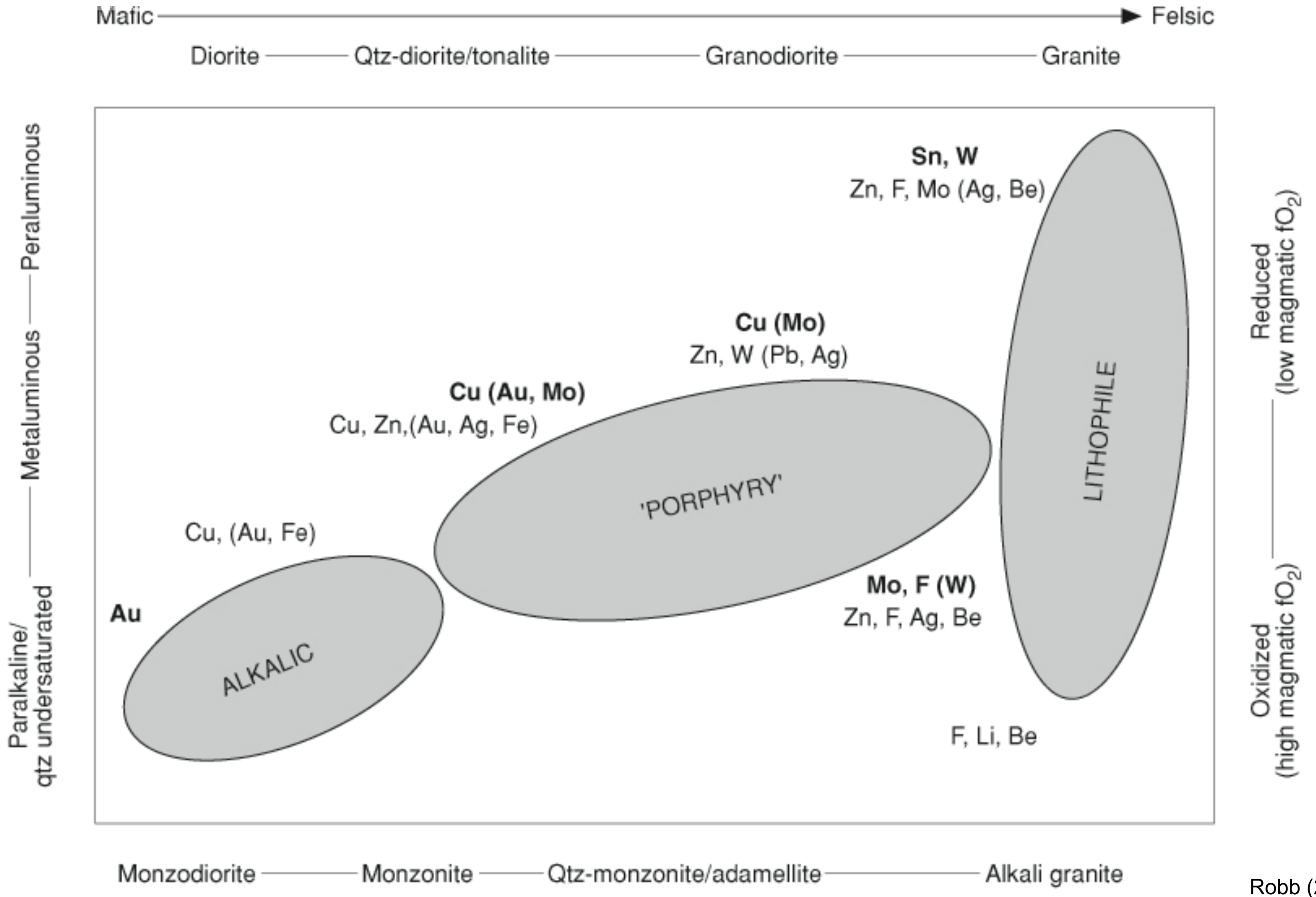
Glen (2005)



Granite bench at the Australian National University

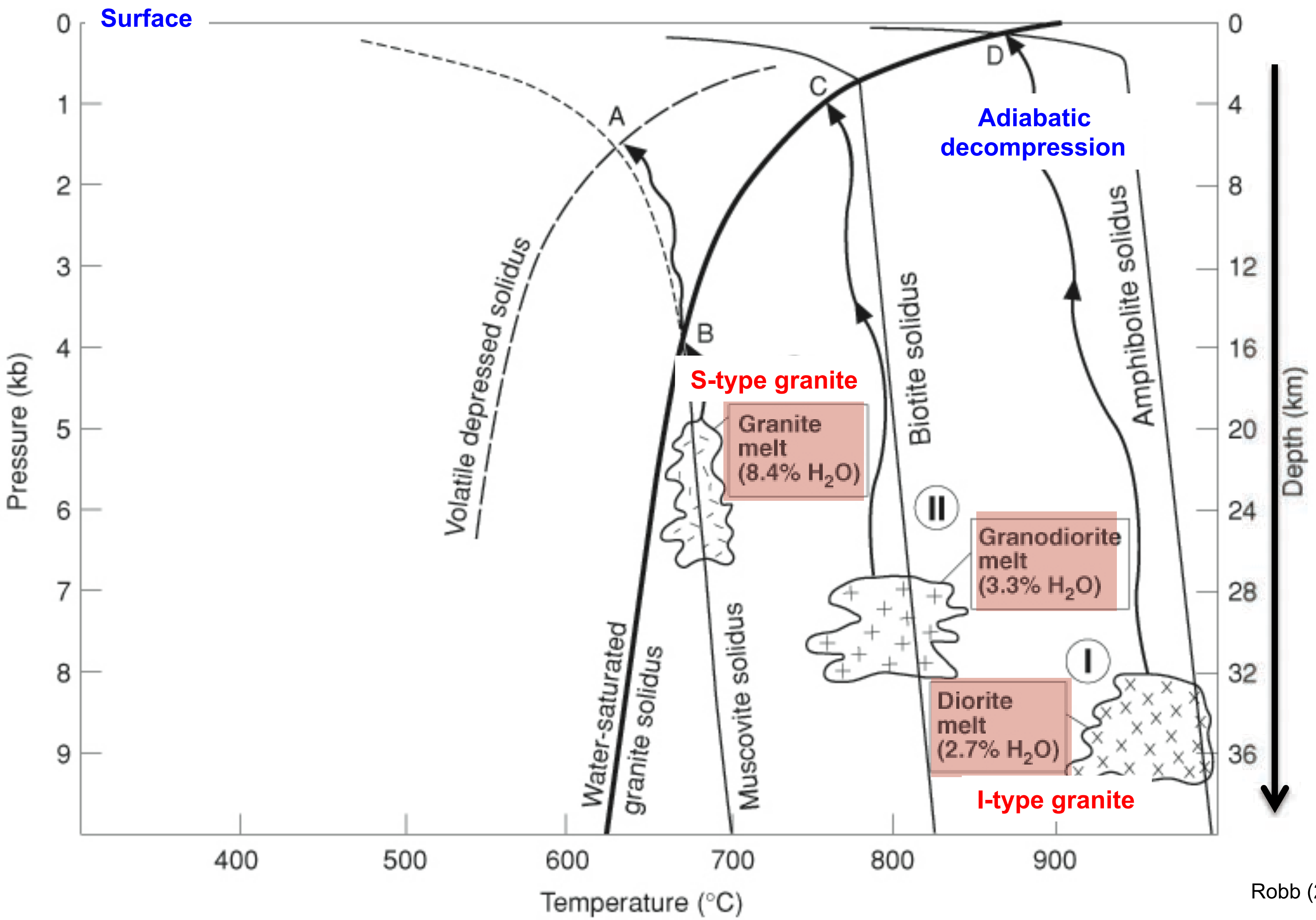
New and thin crust

Old and thick crust



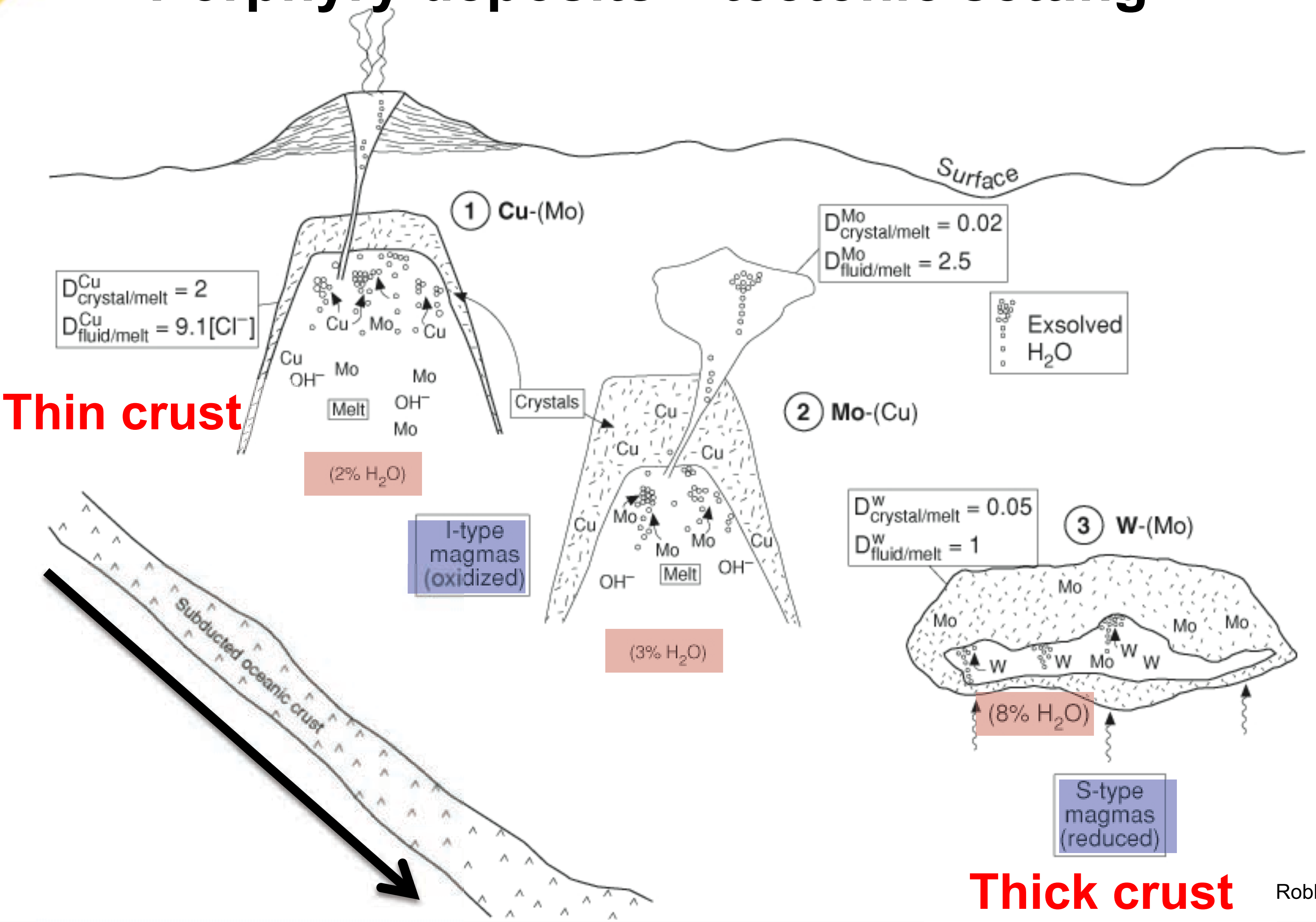
Robb (2005)

Granite H_2O concentrations control their depths of emplacement



Robb (2005)

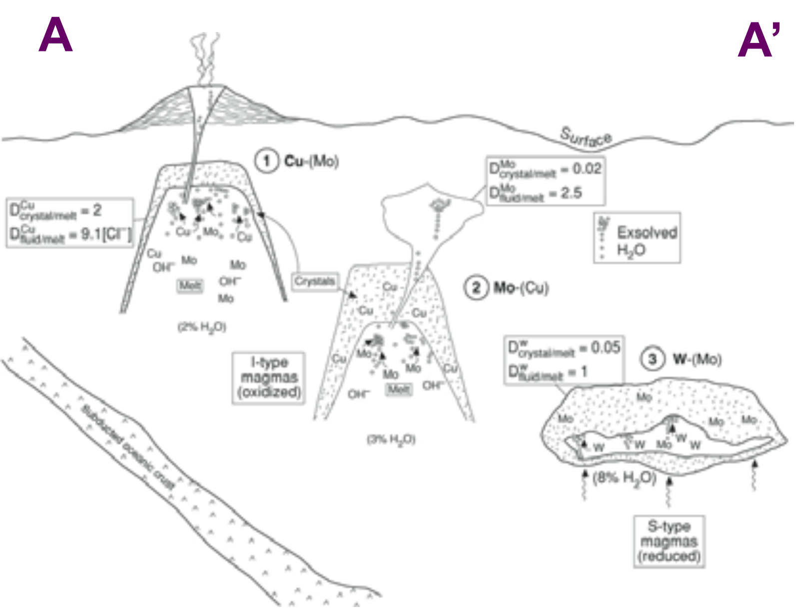
Porphyry deposits – tectonic setting



Robb (2005)

Porphyry deposits – tectonic setting

Cross section



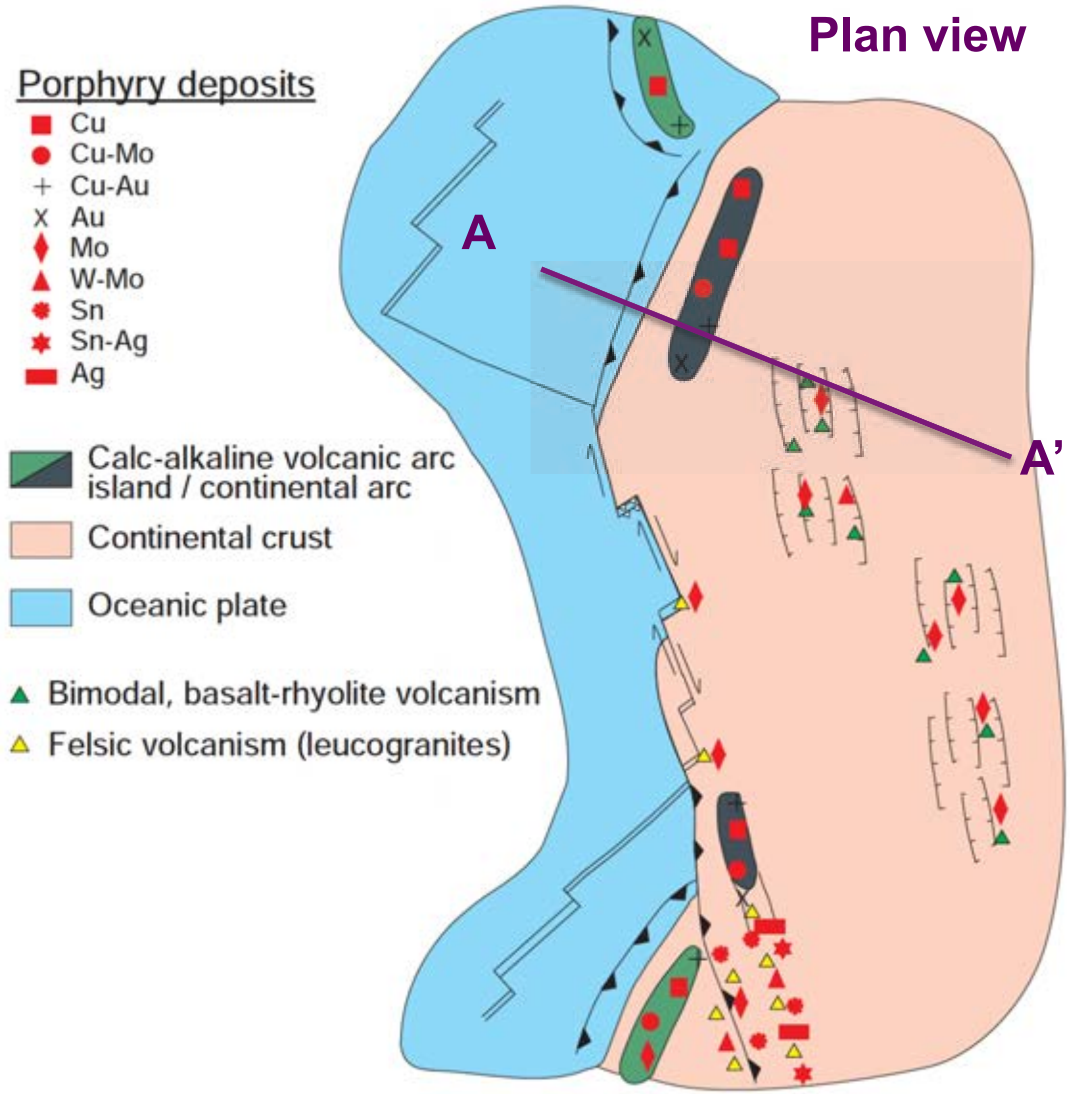
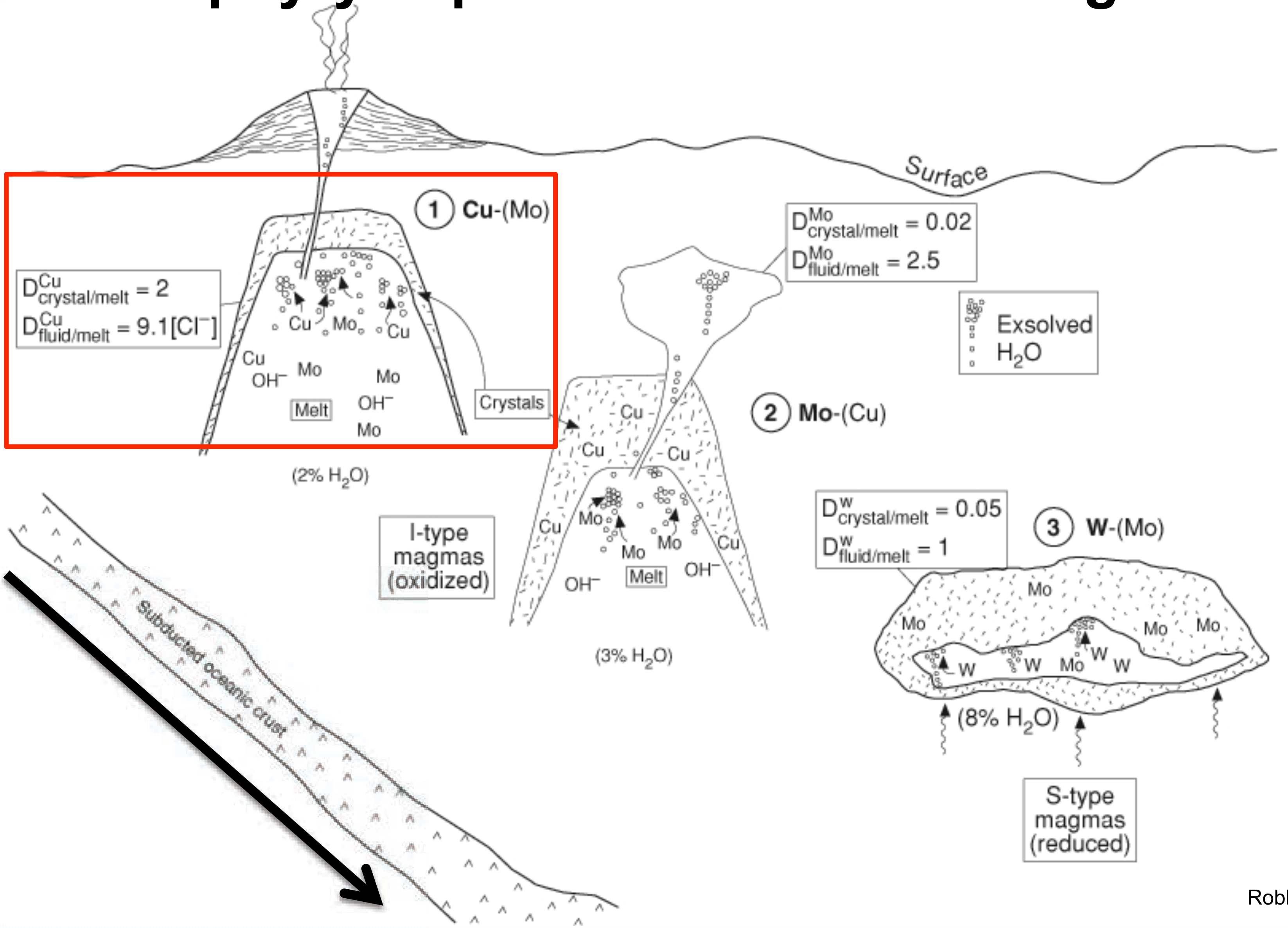


FIGURE 10. Schematic diagram showing the tectonic settings of porphyry deposits (Kirkham and Sinclair, 1995).

Sinclair (2007)

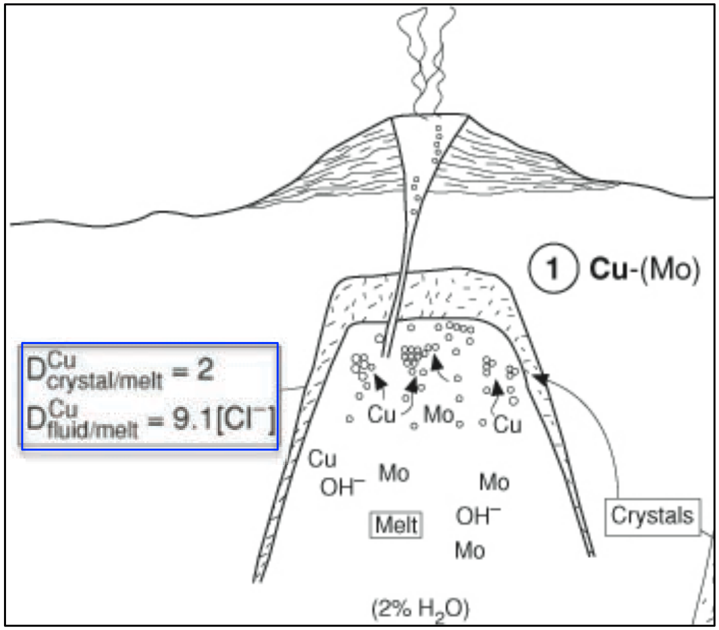
Porphyry deposits – tectonic setting



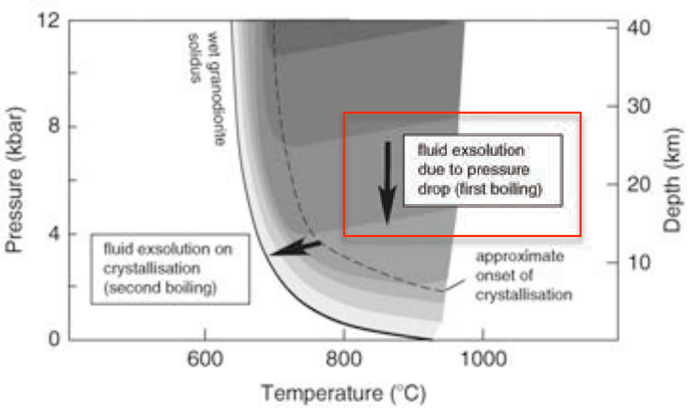
Robb (2005)

Cu–(Mo) porphyry deposits genetic model (1)

- Oxidized, I-type granitic magmas (melting of amphibolite protolith in deep crust above a subduction zone)
- Magma with relatively low H_2O content rises up to shallow crustal levels
- Some melt may be tapped and transported to a volcano at the surface
- First boiling – vapor contains high Cl- concentrations
- In this H_2O-poor magma, Cu is compatible and Mo is incompatible
- However, very little crystallization has occurred so far
- Therefore, Cl^- -rich vapour will scavenge Cu from the silicate melt



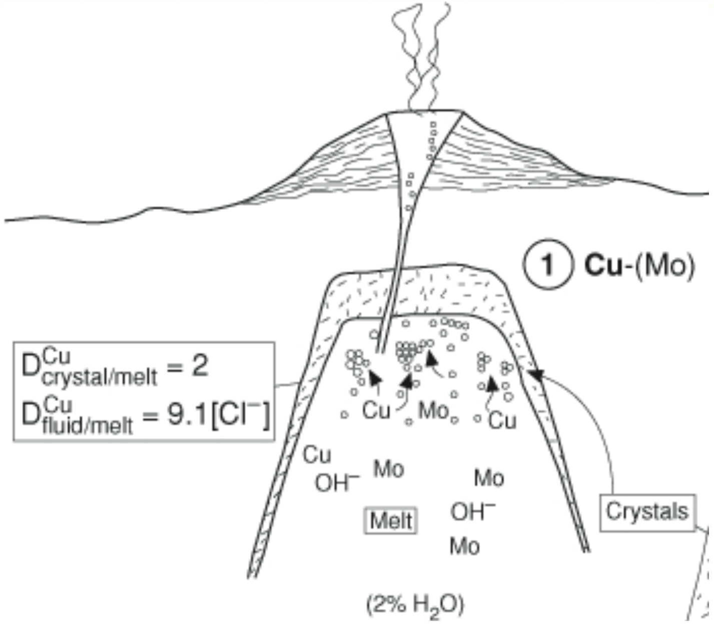
Robb (2005)



Cu–(Mo) porphyry deposits genetic model (2)

- Mo is incompatible and partitions into water-rich vapor
- However, Mo is relatively unaffected by Cl^- concentrations, and doesn't attain significant concentrations in the fluid

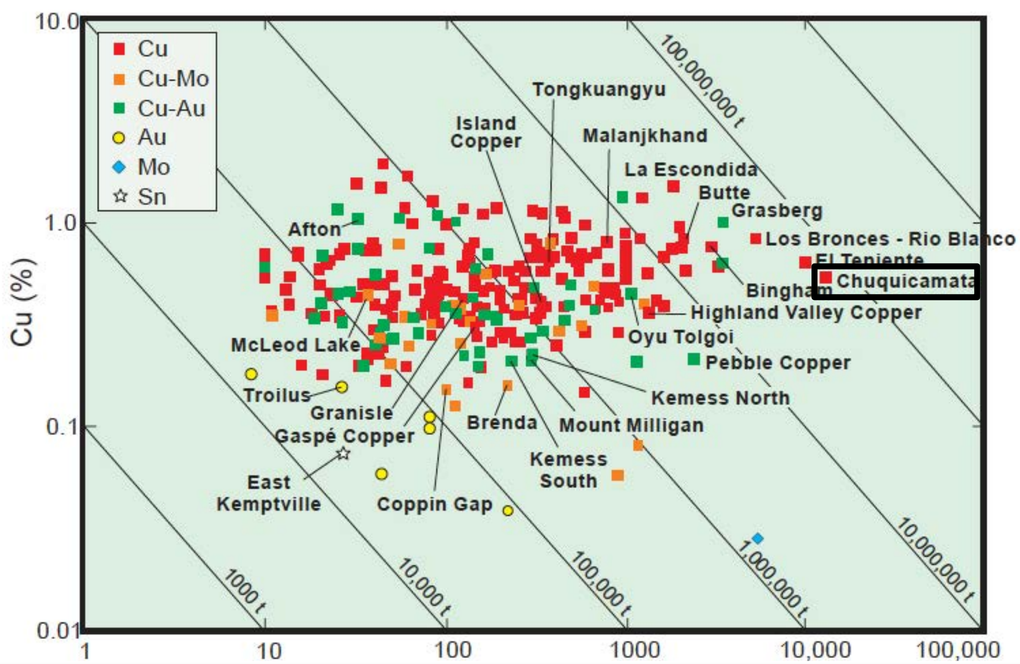
<u>Summary</u>: I-type magma undergoes first boiling at shallow levels in the crust, exsolves a vapor rich in Cl^- and **Cu** with some **Mo**



Robb (2005)

Chuquicamata, Chile

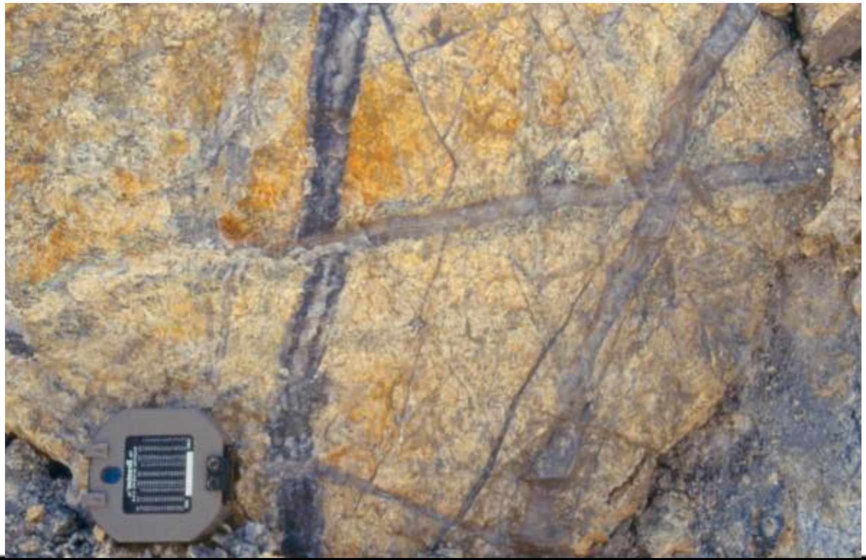
- World's larges Cu ore body
- High grade Cu mined by Incas
- 1879–1912: veins mined underground
- 1915: open pit mining started
- 2.35 Gt have been mined averaging 1.54% Cu (6.45 Gt @ 0.55% Cu remains)

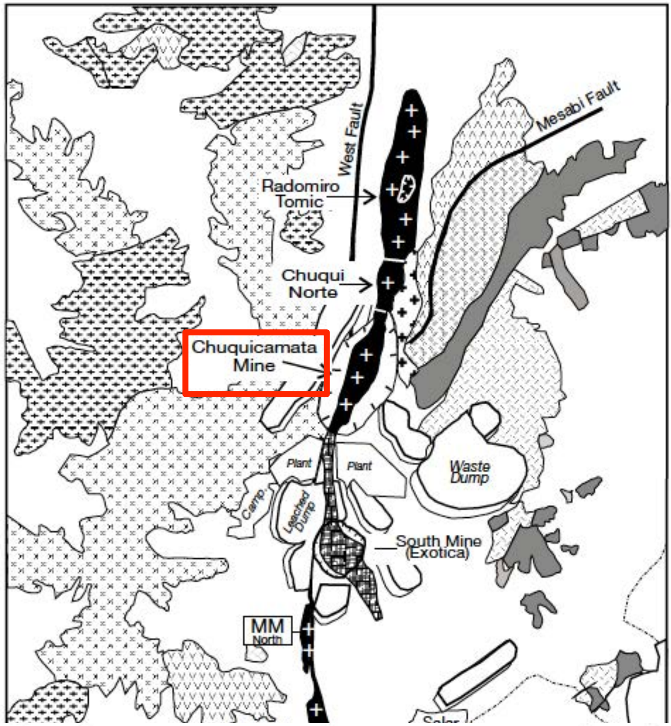


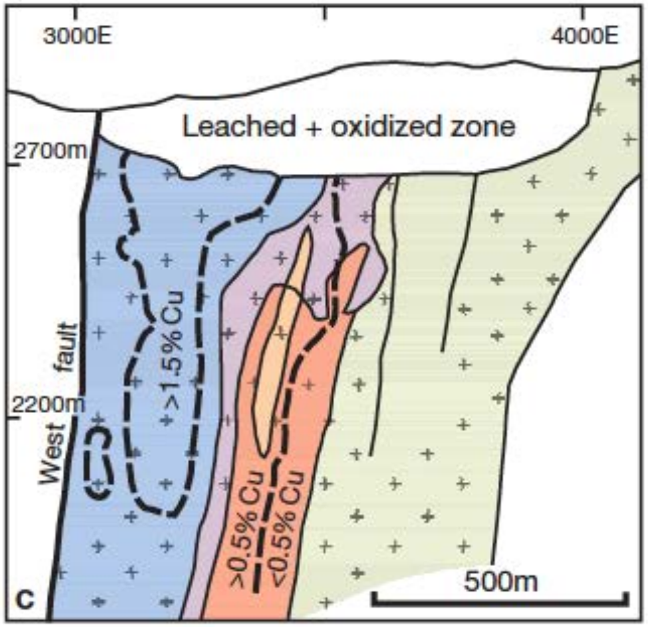
Sillitoe (2010)

Chuqui Geology

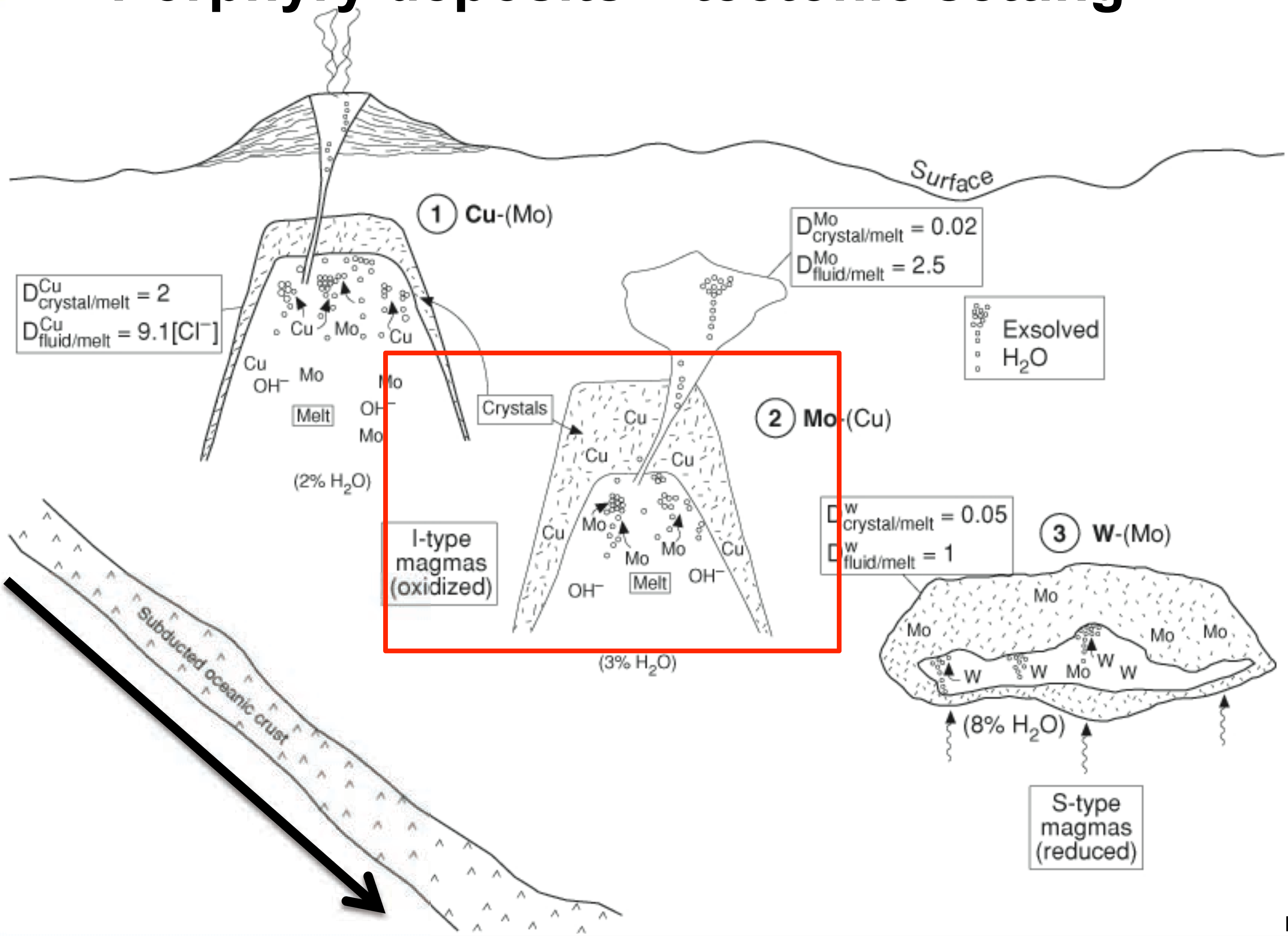
- Eocene–Oligocene porphyritic intrusions associated with the Andean active continental margin
- Strong structural control on magma emplacement and mineralization
- Mineralization focused along West Fault
- Multiple mineralized vein generations (stockwork textures):
  - Main stage: chalcopyrite and bornite
  - Late stage: enargite, digenite, covellite







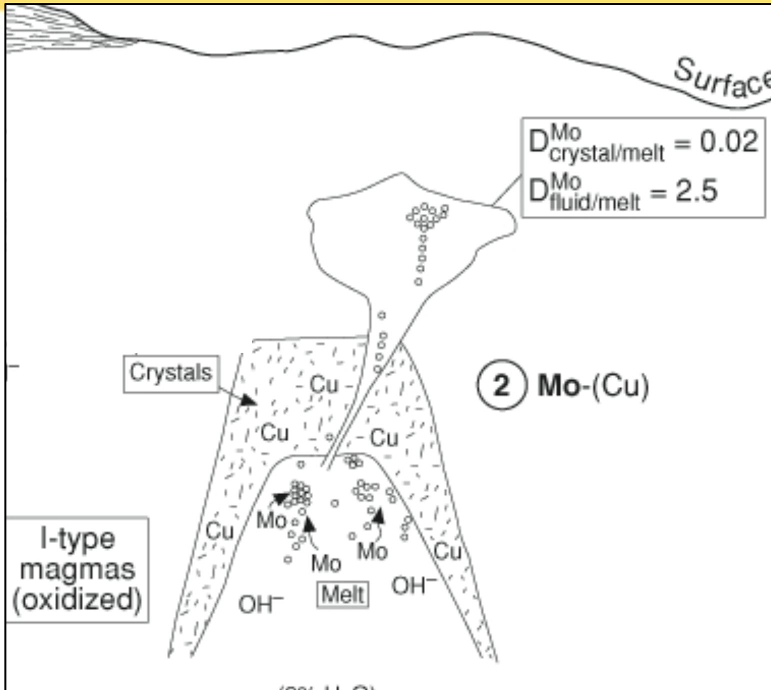
Porphyry deposits – tectonic setting



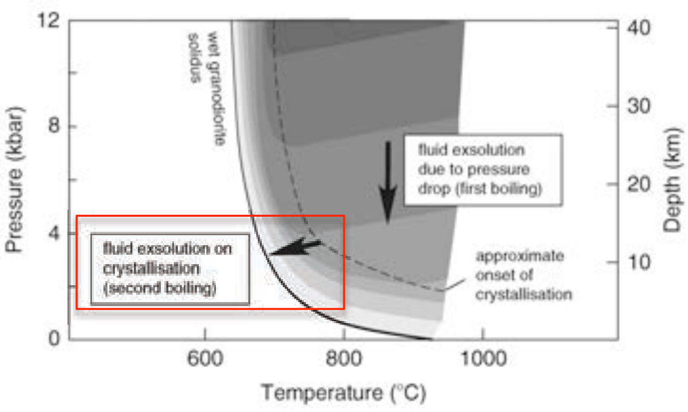
Robb (2005)

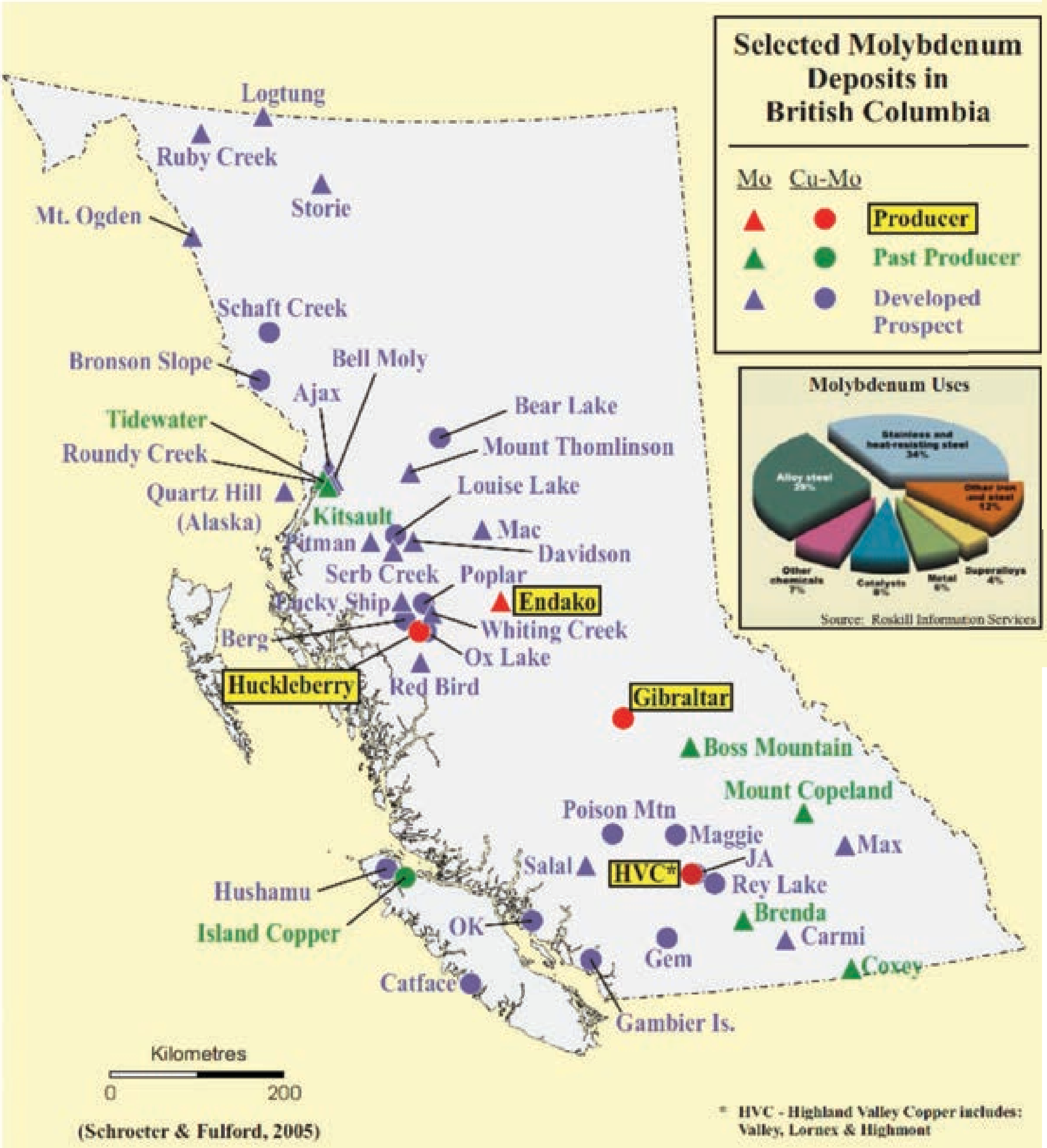
Mo–(Cu) porphyry

- Parental magma has a higher H_2O content than Cu–(Mo) porphyry magma (possibly related to melting of biotite-bearing protolith)
- Magma will be arrested at deep levels compared with Cu–(Mo) type porphyry
- Saturation water content is higher – will crystallize more before boiling (second boiling)
- Cu is compatible and crystallizes out of melt (not available to partition into fluid)
- Mo (incompatible) concentration will increase in the residual melt and will eventually partition into the fluid during boiling



Robb (2005)





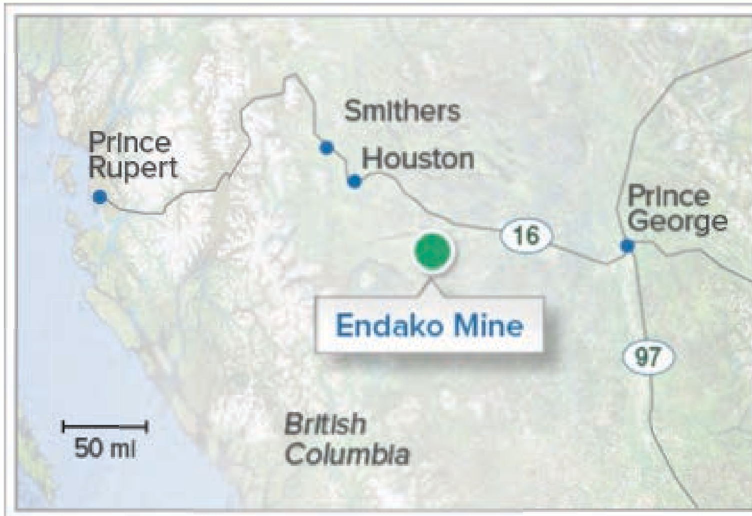
Selected BC Molybdenum Producers (1915-2004)

Mine / Deposit Name	Years of Production (* = Producing)	Mo Produced (t) (10^3)	Other Products
Endako	1965-1998; 2002-2004*	191.3	-
Highland Valley Copper	1972-2004*	75.3	Cu-Ag-Au
Brenda	1070-1990	67.9	Cu-Ag-Au
Island Copper	1971-1995	32.0	Cu-Ag-Au-Re
Boss Mtn.	1965-1983	15.5	-
Kitsault	1967-1972; 1981-1982	13.6	-
Gibraltar	1972-1998; 2004*	9.1	Cu-Ag

Note: At US$20 per pound molybdenum, the total value of BC molybdenum production (320 300 tonnes) is approximately US$14 billion.

Endako porphyry Mo

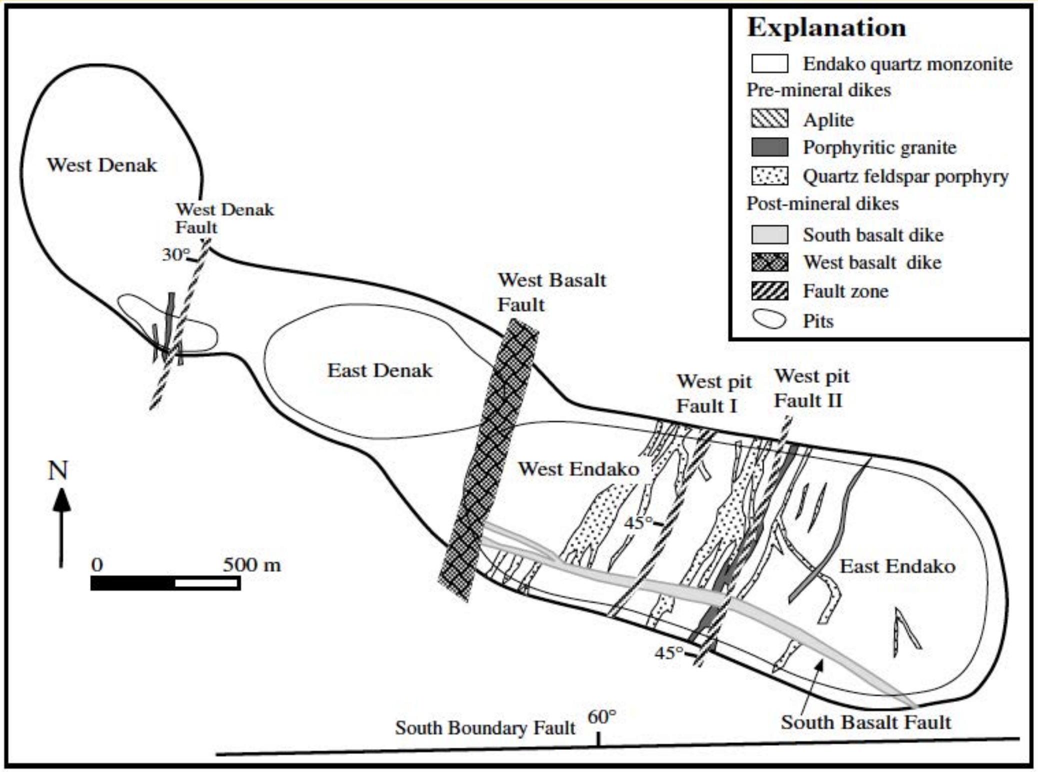
- 1927: mineralized boulders found by two hunters
- 1965: production started
- Produced 71% of Canadian Mo in 2000
- Reserves: 311 Mt @ 0.046% Mo (76 M pounds of Mo)
- Mine life estimated up to 2023
- Three open pits
- On care and maintenance since July 2015 (low Mo prices...)



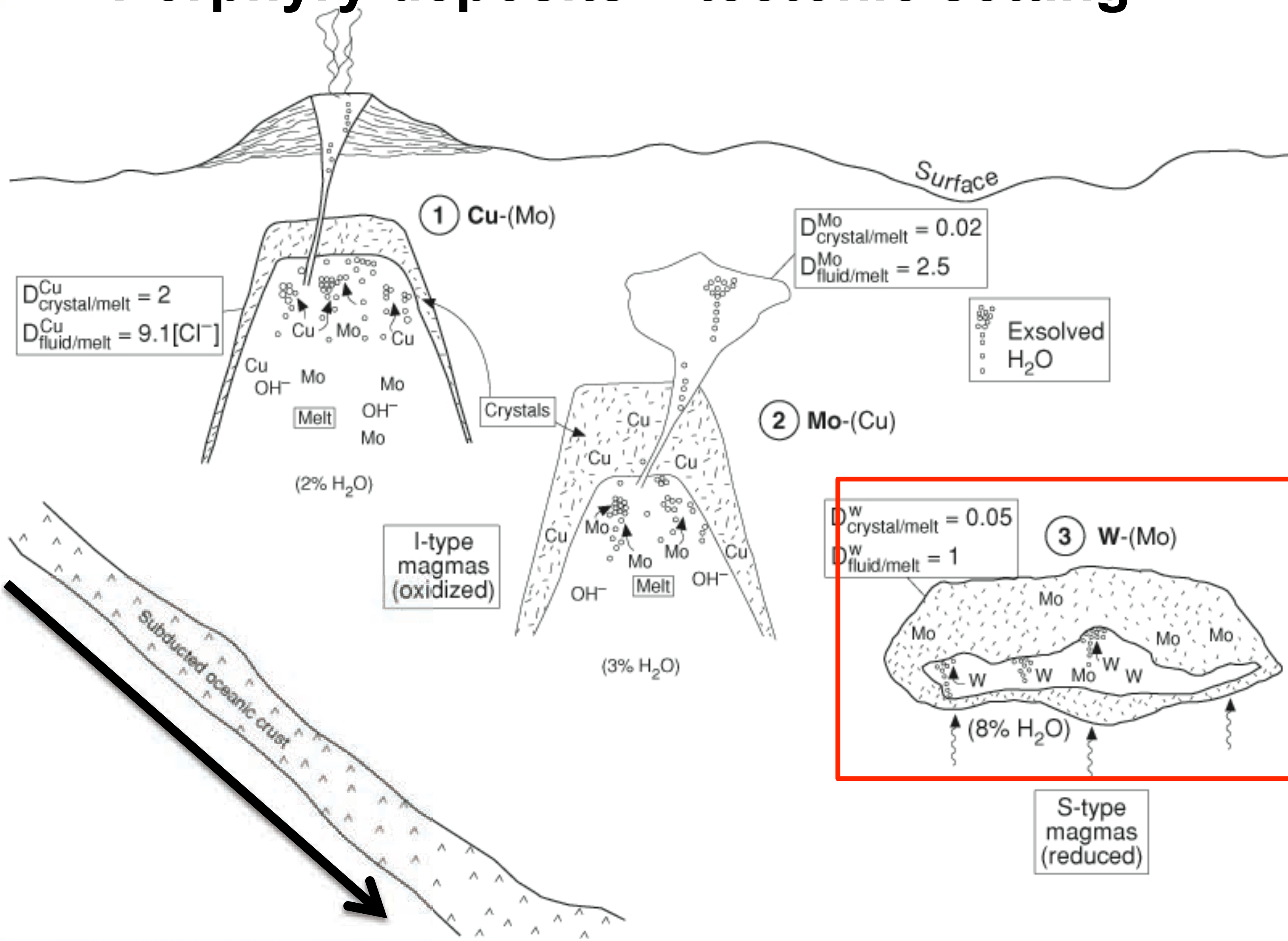
ThompsonCreek METALS COMPANY INC.

Endako Mo geology

- "Endako" is also a type of porphyry Mo deposit that is associated with subduction- related magmatism
- Host is a Jurassic granite suite in the Canadian Cordillera (Francois Lake plutonic suite)
- Multiple granite phases
- Ore occurs as: (1) quartz–molybdenite veins with ribbon textures, (2) stockwork



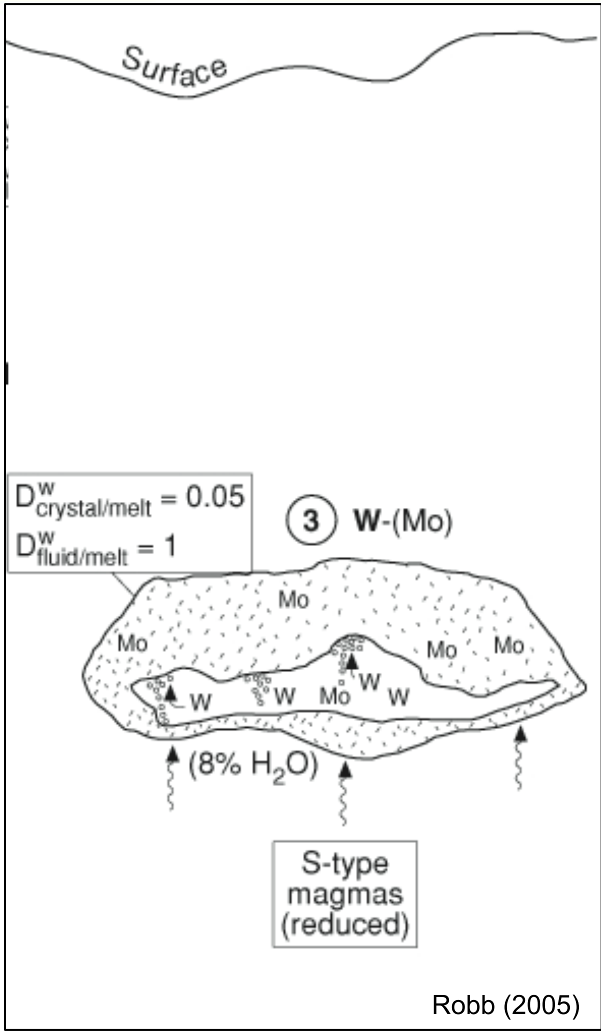
Porphyry deposits – tectonic setting



Robb (2005)

W–(Mo) porphyry deposits

- Parent magmas are more reduced, S-type granites (reduced because of derivation from rocks with organic carbon)
- Water-rich
- Crystallize deep in the crust
- W is not normally extracted from magma under oxidizing conditions
- W incompatible under reducing conditions
- Crystallization will increase W concentration in residual melt
- Second boiling: fluid will scavenge some W

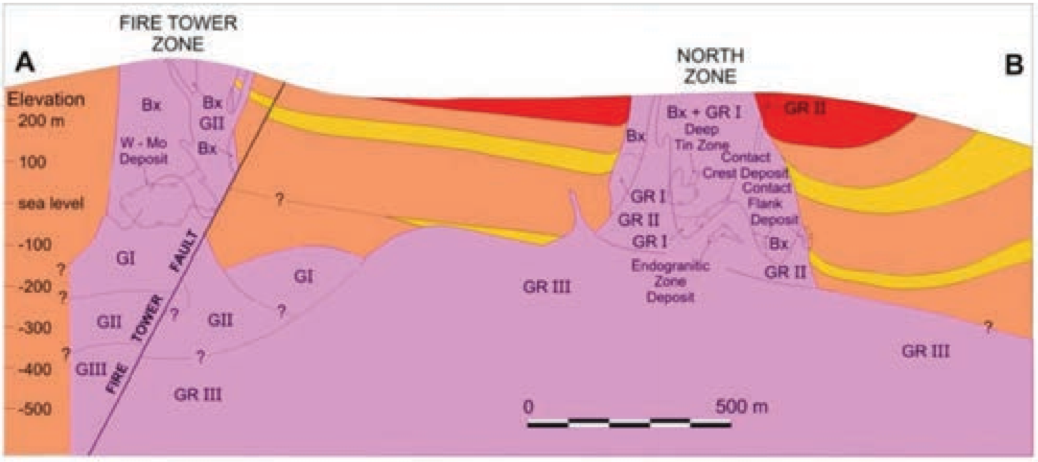


Mount Pleasant (NB) W–Mo porphyry deposit

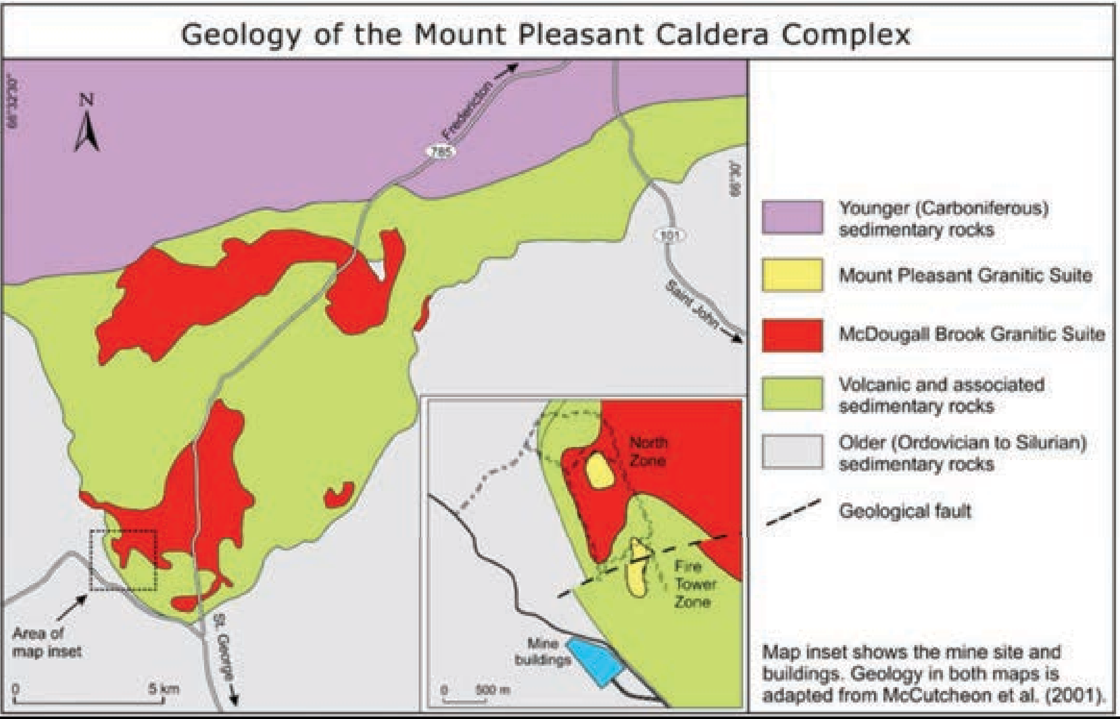
- Mount Pleasant area is a large camp in southern New Brunswick
- Farmer discovers sulfide mineralization in 1937
- Staked in 1954 after regional geochemical survey
- 1983: Production by Mount Pleasant Tungsten Mine
- 1985: Mine closed due to falling Tungsten Prices
- 1995: Ownership acquired by Adex mining
- Also hosts Indium, which has spurred new exploration

Mount Pleasant geology

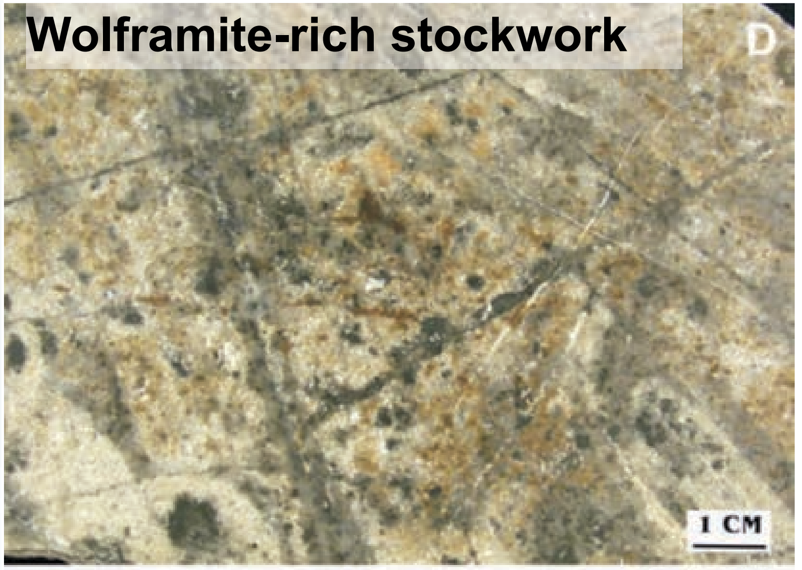
- Hosted by Devonian granites of the Mount Pleasant Caldera Complex
- **Wolframite** is the primary or mineral
- Disseminated in quartz veins, along fractures and in breccia



Cross-section A-B through the Fire Tower and North Zones at Mount Pleasant. View looking west.



Map inset shows the mine site and buildings. Geology in both maps is adapted from McCutcheon et al. (2001).



Porphyry Summary

- Large and low- to medium-grade
- Open-pit mining is usually required
- Related to igneous intrusions
- Ore is hosted in and immediately surrounding intrusions
- Ore textures: stockwork, vein, disseminated
- Magma chemistry (e.g. H_2O) controls the depth of emplacement and the type (Cu, Mo, W) of porphyry deposit (**how might this relate to preservation?**)

Fluid and ligands: magmatic (Cl^- and HS^-)

Source of metals: intermediate–felsic plutons

Transport: hydrofracturing creates permeable conduits

Trap: cooling, fluid–rock interaction, fluid mixing?