Mineral systems in convergent margin settings – Opportunities for discovery in the Tasmanides

Domeyko Cordillera, northern Chile – home to the world's largest porphyry copper province - Recent volcanoes of the Principal Cordillera in the background define the location of the current volcanic arc

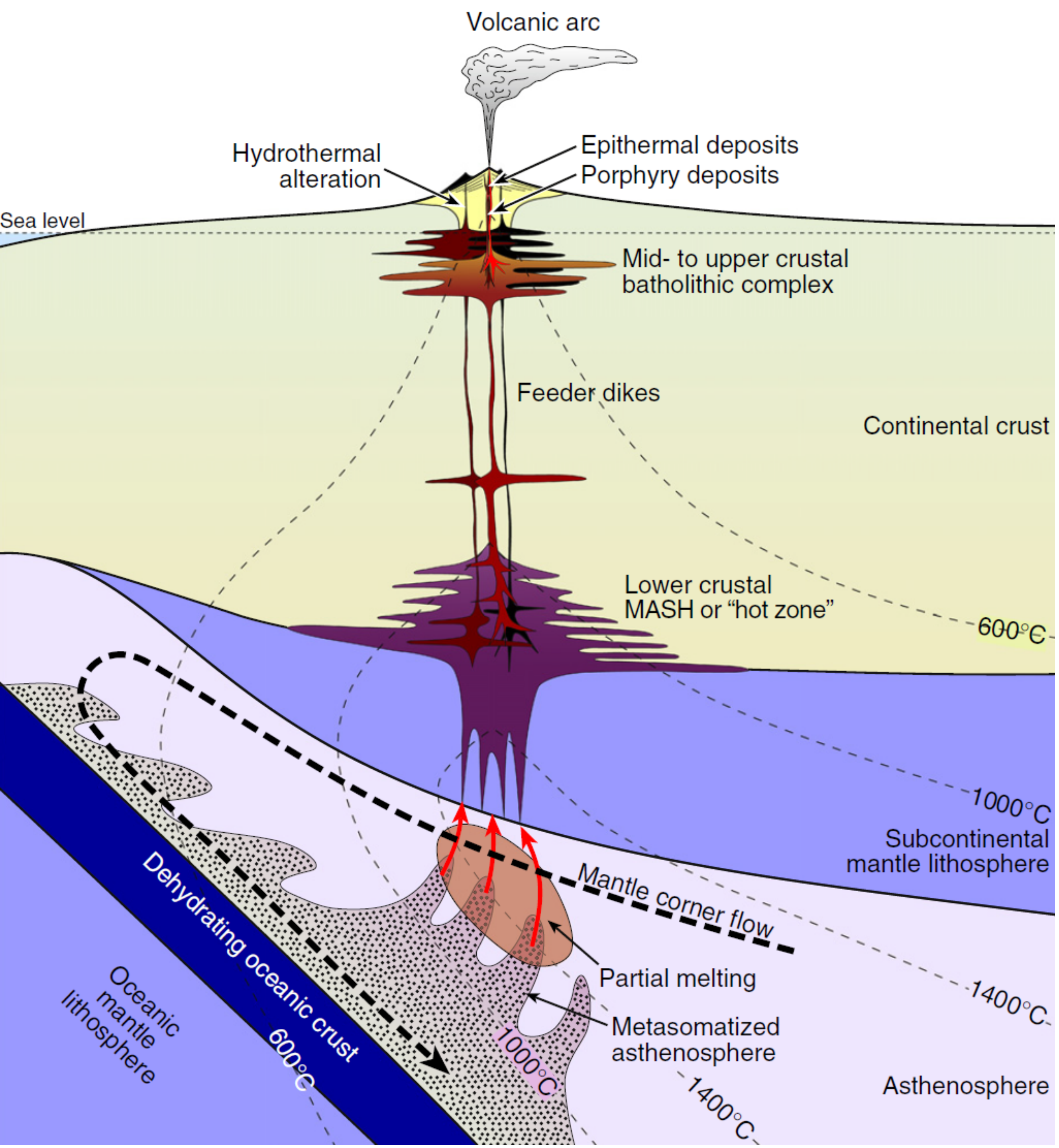
David R Cooke

CODES

Scope of this presentation

- **Overview of mineral systems that form in convergent margin settings around the Pacific rim**
- **Emphasis on porphyry mineral systems**
  - Porphyry copper – gold - molybdenum
  - High sulfidation epithermal gold
  - Intermediate sulfidation epithermal gold
  - Skarn deposits
- **Illustrate some variations on a theme that relate to local environments**
  - *Is there potential for similar discoveries in the Tasmanides?*

Multiple generations of hydrothermal alteration (potassic, phyllic and intermediate argillic alteration) in granodiorite porphyry, Highland Valley porphyry Cu-Au deposit, British Columbia



The porphyry Cu *system* model

- Porphyry magmas – partial melting of metasomatized mantle wedge
- Oxidised, hydrous magmas that can transport metals and sulfur
- Establishment of a mid to upper crustal magma chamber
- Shutdown of volcanism
- Fractional crystallisation and volatile exsolution
- Mineralisation and alteration

Reproduced from Richards (2011)

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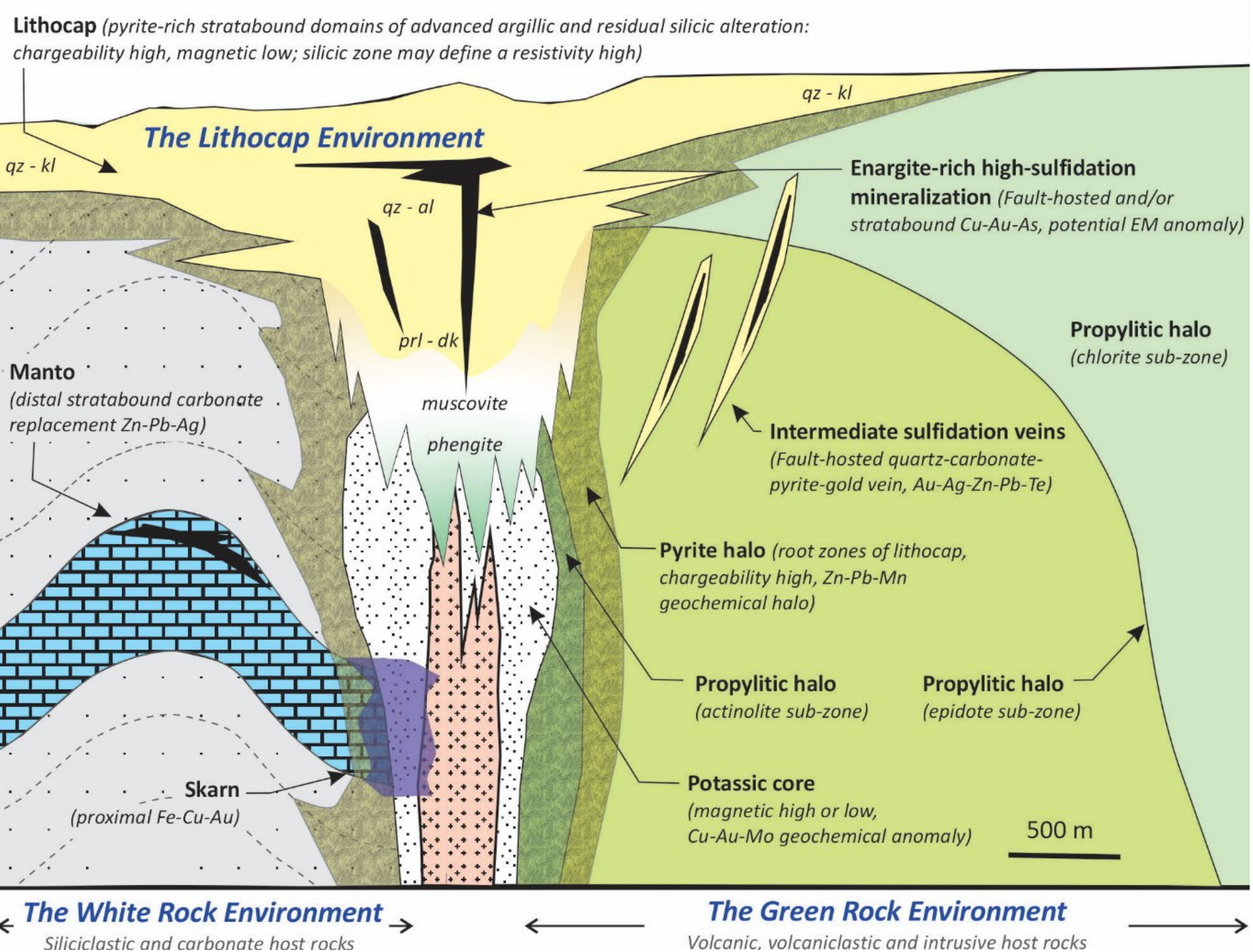
Porphyry districts

Volcanic- and sediment-hosted



Lithocap *(pyrite-rich stratabound domains of advanced argillic and residual silicic alteration: chargeability high, magnetic low; silicic zone may define a resistivity high)*

The Lithocap Environment

Enargite-rich high-sulfidation mineralization *(Fault-hosted and/or stratabound Cu-Au-As, potential EM anomaly)*

Propylitic halo *(chlorite sub-zone)*

Manto *(distal stratabound carbonate replacement Zn-Pb-Ag)*

Intermediate sulfidation veins *(Fault-hosted quartz-carbonate-pyrite-gold vein, Au-Ag-Zn-Pb-Te)*

Pyrite halo *(root zones of lithocap, chargeability high, Zn-Pb-Mn geochemical halo)*

Propylitic halo *(actinolite sub-zone)*

Propylitic halo *(epidote sub-zone)*

Skarn *(proximal Fe-Cu-Au)*

Potassic core *(magnetic high or low, Cu-Au-Mo geochemical anomaly)*

The White Rock Environment
Siliciclastic and carbonate host rocks

The Green Rock Environment
Volcanic, volcaniclastic and intrusive host rocks

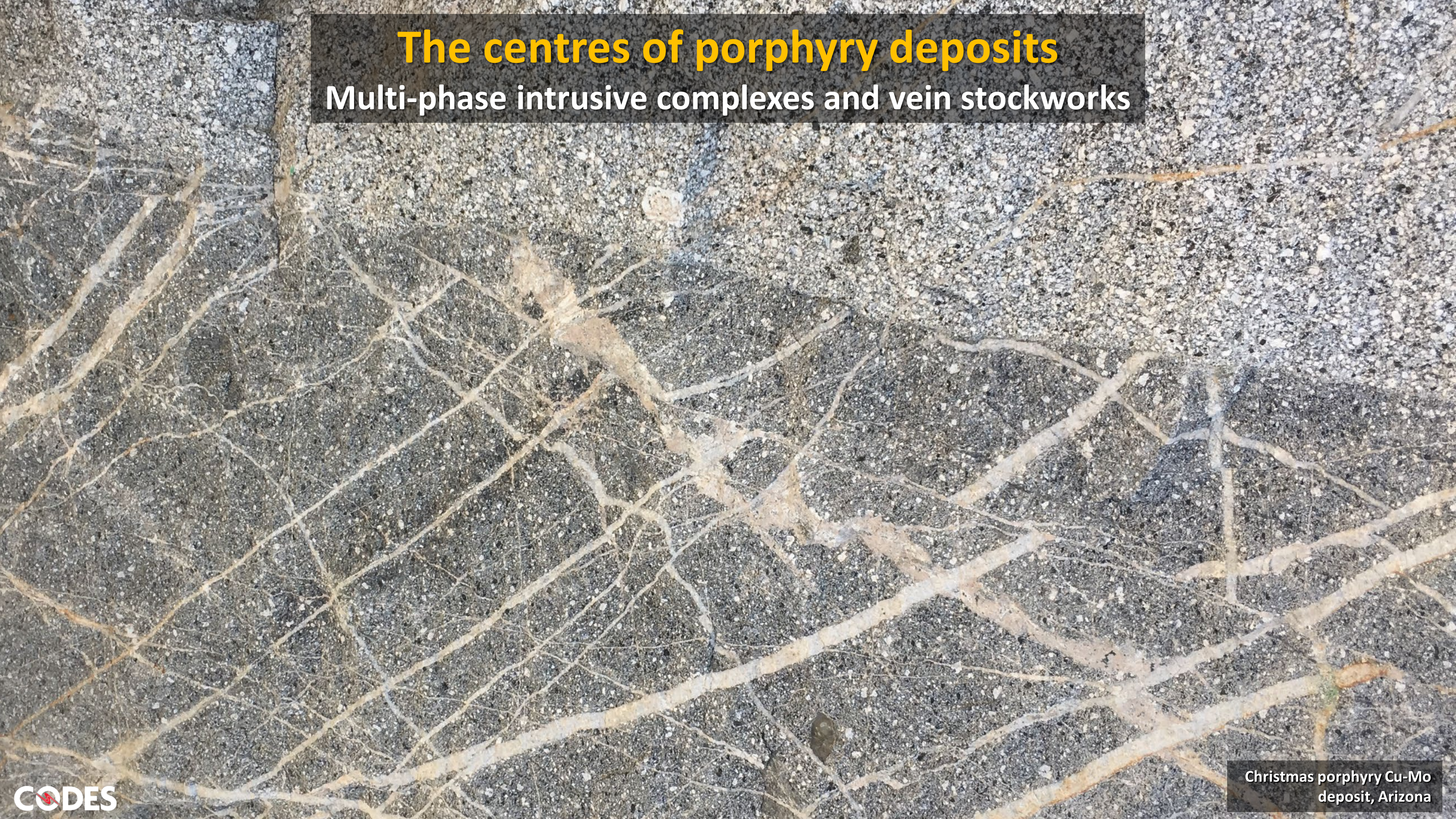
- ▨ **Composite porphyry stock**
- ▨ **Siliciclastic rocks**
- ▨ **Carbonate rocks**
- 🟩 **Volcanic and volcaniclastic rocks**

Alteration assemblages

- 🟨 **Lithocap and upflow zone**
  silicic, advanced argillic, phyllic and IA alteration
- 🟪 **Skarn**
  calc-silicate alteration, magnetite and sulfides
- ▨ **Pyrite halo**
  outer limit can vary markedly
- 🟩 **Propylitic** - chlorite sub-zone:
  chl-py-ab-cb
- 🟩 **Propylitic** - epidote sub-zone:
  epi-chl-py-ab-cb ± hm
- 🟩 **Propylitic** - actinolite sub-zone:
  act-epi-chl-py-ab-cb
- ▨ **Potassic**
  bi-Kf-qz-mt-anh-bn-cp-Au

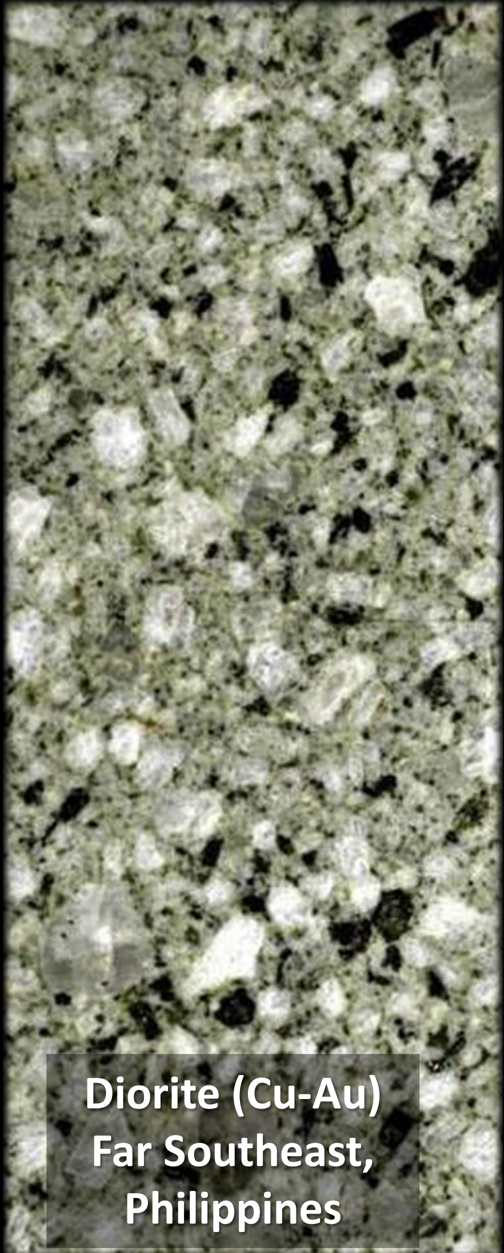
The centres of porphyry deposits

Multi-phase intrusive complexes and vein stockworks



Christmas porphyry Cu-Mo deposit, Arizona

Intrusive rock types



Diorite (Cu-Au)
Far Southeast,
Philippines

Tonalite (Cu-Au)
Tujuh Bukit,
Indonesia

Quartz monzonite
(Cu-Au)
Northparkes, Australia

Dacite (Cu-Mo)
Chuquicamata,
Chile

Granite
(Cu-Mo)
Yerington, USA

Central domains

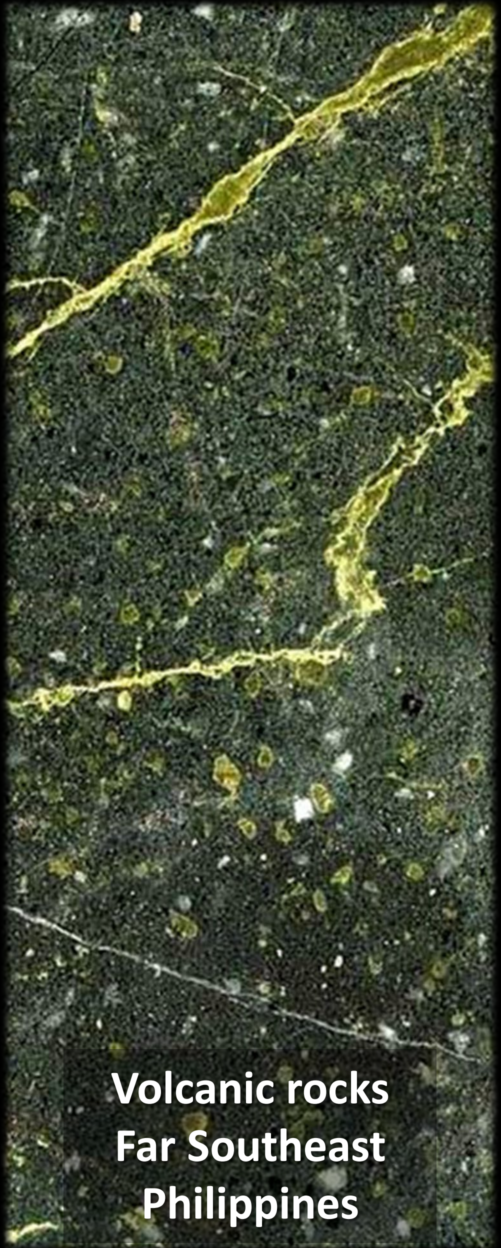
Biotite and/or orthoclase alteration

Selectively pervasive biotite alteration, Ampucao

Orthoclase alteration and quartz vein stockwork, Cerro Casale, Chile

Orthoclase-altered diorite, Boyongan

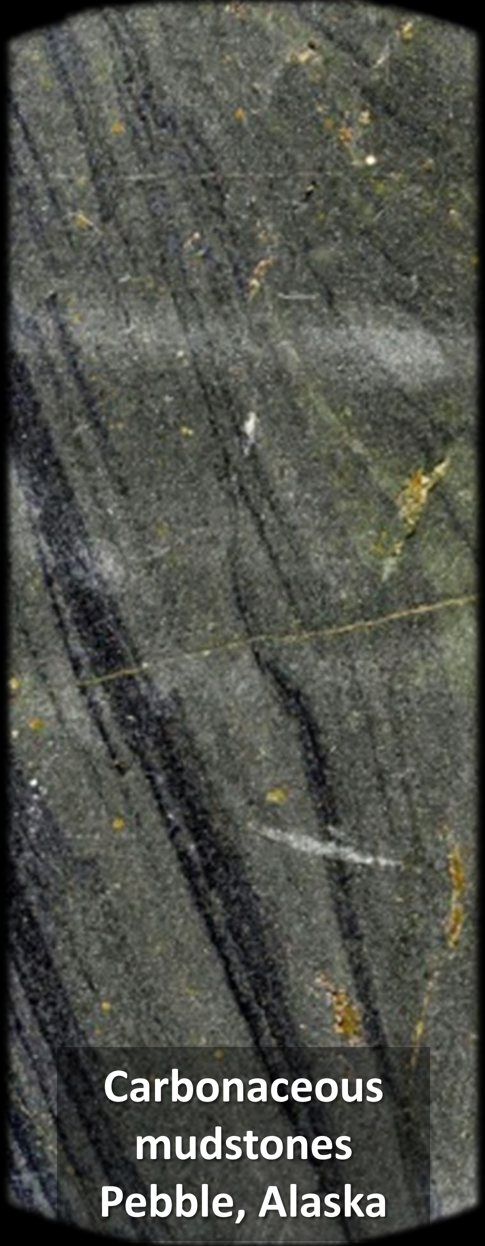
Distal alteration – protolith-dependent



Volcanic rocks
Far Southeast
Philippines

Batholiths
Highland Valley
Canada

Limestones
(skarn, marble)
Yerington, Nevada

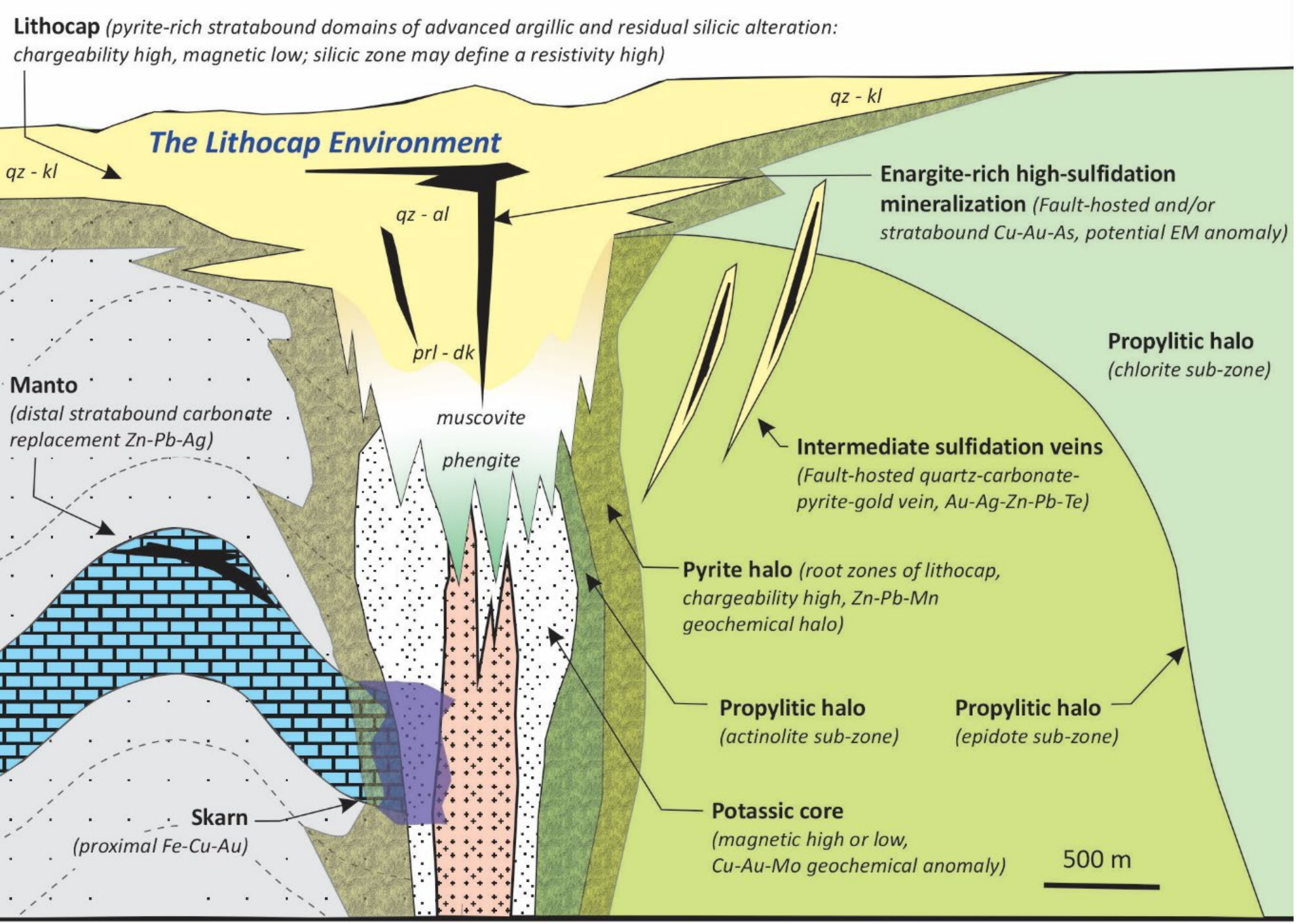


Carbonaceous
mudstones
Pebble, Alaska

Quartz sandstones
(quartzite)
Haquira, Peru

Porphyry districts

Volcanic- and sediment-hosted



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The Lithocap Environment

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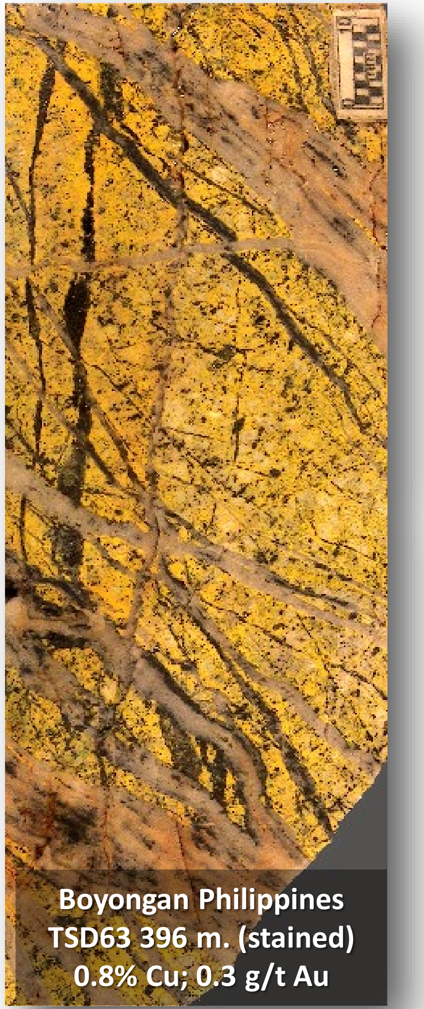
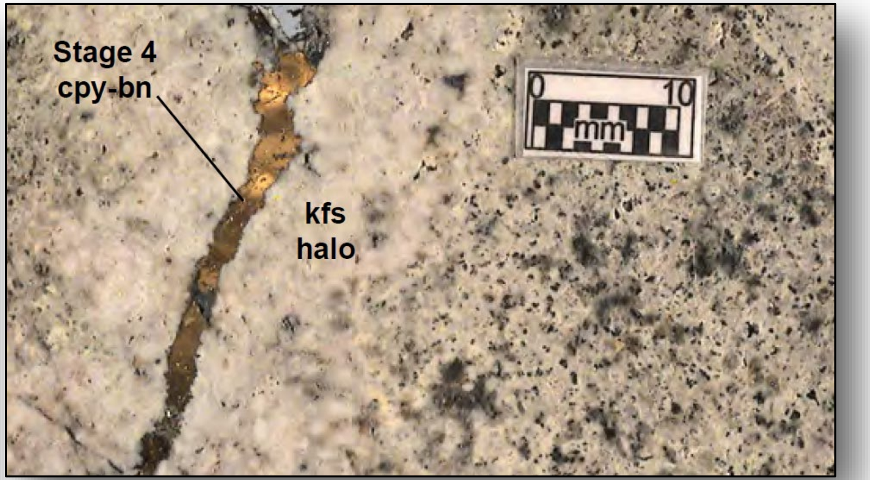
- ▨ **Potassic**
  bi-Kf-qz-mt-anh-bn-cp-Au

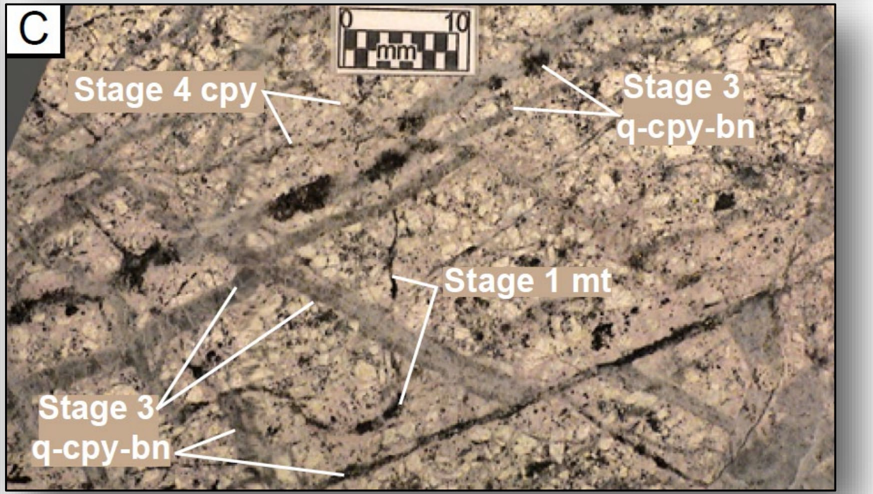
Timing of porphyry mineralisation

Mineralised potassic alteration

Boyongan Cu-Au porphyry, Philippines


Boyongan Philippines
TSD63 396 m. (stained)
0.8% Cu; 0.3 g/t Au





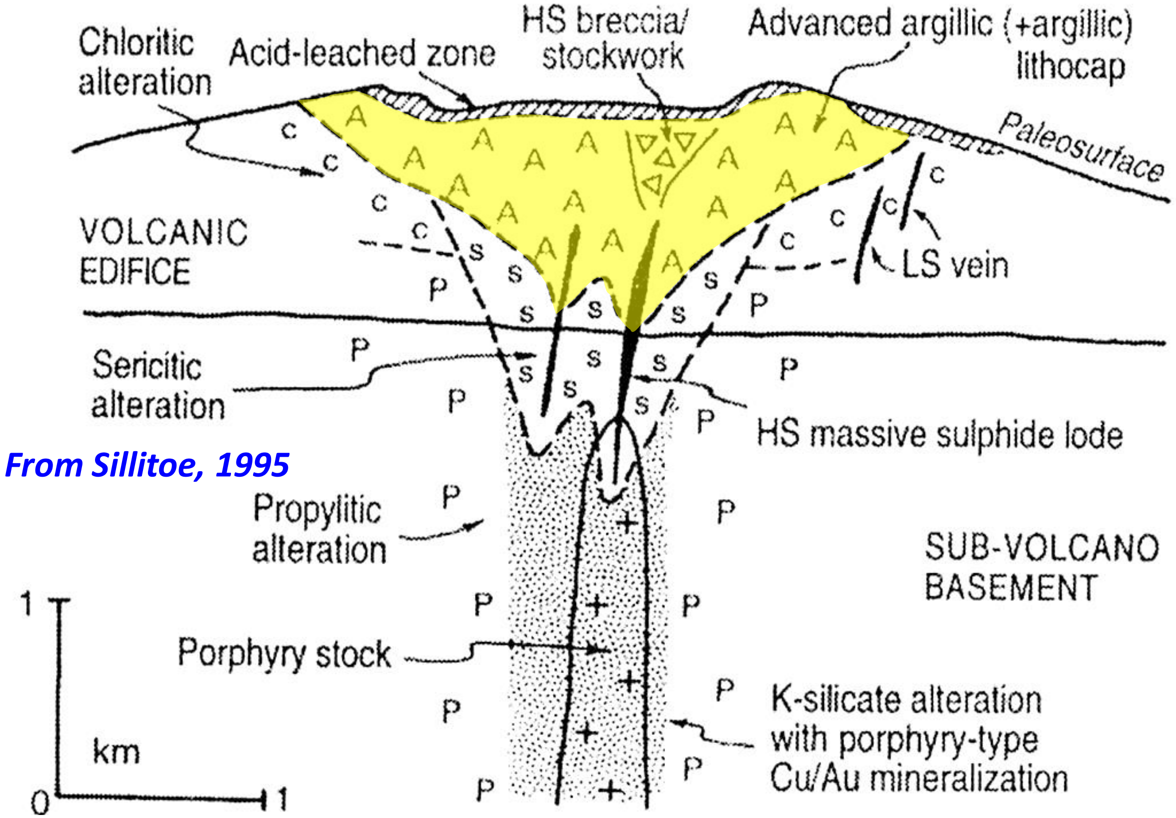
Mineralised phyllic alteration

Rio Blanco, Chile

Lithocaps and high sulfidation epithermal deposits

Cathedral Peak lithocap, Cerro Casale, Chile

What are lithocaps?



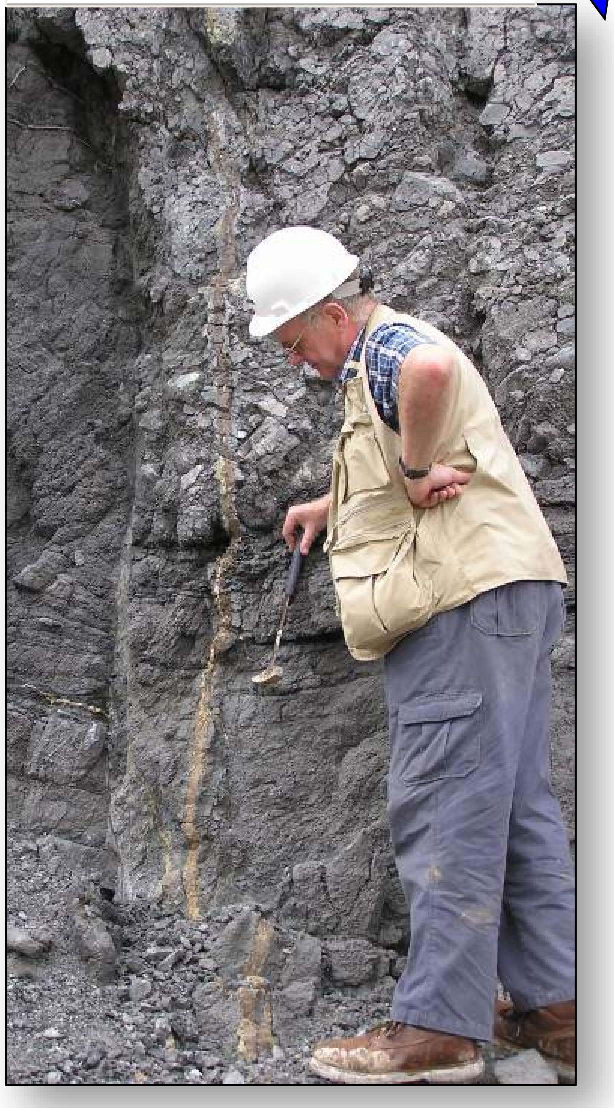
From Sillitoe, 1995

- **Large domains of hypogene pyritic silicic and advanced argillic alteration**
  - **They can be more than 10 km long and 1 km thick**
- **They are related to degassing of shallow-crustal hydrous magmas**
- **They define the main outflow zone between the hydrous intrusion and the paleosurface**
- **They may host HS epithermal deposits and overlie porphyry deposits**

Tantahuatay lithocap, Peru

Lithocaps

Lateral outflow



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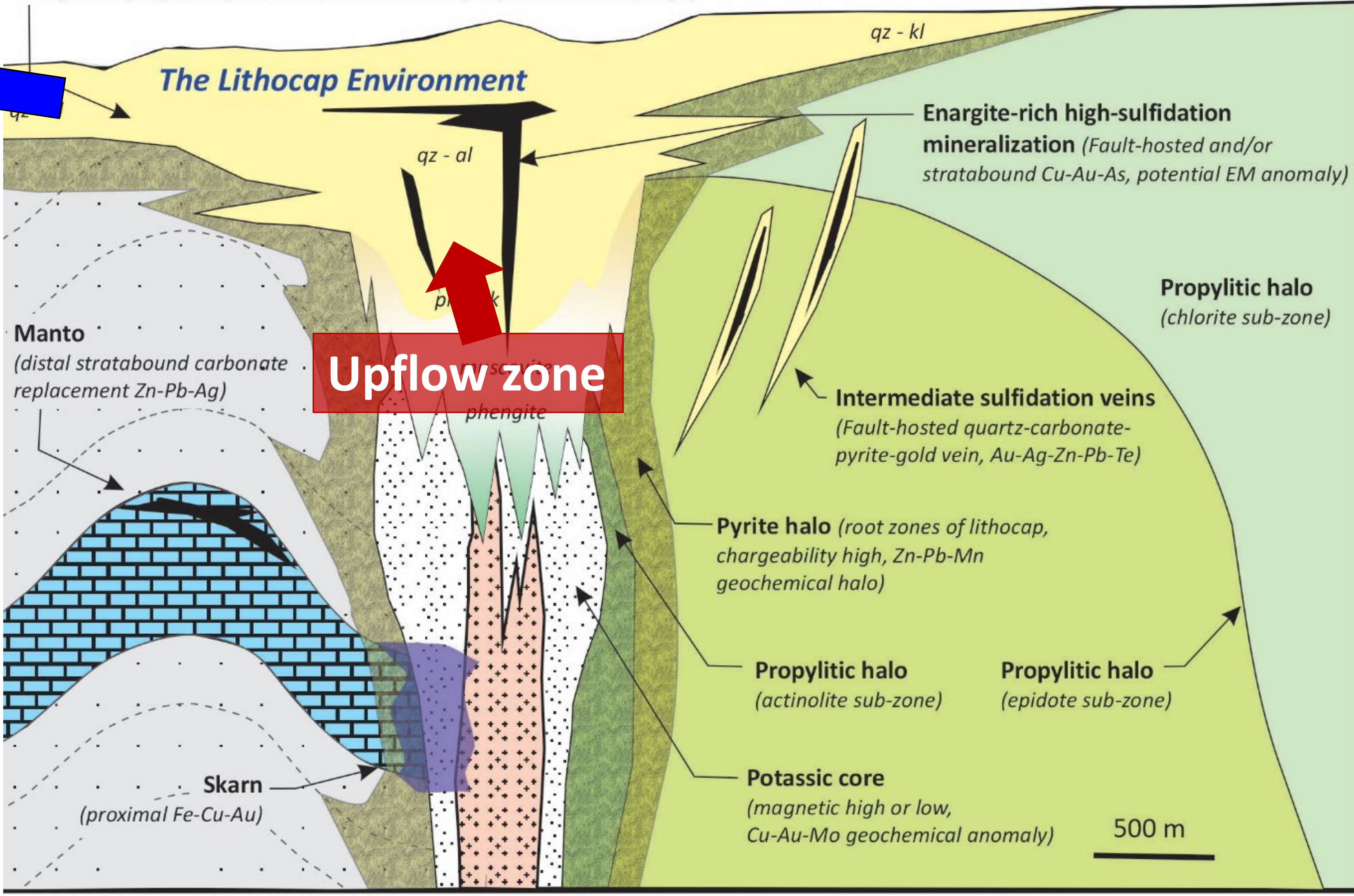


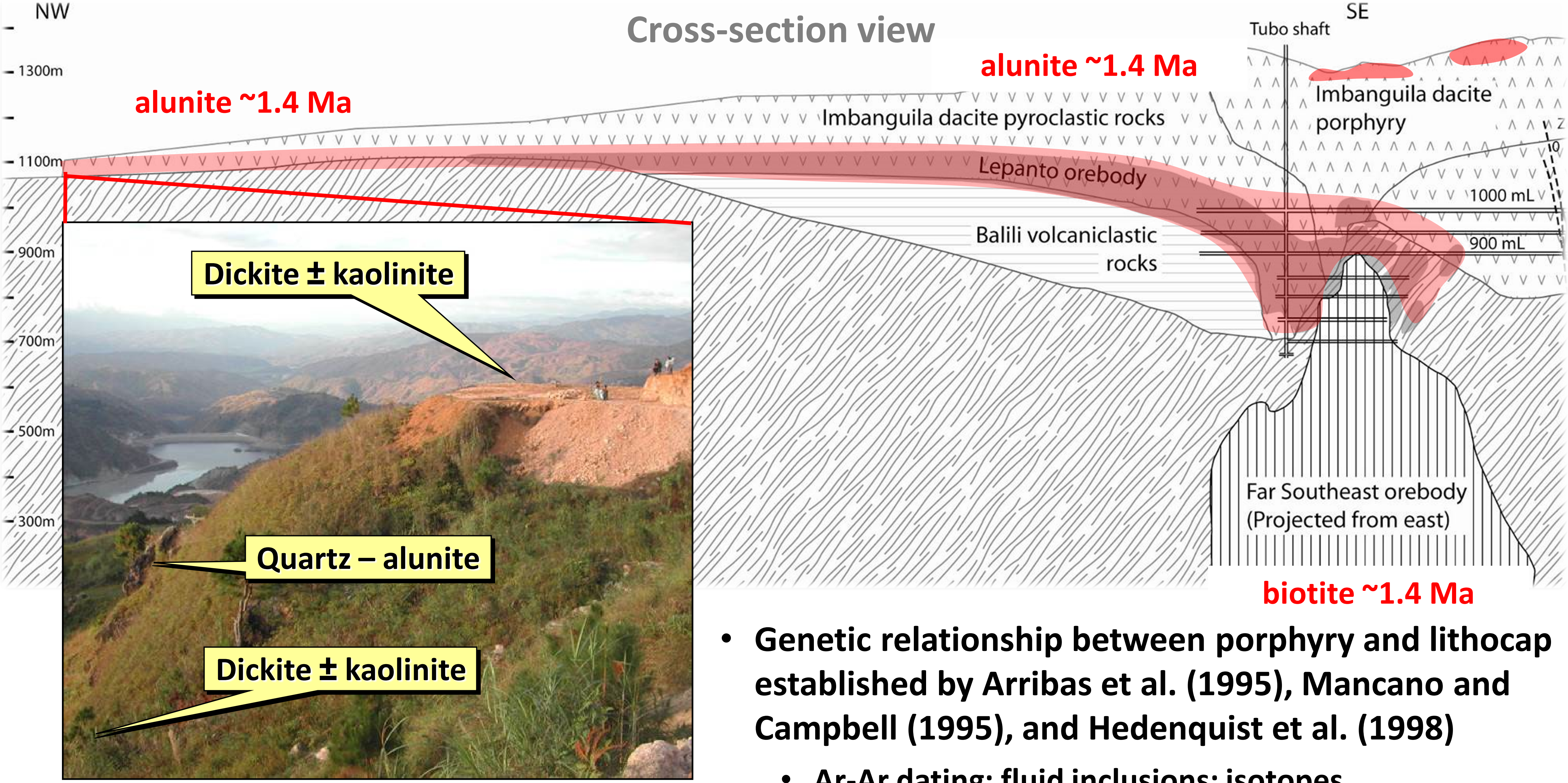
The White Rock Environment

Siliciclastic and carbonate host rocks

The Green Rock Environment

Volcanic, volcaniclastic and intrusive host rocks

FSE porphyry, Mankayan lithocap and Lepanto HS mineralization



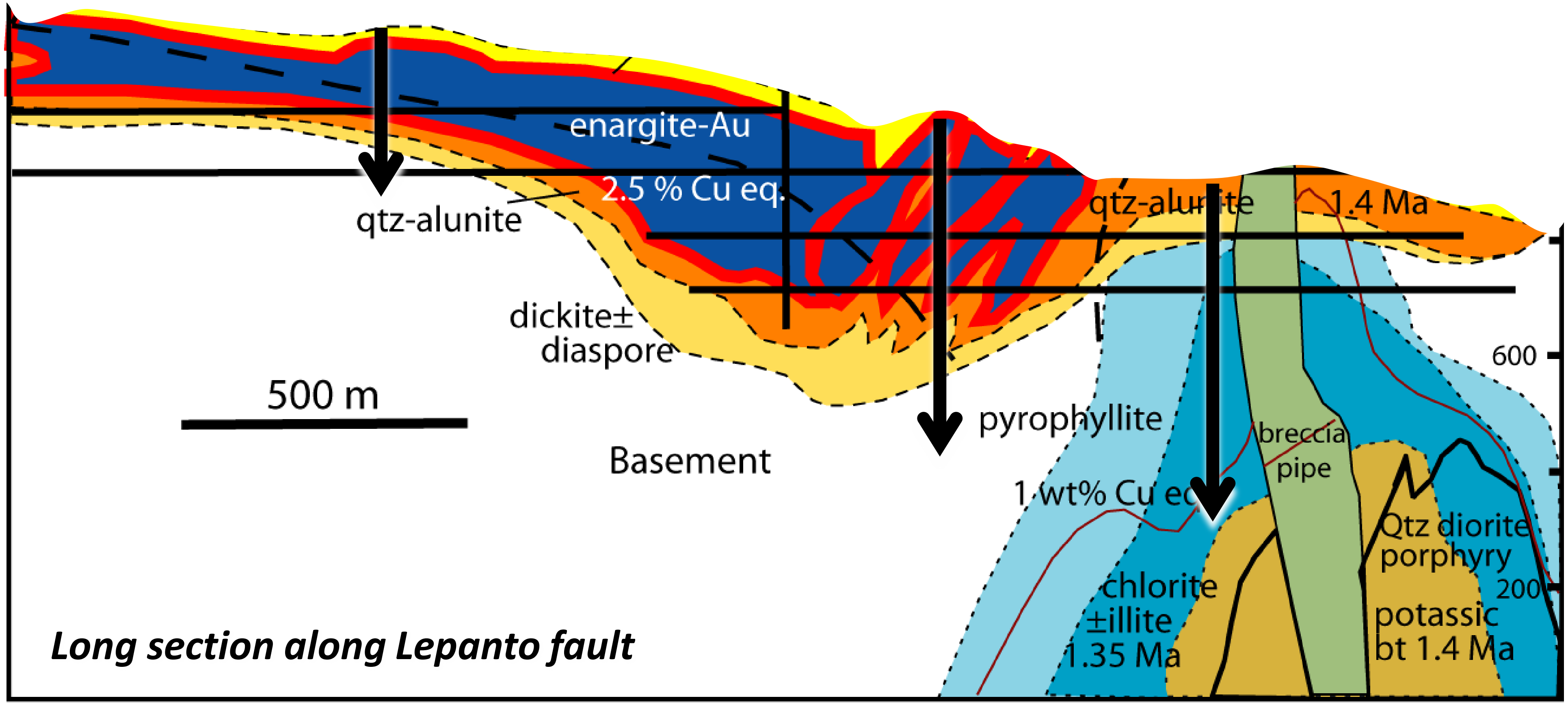
- **Genetic relationship between porphyry and lithocap established by Arribas et al. (1995), Mancano and Campbell (1995), and Hedenquist et al. (1998)**
  - **Ar-Ar dating; fluid inclusions; isotopes**


Vuggy quartz, Lepanto

Lepanto - Far Southeast, Philippines

~1 Mt Cu, 4 Moz Au and 5 Mt Cu, 20 Moz Au

- **Upward flare of leaching due to cooling**
- **Hydraulic gradient causes offset of lithocap from causative intrusion**
- **Asymmetric alteration zonation likely the <u>rule</u> rather than exception**



Long section along Lepanto fault

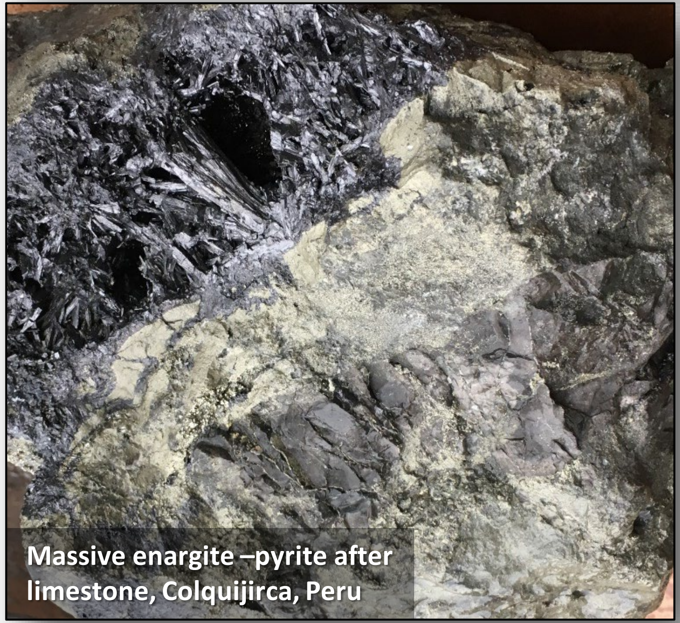
Hedenquist et al. (1998); Hedenquist and Taran (2010)

Section courtesy of Jeff Hedenquist

Lithocaps and HS deposits

Vertical alteration zonation

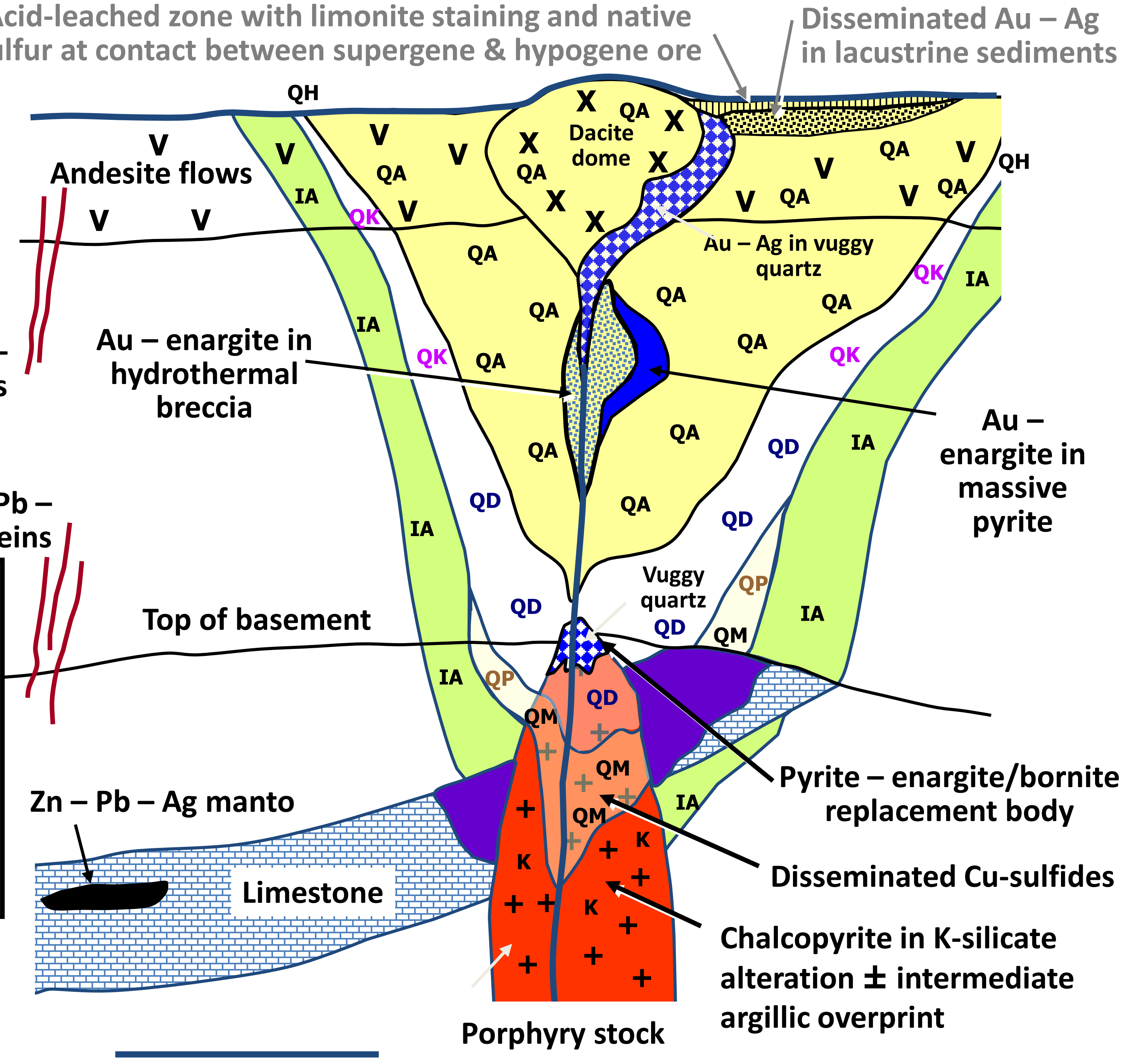
Au in vuggy quartz – La Zanja, Peru



Massive enargite –pyrite after limestone, Colquijirca, Peru

ALTERATION

- IA: Intermediate argillic
- K: K-silicate
- QA: quartz – alunite
- QD: quartz – dickite
- QH: quartz – halloysite
- QK: quartz – kaolinite
- QP: quartz – pyrophyllite
- QM: quartz – muscovite



Section modified from Sillitoe (1999)

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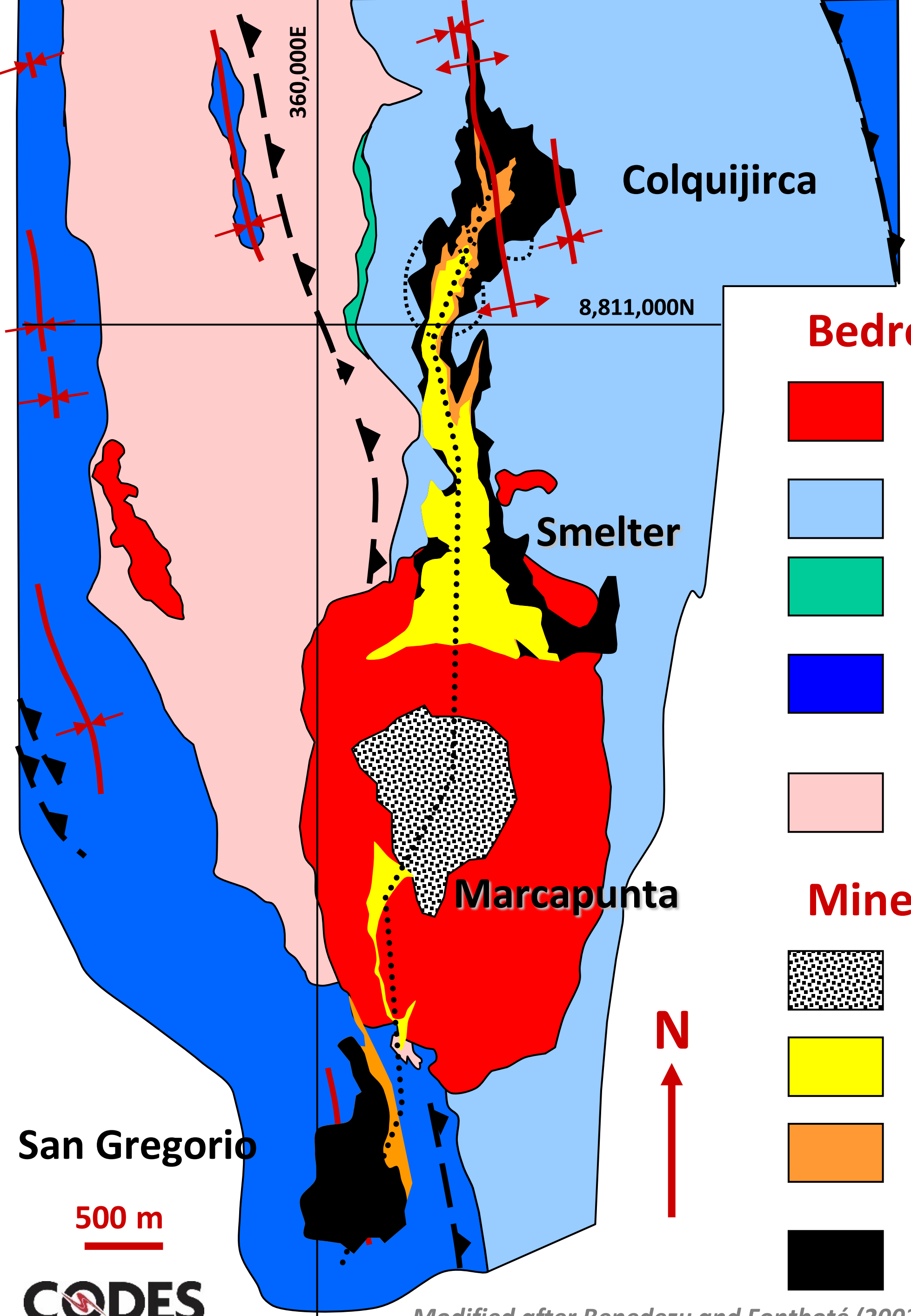
Colquijirca, Peru

Geology



Modified after Benedezu and Fontboté (2003)

Bedrock Geology (pre-Quaternary)

🟥 Marcapunta Diatreme and Dome Complex *(Miocene)*

🟦 Calera Member Limestones } Pocobamba Fm *(Eocene)*

🟩 Shuco Conglomerate

🟦 Pucara Group limestones and dolostones *(Upper Triassic – Lower Jurassic)*

⬜ Mitu Group redbeds, sandstones *(Permian-Triassic)*

Mineralisation

▨ Vuggy quartz – alunite – dickite – kaolinite (pyrophyllite-zunyite-illite)

🟨 Enargite – pyrite - alunite (Cu ± Au)

🟧 Pyrite – chalcopyrite – tennantite – bornite -dickite – kaolinite (± alunite – Bi-sulfosalts)

⬛ Pyrite – sphalerite – galena – kaolinite – dickite (± alunite – siderite – ankerite – hematite)

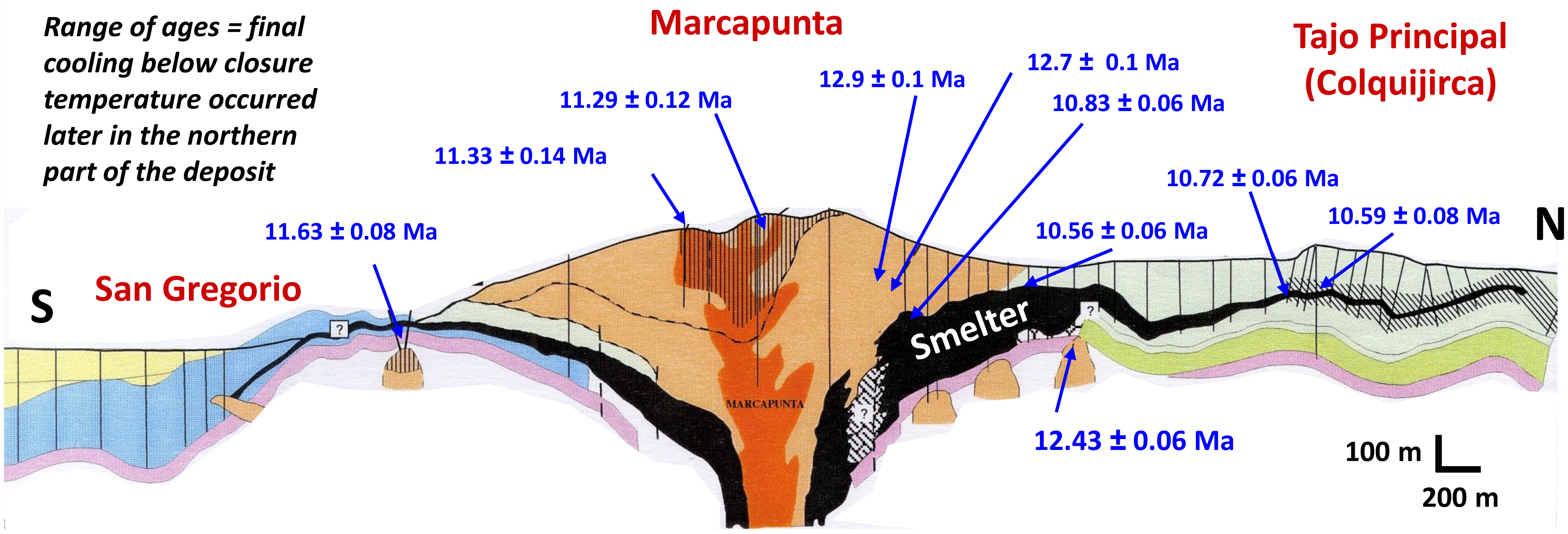
Covellite – gold mineralisation, Vuggy quartz, Marcapunta

Colquijirca: N-S Cross-section

Geochronology from Benedezú et al. (2003)

Marcapunta: enargite-pyrite ore (CM2-452-03-273.50m)

Range of ages = final cooling below closure temperature occurred later in the northern part of the deposit



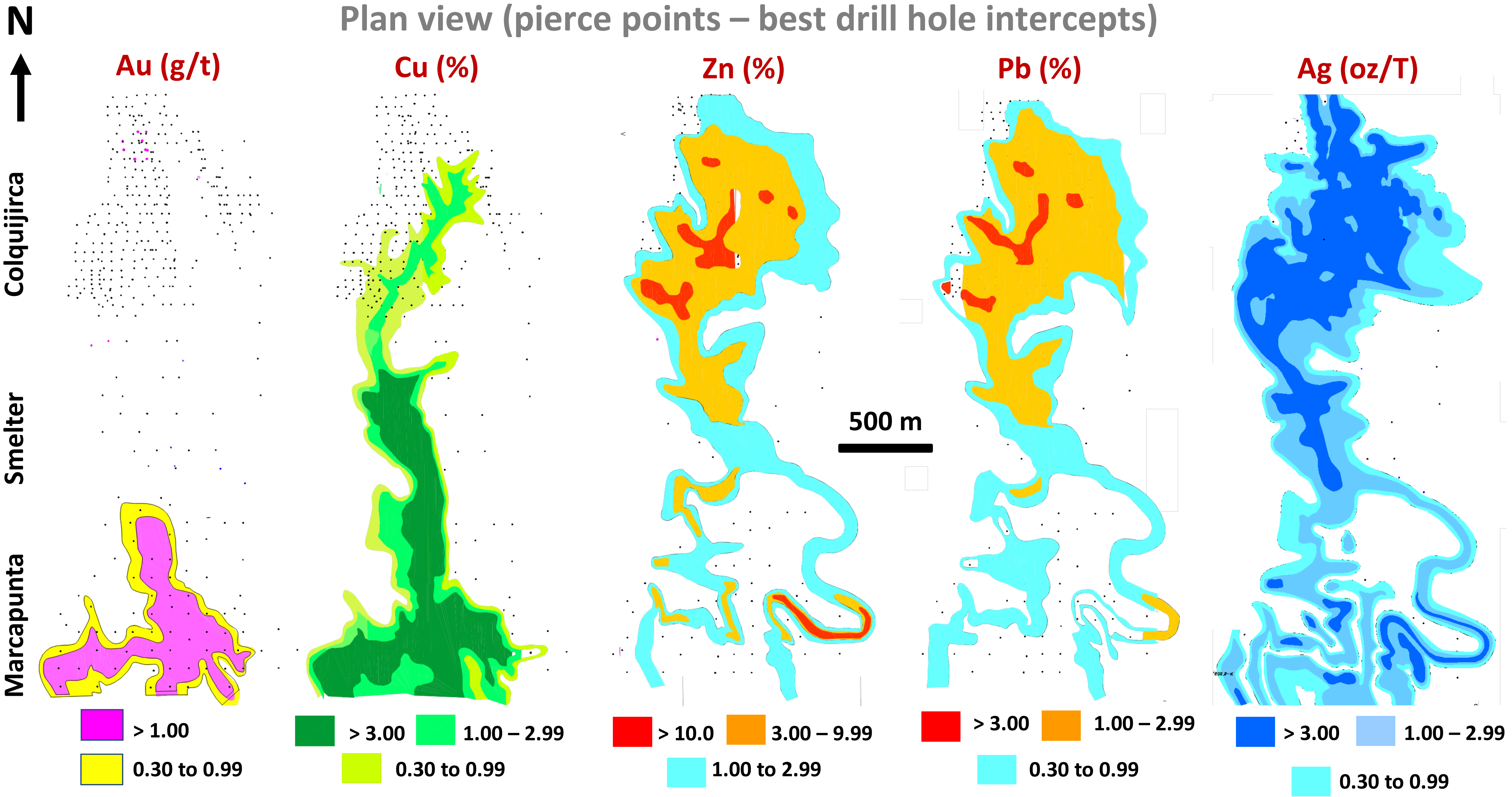
- Quaternary deposits
- Breccias / pyroclastics } *Marcapunta Complex (Miocene)*
- Domes
- Calera Member } *Pocobamba Fm (Eocene)*
- Shuco member
- Pucara Group (Upper Tr – Lower J)
- Mitu Group (Permo-Triassic)

- Vuggy quartz – alunite – dickite – kaolinite (pyrophyllite)
- Enargite – pyrite – cpy – tennantite ore
- Sphalerite – galena – pyrite – dickite / kaolinite – siderite – alunite

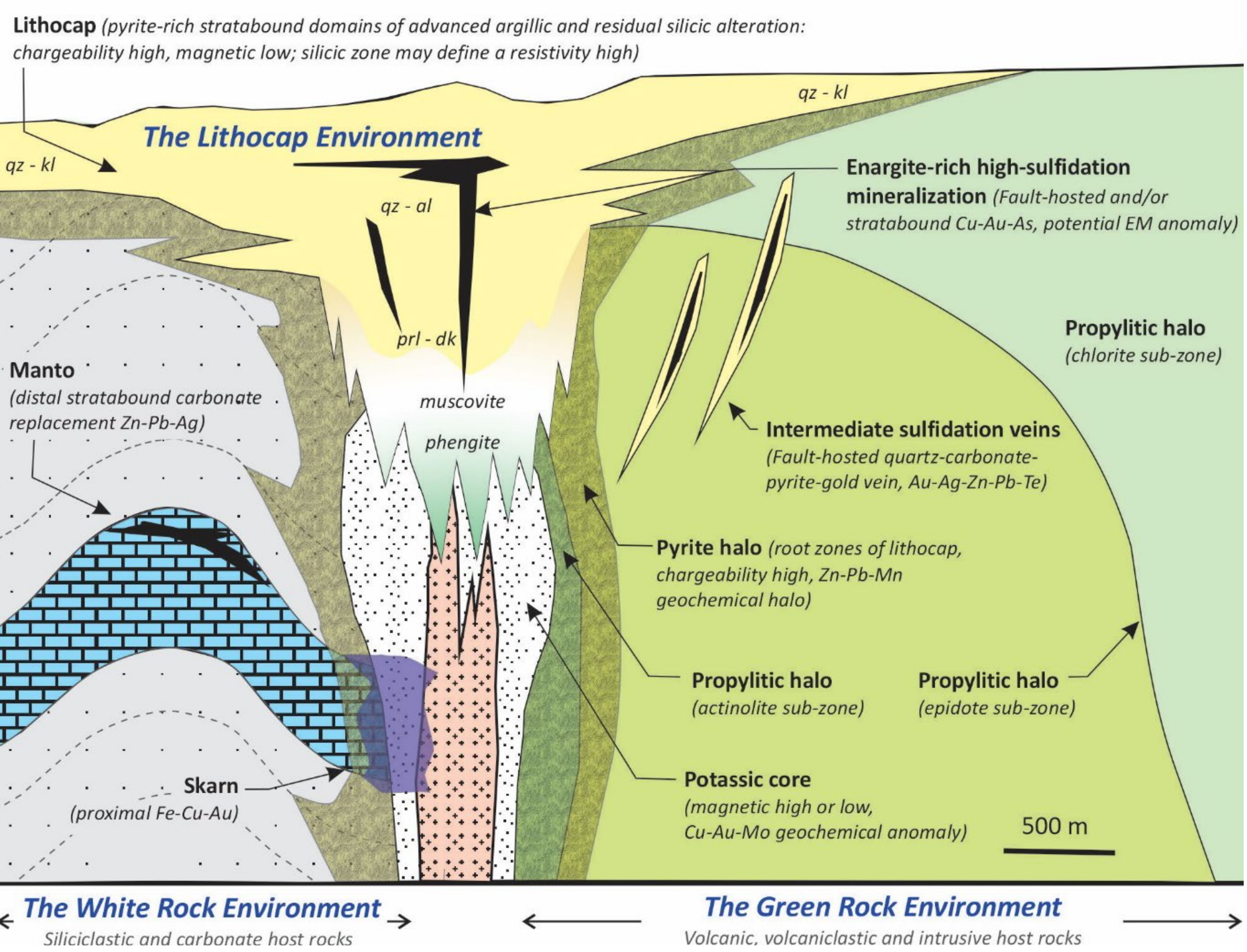
After Coughlin and Munoz (2003) and Benedezu and Fontbote (2002)

Colquijirca, Peru – Metal zoning

Plan view (pierce points – best drill hole intercepts)



IS-LS epithermal deposits



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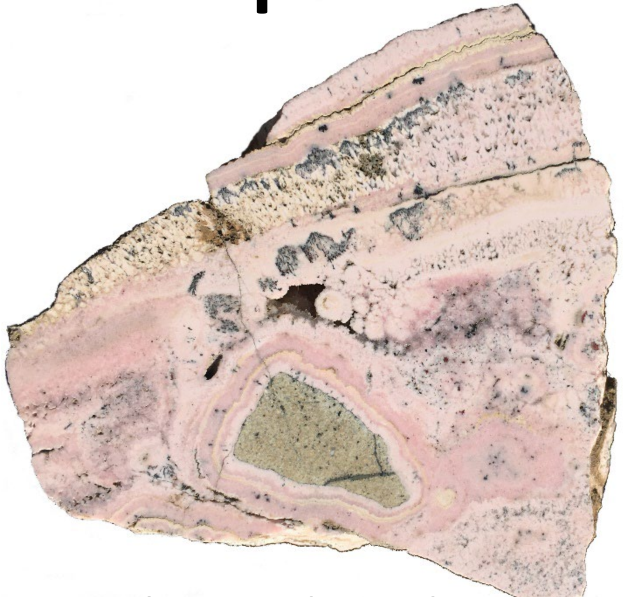
The White Rock Environment

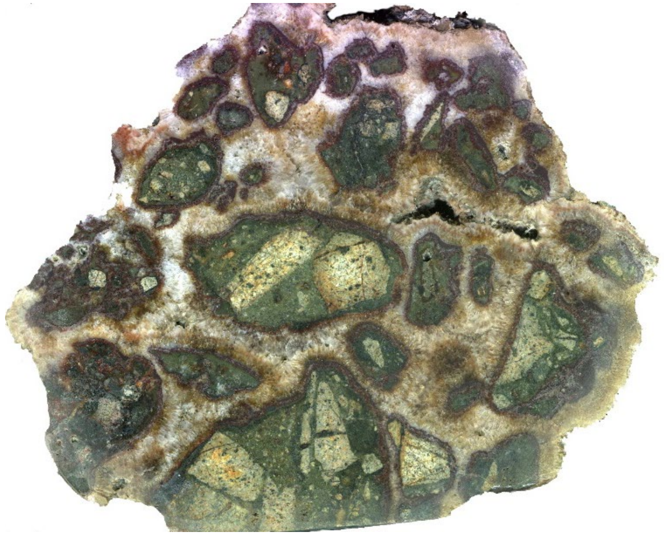
Siliciclastic and carbonate host rocks

The Green Rock Environment

Volcanic, volcaniclastic and intrusive host rocks

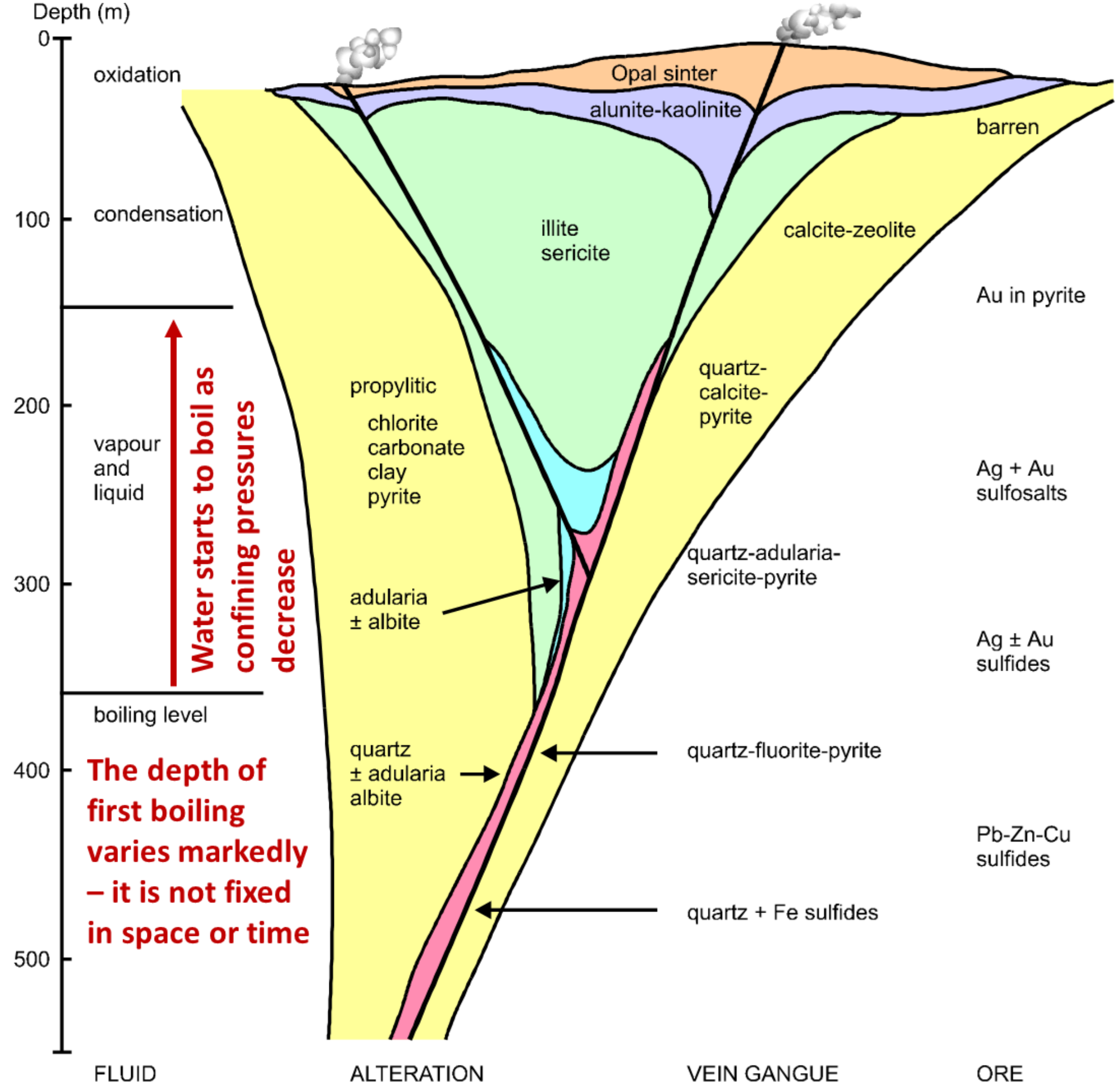


Kelian IS Au-Ag deposit, Indonesia



Sierra Oro IS Au-Ag deposit, Philippines

Intermediate and low sulfidation epithermal deposits



Water starts to boil as confining pressures decrease

The depth of first boiling varies markedly – it is not fixed in space or time

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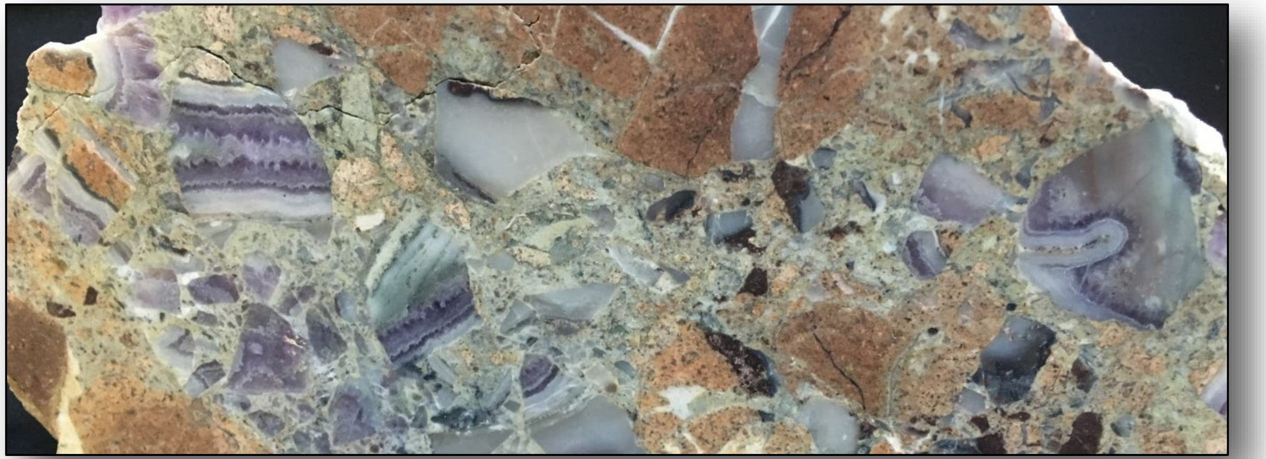
Epithermal model for LS veins – modified from Buchanan (1981)

Creede LS Au-Ag deposit, Colorado



Yueyang IS epithermal Ag breccia vein, Zijinshan, China

Skarns

Garnet skarn in marble, Copper Casting skarn, Yerington district, Nevada

Reaction skarns

Thermal metamorphism – local chemical mass transfer across bedding planes

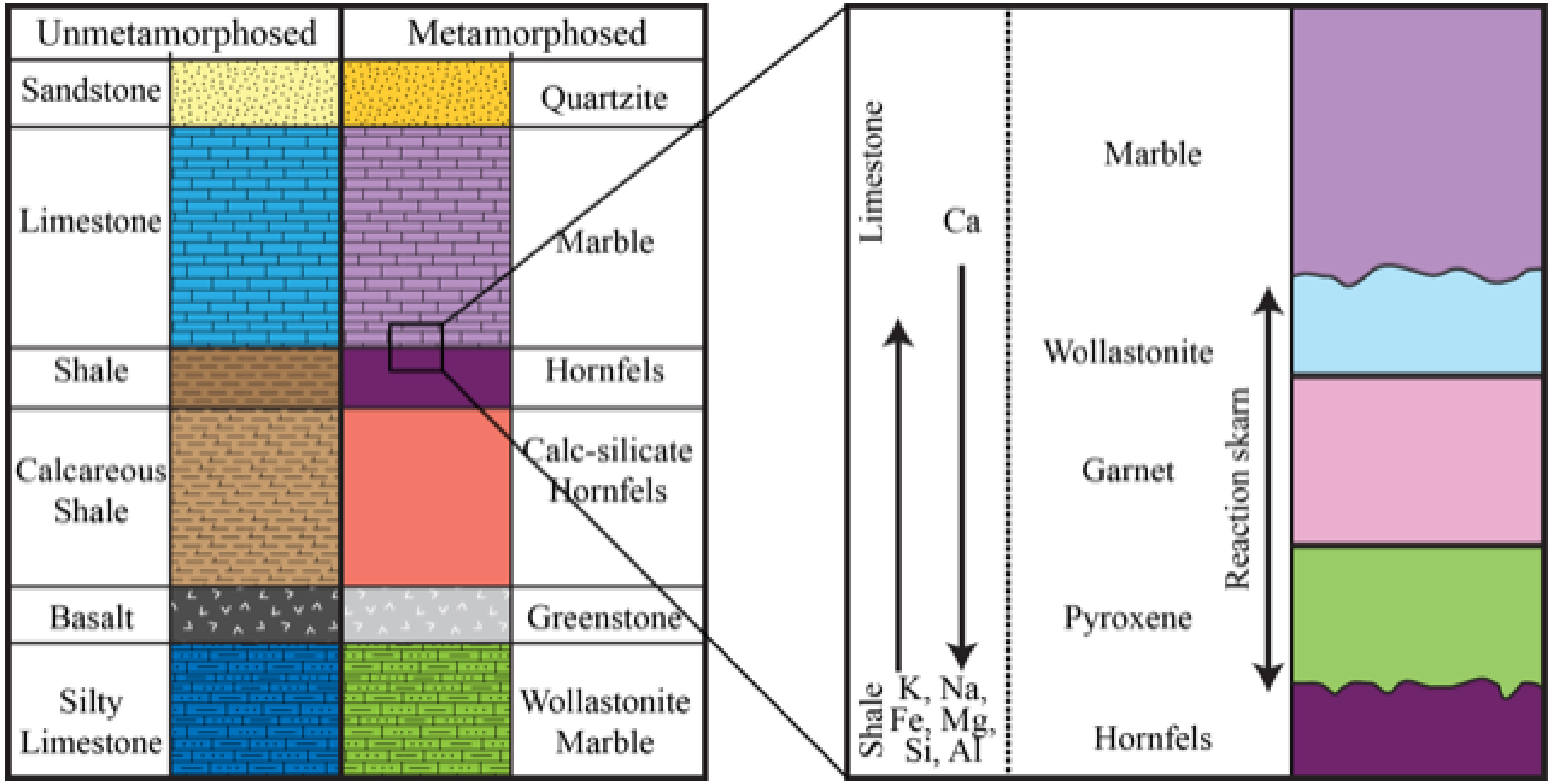
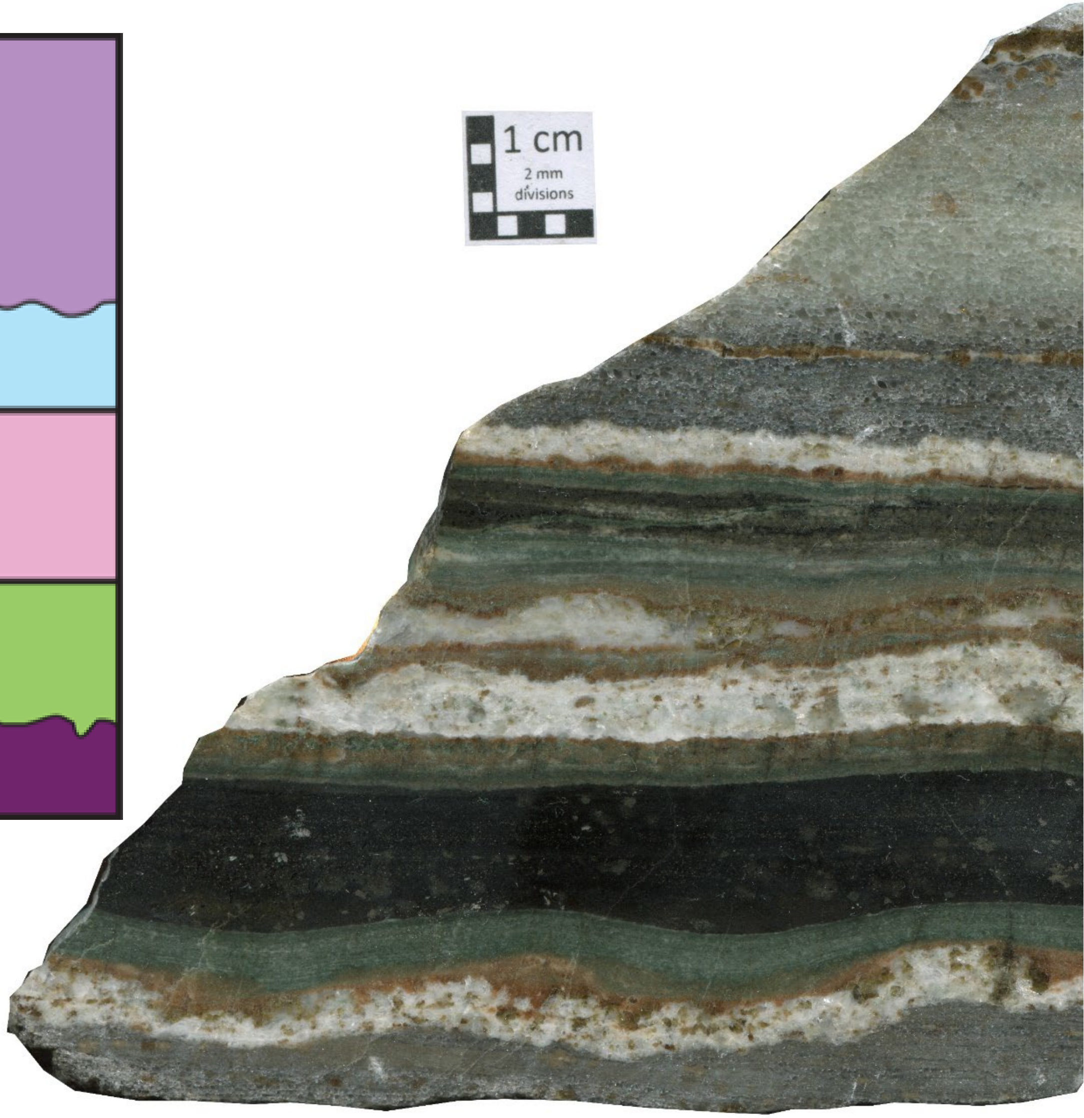


Figure modified from Meinert (1992)



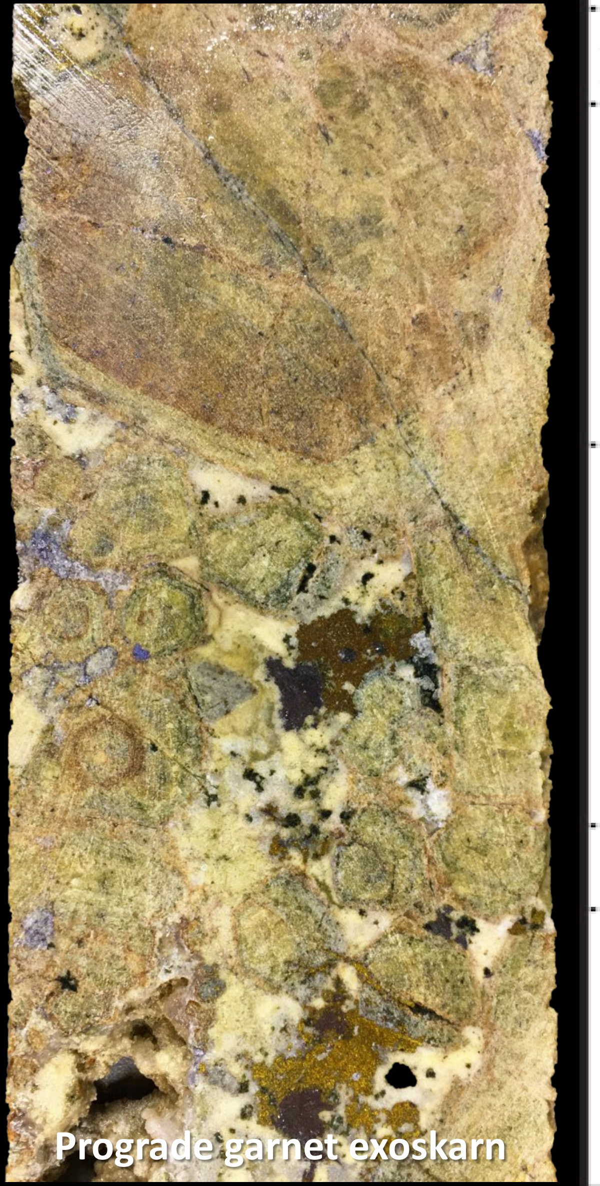
Banded reaction skarn: garnet and pyroxene layers intercalated with biotite hornfels and calcic marble, King Island scheelite deposit, Tasmania

Infiltration skarns

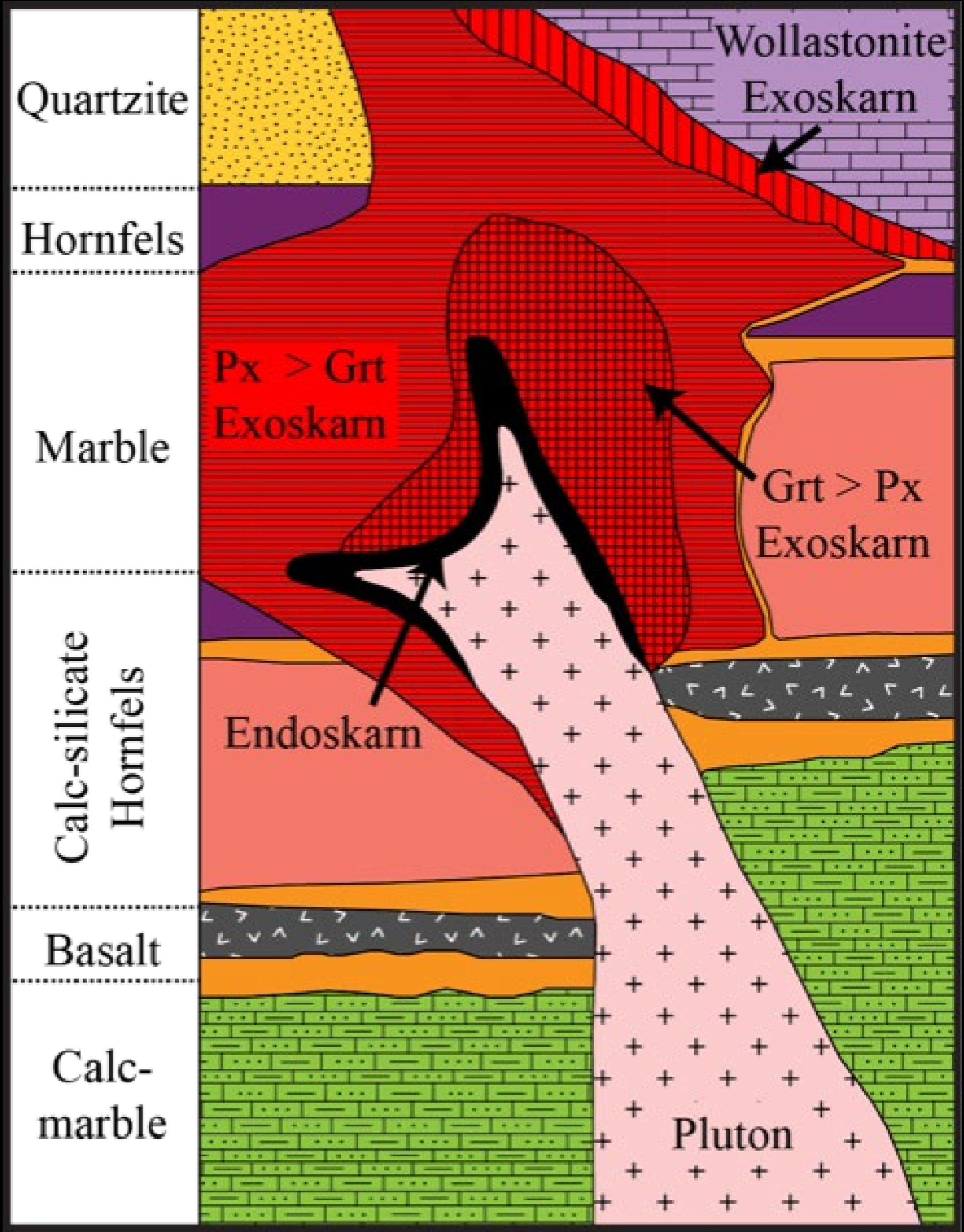
Metasomatism due to magmatic fluid release


Endoskarn


Exoskarn


Prograde garnet exoskarn

- Endoskarn – within intrusion
- Exoskarn – outside intrusion (forms in adjacent wallrocks)
- Prograde – early, high T skarn



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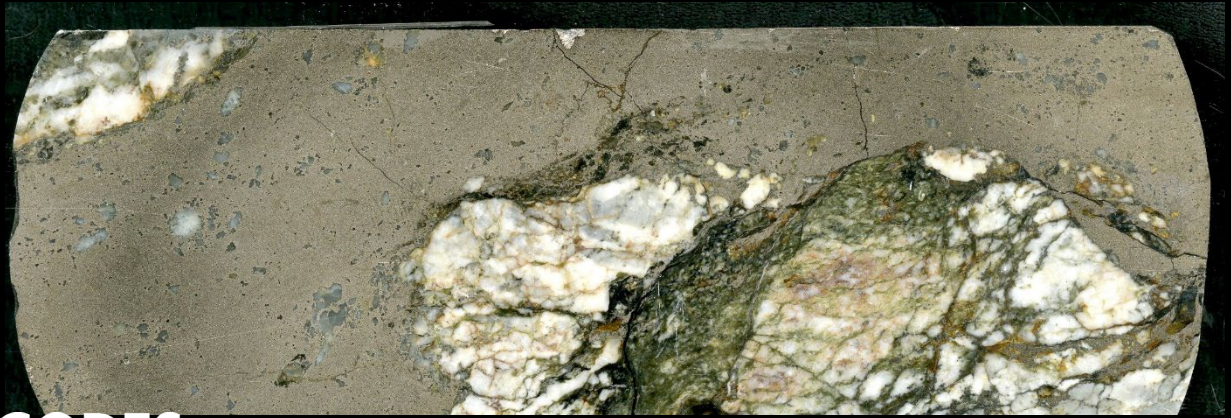
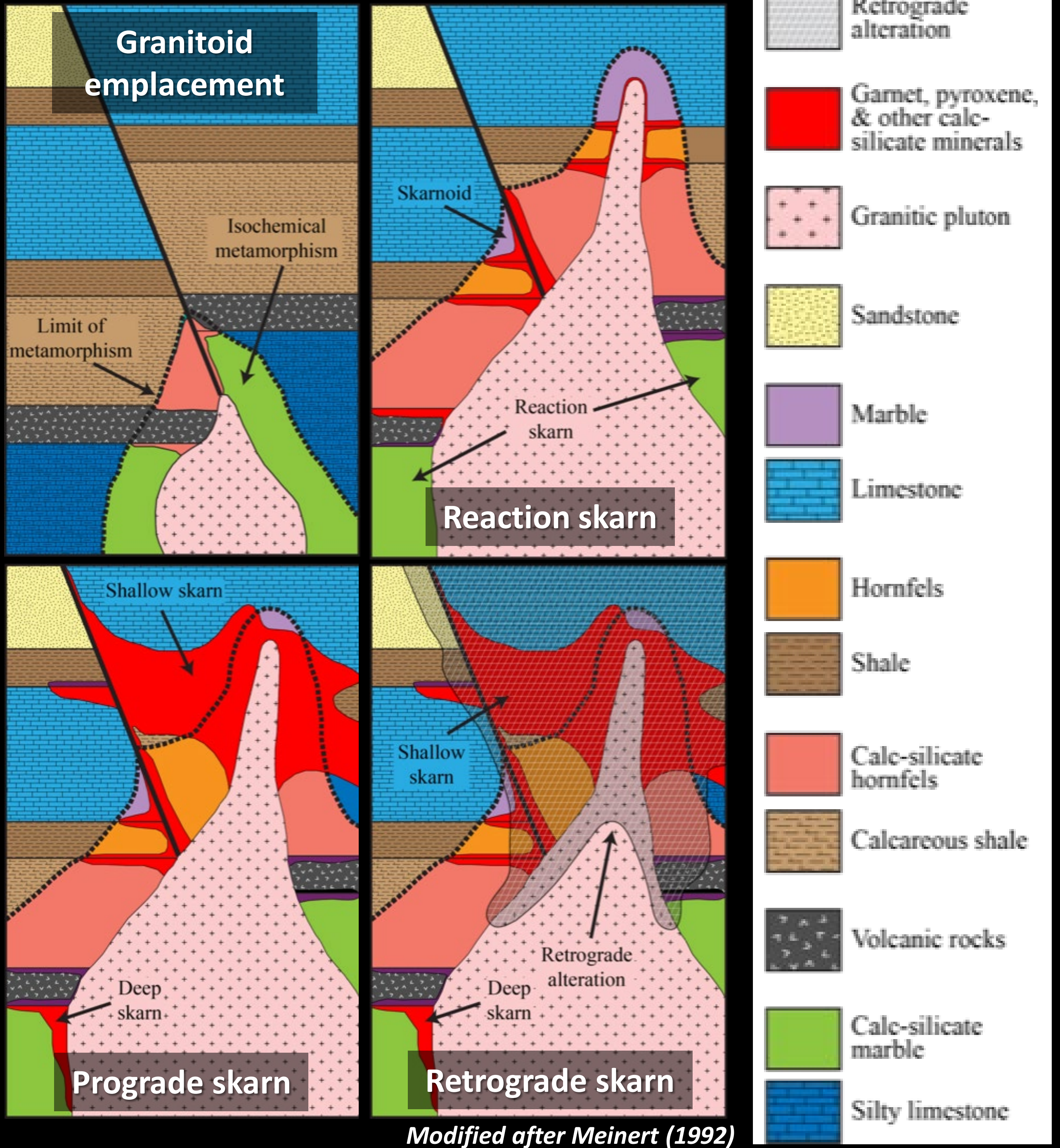
Retrograde skarns

Lower-T alteration and mineralisation

Massive epidote skarn cut by calcite veins with chrysocolla coatings, Yerington, Nevada



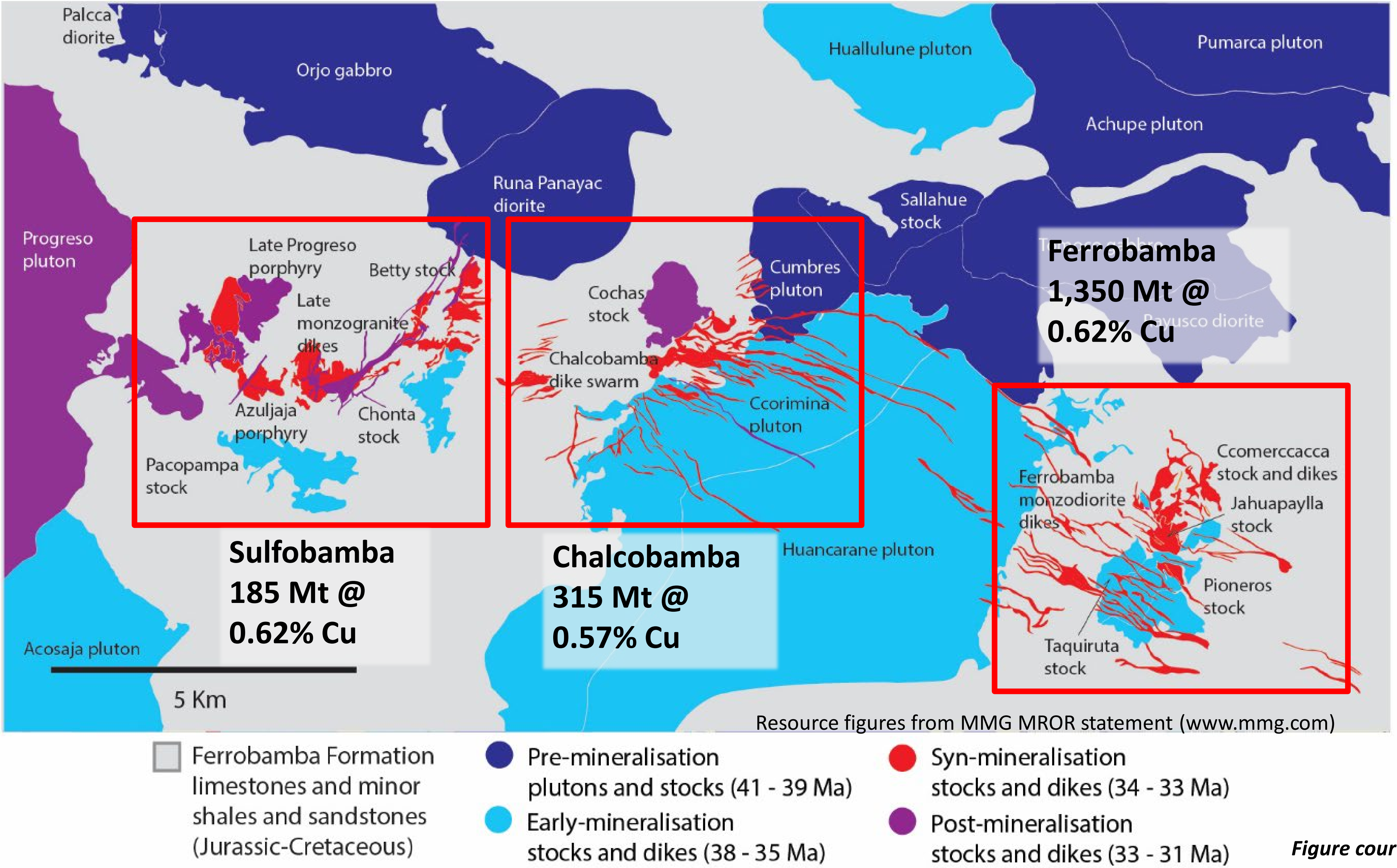
Massive pyrrhotite – cassiterite replacement of dolomite, Renison Bell Sn mine, Tasmania



Modified after Meinert (1992)

Las Bambas Cu skarn district, Peru

Ferrobamba, Chalcobamba, and Sulfobamba



Sulfobamba
185 Mt @
0.62% Cu

Chalcobamba
315 Mt @
0.57% Cu

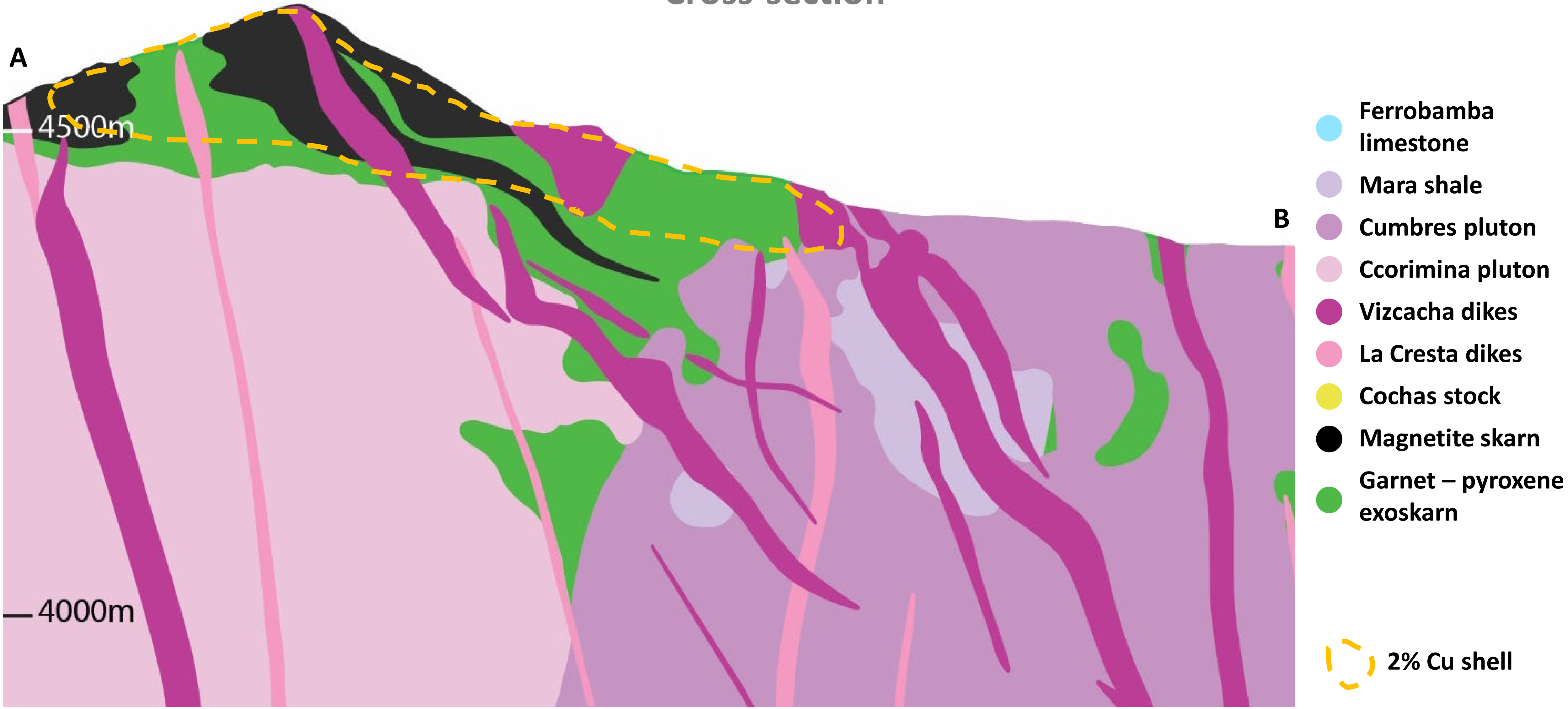
Ferrobamba
1,350 Mt @
0.62% Cu

Resource figures from MMG MROR statement (www.mmg.com)

Figure courtesy of Amos Garay

Chalcobamba

Cross-section



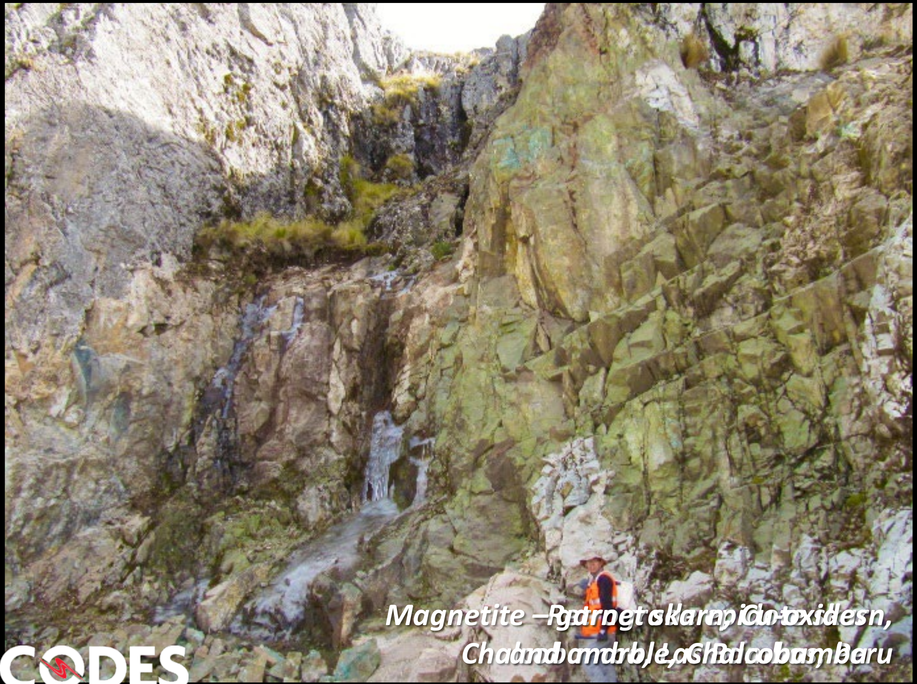
Chalcobamba section courtesy of Las Bambas

Slide courtesy of Amos Garay

Chalcobamba

Retrograde skarn

Retrograde epidote skarn, Chalcobamba



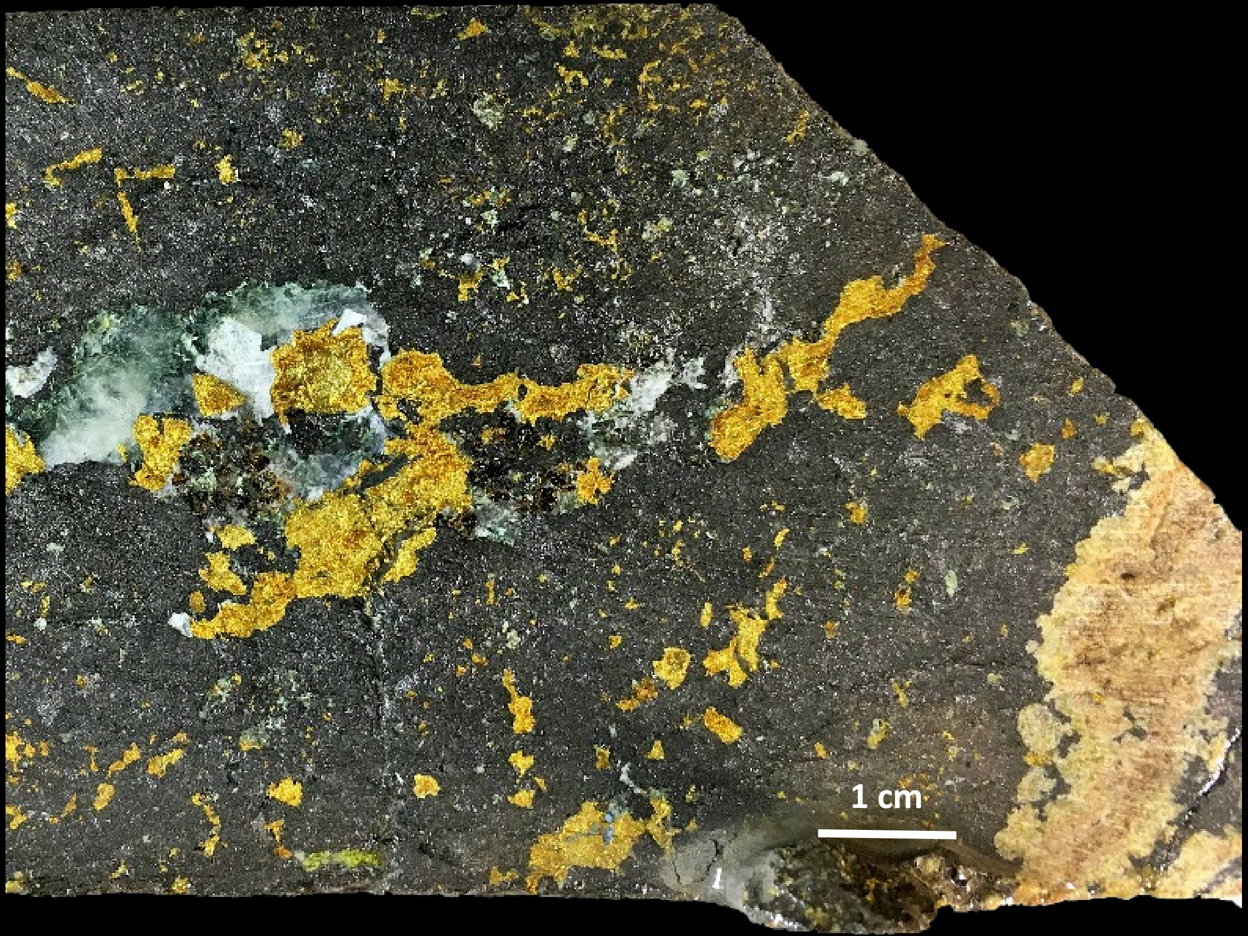
Magnetite – garnet skarn and marble, Chalcobamba

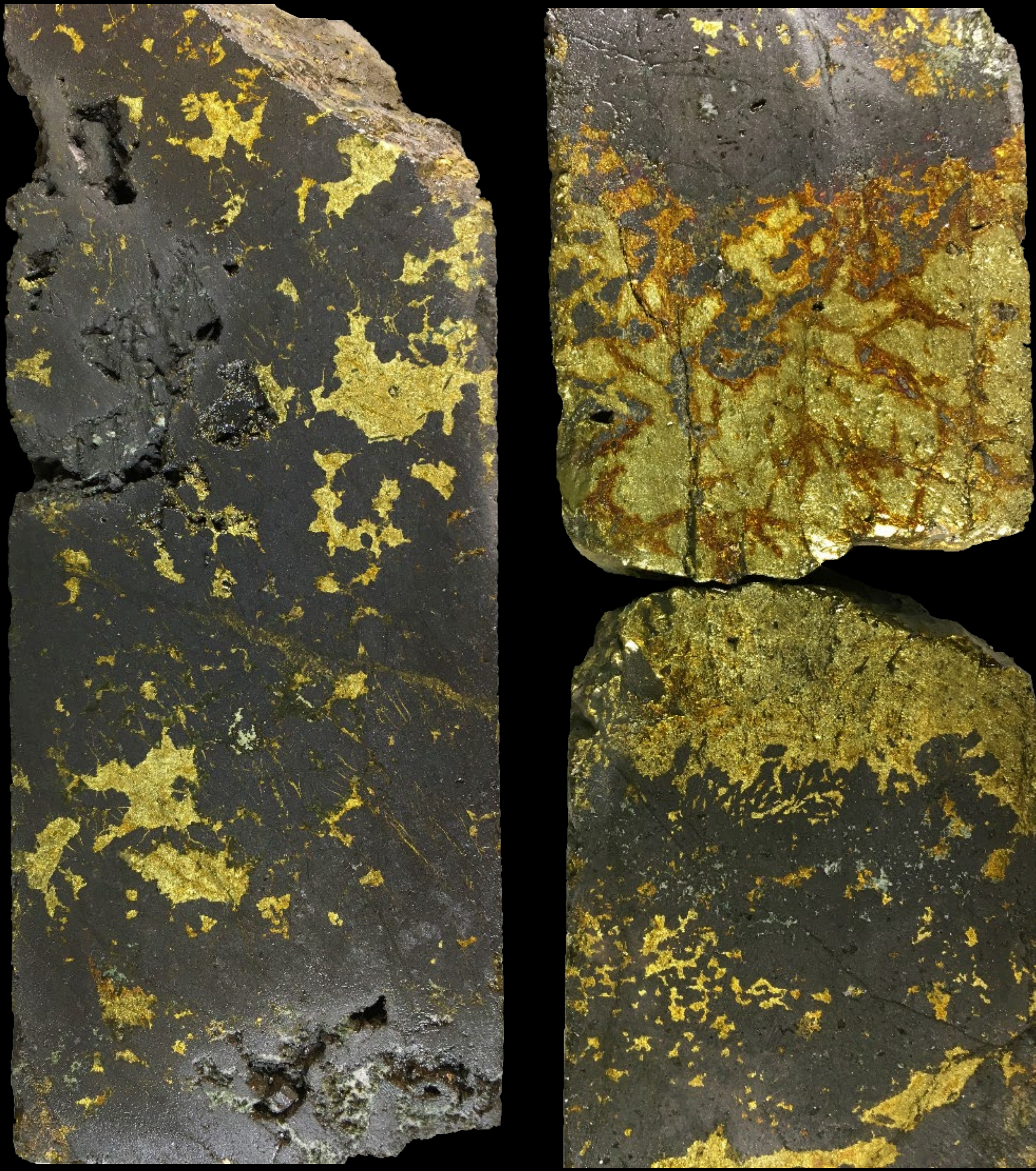
[illegible] skarn, Cu-oxides, [illegible], Peru

Magnetite – garnet skarn and marble, Chalcobamba

Chalcobamba

Late-stage chalcopyrite



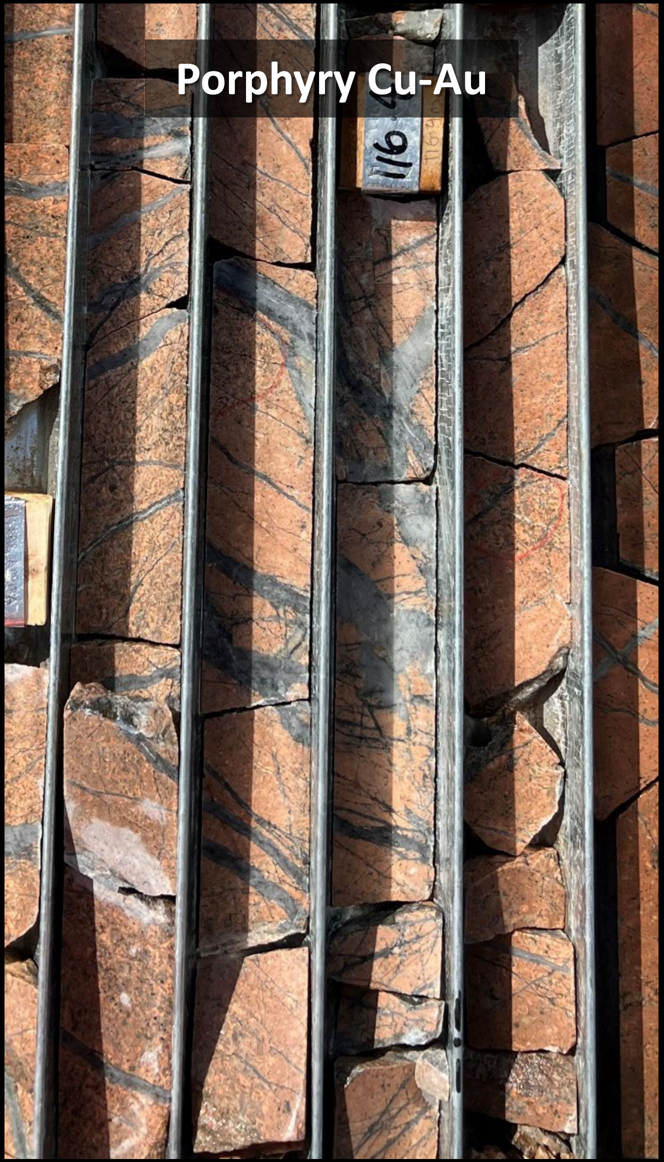


- **Sulfides commonly have a late timing in skarn deposits**
    - **Void fill, veins and replacements**

Photos courtesy of Amos Garay

Opportunities for discovery in the Tasmanides

All elements of the porphyry mineral system are viable targets for exploration



E26, Northparkes

Peak Hill

E44, Northparkes

GRE46, Cowal

Trundle Park

Conclusions and exploration implications

Vuggy quartz, Tujuh Bukit, Indonesia (photo courtesy of Lejun Zhang)

- **Porphyry mineral systems typify oceanic island arcs and continental arcs around the Pacific Rim**
  - They are mostly subduction-related
  - Alkalic porphyries may form in post-collisional environments
- **Arc segments in the Tasmanides (e.g., Macquarie Arc) are prospective for porphyry, epithermal and skarn deposits**
  - Porphyry deposits require oxidized hydrous magmas
  - HS and IS epithermal deposits form in the shallowest parts of magmatic arcs and can be eroded soon after formation
  - Skarns and carbonate replacement deposits require reactive protoliths (limestones, ultramafic rocks) but can have a greater diversity of metal endowment and magma associations
  - Carbonate-hosted HS deposits are an attractive exploration target yet to be discovered in the Tasmanides