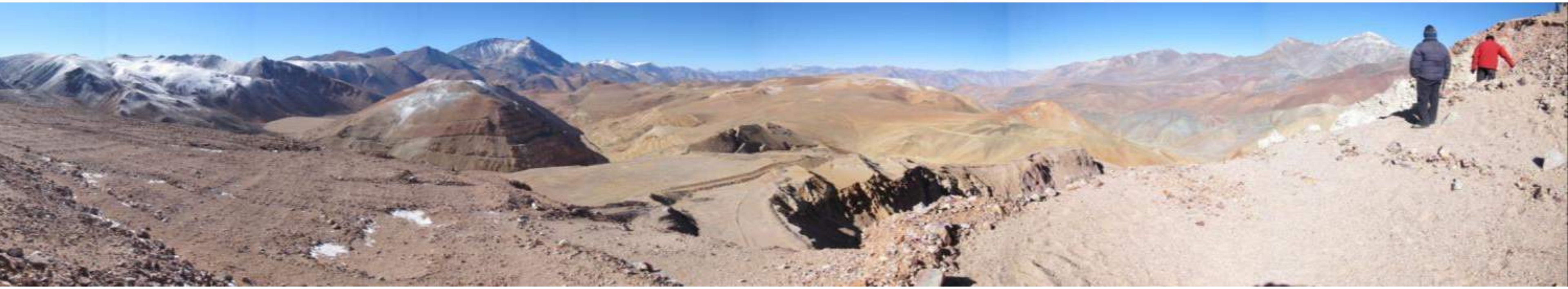
www.faultrocks.com
Bissig Geoscience Consulting

The physiographic and tectonic setting of Andean high-sulfidation epithermal gold-silver deposits



Thomas Bissig, Amelia Rainbow, Allan Montgomery, Alan Clark

Thanks to students and collaborators too numerous to mention on a slide. Thanks also to industry partners who funded research on HS systems over the years, most importantly **Barrick** but also Kinross, IamGold, Eco Oro, Ventana Gold Corp.

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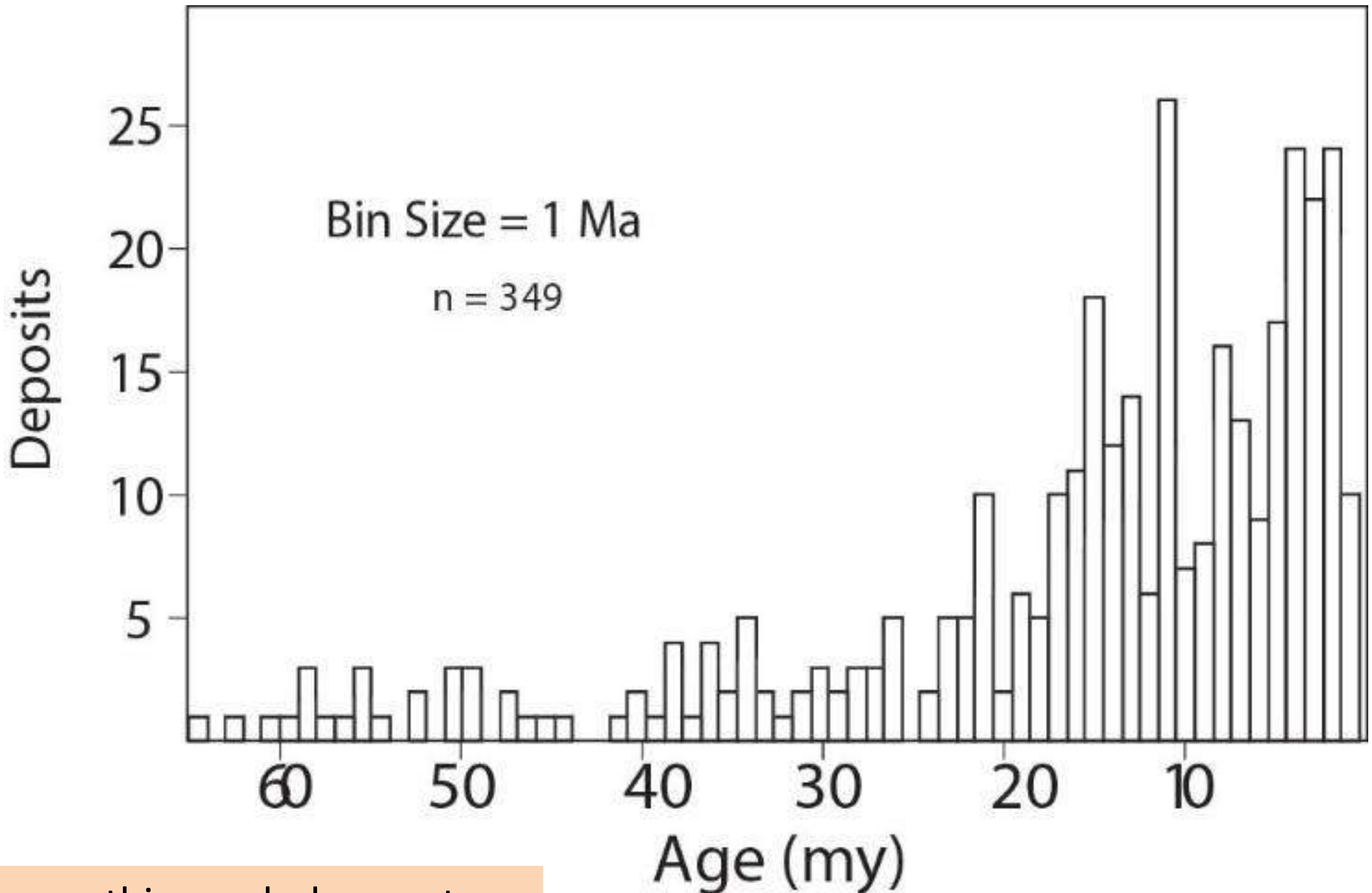
El poeta maldito

Se entretiene tirando pájaros a las piedras

Nicanor Parra, from: Siete trabajos voluntarios y un acto sedicioso (1983)

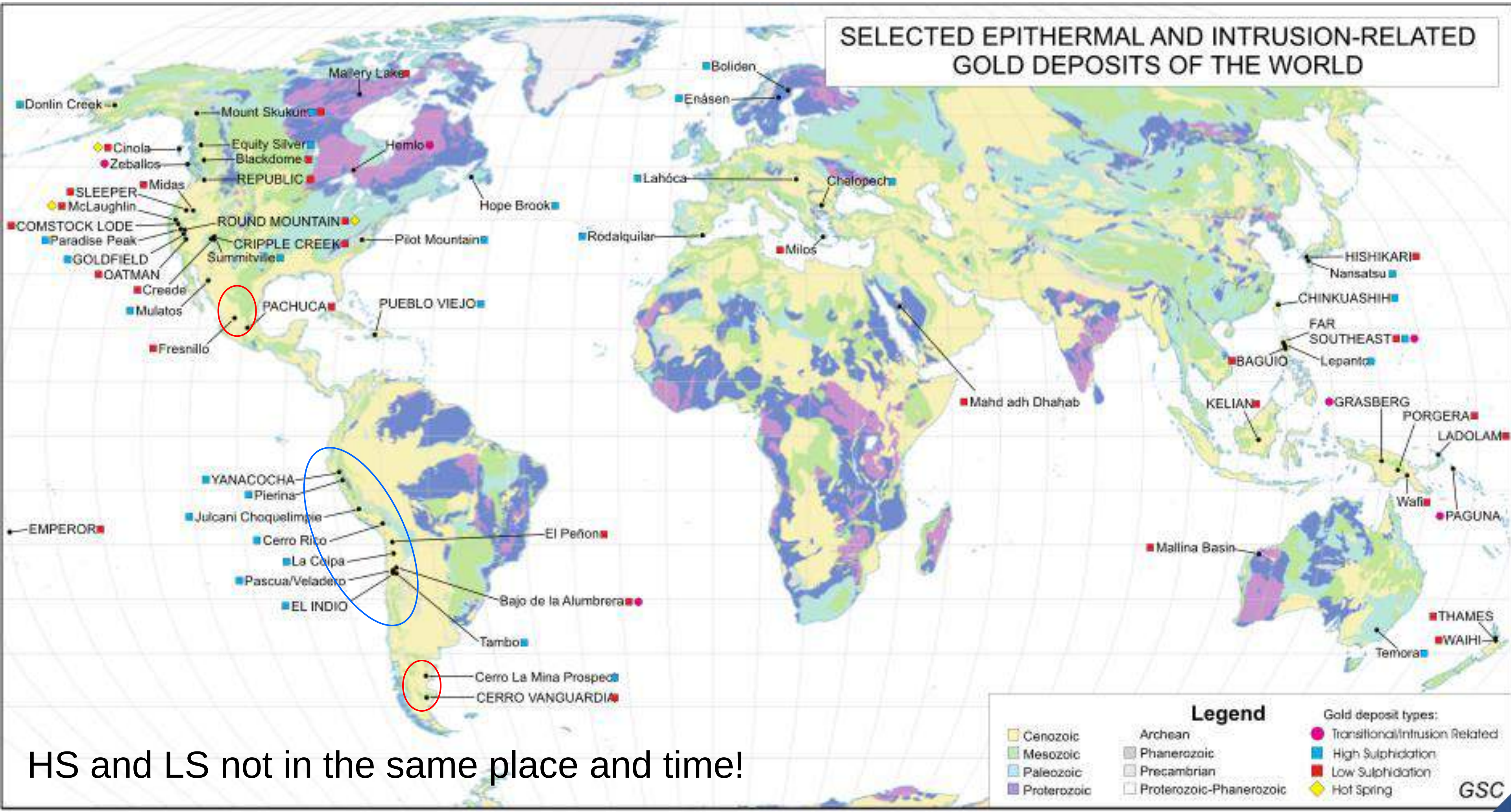
Epithermal deposits



However, this graph does not differentiate between high and low sulfidation deposits!

Mod from Kesler and Wilkinson, 2009

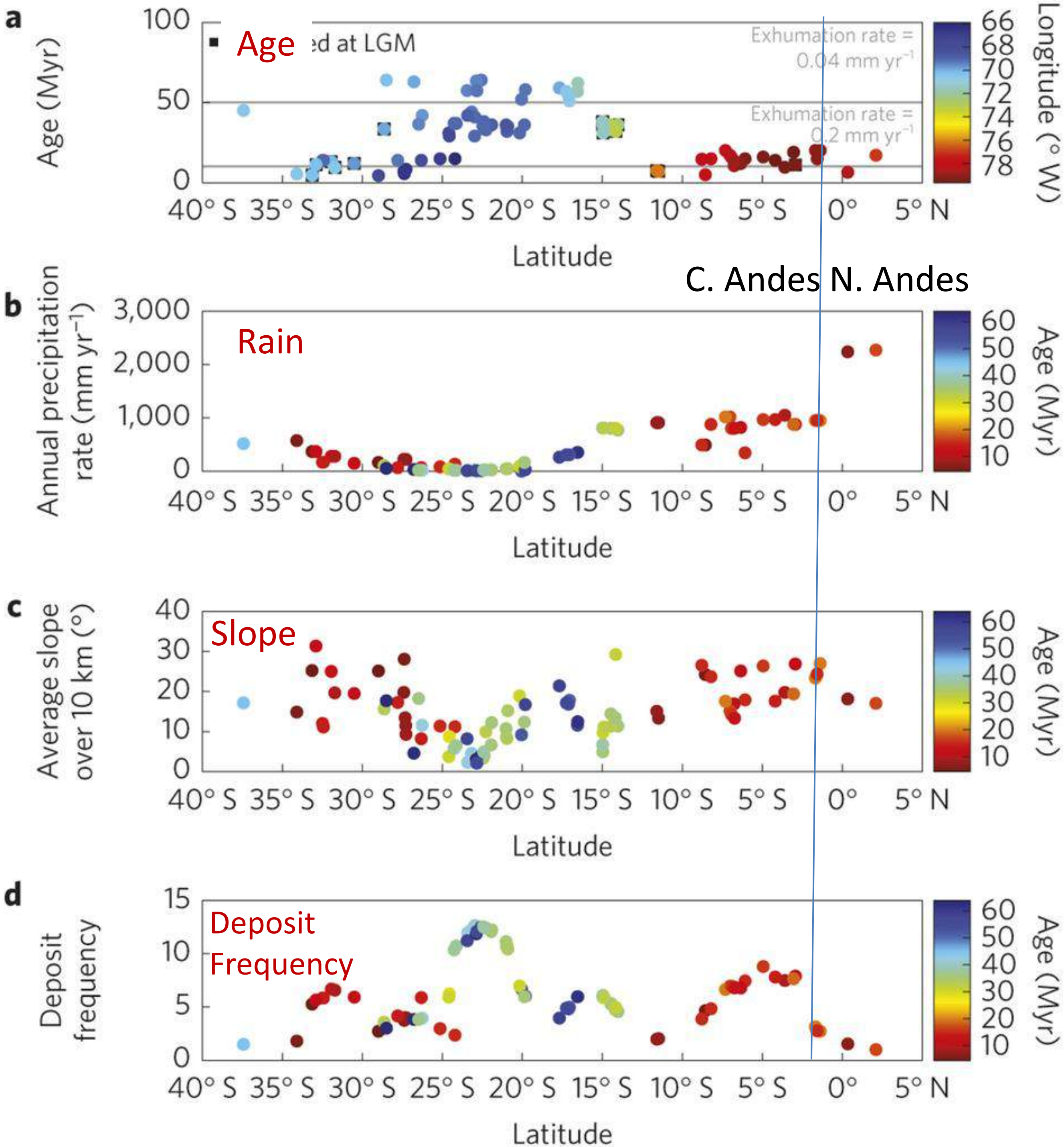
General character – Tectonic environment



HS and LS not in the same place and time!

Fig. 2 in Taylor, B. E. (2007). Epithermal gold deposits. Mineral Deposits of Canada: A Synthesis of Major Deposit-types, District Metallogeny, the Evolution of Geological Provinces, and Exploration Methods. W. D. Goodfellow, Special Publication 5, Mineral Deposits Division, Geological Association of Canada: 113-139.

The Andes



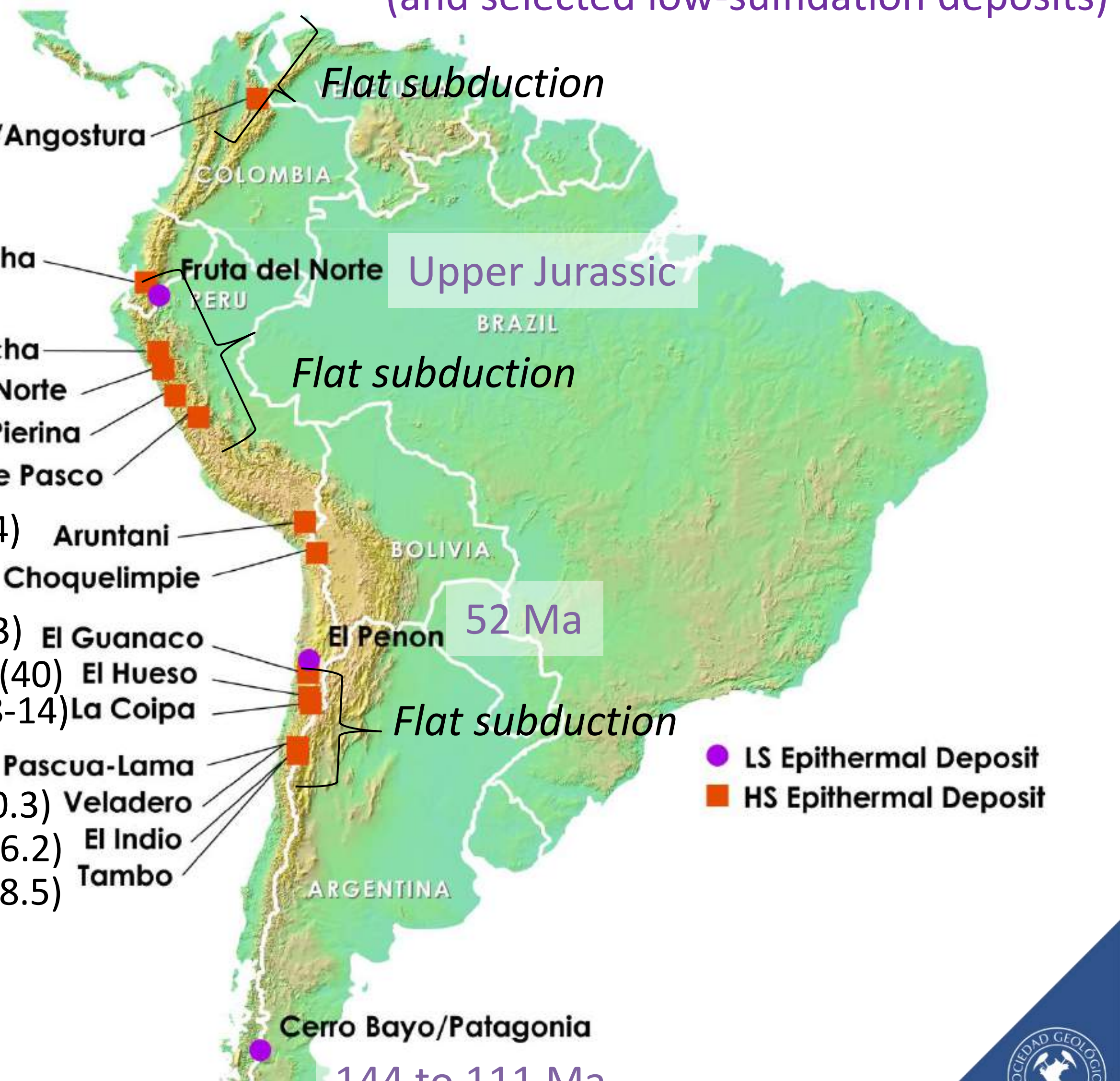
Oldest porphyries where rain is lowest

Absence of young porphyry deposits in N. Chile& S Peru

Yanites and Kesler 2015, Nature

Most significant high-sulfidation epithermal deposits of the Andes

(and selected low-sulfidation deposits)

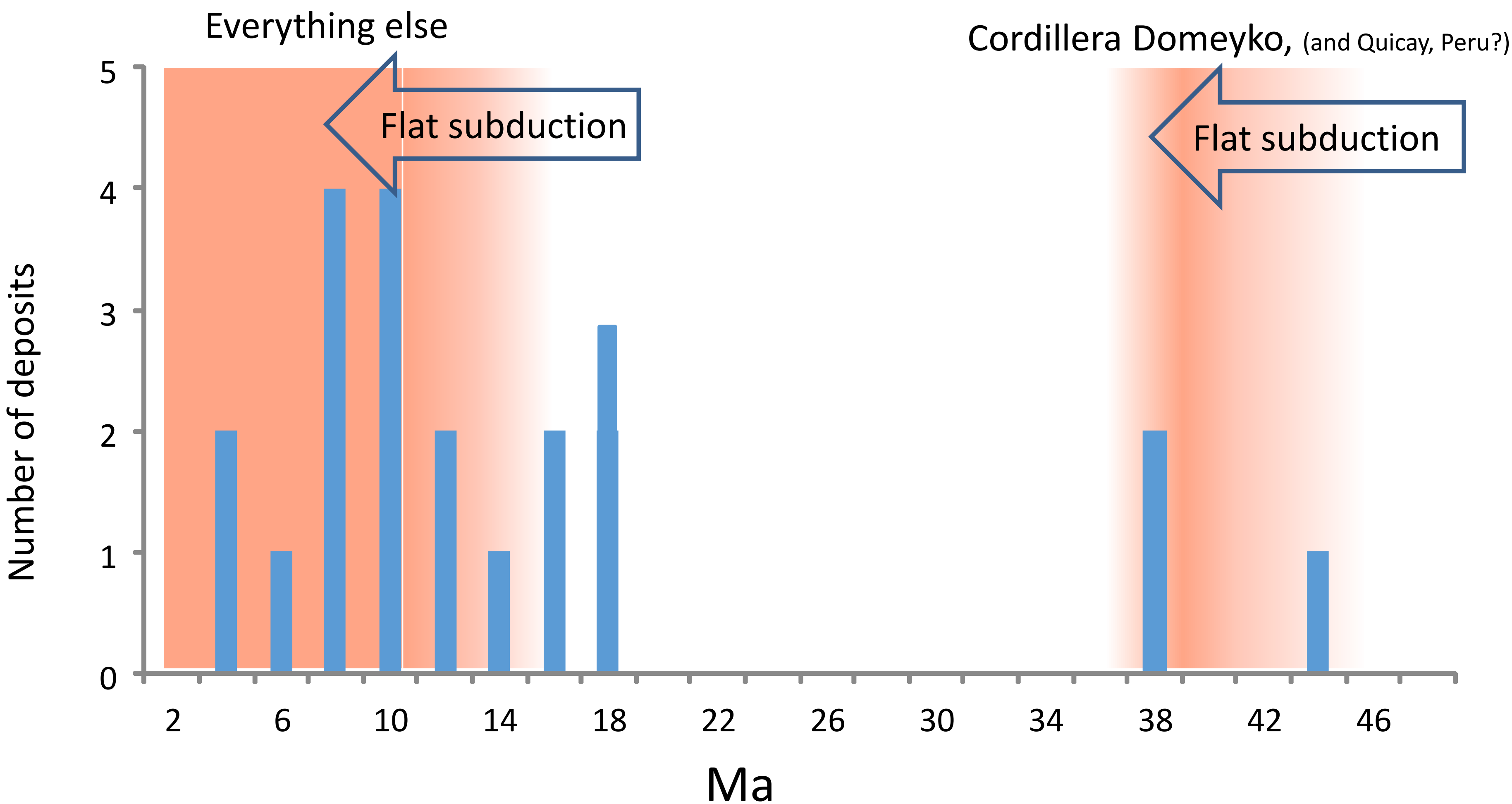


All high-sulfidation deposits < 17 Ma except those in the driest regions!

Most > 3500 m a.s.l.

Low sulfidation deposits as old as Jurassic, lower elevation

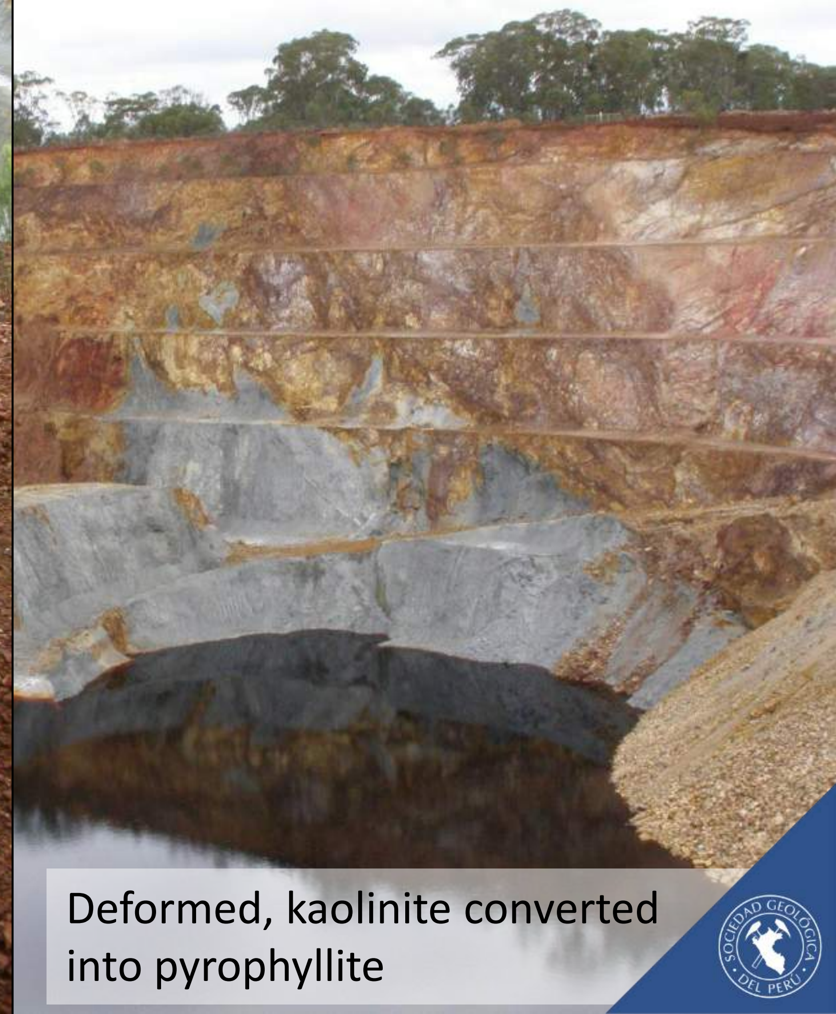
Ages of Andean high-sulfidation deposits



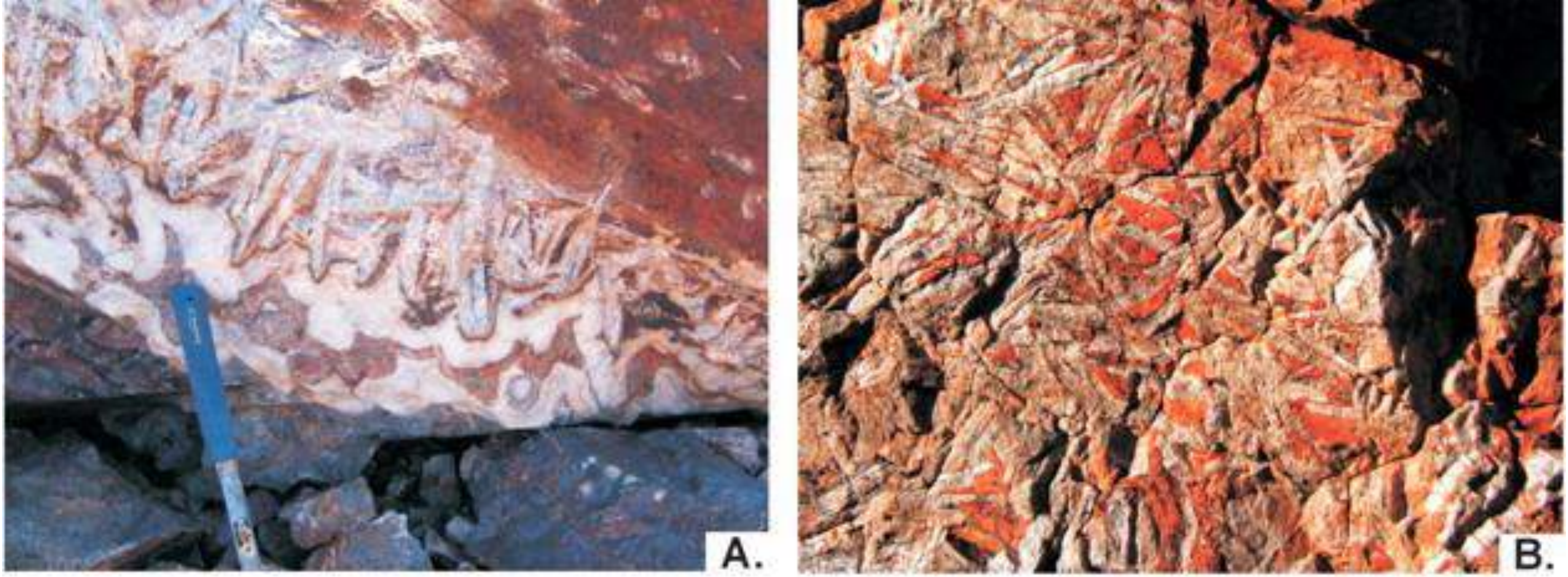
All are younger than ~43 Ma, Most are younger than 17 Ma!

Cf. Many low-sulfidation deposits, e.g., Fruta del Norte, Deseado Massif, El Peñón are > 52 Ma to as old as Jurassic

Peak Hill, an Ordovician High-Sulfidation deposit, MacQuarie arc, Australia



Deformed, kaolinite converted into pyrophyllite

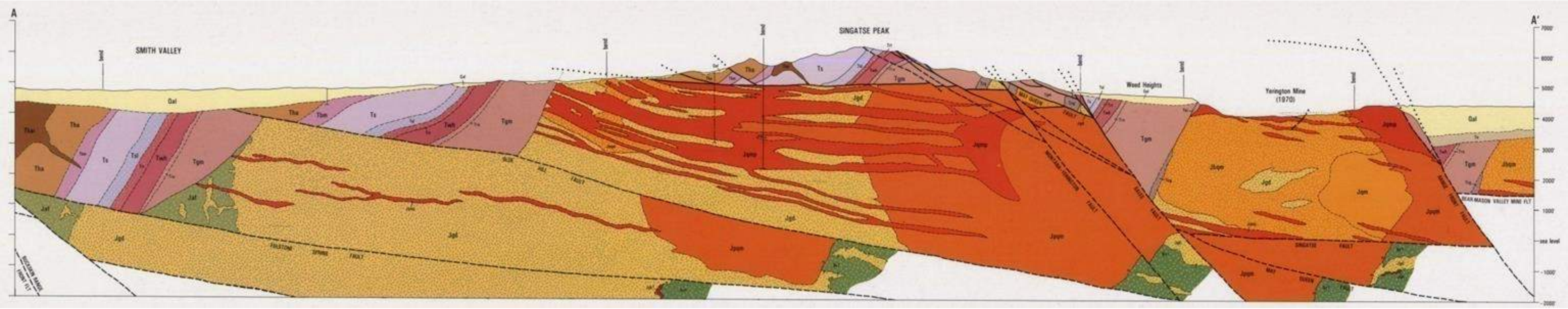


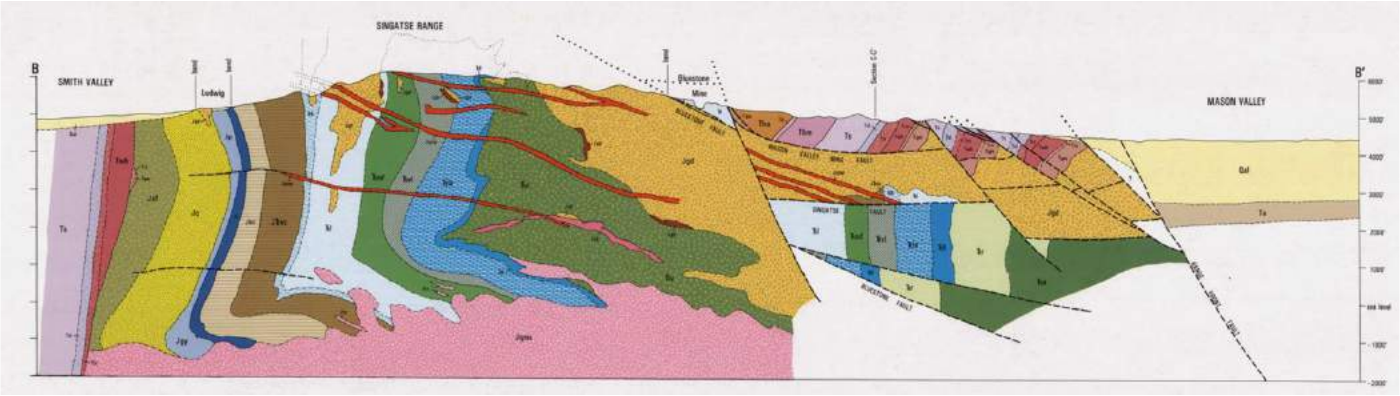
Early Archean Epithermal Veins, North Pole, Western Australia

Thus, under special circumstances, really old deposits emplaced at shallow levels can be preserved over a really long time

Harris et al. 2009

One way of preserving a porphyry deposit…

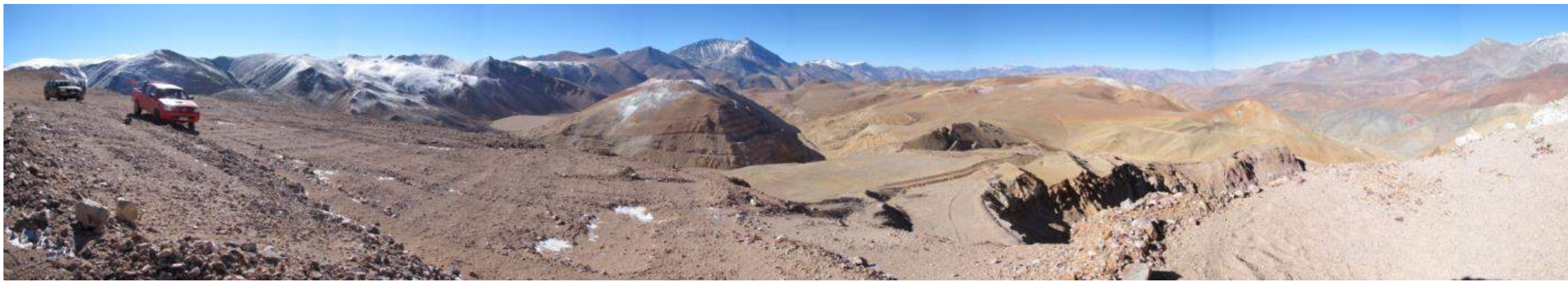


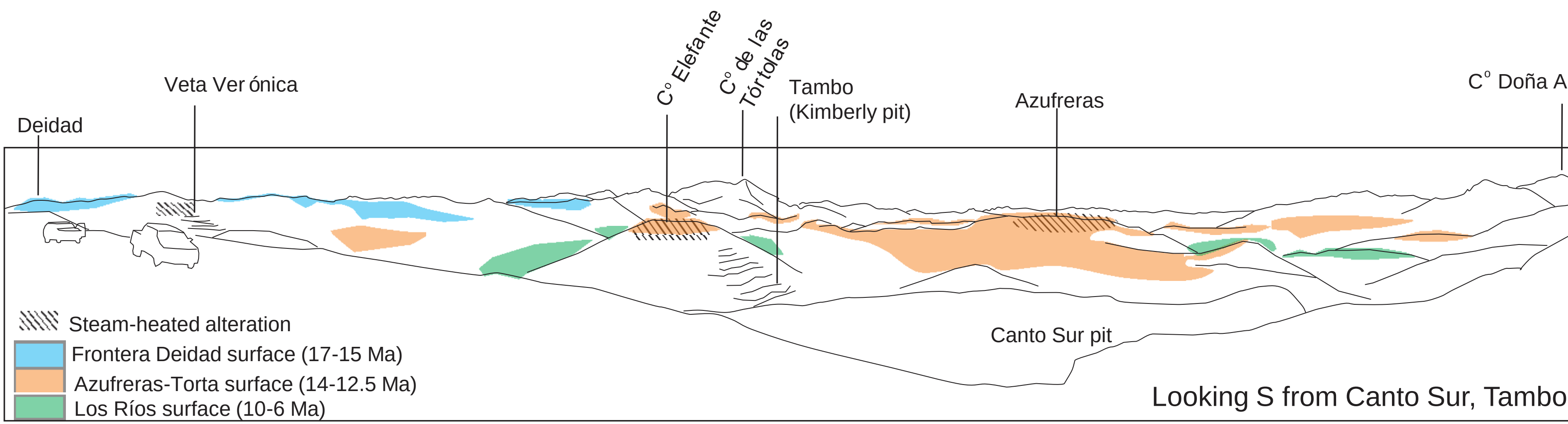


Titling-extensional tectonics: Yerington, Nevada (SW US!)

Dilles & Proffett, 1994

Flat landscape and gold: Tambo, El Indio belt





Landscape elements from Bissig et al. 2002

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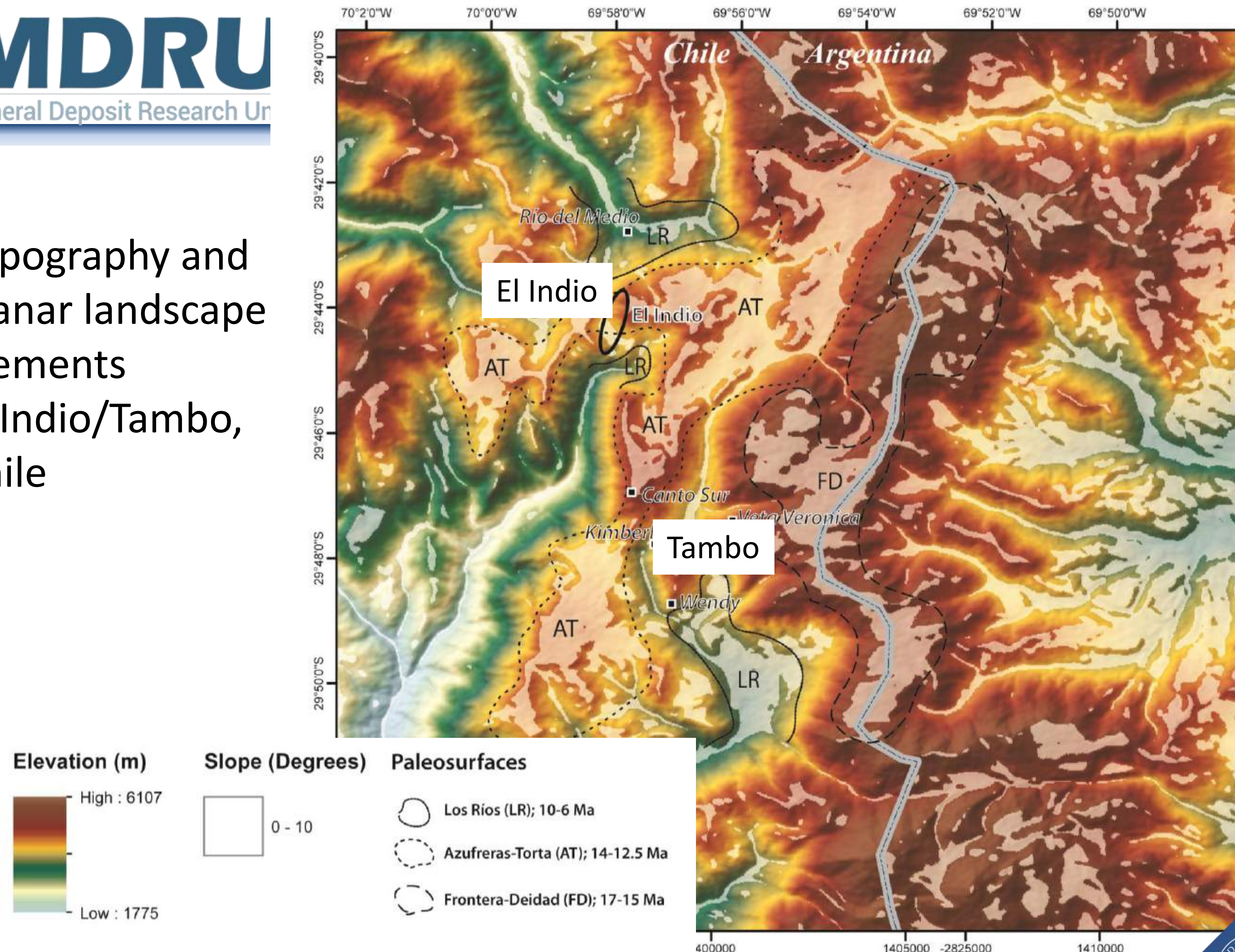
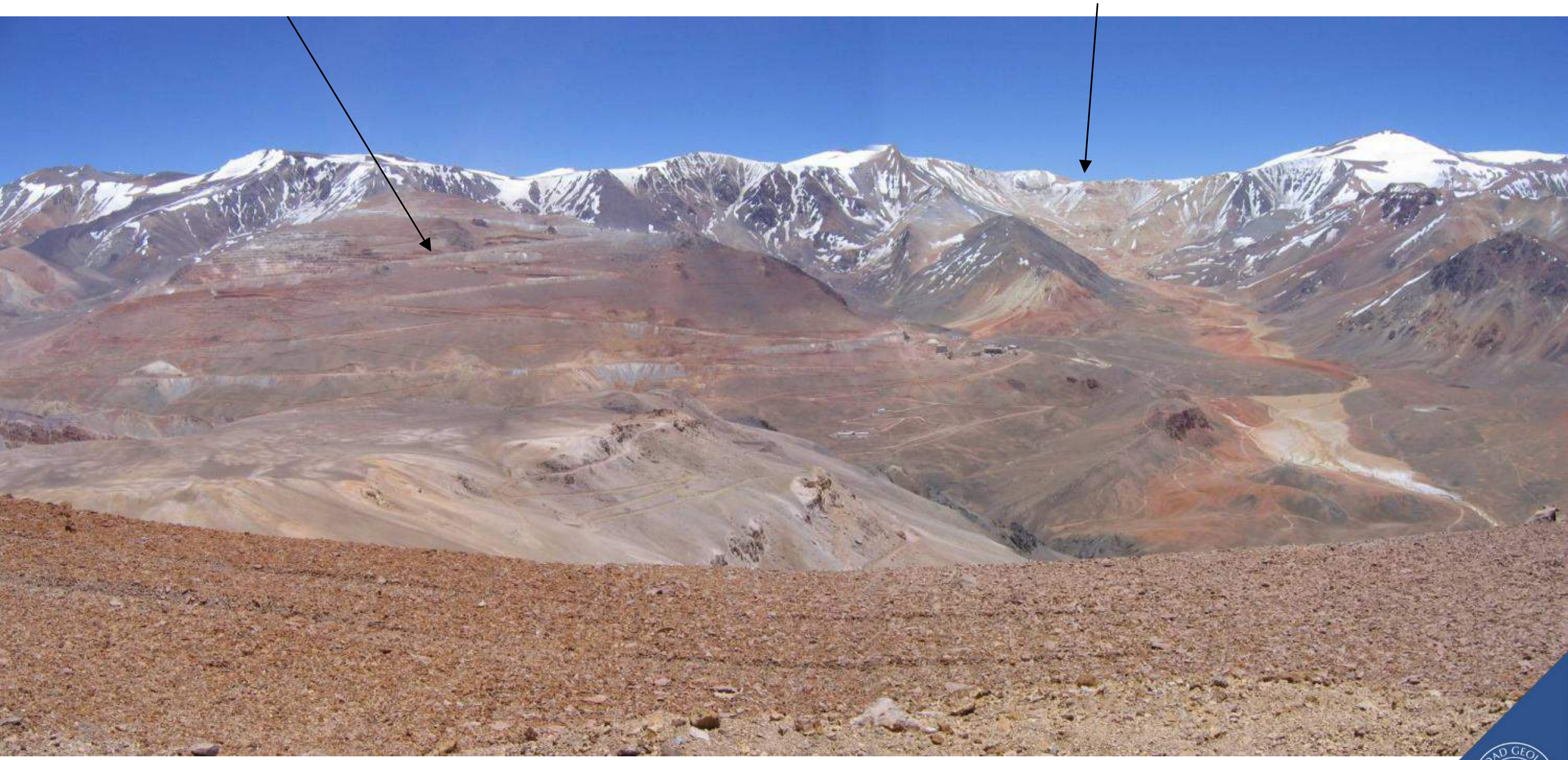
Topography and planar landscape elements El Indio/Tambo, Chile



Landscape elements from Bissig et al. 2002

Examples of well endowed high-sulfidation epithermal deposits

Veladero (~12.2 Moz Au) Pascua-Lama (~17.6 Moz Au)



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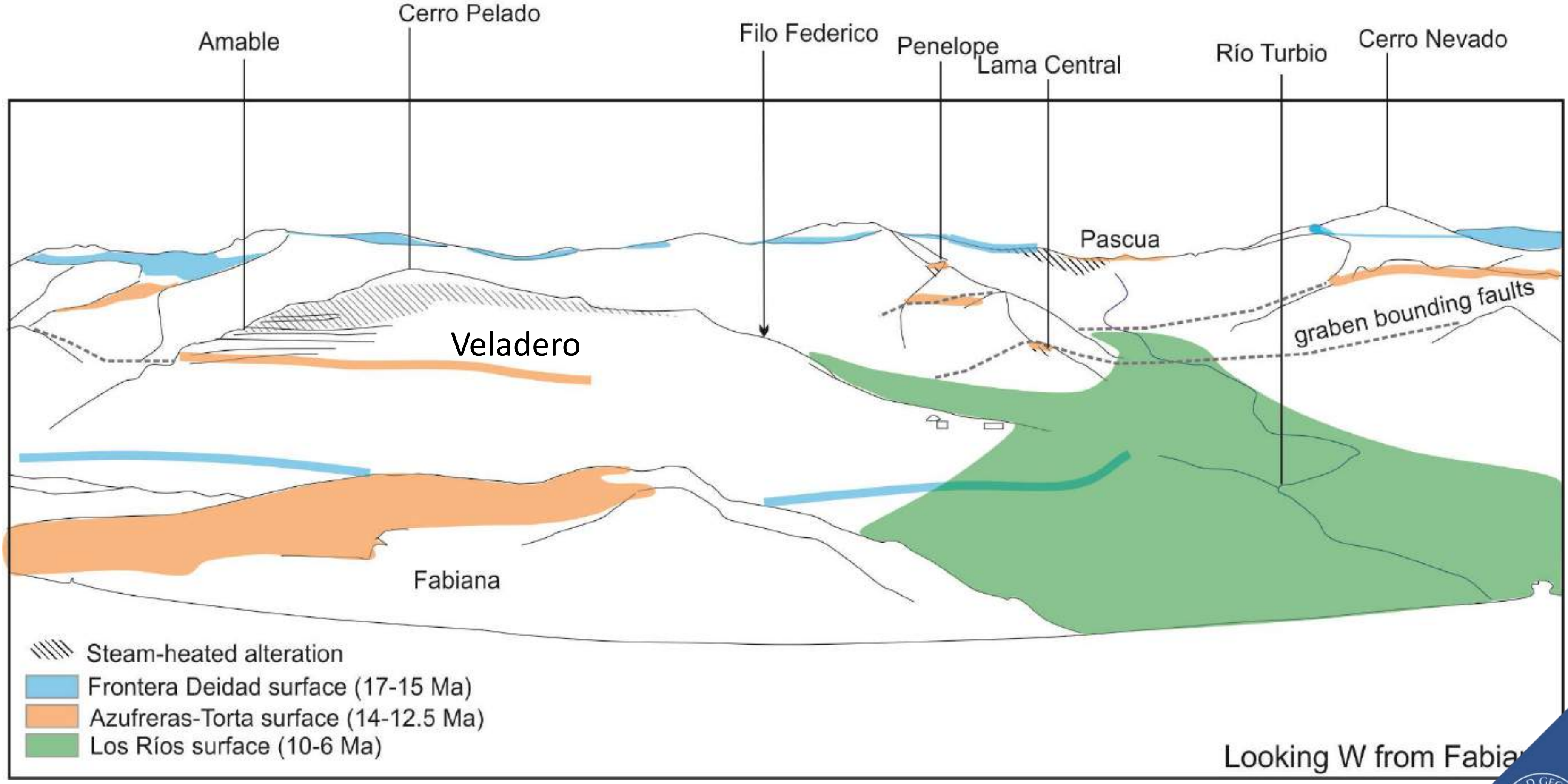
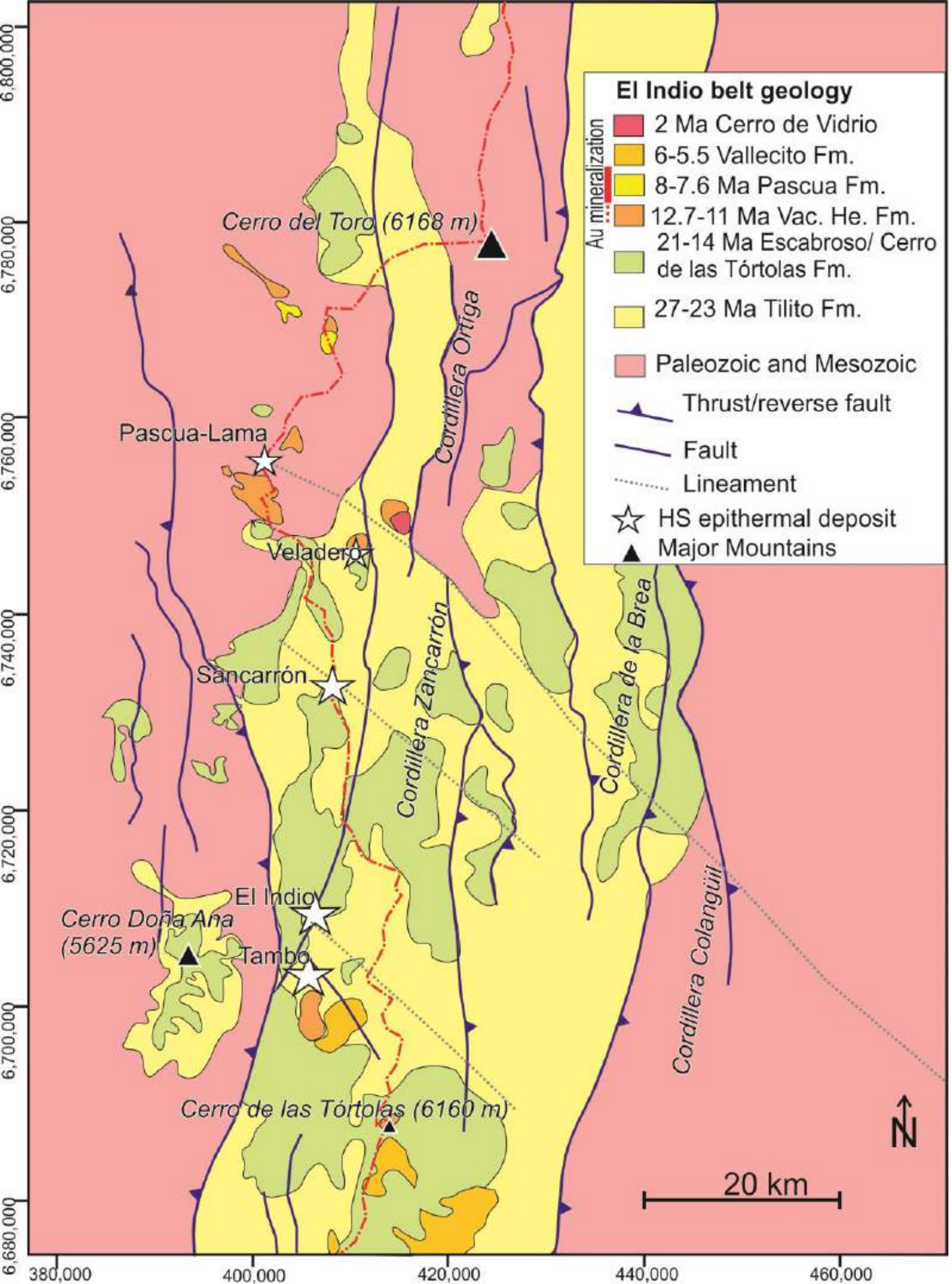


Landscape elements from Bissig et al. 2002, Charchaflie et al. 2007



Voluminous volcanism from Oligocene to middle Miocene

Reduction of volcanism at ~ 14 Ma

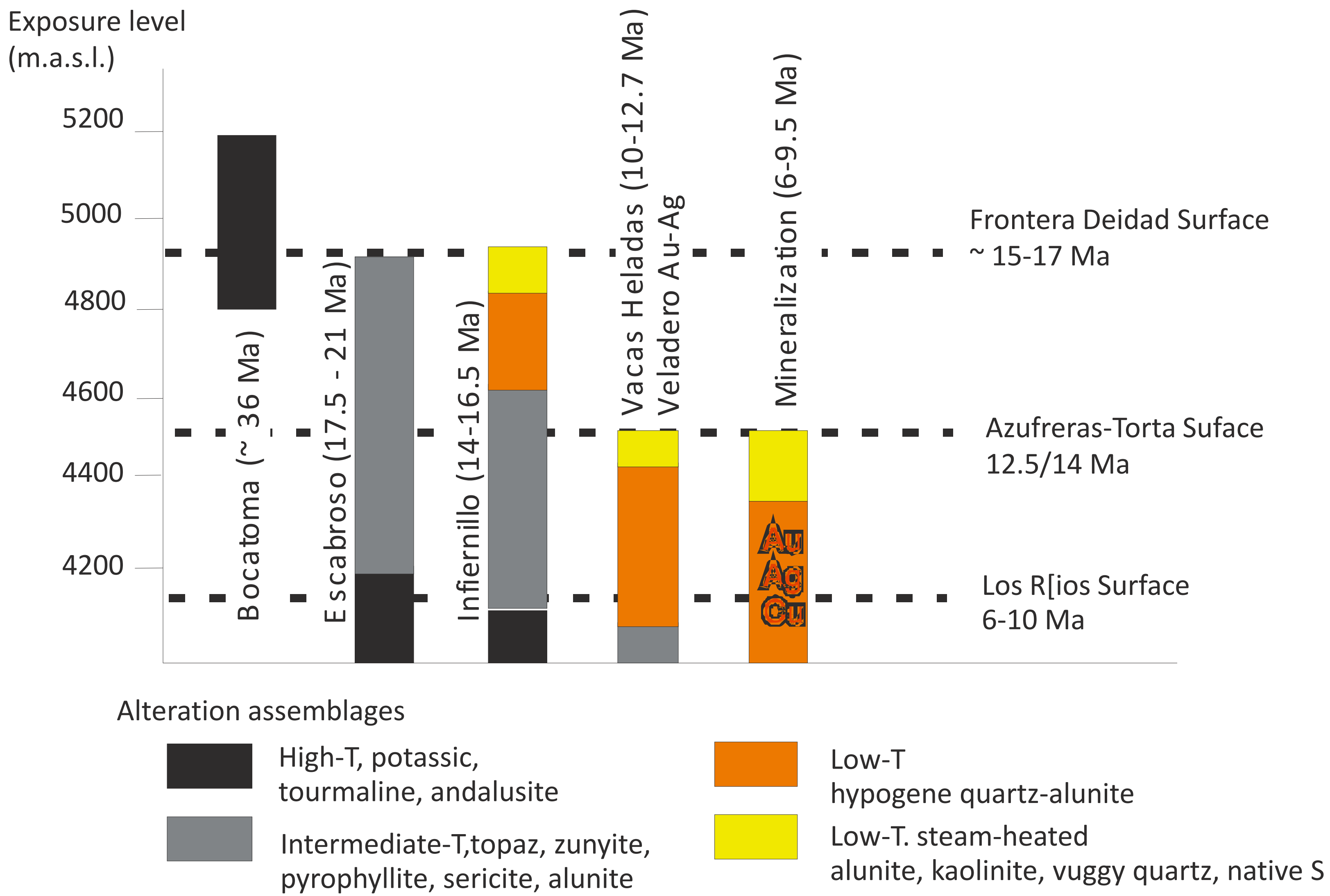
Isolated centers between 13 y 5 Ma. Gradual transition from andesite to dacite and rhyolite

Mineralization during this time!

Youngest event: Rhyolite of 2 Ma. (post mineral)

Bissig et al. 2001, Winocur et al. 2014 and references therein

Vertical zoning in El Indio belt depending on age and elevation



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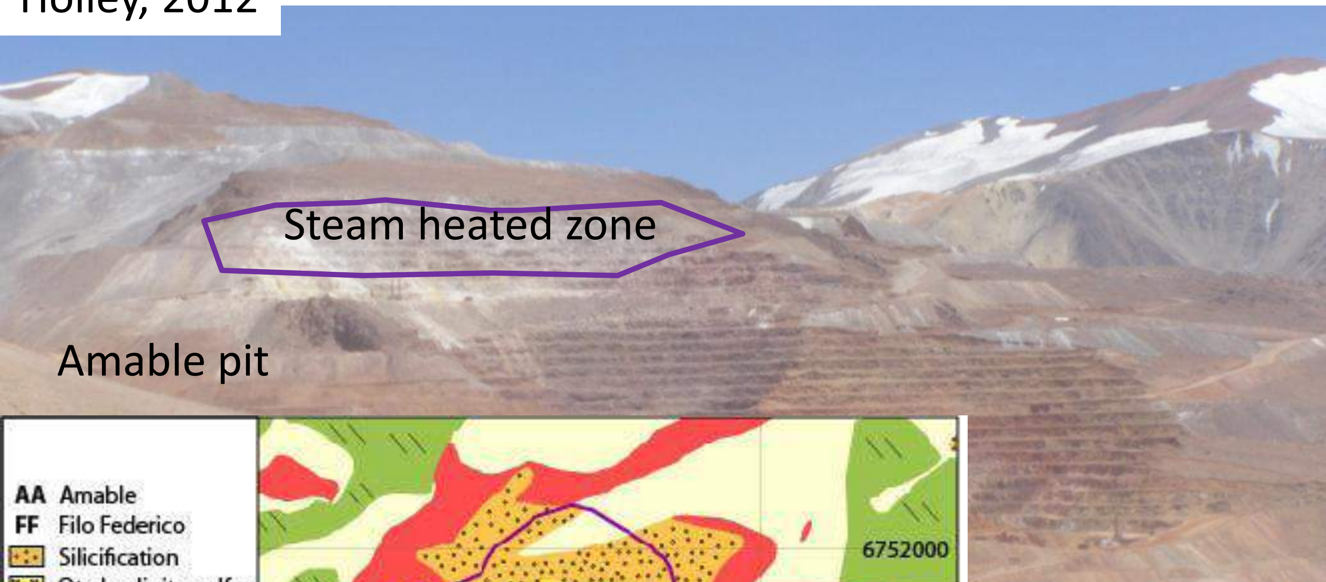
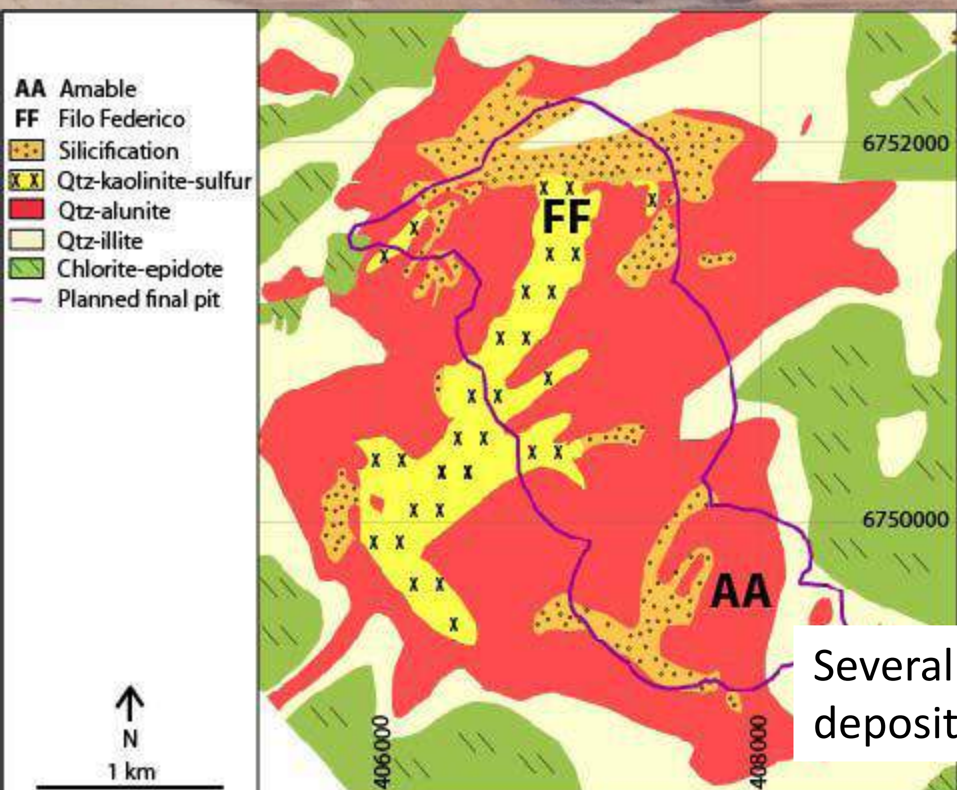
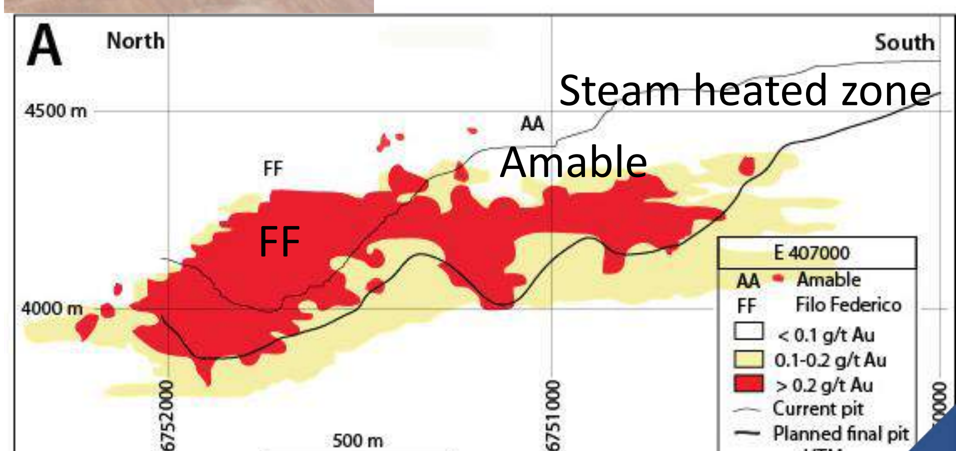
Veladero Geology

Holley, 2012

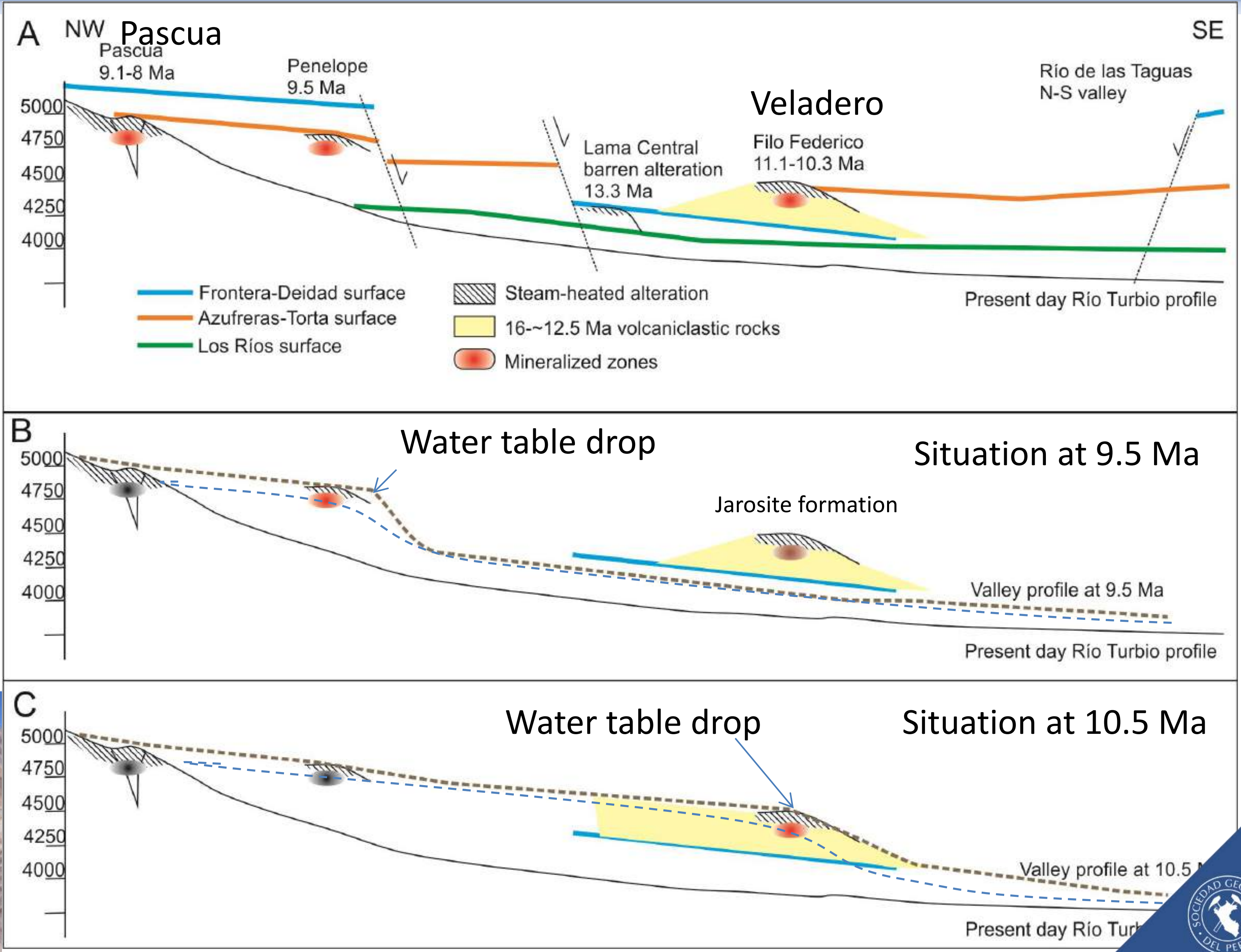




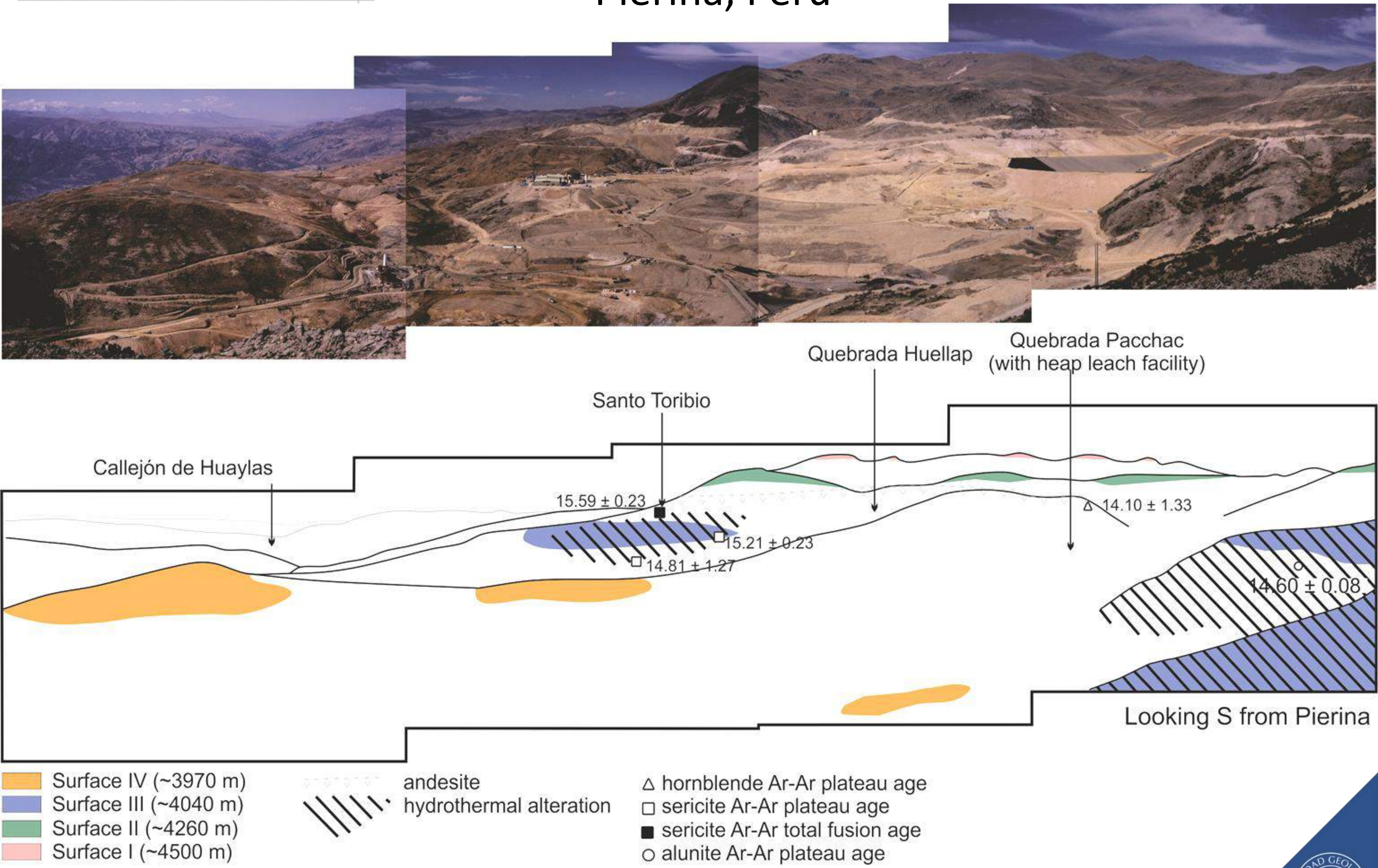


Several 100 m of steam heated alteration atop the deposit, implies large vadose zone, dry climate

Erosion and hydrothermal activity, Veladero (Filo Federico) to Pascua

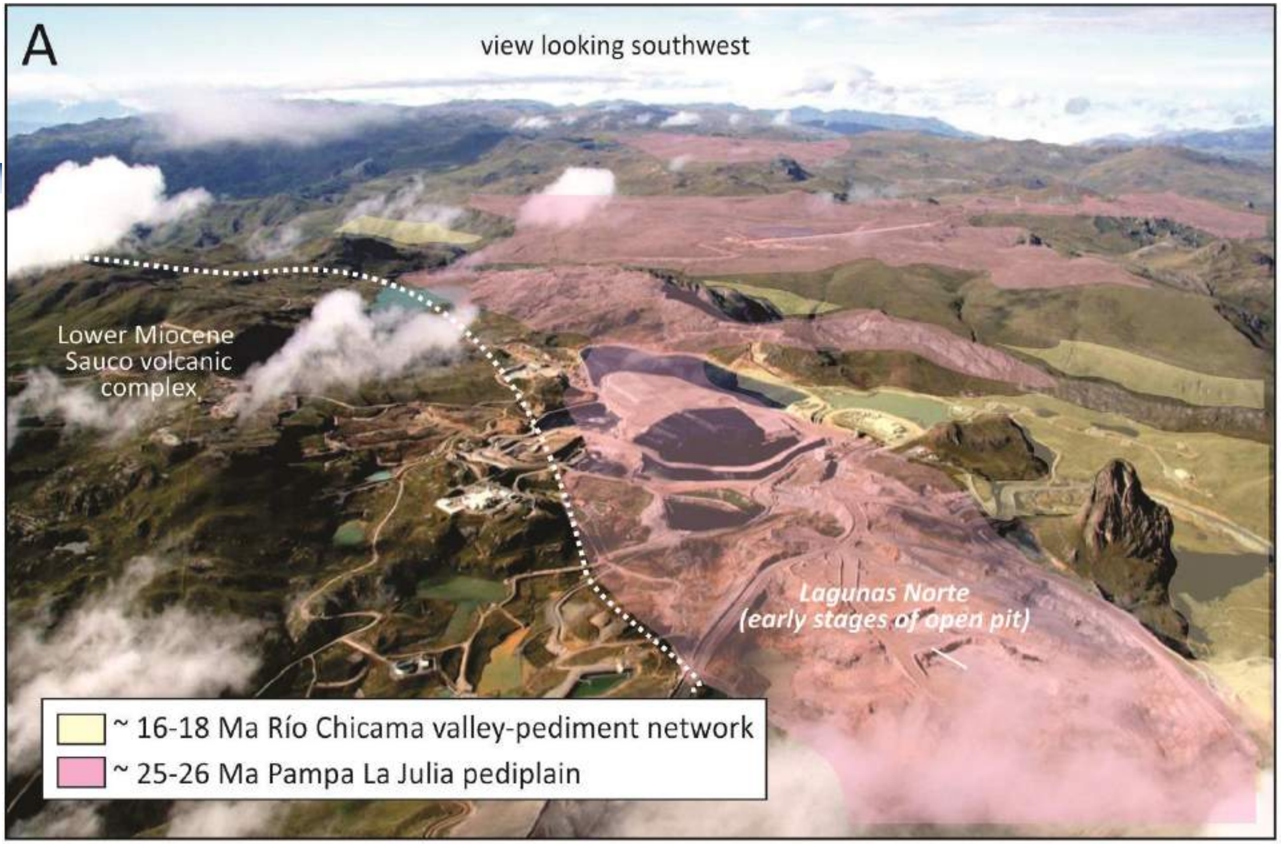


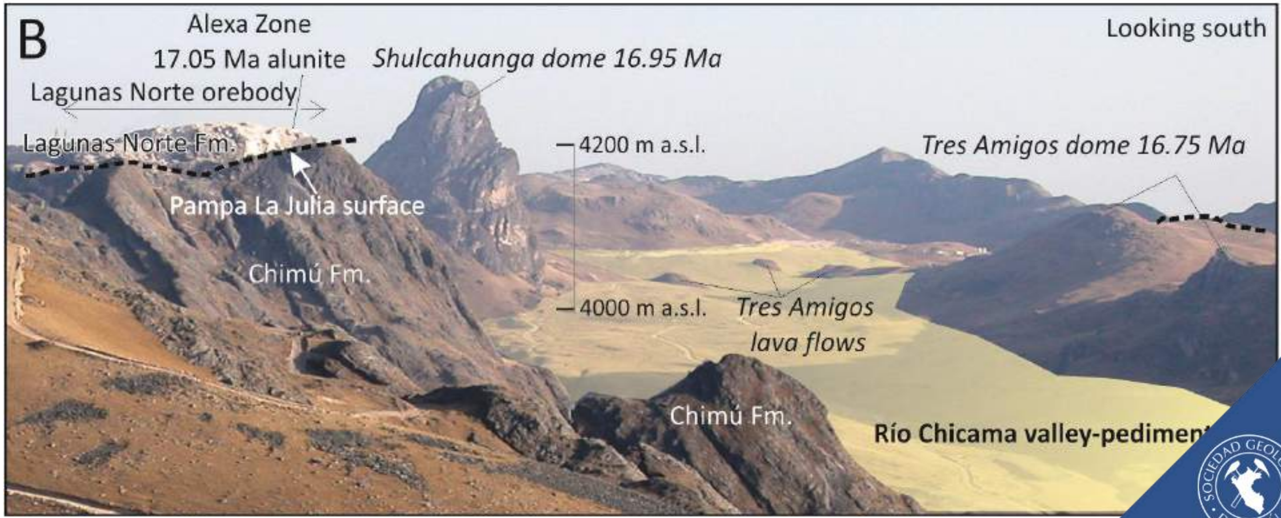
Pierina, Peru



Rainbow, 2009

Lagunas Norte: Erosion during mineralization





Montgomery 2012

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Lagunas Norte Area, Peru

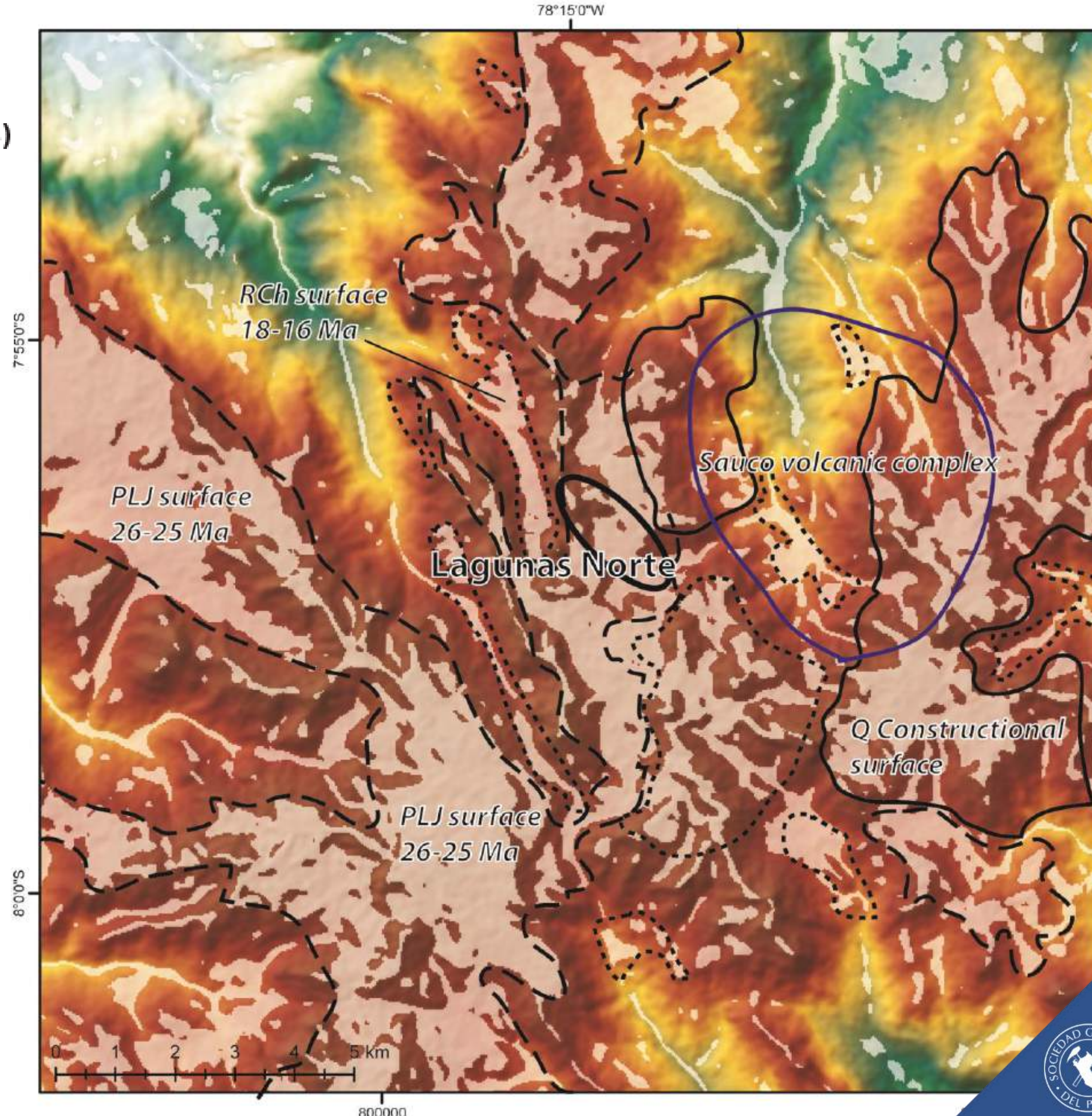
Elevation (m)

High : 4254

Low : 2275

Slope (Degrees)

0 - 8



Montgomery 2012

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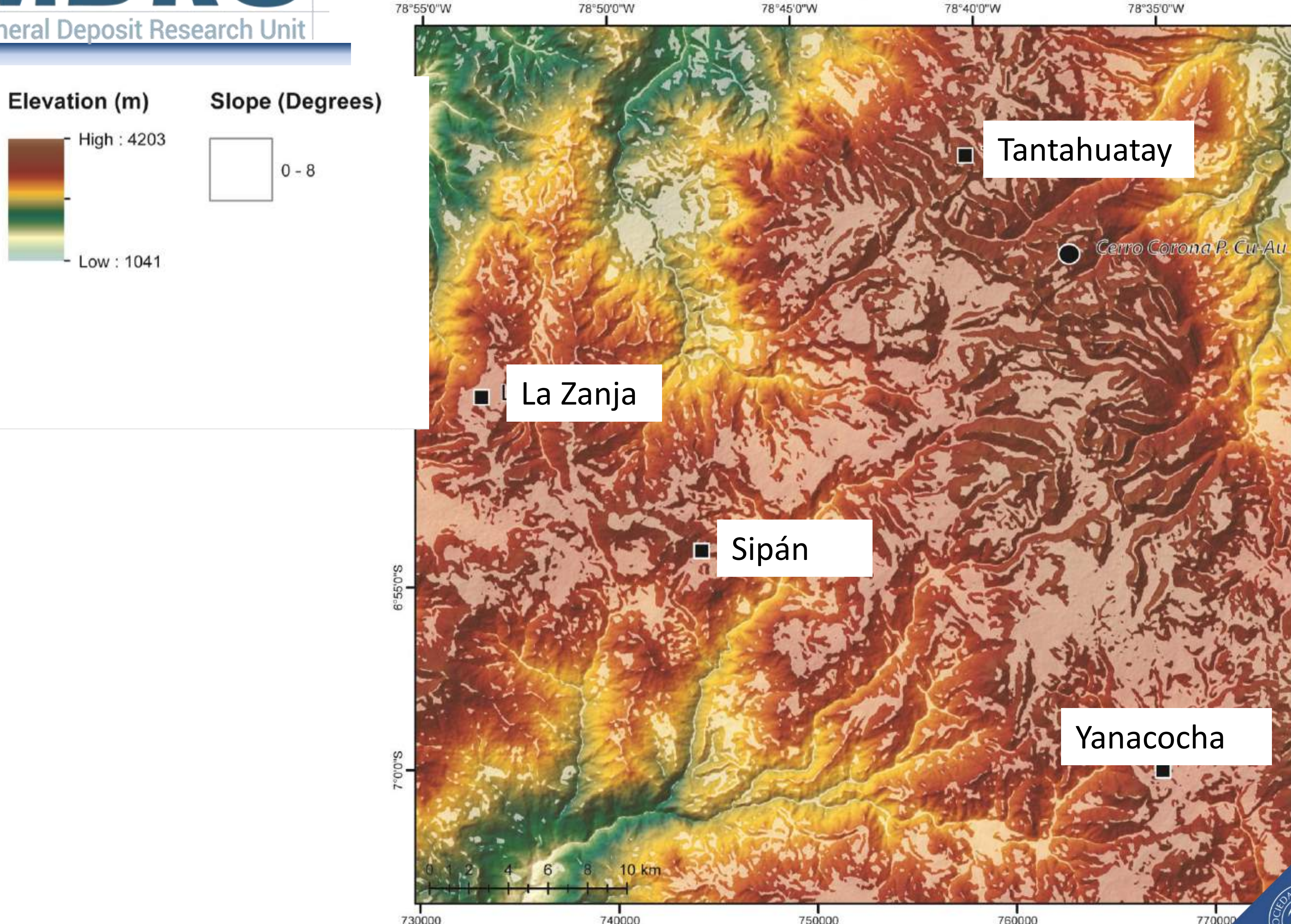
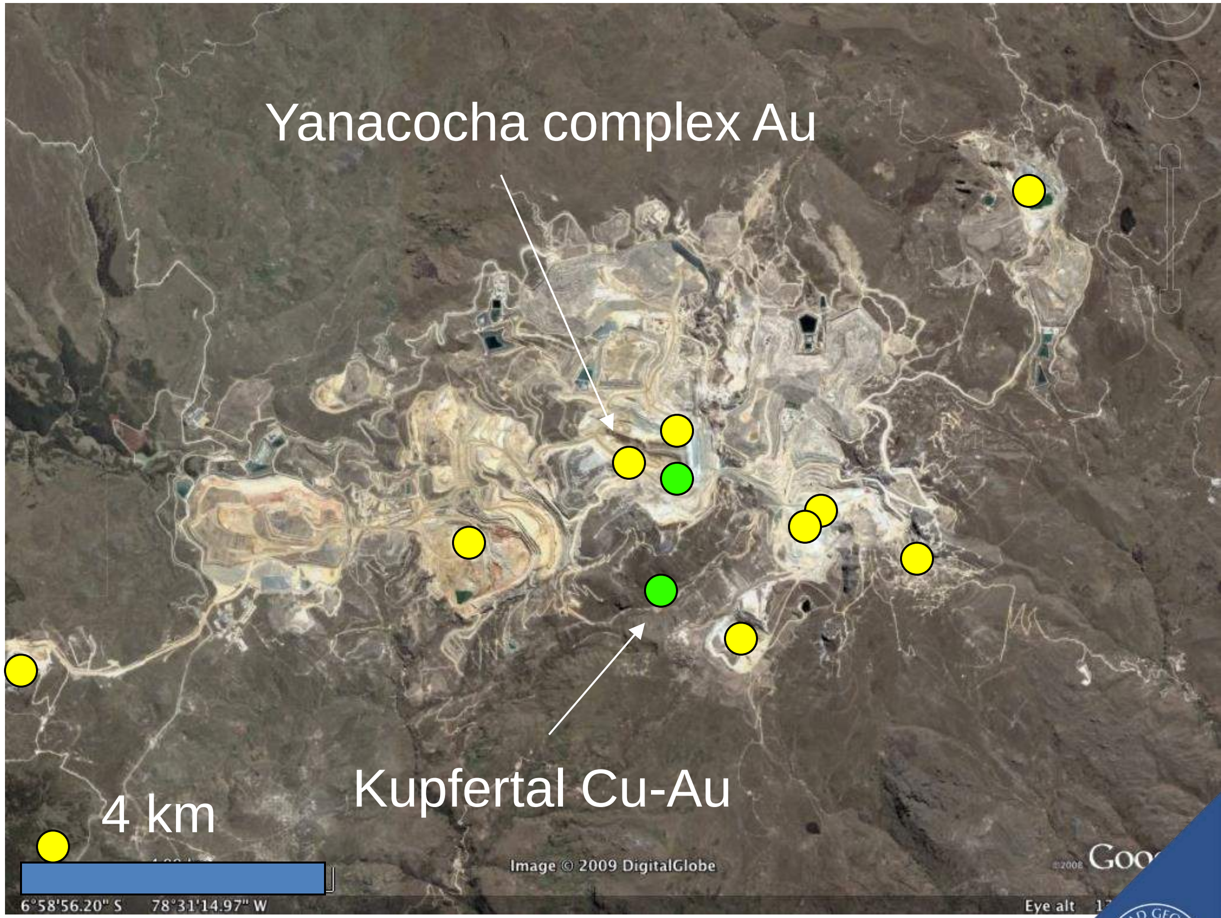
Yanacocha/Sipan/Tantahuatay/La Zanja Area, Peru



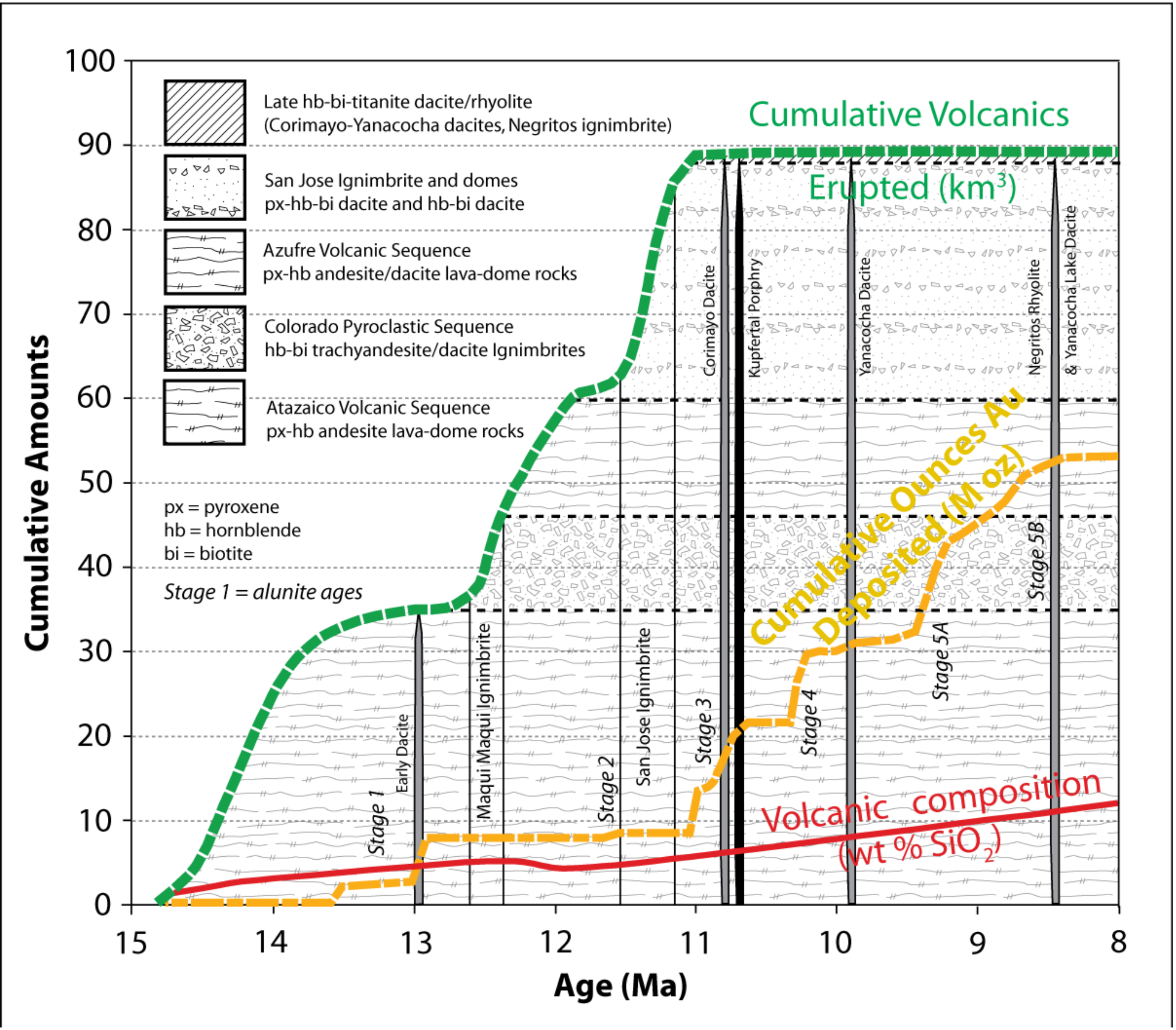
Yanacocha, largest Au mine in world (~2001-2006)

- Mined >30 Million troy oz of a 50 Million tr oz (1500 t) Au resource in low grade (0.5-1 g/t Au) quartz-alunite (high sulfidation) oxidized epithermal deposits
- *Value ~$50 B*

- Deeper sulfide-bearing porphyry Cu-Au resource with advanced argillic alteration (covellite-enargite-pyrite) contains > 5 M t Cu
- *Value ~ $30 B.*



Yanacocha, Peru; 7 Ma of magmatism; 5 Ma of Au(Cu) mineralization Decreased magmatic volumes, increased SiO_2, increased HS Au with time



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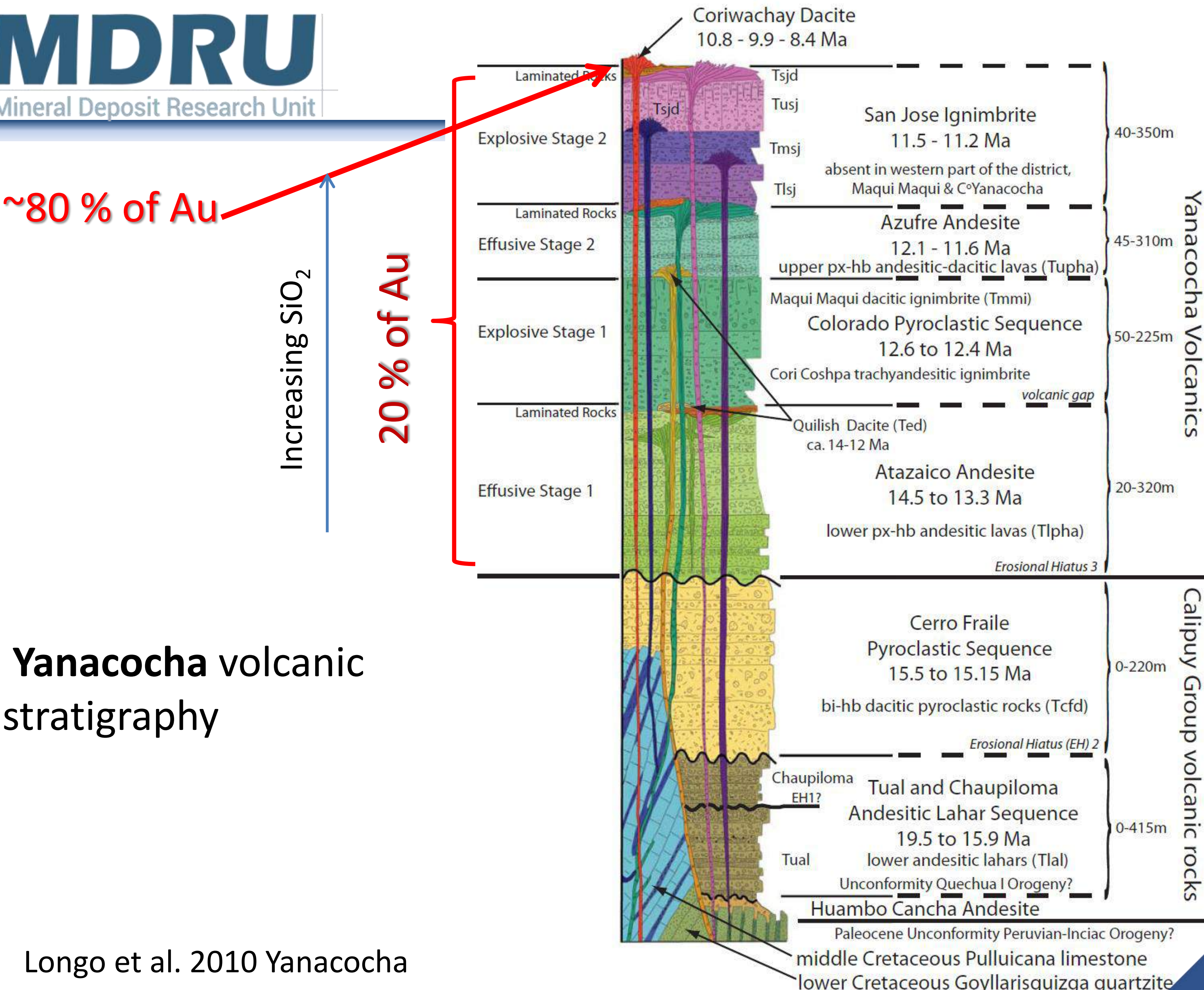
Yanacocha volcanic stratigraphy



Longo et al. 2010 Yanacocha

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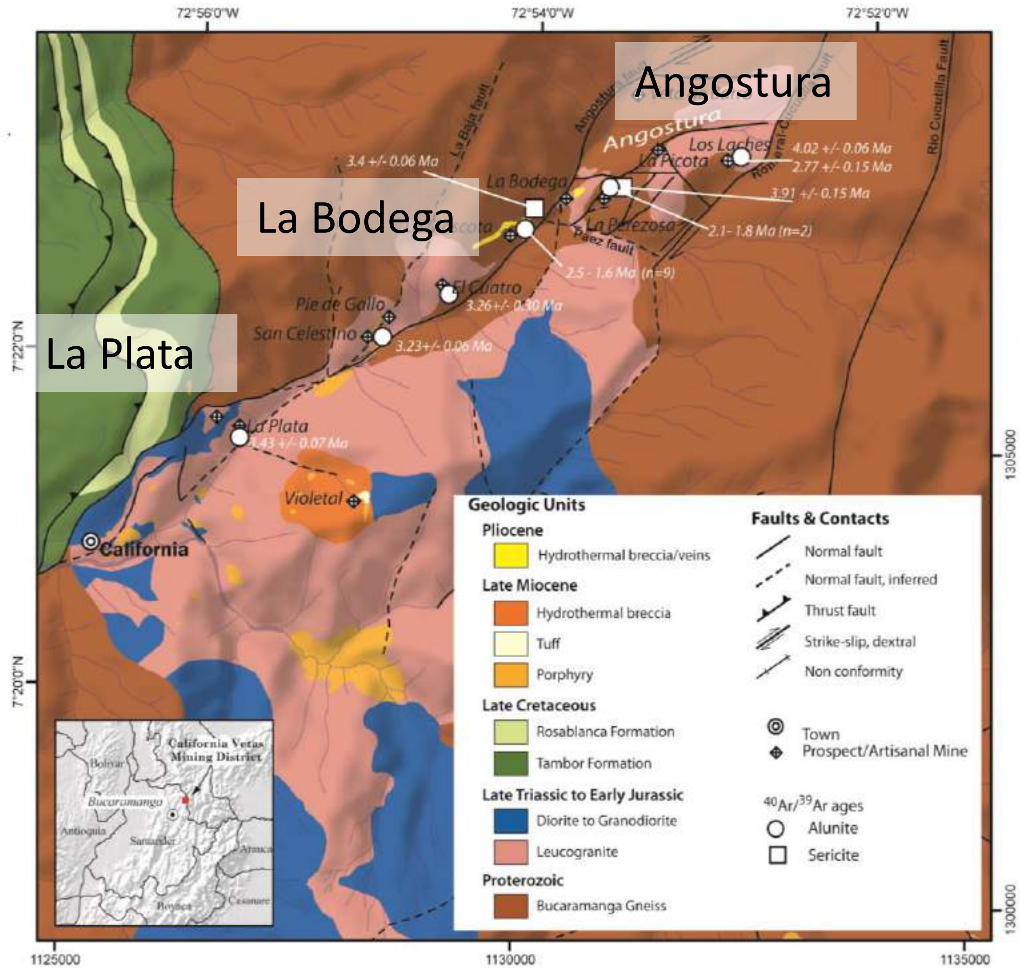
California-Vetas district Colombia



Mod from Rodriguez 2014

SOCIEDAD GEOLÓGICA DEL PERÚ

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La Bodega/La Mascota/Angostura Area, Colombia

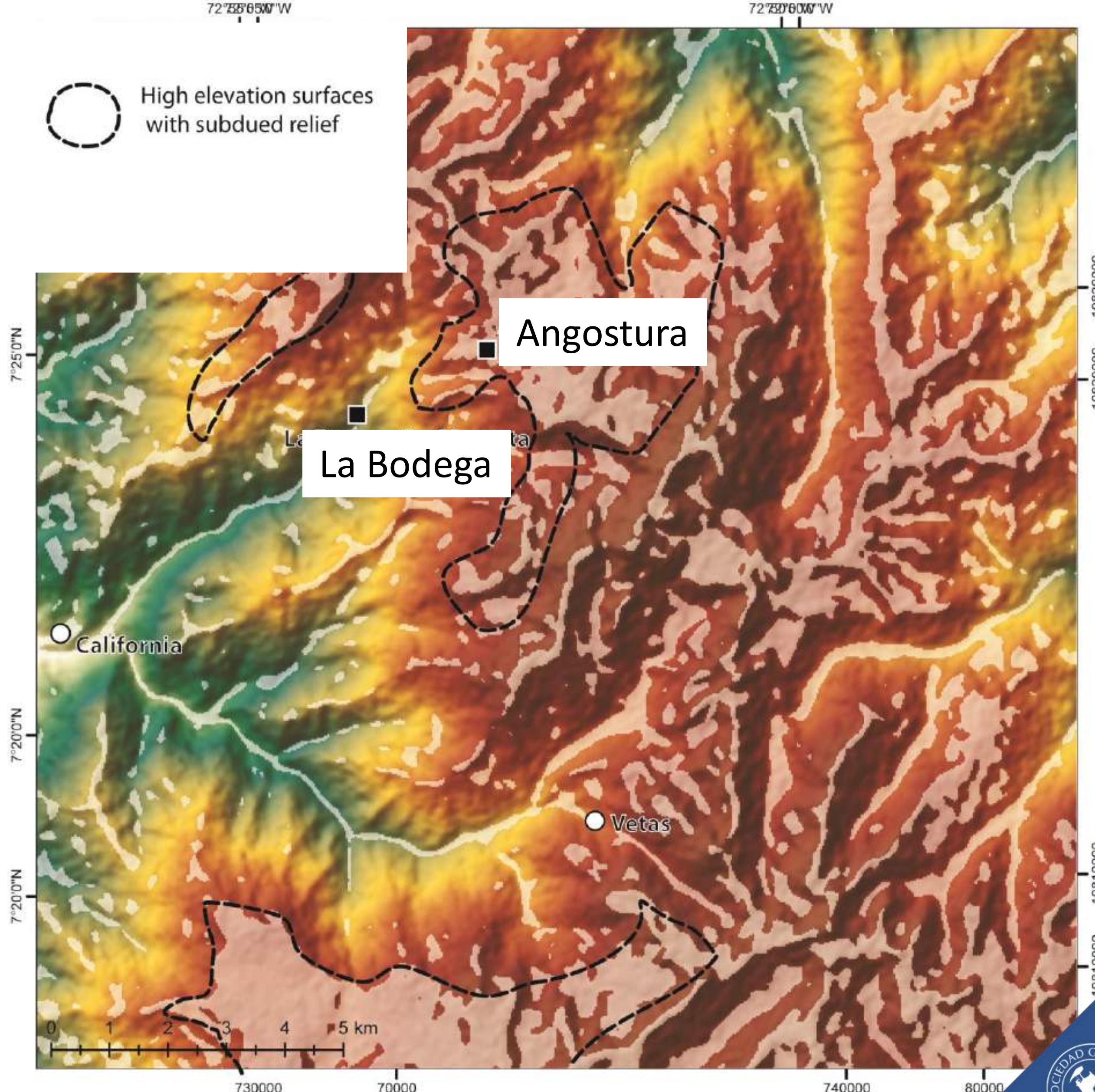
Elevation (m)

High : 4272

Low : 1358

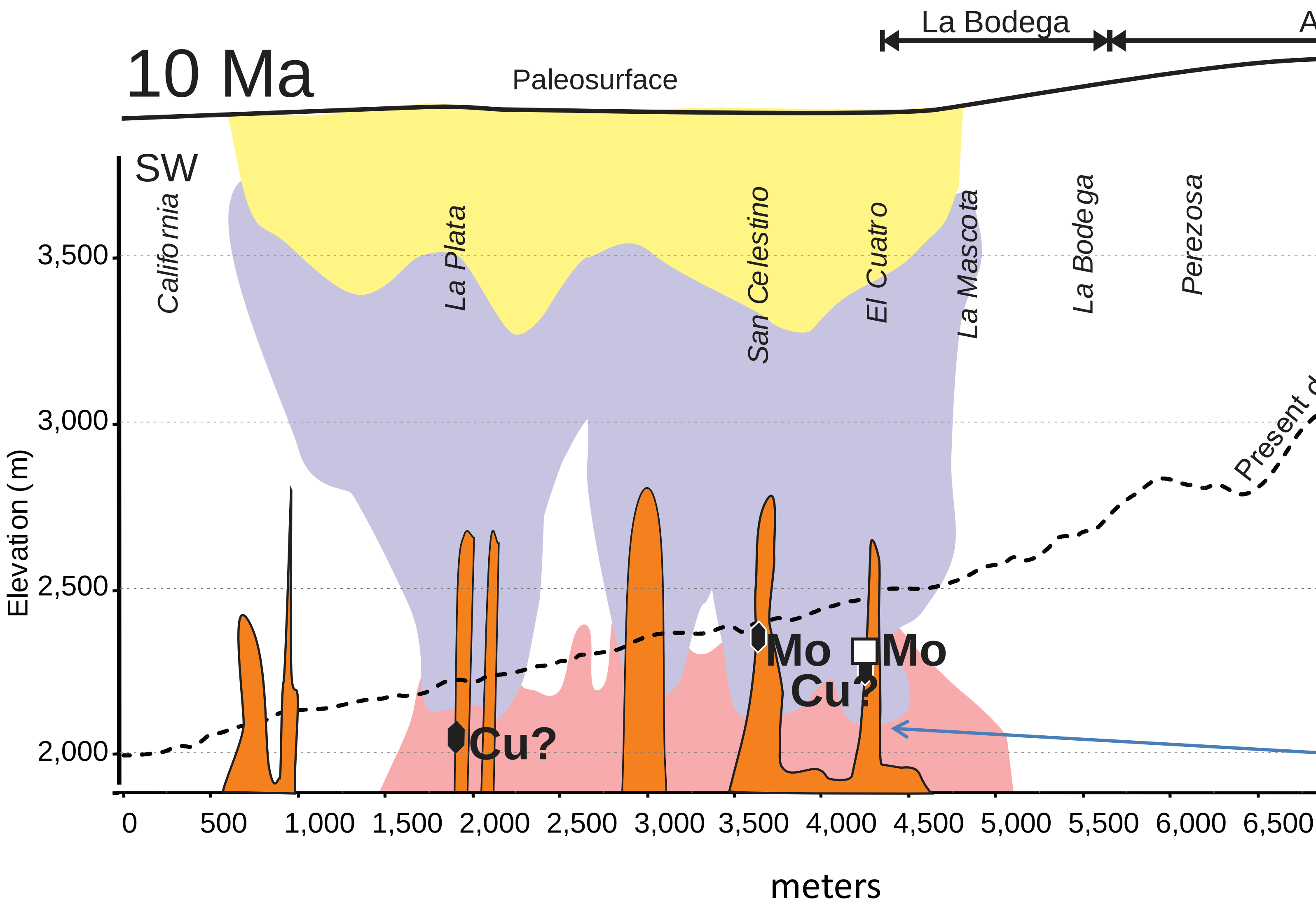
Slope (Degrees)

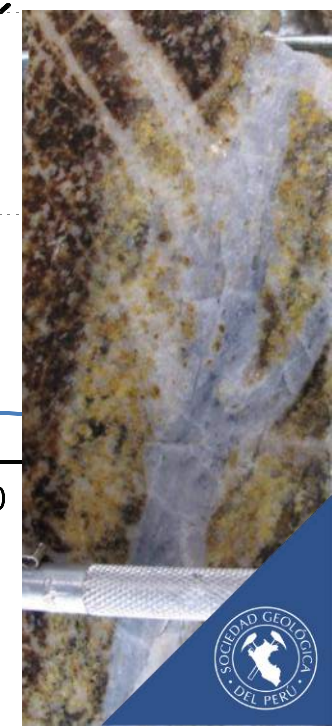
0 - 16



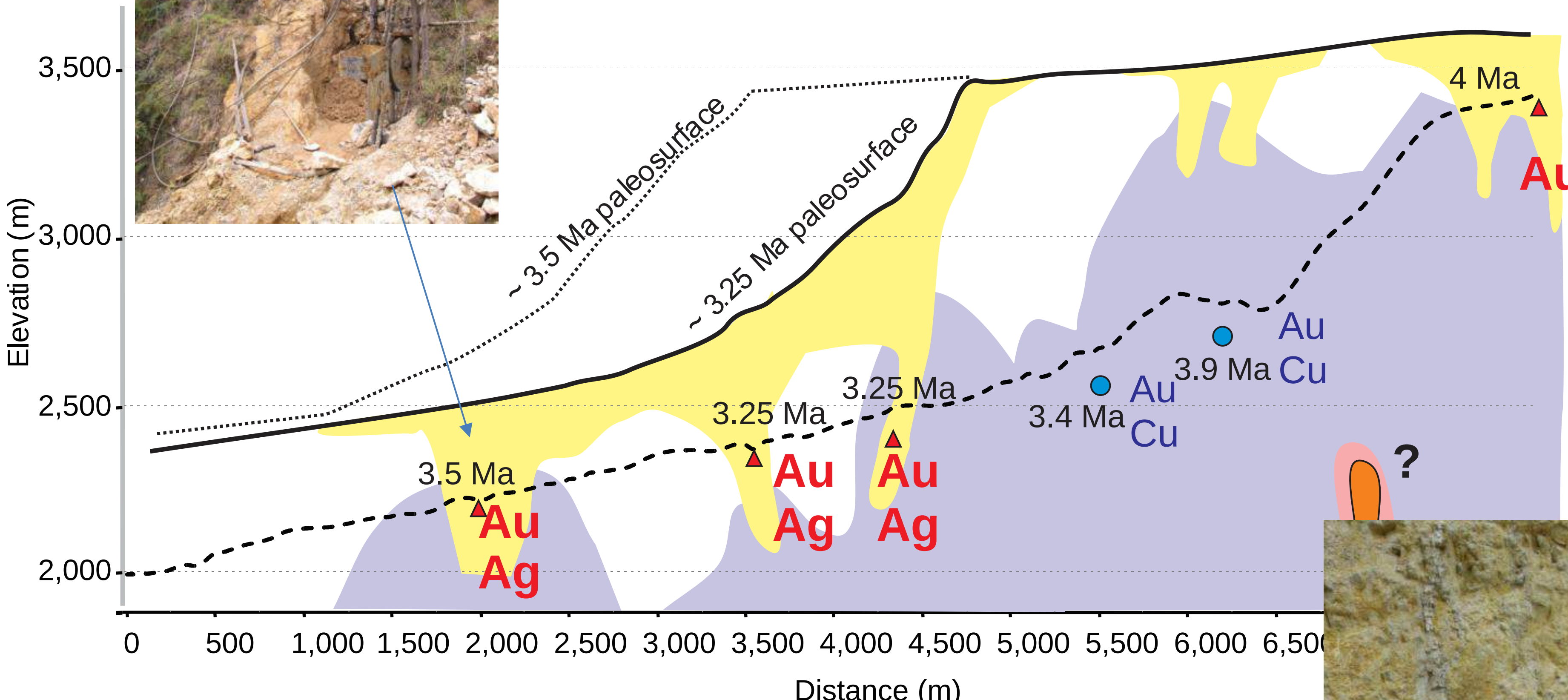
High elevation paleosurface incised by steep drainages

To date no igneous rocks contemporaneous with mineralization known from the district

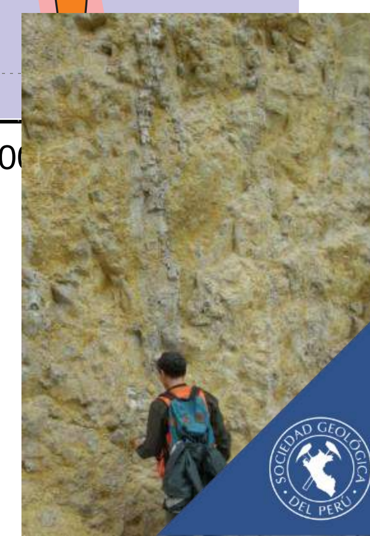

10 Ma
Paleosurface
La Bodega
Angostura
SW
NE
California
La Plata
San Celestino
El Cuatro
La Mascota
La Bodega
Perezosa
Los Laches
Present day surface
Mo
Mo
Cu?
Cu?
3,500
3,000
2,500
2,000
Elevation (m)
0
500
1,000
1,500
2,000
2,500
3,000
3,500
4,000
4,500
5,000
5,500
6,000
6,500
meters


SOCIEDAD GEOLÓGICA DEL PERÚ

4 - 3.25 Ma



~ 3.5 Ma paleosurface
~ 3.25 Ma paleosurface
4 Ma
Au
3.9 Ma
Au
Cu
3.4 Ma
Au
Cu
3.25 Ma
3.25 Ma
Au
Ag
Au
Ag
3.5 Ma
Au
Ag
?
Elevation (m)
3,500
3,000
2,500
2,000
0
500
1,000
1,500
2,000
2,500
3,000
3,500
4,000
4,500
5,000
5,500
6,000
6,500
Distance (m)



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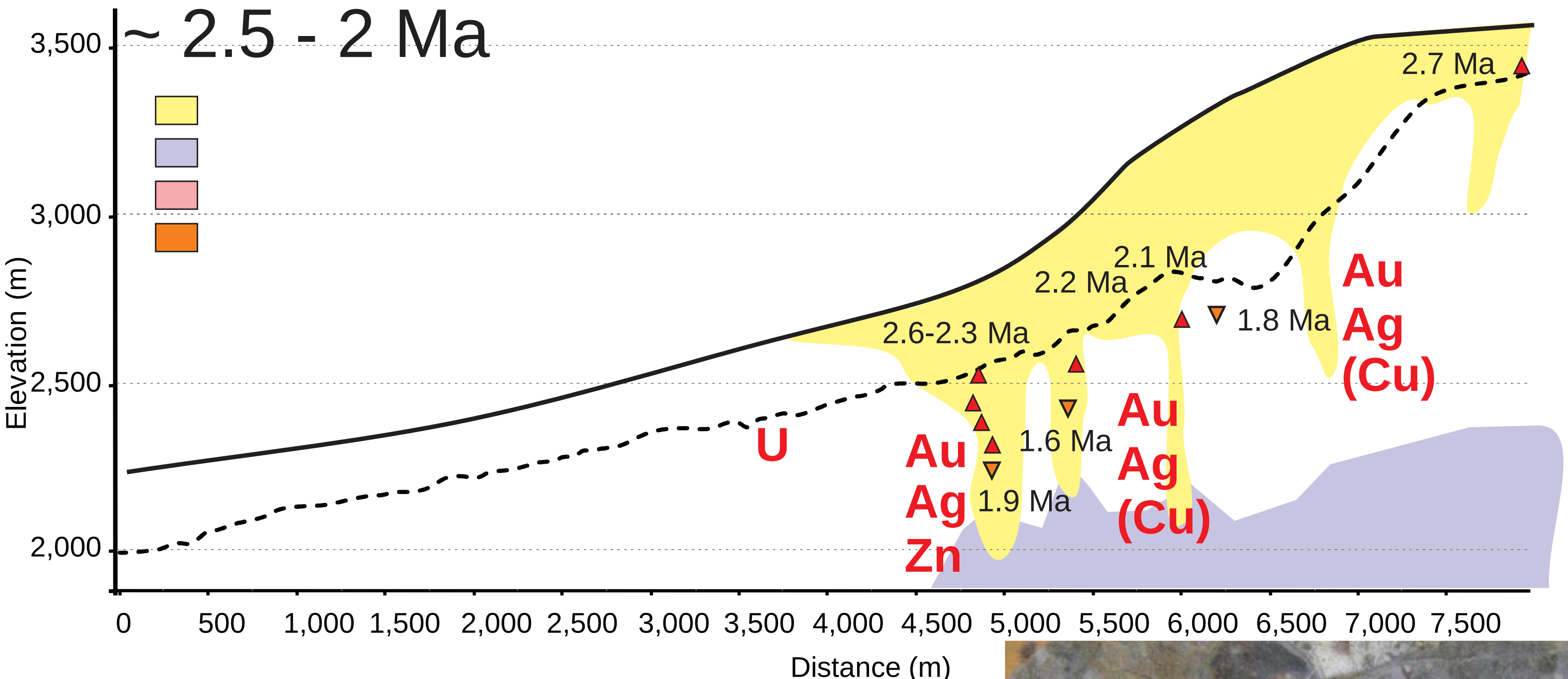
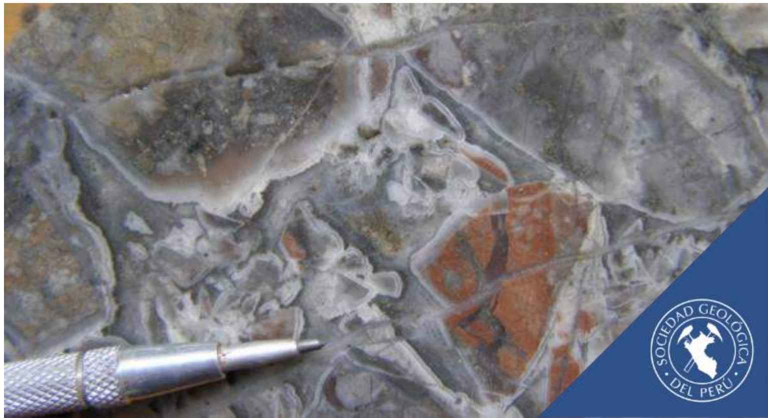
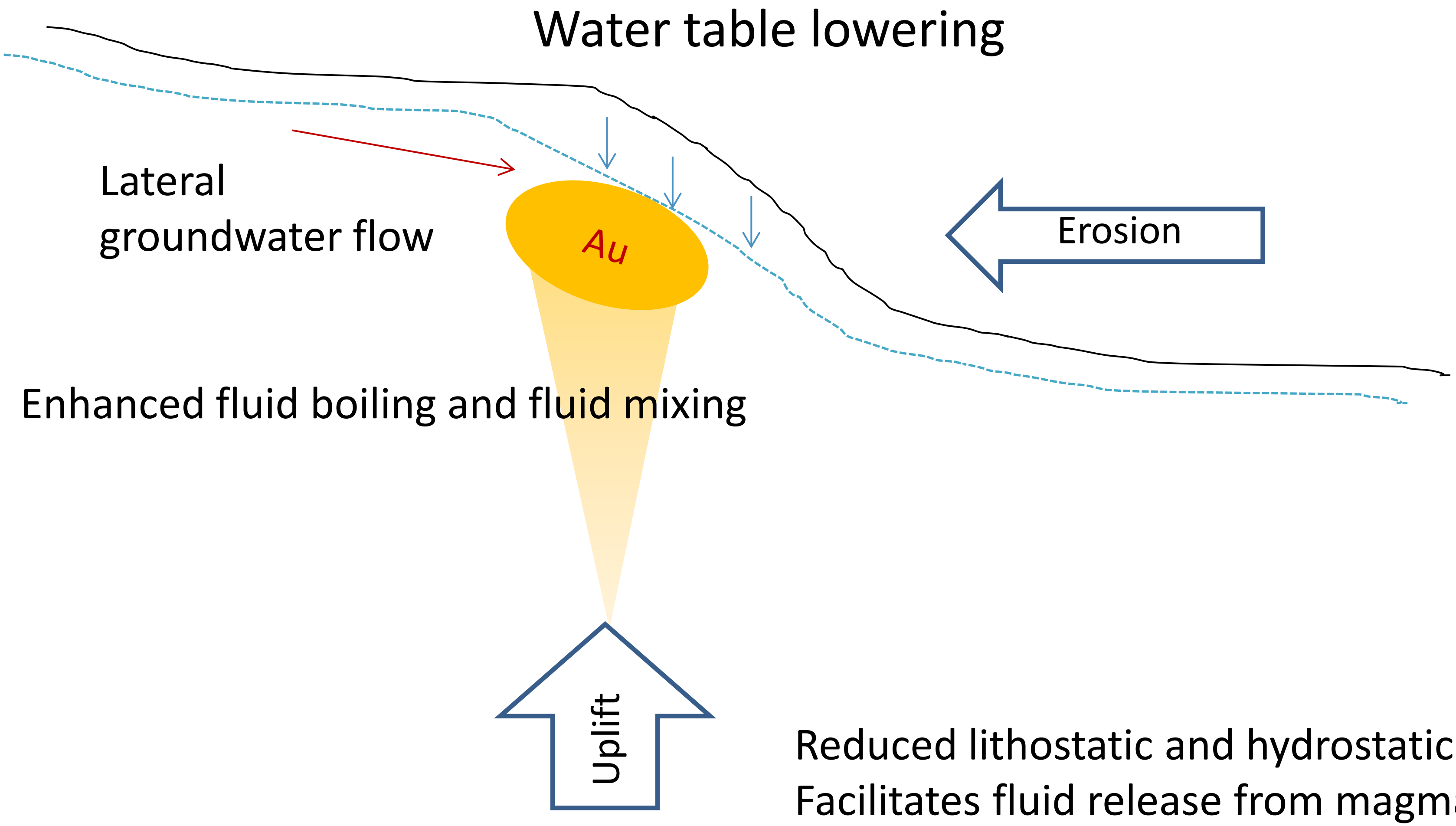




Erosion during hydrothermal activity: favorable for mineralization



Reduced lithostatic and hydrostatic load,
Facilitates fluid release from magma?

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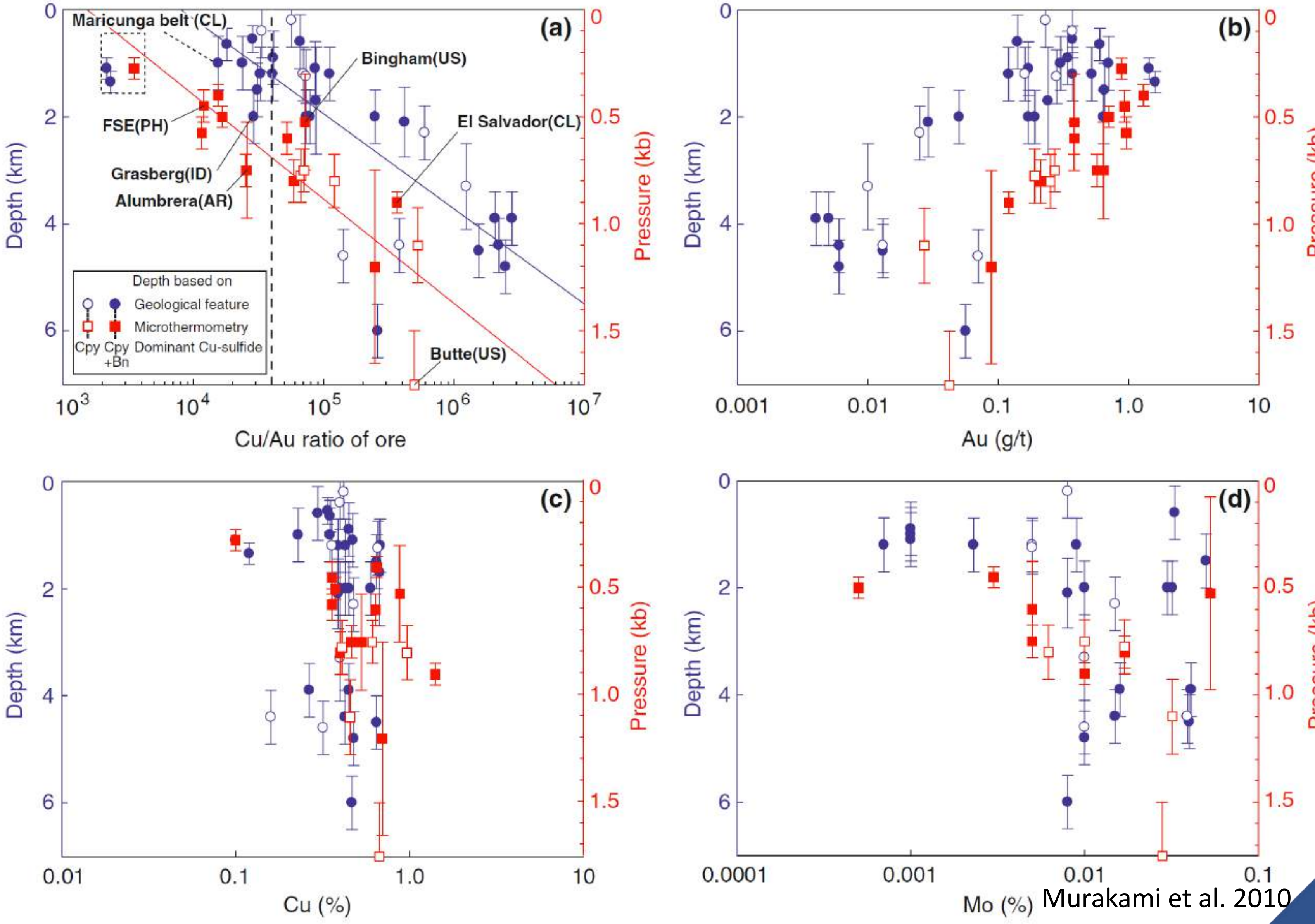
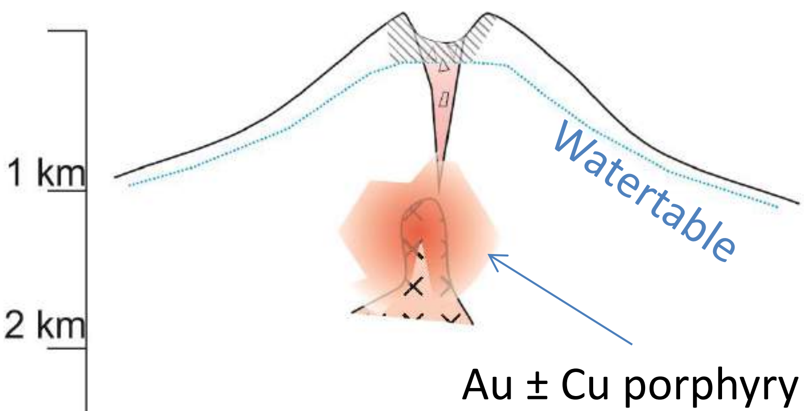
Depth of emplacement of porphyry and implications for epithermal deposits

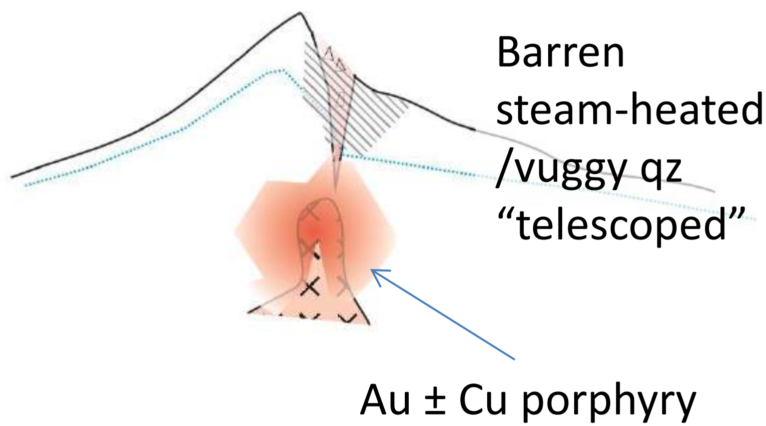


Murakami et al. 2010

Scenario 1: Stratovolcano, shallow intrusion

Sector collapse/erosion

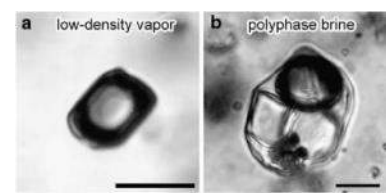




3 km

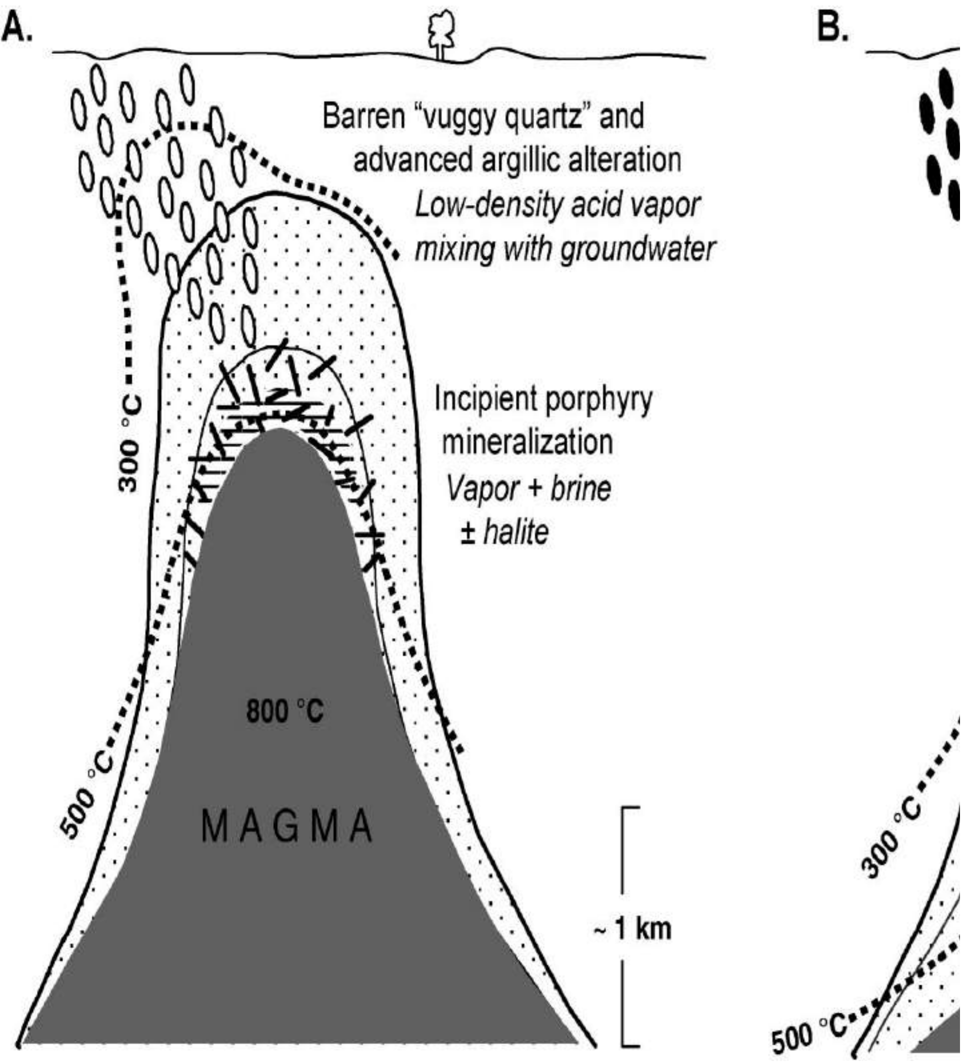
4 km

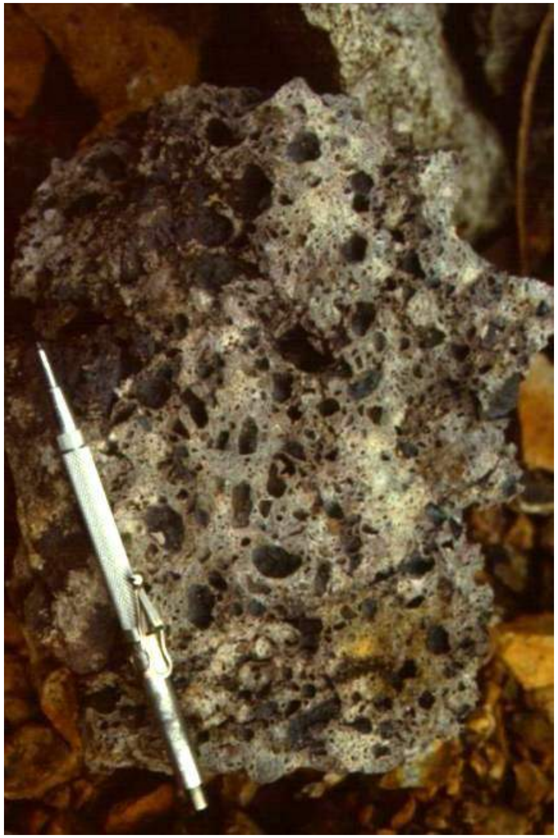
Depth of porphyry emplacement < 2 km
Low density vapor



Gold not transported to near-surface

High-sulfidation eptihermal deposits form in two stages: 1. Ground preparation

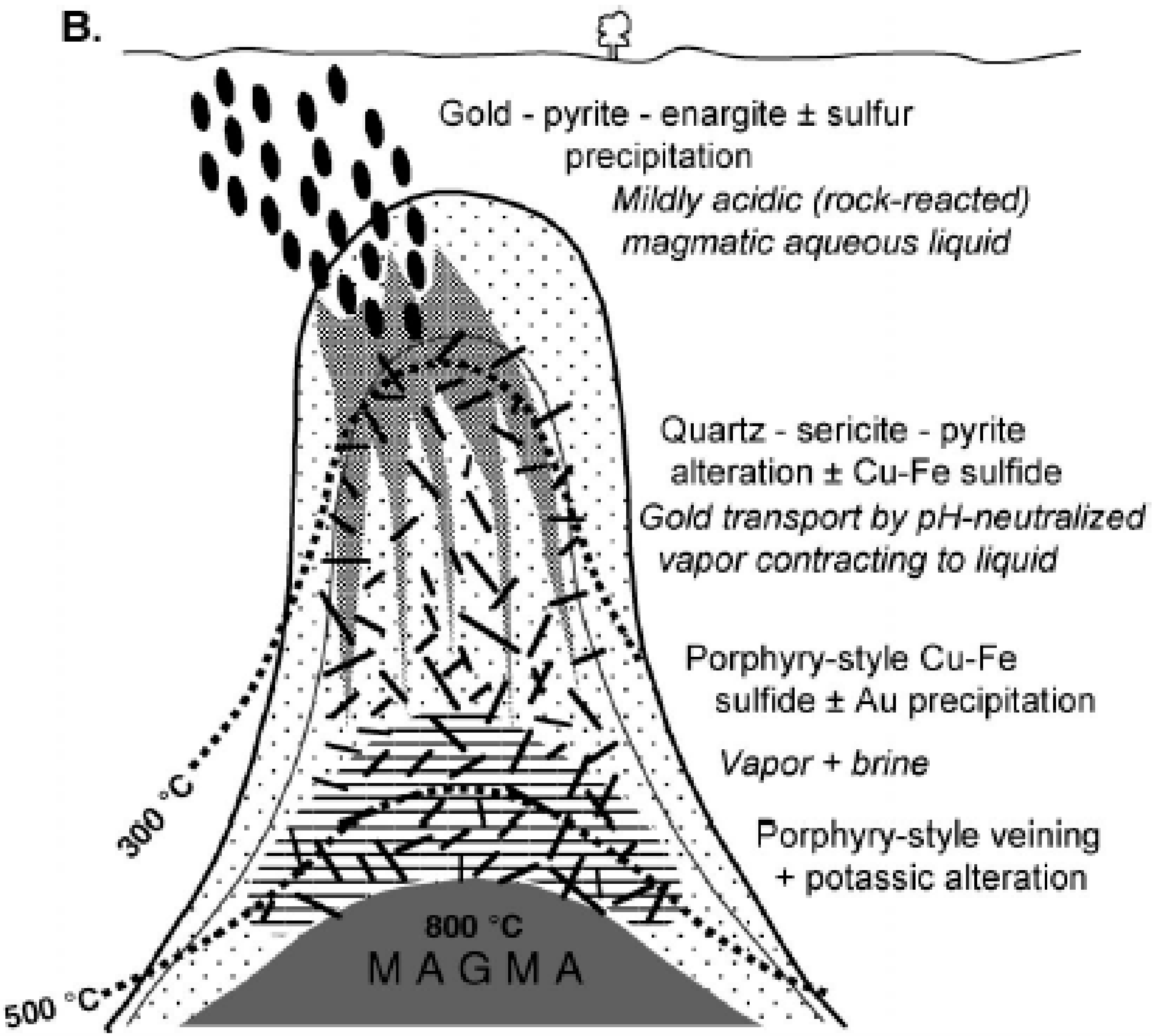




Shallow exsolution of low density vapor

Heinrich et al., 2004

2. Mineralization



Magma exsolves higher density vapor at greater depth.

Heinrich et al., 2004

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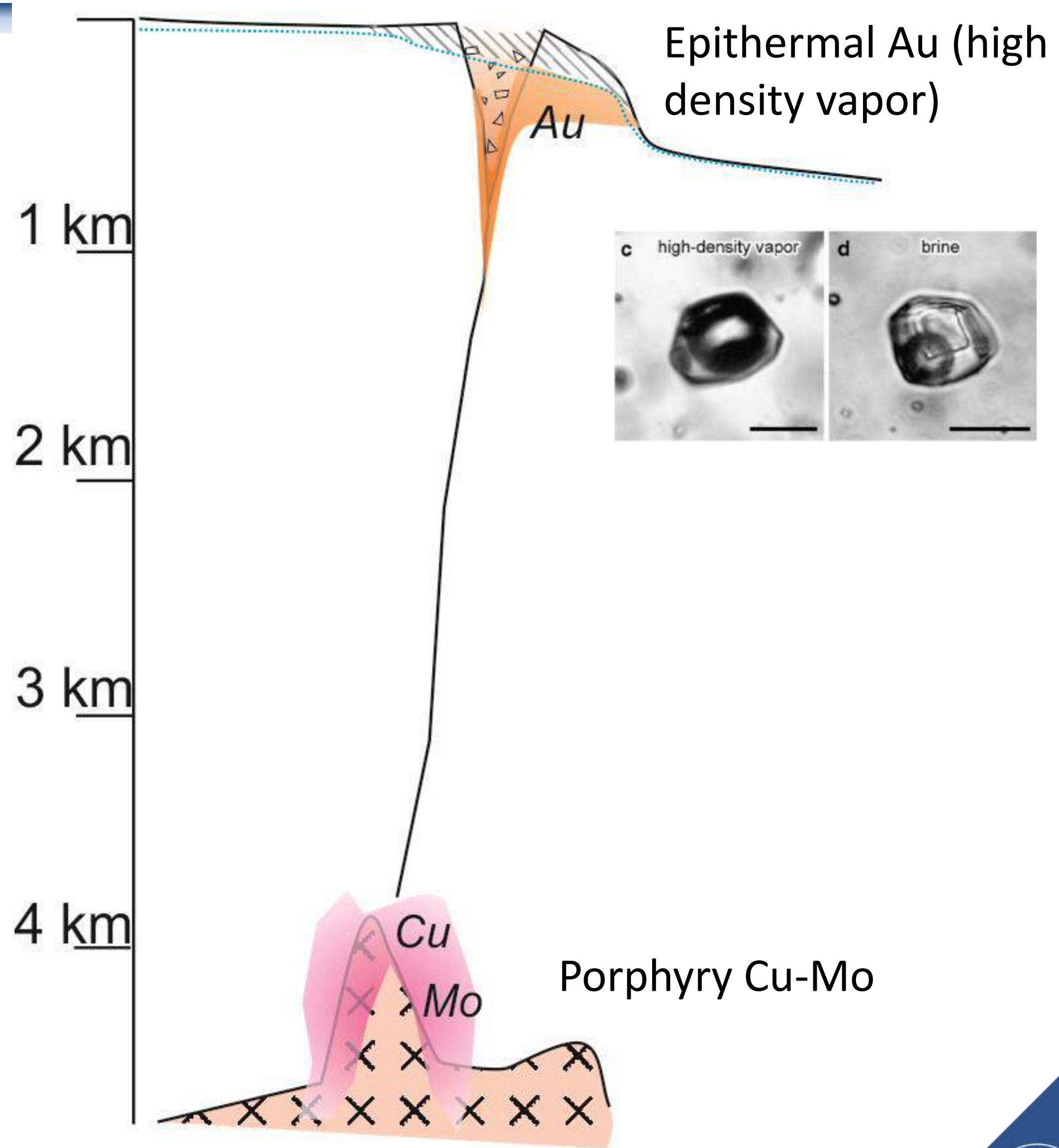
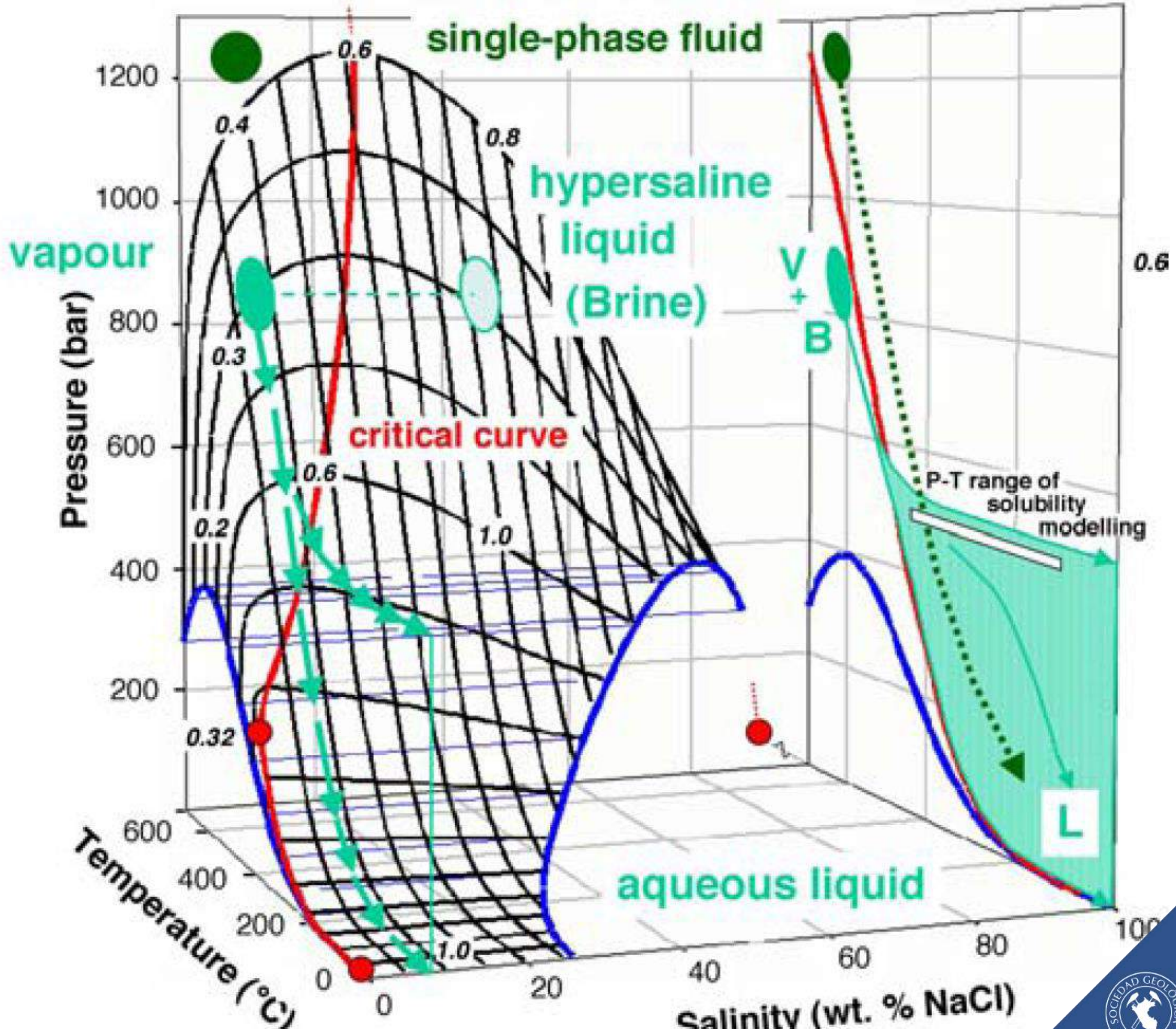
Scenario 2: Deep intrusion, no volcano



High-density vapor
Capable of transporting Au

Vapor must condense into aqueous liquid and physically separate from the porphyry (that's where the structure comes in).


single-phase fluid
hypersaline
liquid
(Brine)
vapour
V
+
B
critical curve
P-T range of
solubility
modelling
L
aqueous liquid
Pressure (bar)
1200
1000
800
600
400
200
0.6
0.4
0.8
0.3
0.6
0.2
1.0
0.32
1.0
0.6
Temperature (°C)
600
400
200
0
0
20
40
60
80
100
Salinity (wt. % NaCl)

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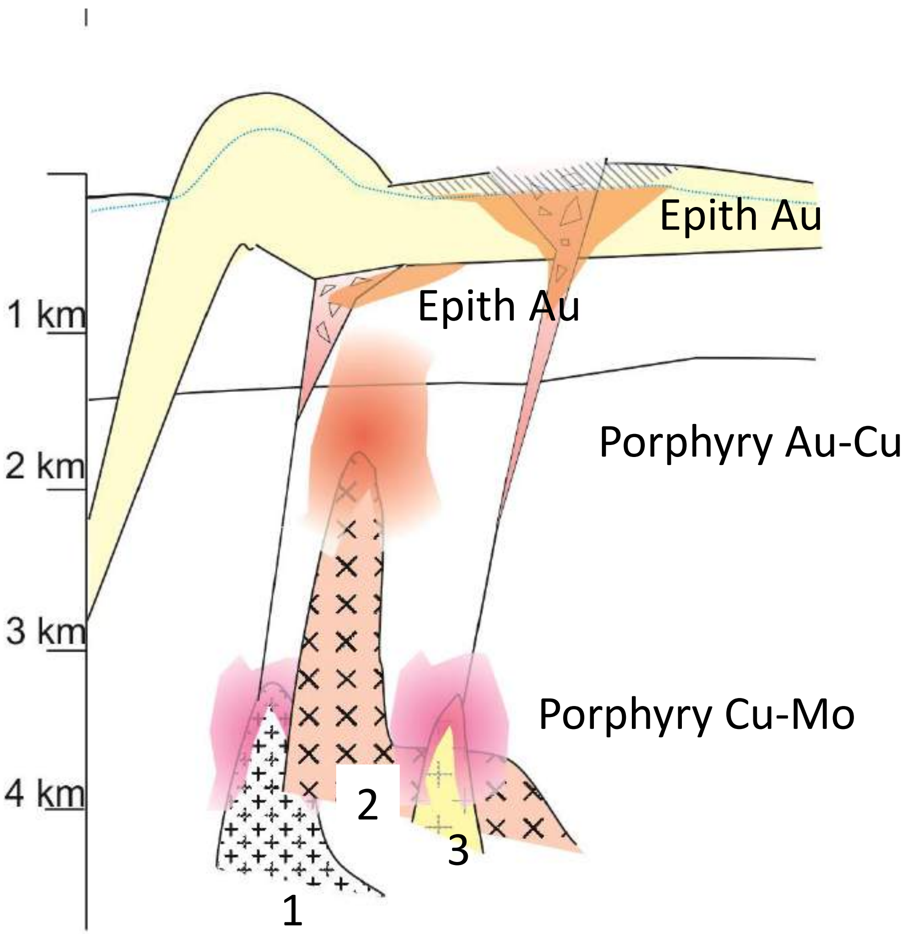
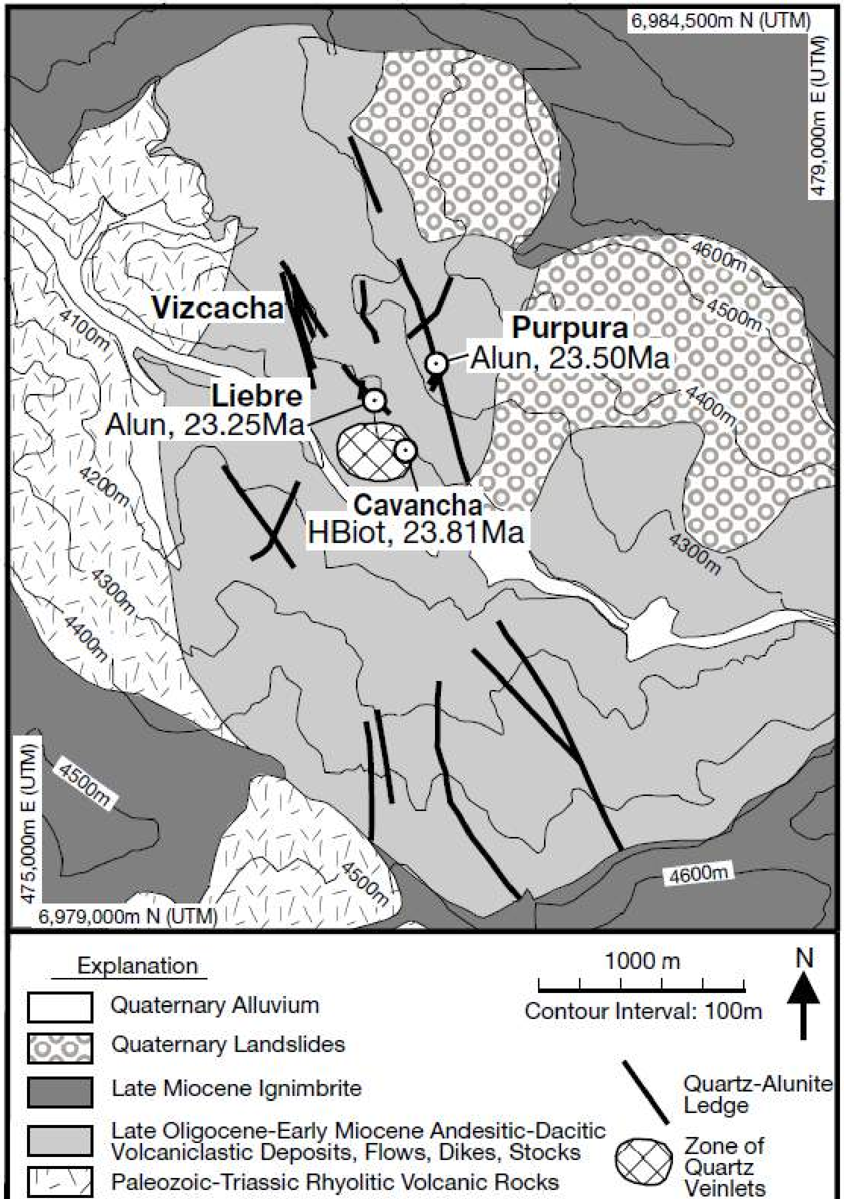


Scenario 3: Multi stage, porphyry and epithermal (e.g., Yanacocha)

Several overprinting porphyry intrusive events over several Ma

Overprint vs. Telescoping



Example La Pepa, Maricunga belt

Au mineralized quartz-alunite ledges are 0.5 Ma younger than porphyry (overprint)

At Refugio and Cerro Casale, for example, alunite and porphyry are indistinguishable in age (telescoping), there, quartz-alunite ledges are barren.

Muntean and Einaudi, 2001

Conclusions 1

- Deposits are commonly located near age equivalent incising lower elevation landforms (valleys and pediments)
- Geomorphology indicates uplift and erosion concurrent with mineralization.
- Erosion lowers water table at back-scarp and may stimulate boiling and fluid mixing leading to ore formation.
- Mineralization mostly post dates volcanism, in some cases by 100’s of Ma

Conclusions 2

Stratovolcanoes? Probably not a good host for high-sulfidation epithermal deposits (but maybe for porphyry Au-Cu).

Look for the porphyry below the high-sulfidation deposit? Yes, there may be one, but it is probably >3 km deep, unless there is indication of several overprinting systems.

Long term preservation of high-sulfidation deposits only possible if favorable structural evolution (protected from erosion somehow).

Low-sulfidation deposits in the Andean context are more likely to be preserved over time due to extensional regime and cover by younger sediments.

See also Bissig, Clark, Montgomery and Rainbow 2015, Ore Geology Reviews.

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