Porphyry and epithermal ore formation in post-subduction tectonic settings

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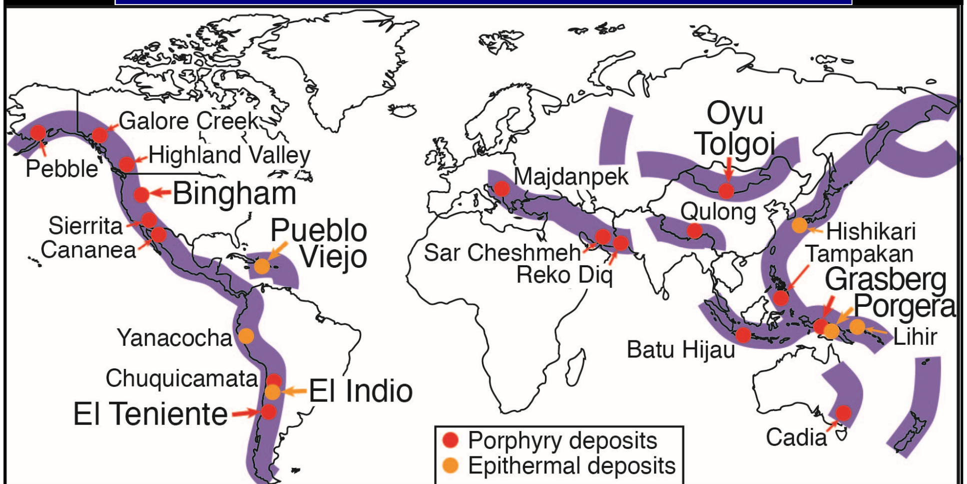
ÉCOLE DES SCIENCES DE LA TERRE

Global distribution of major porphyry Cu±Mo±Au and related epithermal Au-Ag-Cu deposits: Many deposits in the Tethyan belt post-date collisional ocean basin closure

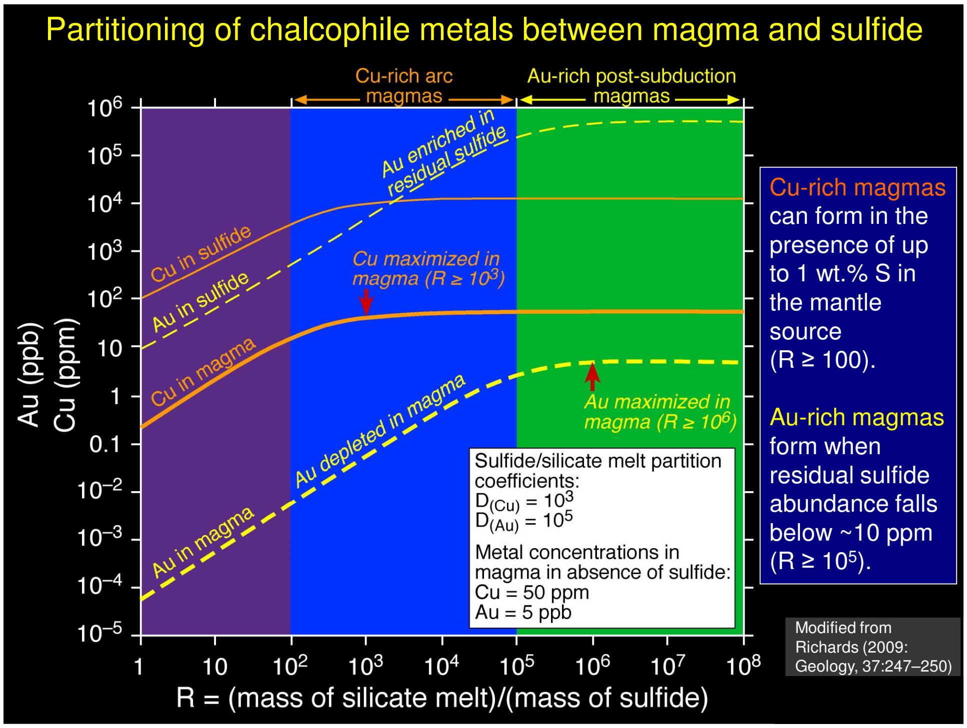


Richards, J.P., 2013, Giant ore deposits form by optimal alignments and combinations of geological processes: Nature Geoscience, v. 6, p. 911–916.

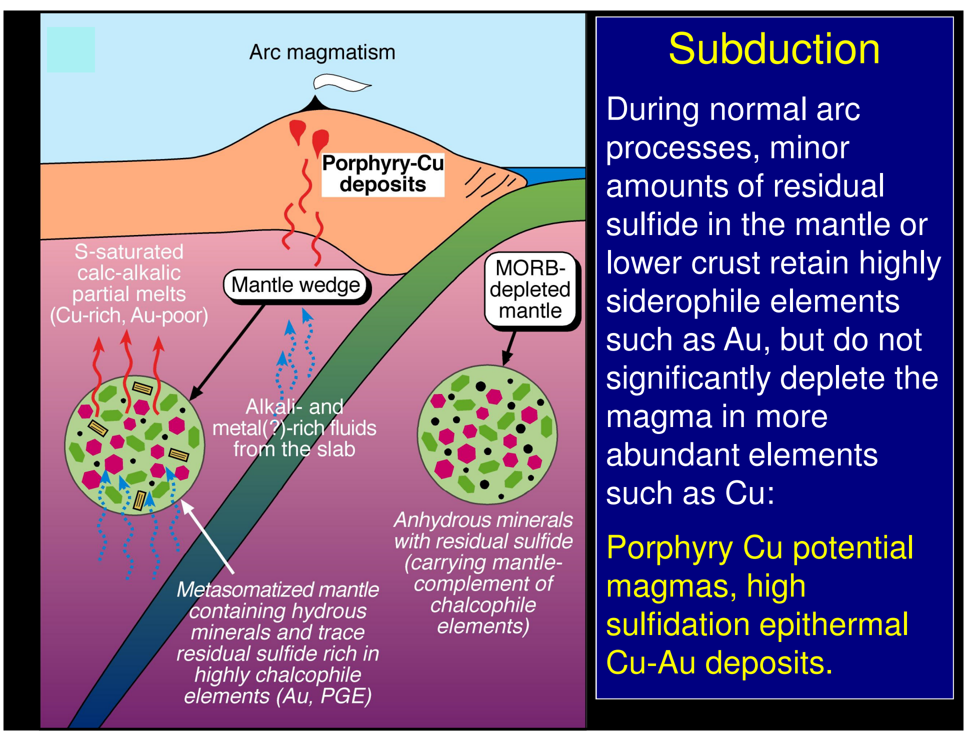
Post-subduction or collisional tectonic settings

- Potential for generation of Au-rich magmas: Porphyry Au and alkalic epithermal Au deposits.
- Behaviour of highly siderophile elements (e.g., Au) may be controlled by the amount of residual sulfide remaining in the mantle or lower crustal source.

Richards, J.P., 2009, Postsubduction porphyry Cu-Au and epithermal Au deposits: Products of remelting of subduction-modified lithosphere: Geology, v. 37, p. 247–250.



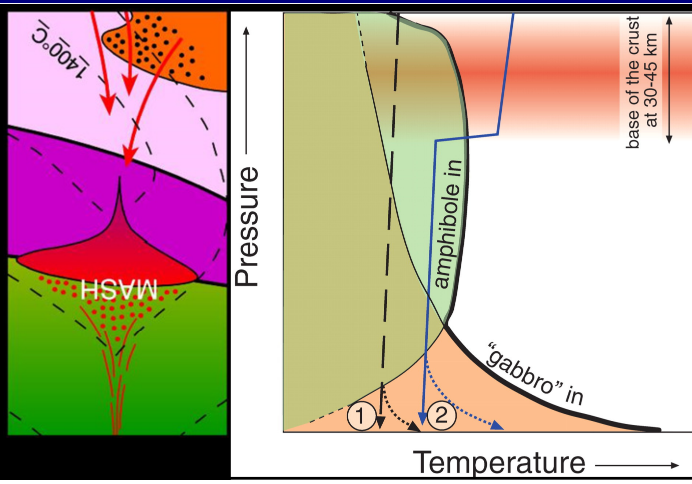
Partitioning of chalcophile metals between magma and sulfide
Cu-rich arc magmas
Au-rich post-subduction magmas
Au enriched in residual sulfide
Cu in sulfide
Au in sulfide
Cu maximized in magma (R ≥ 10³)
Cu in magma
Au depleted in magma
Au maximized in magma (R ≥ 10⁶)
Au in magma
Sulfide/silicate melt partition coefficients:
D(Cu) = 10³
D(Au) = 10⁵
Metal concentrations in magma in absence of sulfide:
Cu = 50 ppm
Au = 5 ppb
Au (ppb)
Cu (ppm)
R = (mass of silicate melt)/(mass of sulfide)
Cu-rich magmas can form in the presence of up to 1 wt.% S in the mantle source (R ≥ 100).
Au-rich magmas form when residual sulfide abundance falls below ~10 ppm (R ≥ 10⁵).
Modified from Richards (2009: Geology, 37:247–250)



Arc magmatism
Porphyry-Cu deposits
S-saturated calc-alkalic partial melts (Cu-rich, Au-poor)
Mantle wedge
MORB-depleted mantle
Alkali- and metal(?)-rich fluids from the slab
Anhydrous minerals with residual sulfide (carrying mantle-complement of chalcophile elements)
Metasomatized mantle containing hydrous minerals and trace residual sulfide rich in highly chalcophile elements (Au, PGE)
Subduction
During normal arc processes, minor amounts of residual sulfide in the mantle or lower crust retain highly siderophile elements such as Au, but do not significantly deplete the magma in more abundant elements such as Cu:
Porphyry Cu potential magmas, high sulfidation epithermal Cu-Au deposits.

Arc cumulate roots

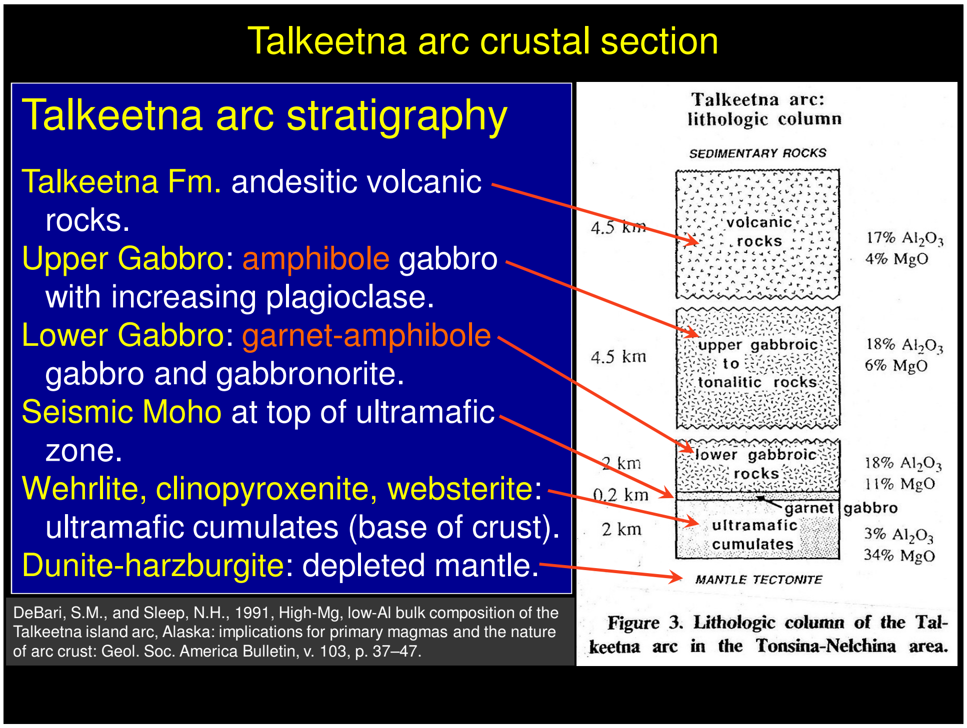
Dense, hydrous basaltic arc magmas will tend to pool at the base of the crust, forming a hot, underplated layer. Here they will interact with lower crustal rocks and fractionate (MASH process), leaving an ultramafic amphibolitic cumulate root.

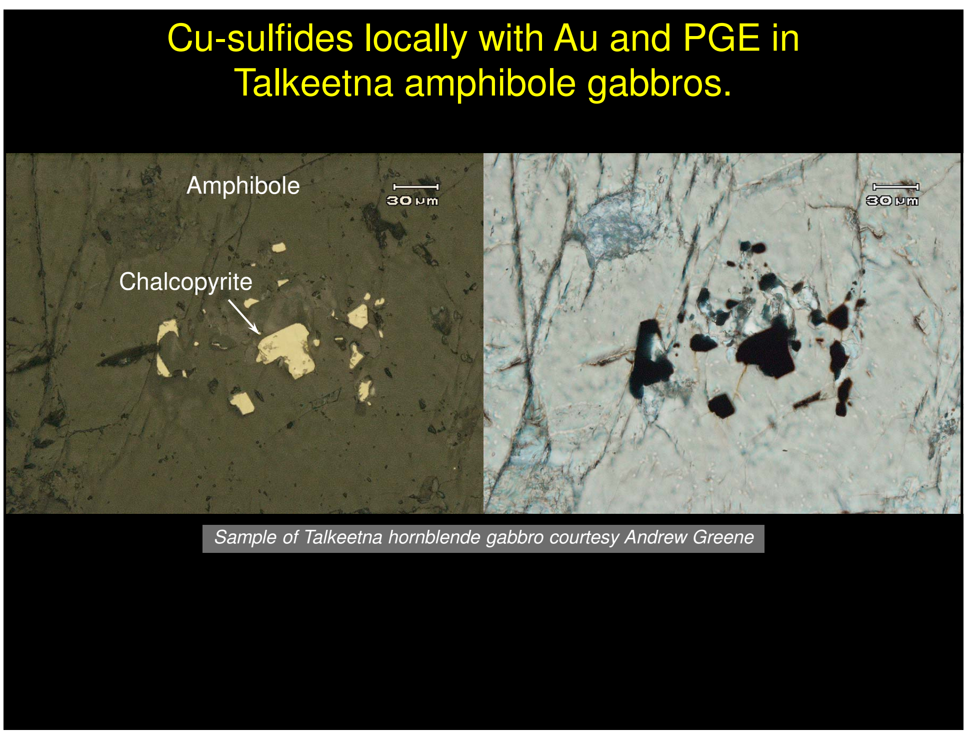


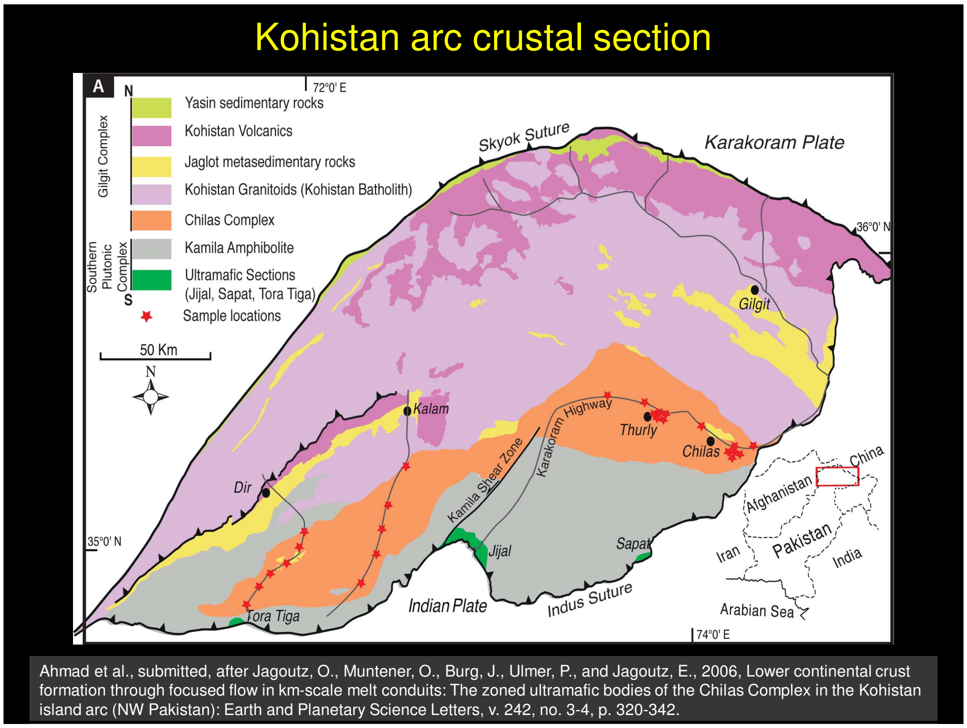
Davidson, J., Turner, S., Handley, H., Macpherson, C., and Dosseto, A., 2007, Amphibole “sponge” in arc crust? Geology, v. 35, p. 787–790.

Residual sulfides in arc cumulates:

- Lower crustal fractionation of hydrous, S-rich, mafic arc magmas is likely to result in minor sulfide saturation, despite the bulk of S being present in oxide form (SO_4^{2-}).
- Sulfides including chalcopyrite are present in Talkeetna (Alaska) and Kohistan (northern Pakistan) arc lower-crustal hornblende-gabbros.
- Preliminary data indicate that some of these sulfides are Au- and PGE-rich.

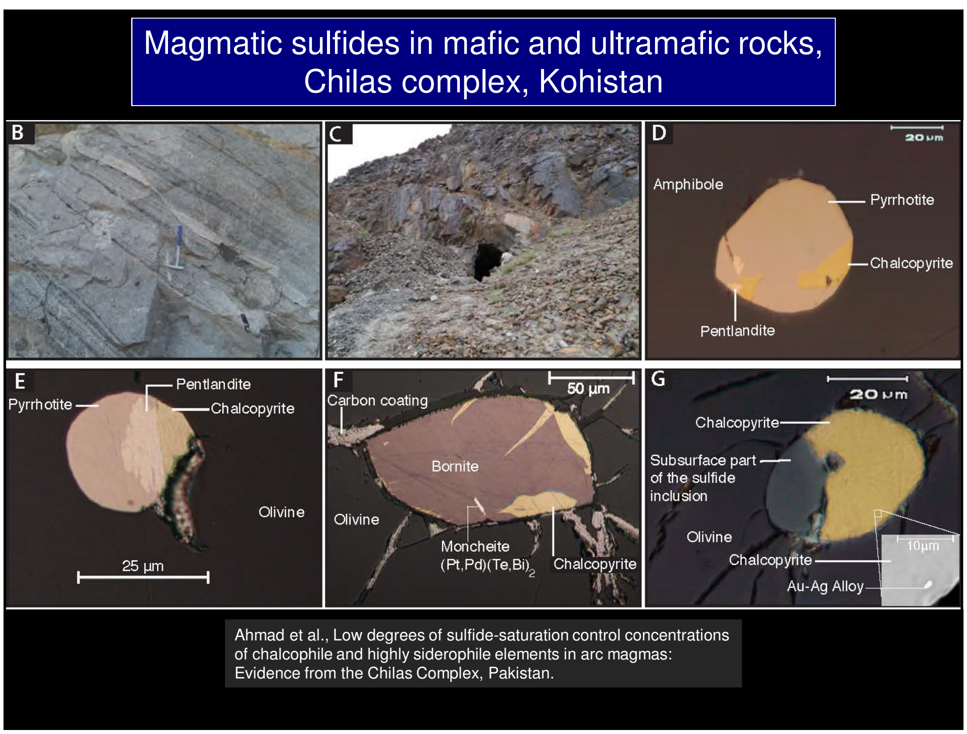

Talkeetna arc crustal section
Talkeetna arc stratigraphy
Talkeetna Fm. andesitic volcanic rocks.
Upper Gabbro: amphibole gabbro with increasing plagioclase.
Lower Gabbro: garnet-amphibole gabbro and gabbronorite.
Seismic Moho at top of ultramafic zone.
Wehrlite, clinopyroxenite, websterite: ultramafic cumulates (base of crust).
Dunite-harzburgite: depleted mantle.
DeBari, S.M., and Sleep, N.H., 1991, High-Mg, low-Al bulk composition of the Talkeetna island arc, Alaska: implications for primary magmas and the nature of arc crust: Geol. Soc. America Bulletin, v. 103, p. 37–47.
Talkeetna arc: lithologic column
SEDIMENTARY ROCKS
4.5 km
volcanic rocks
17% Al_2O_3 4% MgO
4.5 km
upper gabbroic to tonalitic rocks
18% Al_2O_3 6% MgO
2 km
lower gabbroic rocks
18% Al_2O_3 11% MgO
0.2 km
garnet gabbro
2 km
ultramafic cumulates
3% Al_2O_3 34% MgO
MANTLE TECTONITE
Figure 3. Lithologic column of the Talkeetna arc in the Tonsina-Nelchina area.


Cu-sulfides locally with Au and PGE in Talkeetna amphibole gabbros.
Amphibole
Chalcopyrite
30 μm
30 μm
Sample of Talkeetna hornblende gabbro courtesy Andrew Greene


Kohistan arc crustal section
A
N
S
72°0' E
74°0' E
36°0' N
35°0' N
Gilgit Complex
Southern Plutonic Complex
Yasin sedimentary rocks
Kohistan Volcanics
Jaglot metasedimentary rocks
Kohistan Granitoids (Kohistan Batholith)
Chilas Complex
Kamila Amphibolite
Ultramafic Sections (Jijal, Sapat, Tora Tiga)
Sample locations
50 Km
Skyok Suture
Karakoram Plate
Gilgit
Kalam
Dir
Thurly
Chilas
Karakoram Highway
Kamila Shear Zone
Jijal
Sapat
Tora Tiga
Indian Plate
Indus Suture
China
Afghanistan
Pakistan
Iran
India
Arabian Sea
Ahmad et al., submitted, after Jagoutz, O., Muntener, O., Burg, J., Ulmer, P., and Jagoutz, E., 2006, Lower continental crust formation through focused flow in km-scale melt conduits: The zoned ultramafic bodies of the Chilas Complex in the Kohistan island arc (NW Pakistan): Earth and Planetary Science Letters, v. 242, no. 3-4, p. 320-342.


Chilas Complex layered gabbros


Small Cu-PGE mine in ultramafic cumulates, Chilas Complex, Kohistan
30 μm
Cp
Bn
Moncheite (Pt,Pd)(Te,Bi)2
Approach at own risk!
Cu-Fe-sulfides and moncheite in dunite.
Photo: Ijaz Ahmad

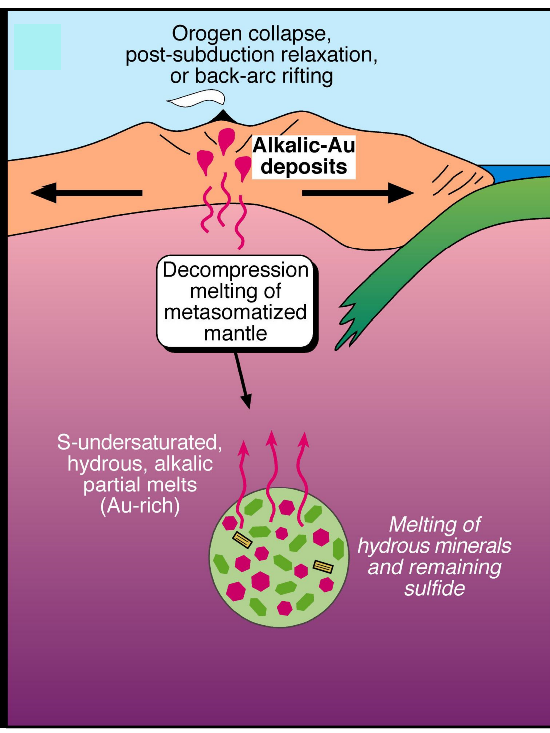

Magmatic sulfides in mafic and ultramafic rocks, Chilas complex, Kohistan
B
C
D
20 μm
Amphibole
Pyrrhotite
Chalcopyrite
Pentlandite
E
Pentlandite
Pyrrhotite
Chalcopyrite
Olivine
25 μm
F
50 μm
Carbon coating
Bornite
Olivine
Moncheite (Pt,Pd)(Te,Bi)2
Chalcopyrite
G
20 μm
Chalcopyrite
Subsurface part of the sulfide inclusion
Olivine
Chalcopyrite
10μm
Au-Ag Alloy
Ahmad et al., Low degrees of sulfide-saturation control concentrations of chalcophile and highly siderophile elements in arc magmas: Evidence from the Chilas Complex, Pakistan.

Post-subduction or collisional tectonic settings:

Potential for generation of Au-rich magmas by breakdown of residual Cu-Au-rich sulfides in mantle or lower crustal sources.

These magmas will have relatively low sulfur contents (low f_{S_2}), and resulting ore deposits will tend to be relatively S-poor.

Potential to form porphyry Cu-Au, low sulfidation epithermal Au, and magmatic-hydrothermal IOCG deposits.



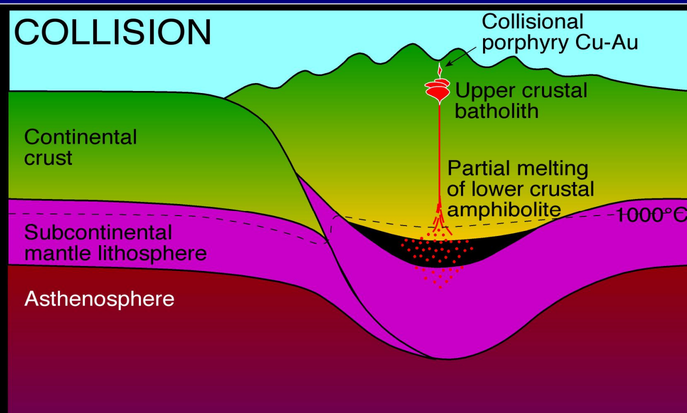
Post-subduction

Thermal relaxation after subduction ceases may cause second-stage partial melting of the metasomatized asthenosphere or lithosphere, leading to final breakdown of residual sulfides and release of highly siderophile elements (e.g., Au) to the melt:

Au potential magmas

Post-subduction settings: Collision

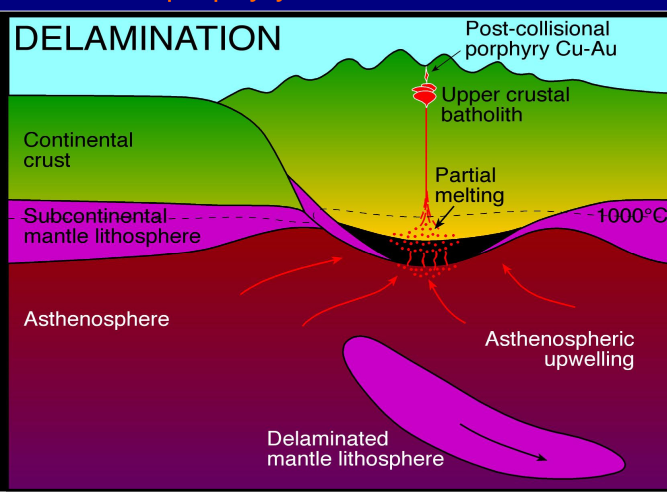
Partial melting of subduction-metasomatized subcontinental mantle lithosphere and lower crustal amphibolites during crustal thickening and thermal rebound can generate calc-alkaline to mildly alkaline magmas with potential for porphyry Cu-Au mineralization.



Modified from Richards (2009: Geology, 37:247–250)

Post-subduction settings: Delamination

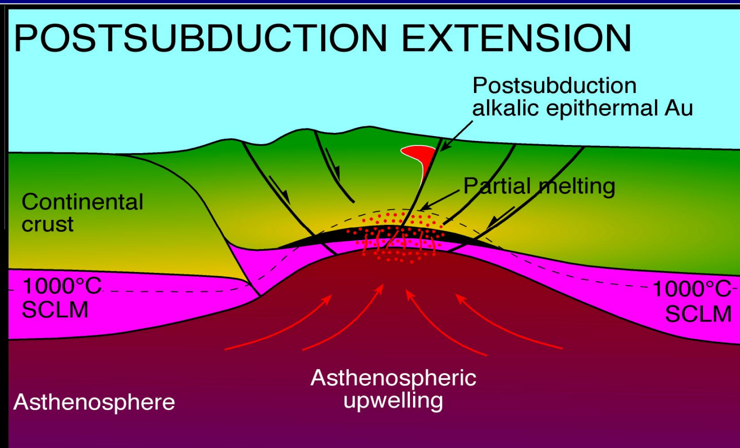
Delamination of subcontinental mantle lithosphere can result in partial melting of subduction-modified lower crustal lithologies to generate calc-alkaline magmas with the potential for porphyry Cu-Au mineralization.



Richards (2009)

Post-subduction settings: Extension

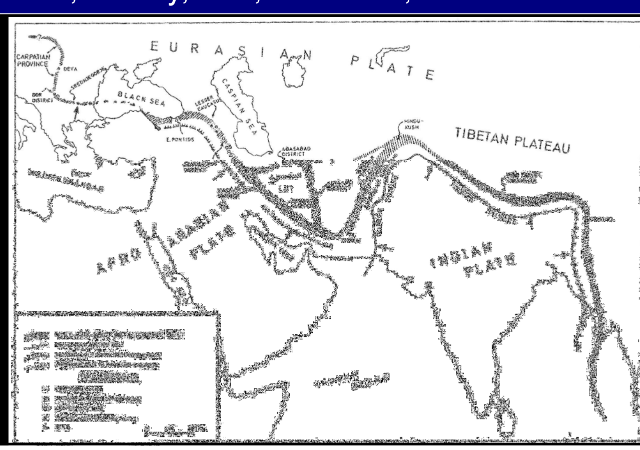
Post-collisional or back-arc extension of subduction-modified lithosphere and asthenospheric melt invasion can generate mafic alkalic magmas with the potential for alkalic-type porphyry ± epithermal Au mineralization.



Richards (2009)

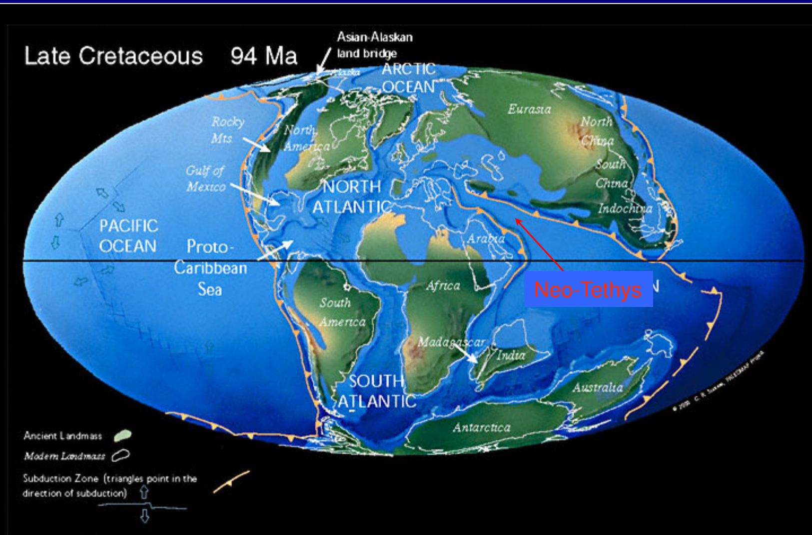
Examples of gold deposits in post-subduction tectonic settings:

A number of Au-rich porphyry and related epithermal deposits occur in collisional and post-collisional tectonic settings, such the Neo-Tethyan collided arcs of the Balkans, Turkey, Iran, and Tibet, and the SW Pacific.



Jankovic, S., 1977, The copper deposits and geotectonic setting of the Tethyan Eurasian metallogenic belt: Mineralium Deposita, v. 12, p. 37–47.

The Mesozoic Neo-Tethys Ocean consisted of a number of small ocean basins and microcontinental blocks and arcs, which closed by progressive collision throughout the Cenozoic.



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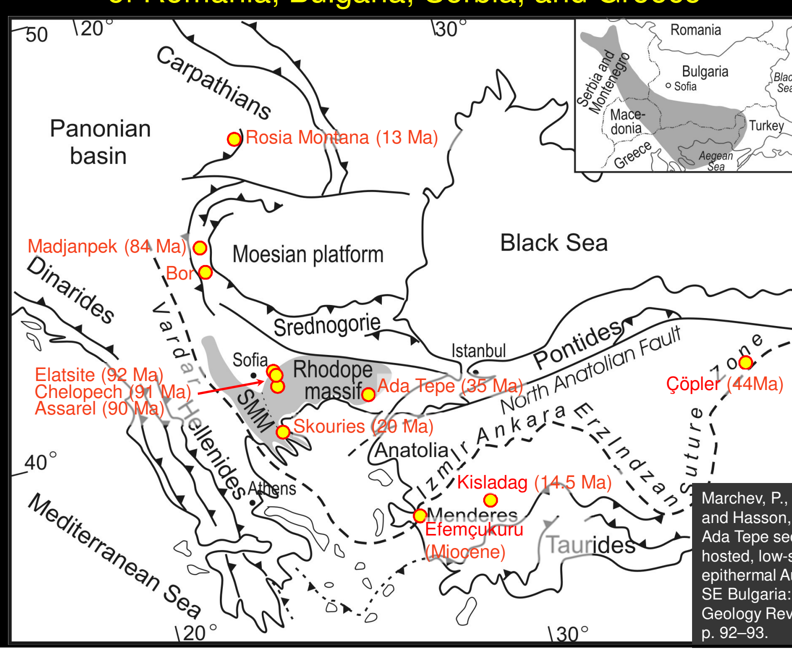
The collided Carpathian and Balkan Neo-Tethyan arcs of Romania, Bulgaria, Serbia, and Greece



Marchev, P., Jelev, D., and Hasson, S., 2005, Ada Tepe sedimentary-hosted, low-sulphidation epithermal Au deposit, SE Bulgaria: Ore Geology Reviews, v. 27, p. 92–93.

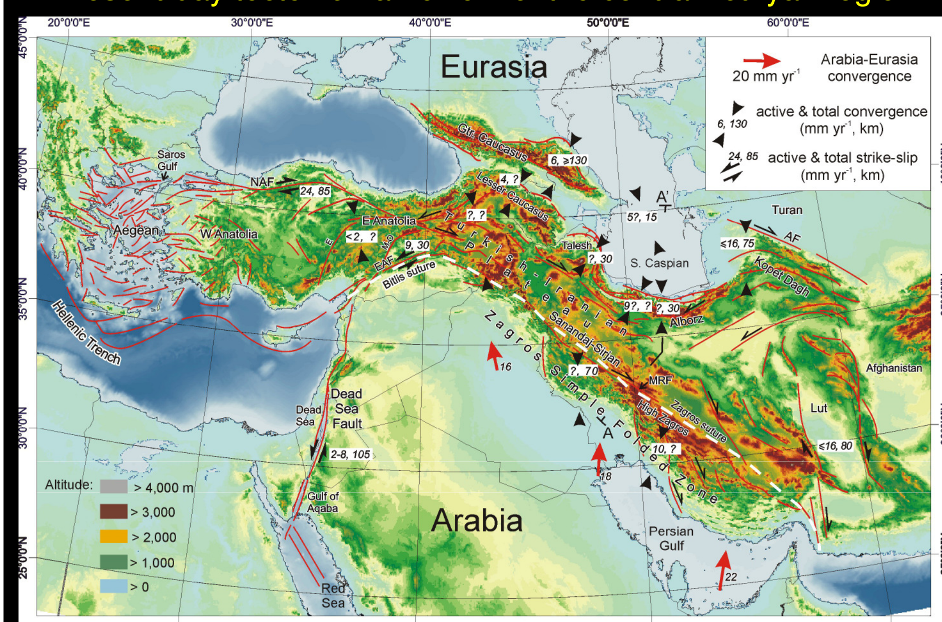
The Rosia Montana epithermal gold deposit (13 Ma), Romania:
Resource of 400.4 Mt @ 1.3 g/t Au and 6.0 g/t Ag

Assarel porphyry Cu deposit, Bulgaria
Reserve of 260 Mt @ 0.46% Cu

Vlaykov Vruh porphyry Cu-Mo deposit (86–82 Ma) with Elshitsa (86 Ma) high-sulfidation epithermal Cu-Au deposit in background

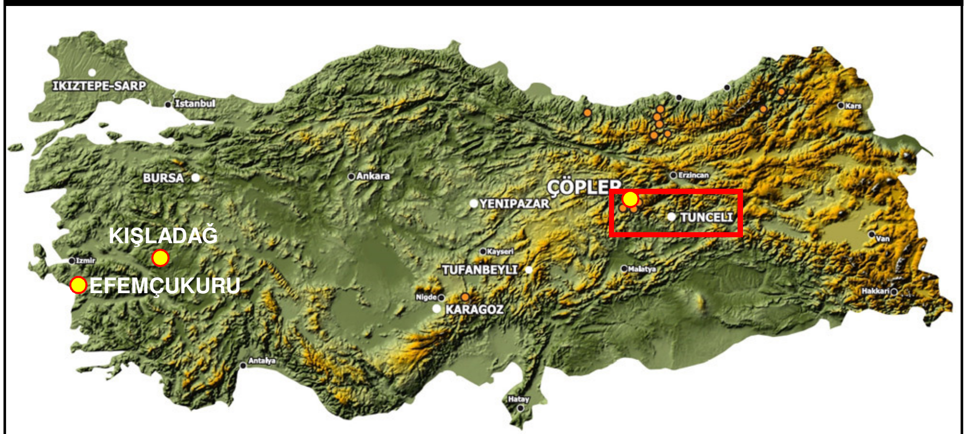
(Grades ~5.6% Cu, 0.2–0.4 g/t Au)

Present-day tectonic framework of the central Tethyan region



Allen, M., Jackson, J., and Walker, R., 2004, Late Cenozoic reorganization of the Arabia-Eurasia collision and the comparison of short-term and long-term deformation rates: Tectonics, v. 23, No. 2, TC2008, doi: 10.1029/2003TC001530

Major porphyry and epithermal gold deposits in Turkey

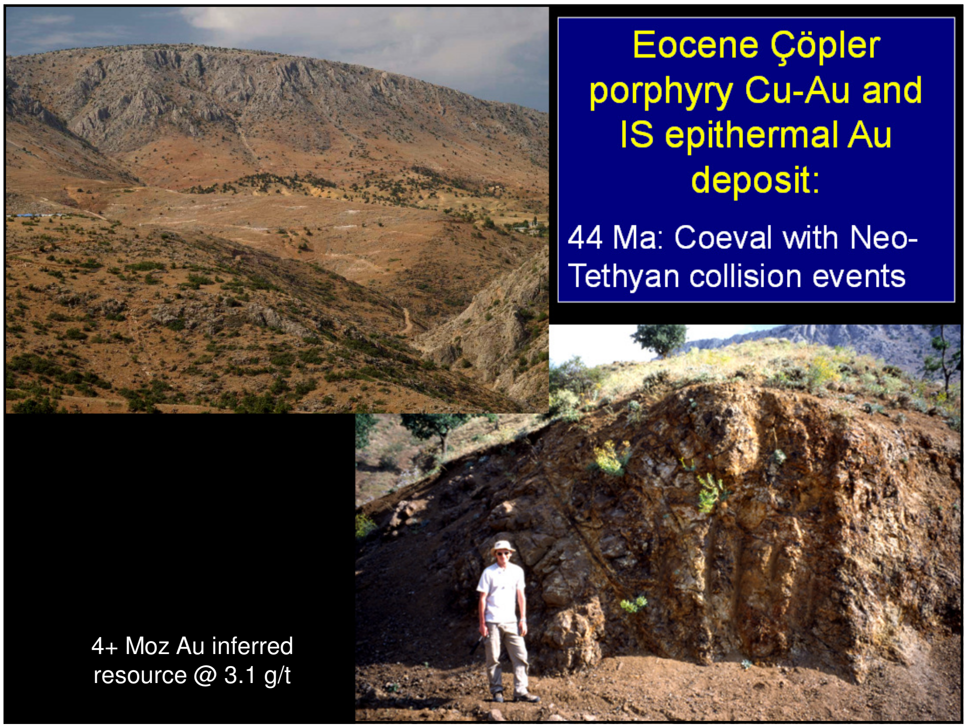


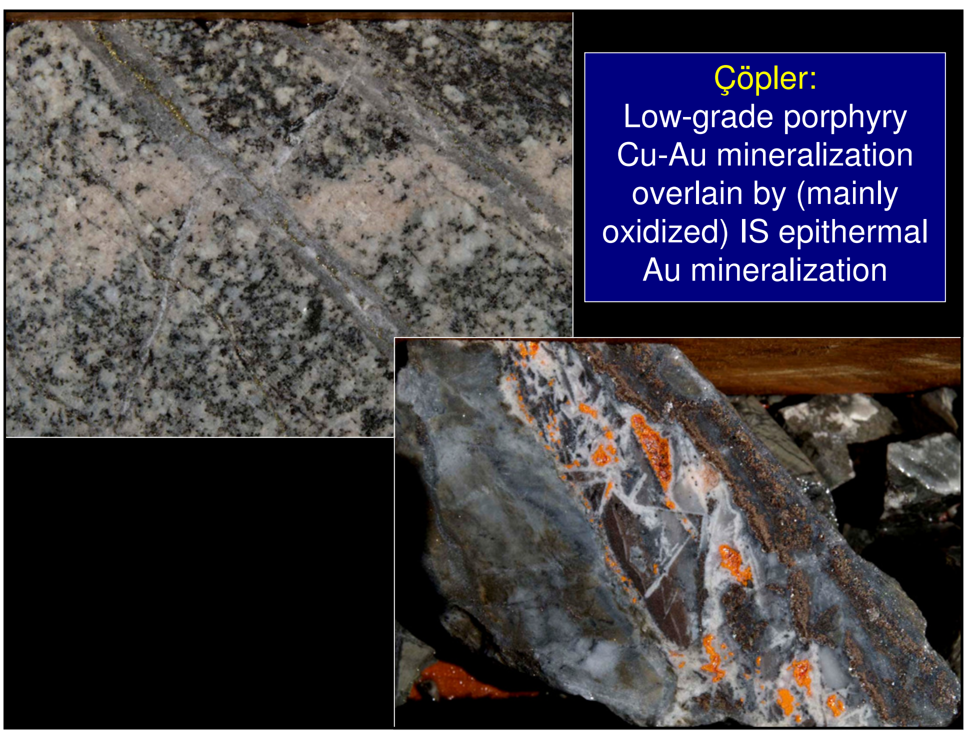
www.anatoliaminerals.com

Efemçukuru IS Au deposit, Western Turkey (<12 Ma)

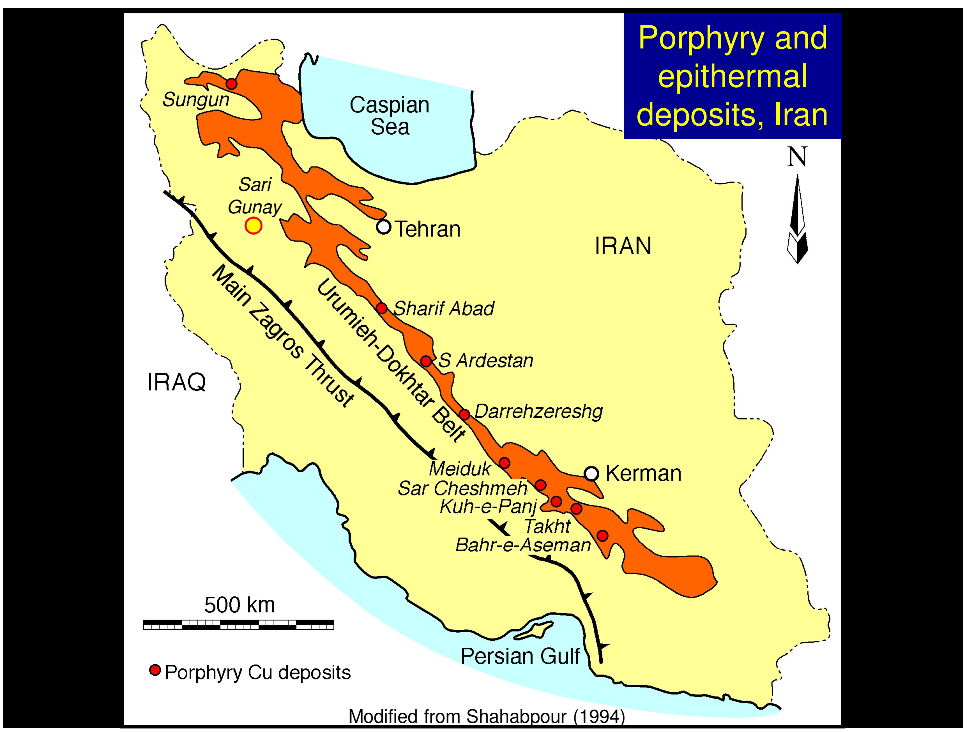
High grades (up to 210 g/t Au over 1 m) in quartz-rhodonite-rhodochrosite veins, with minor sphalerite and galena.

Proven + probable reserves (2010): 1.5 Mt @ 9.10 g/t Au

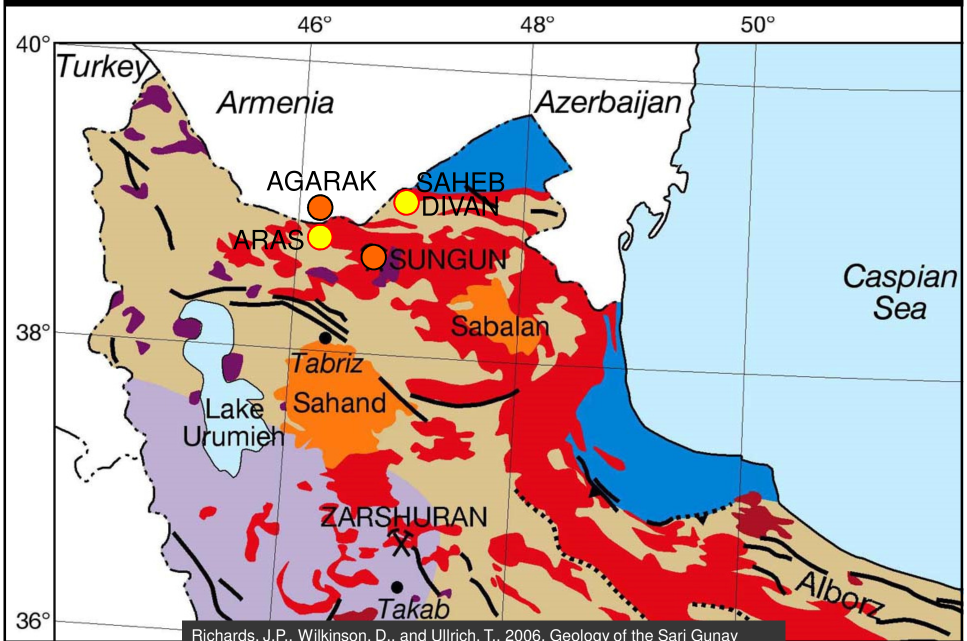

Eocene Çöpler porphyry Cu-Au and IS epithermal Au deposit:
44 Ma: Coeval with Neo-Tethyan collision events
4+ Moz Au inferred resource @ 3.1 g/t


Çöpler:
Low-grade porphyry Cu-Au mineralization overlain by (mainly oxidized) IS epithermal Au mineralization


Oligocene Kizilviran porphyry
Cu prospect, Tunçeli belt


Porphyry and
epithermal
deposits, Iran
Caspian
Sea
Sungun
Sari
Gunay
Tehran
IRAN
N
Sharif Abad
S Ardestan
Darrehzereshg
Main Zagros Thrust
Urumieh-Dokhtar Belt
IRAQ
Kerman
Meiduk
Sar Cheshmeh
Kuh-e-Panj
Takht
Bahr-e-Aseman
500 km
Persian Gulf
Porphyry Cu deposits
Modified from Shahabpour (1994)

NW Iran (Azerbaijan Province) and Armenia



Richards, J.P., Wilkinson, D., and Ullrich, T., 2006, Geology of the Sari Gunay epithermal gold deposit, northwest Iran: Economic Geology, v. 101, p. 1455–1496.

Agarak porphyry Cu-Mo mine (39.5 Ma), Armenia

38.5 Mt @ 0.38% Cu and 0.025% Mo

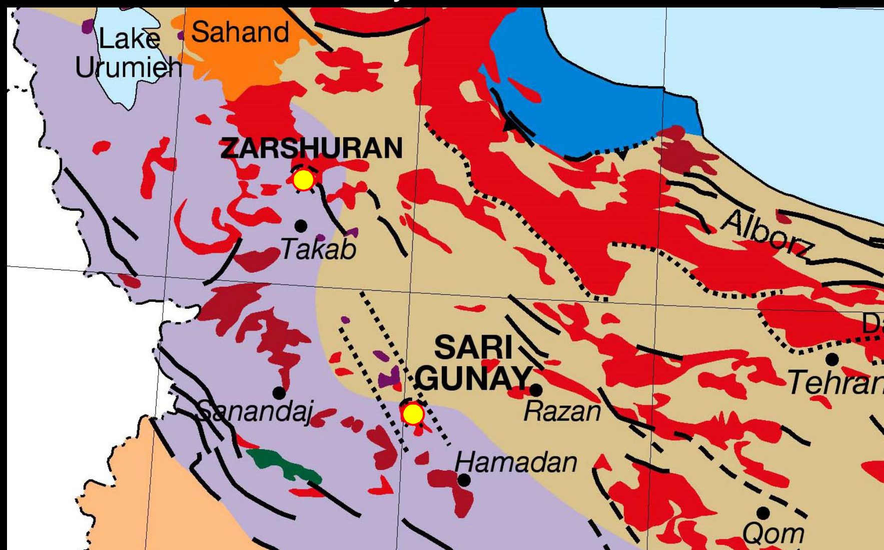
High sulfidation alteration (silica, alunite), Aras prospect, Iran

Saheb Divan village, built out of hydrothermal clays

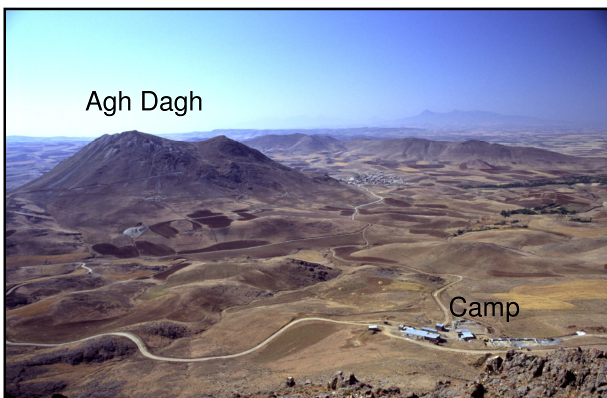
High sulfidation alteration and silica lithocap, Saheb Divan, Iran

The early Miocene Sungun porphyry Cu mine (21 Ma), Iran
~500 Mt @ 0.76% Cu, 0.01% Mo

Zarshuran Carlin-type and and Sari Gunay epithermal gold deposits, NW Iran: Post-date Paleogene–early Neogene Neo-Tethyan collision

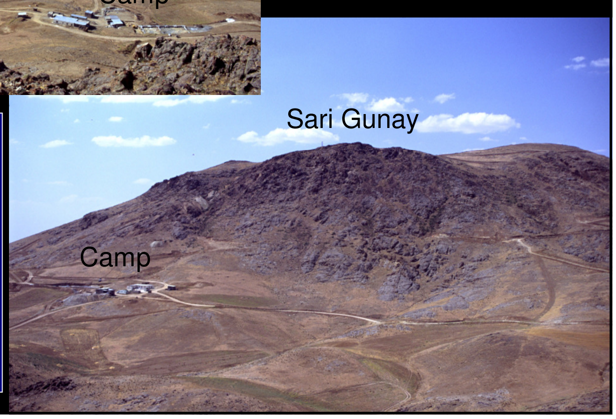


Richards, J.P., Wilkinson, D., and Ullrich, T., 2006, Geology of the Sari Gunay epithermal gold deposit, northwest Iran: Economic Geology, v. 101, p. 1455–1496.

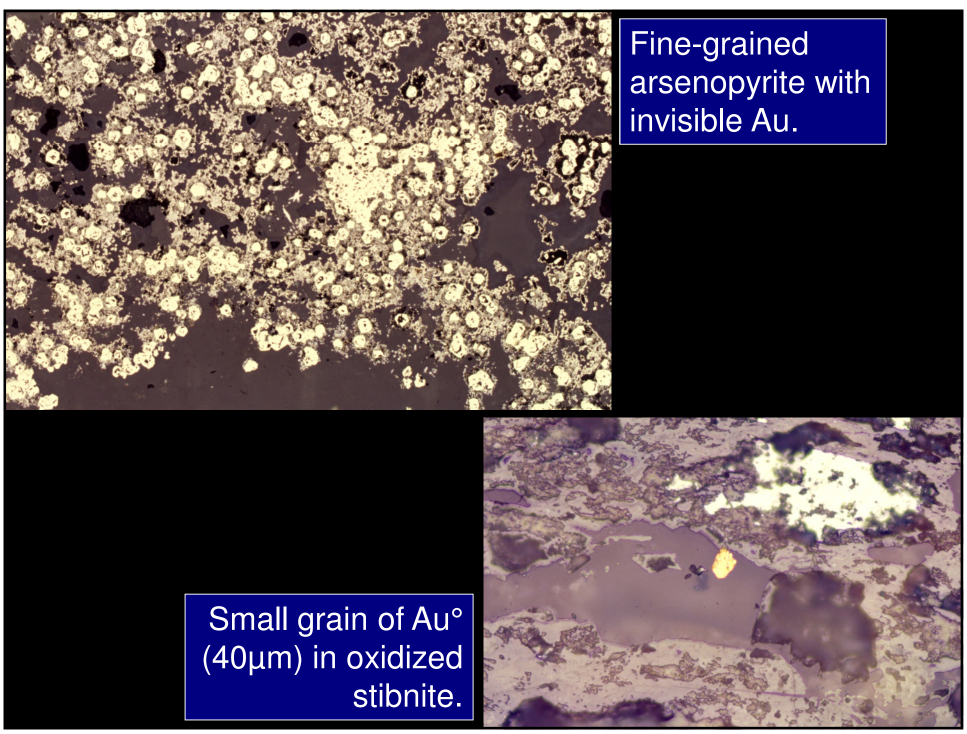


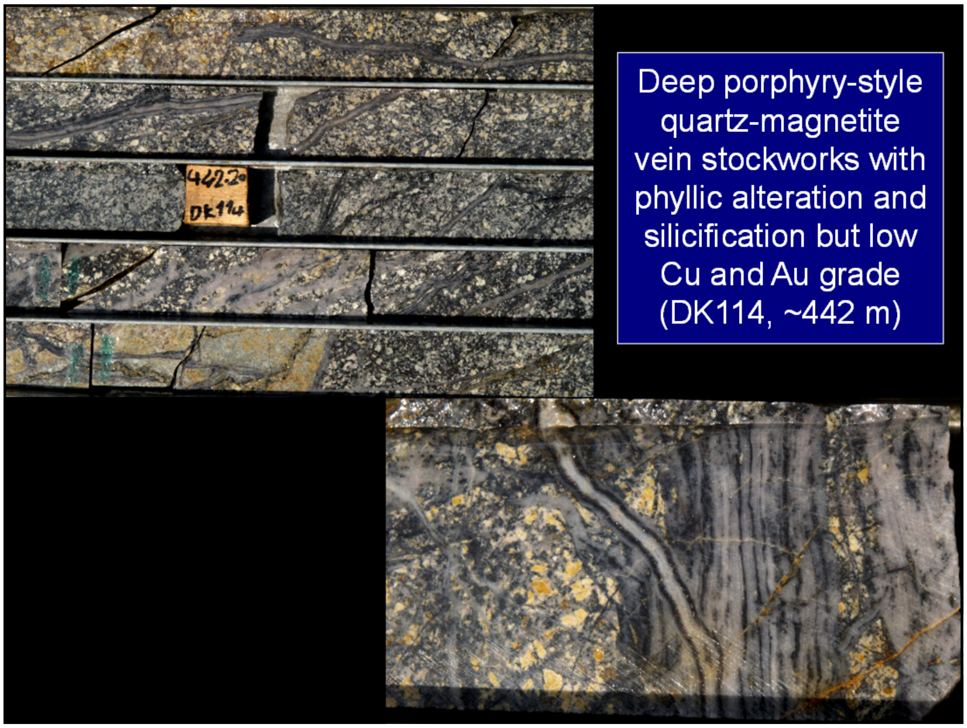
Miocene (11 Ma) Sari Gunay volcanic complex and Au deposit (Rio Tinto)

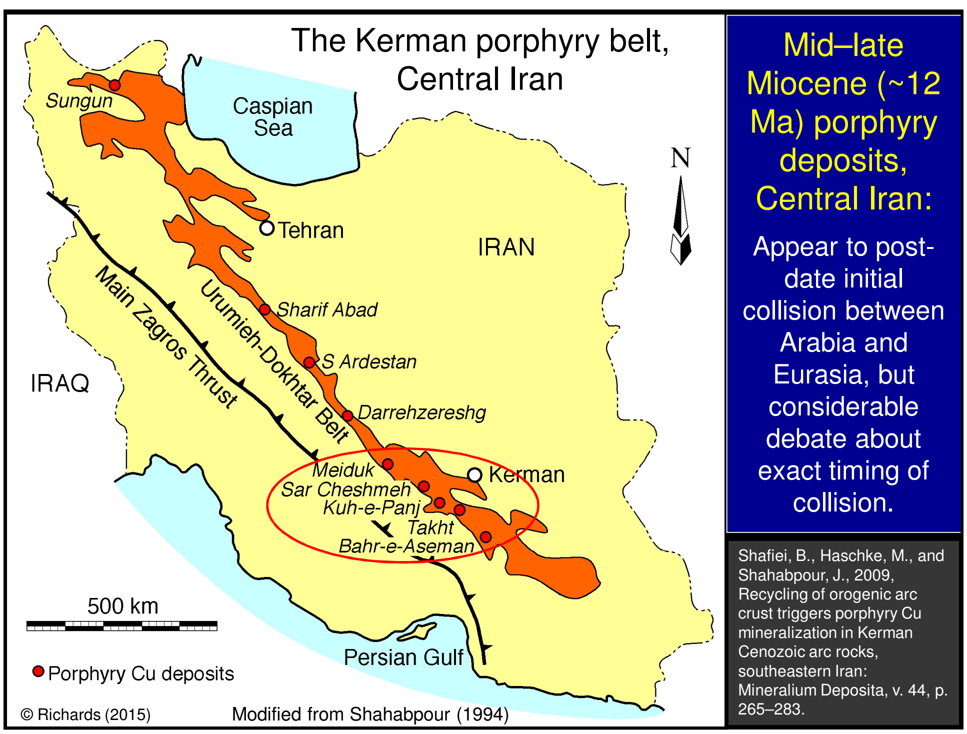
Oxide resource of 52 Mt containing 1.77 g/t Au (1.0 g/t cutoff; 3.25 Moz contained Au) within an area of 600 x 1200 m and to a depth of at least 350 m.

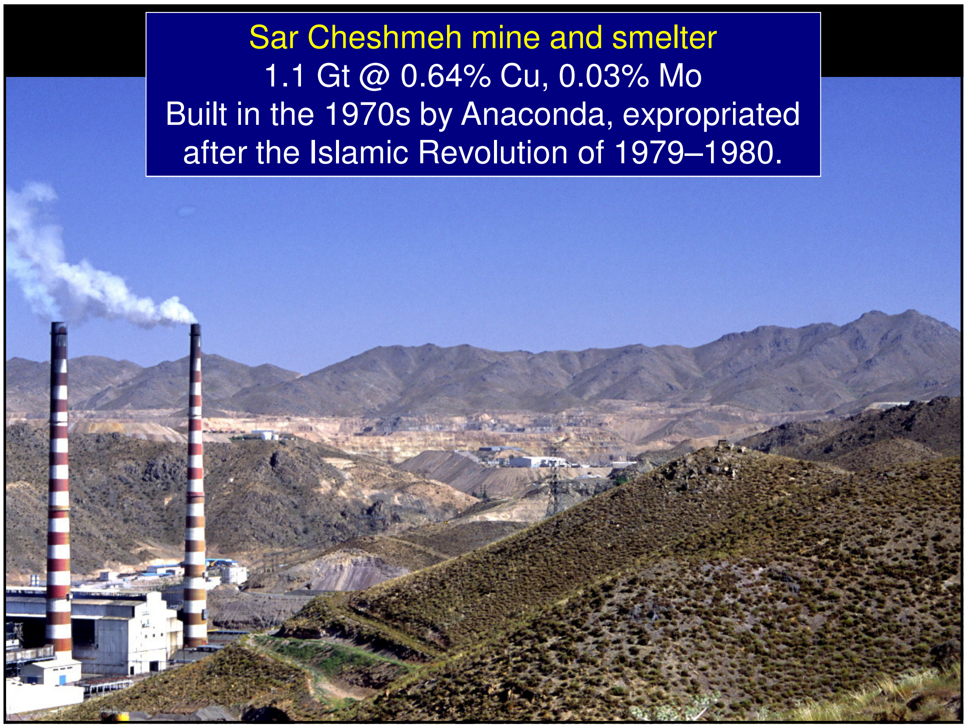



Sari Gunay:
Quartz-tourmaline breccias, followed by epithermal realgar, orpiment, and stibnite mineralization (with invisible Au).
0 1 2
Centimetres

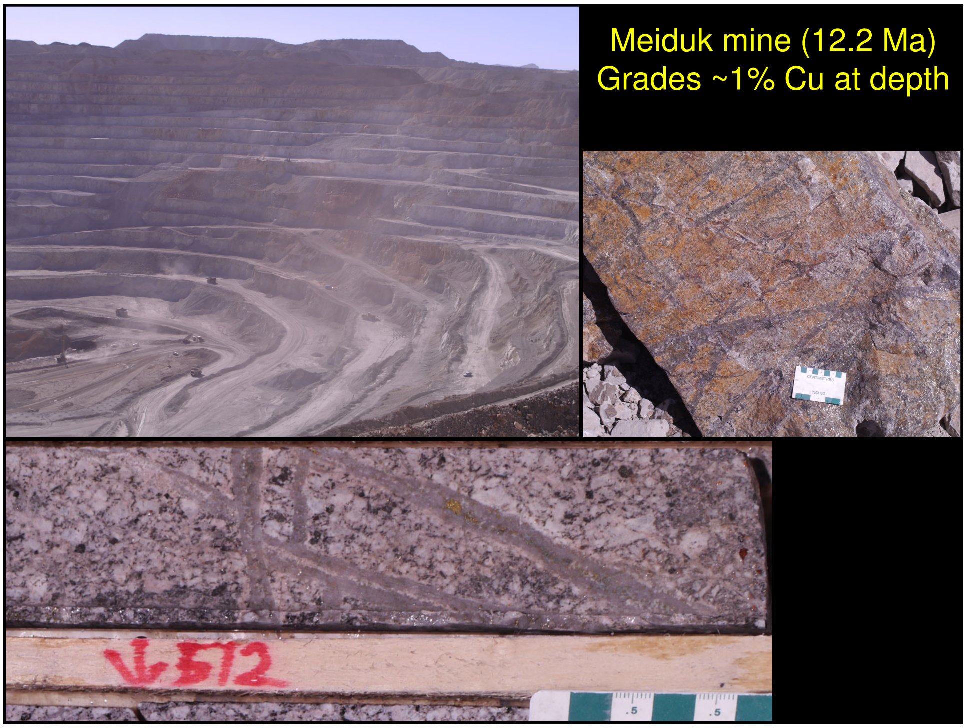

Fine-grained arsenopyrite with invisible Au.
Small grain of Au° (40µm) in oxidized stibnite.

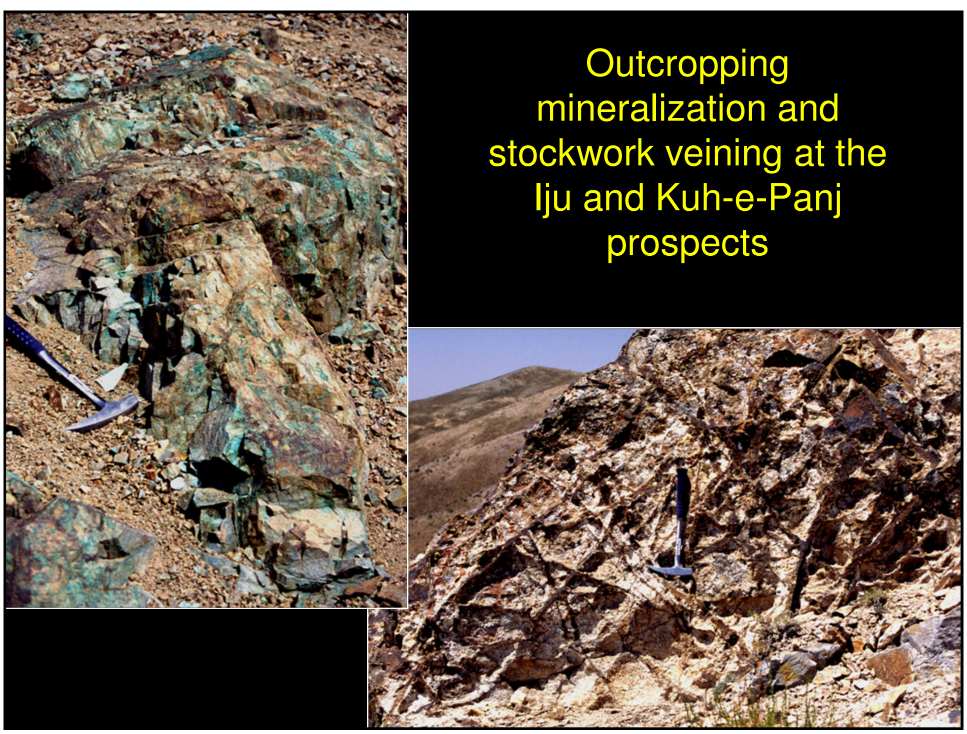

4422
DK114
Deep porphyry-style quartz-magnetite vein stockworks with phyllic alteration and silicification but low Cu and Au grade (DK114, ~442 m)


The Kerman porphyry belt, Central Iran
Caspian Sea
Sungun
Tehran
IRAN
N
IRAQ
Main Zagros Thrust
Urumieh-Dokhtar Belt
Sharif Abad
S Ardestan
Darrehzereshg
Meiduk
Sar Cheshmeh
Kuh-e-Panj
Takht
Bahr-e-Aseman
Kerman
Persian Gulf
500 km
Porphyry Cu deposits
© Richards (2015)
Modified from Shahabpour (1994)
Mid–late Miocene (~12 Ma) porphyry deposits, Central Iran:
Appear to post-date initial collision between Arabia and Eurasia, but considerable debate about exact timing of collision.
Shafiei, B., Haschke, M., and Shahabpour, J., 2009, Recycling of orogenic arc crust triggers porphyry Cu mineralization in Kerman Cenozoic arc rocks, southeastern Iran: Mineralium Deposita, v. 44, p. 265–283.

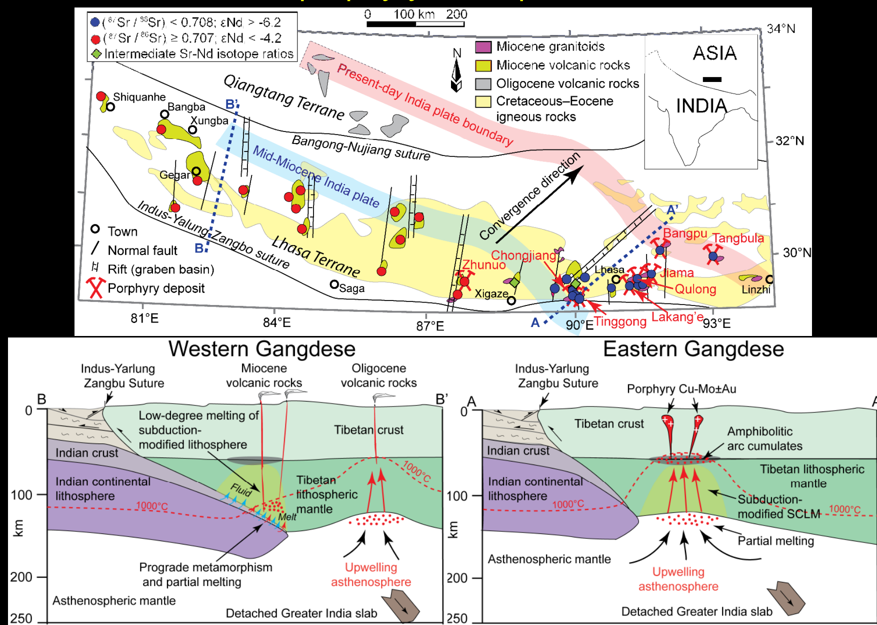

Sar Cheshmeh mine and smelter
1.1 Gt @ 0.64% Cu, 0.03% Mo
Built in the 1970s by Anaconda, expropriated
after the Islamic Revolution of 1979–1980.


Sar Cheshmeh mine, July 2017


Meiduk mine (12.2 Ma)
Grades ~1% Cu at depth


Outcropping mineralization and stockwork veining at the Iju and Kuh-e-Panj prospects

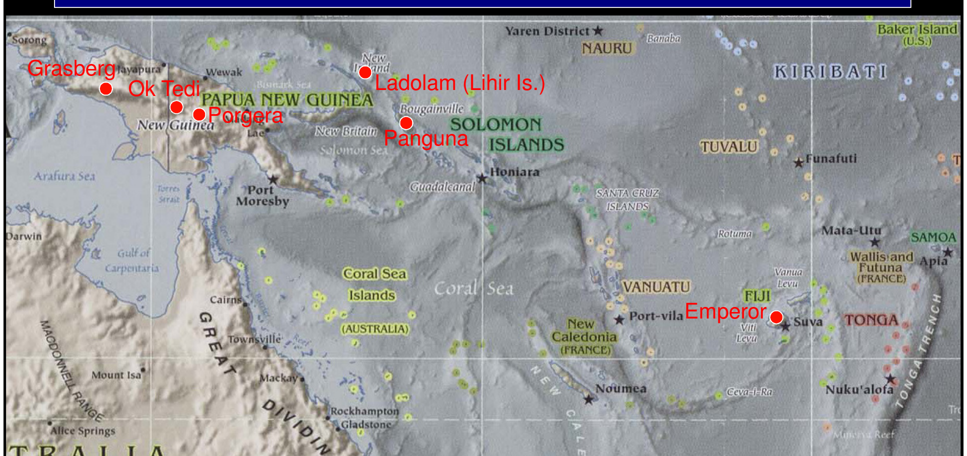
Collisional porphyry Cu deposits in Tibet



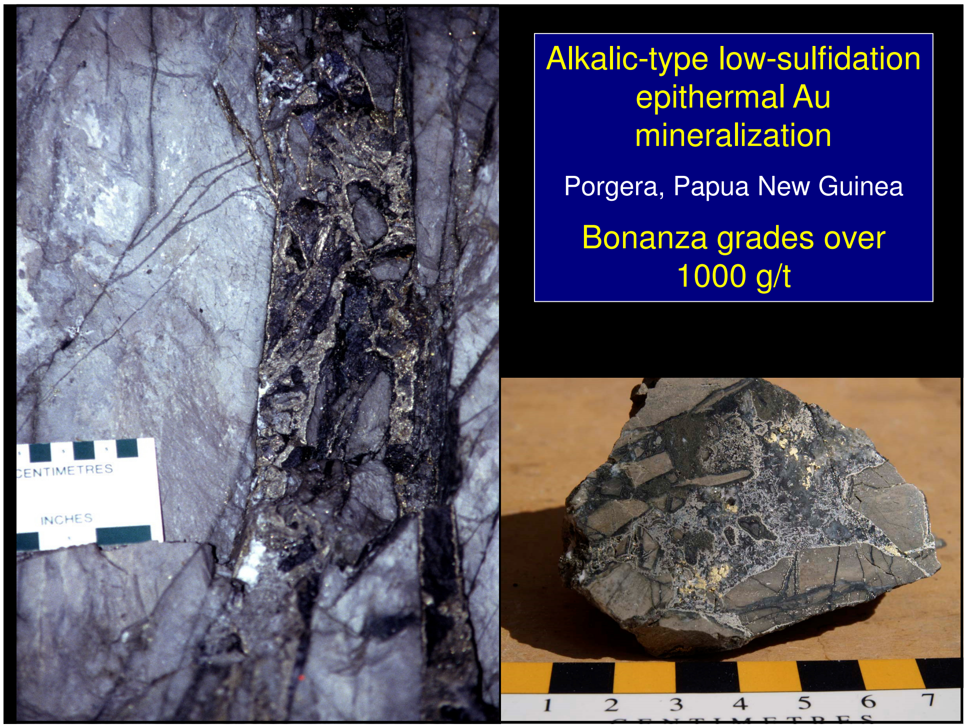
Wang, R., Richards, J.P., Hou, Z., and Yang, Z., 2014, The extent of underthrusting of the Indian plate beneath Tibet controlled the distribution of Miocene porphyry Cu-Mo±Au deposits: Mineralium Deposita, v. 49, p. 165–173.

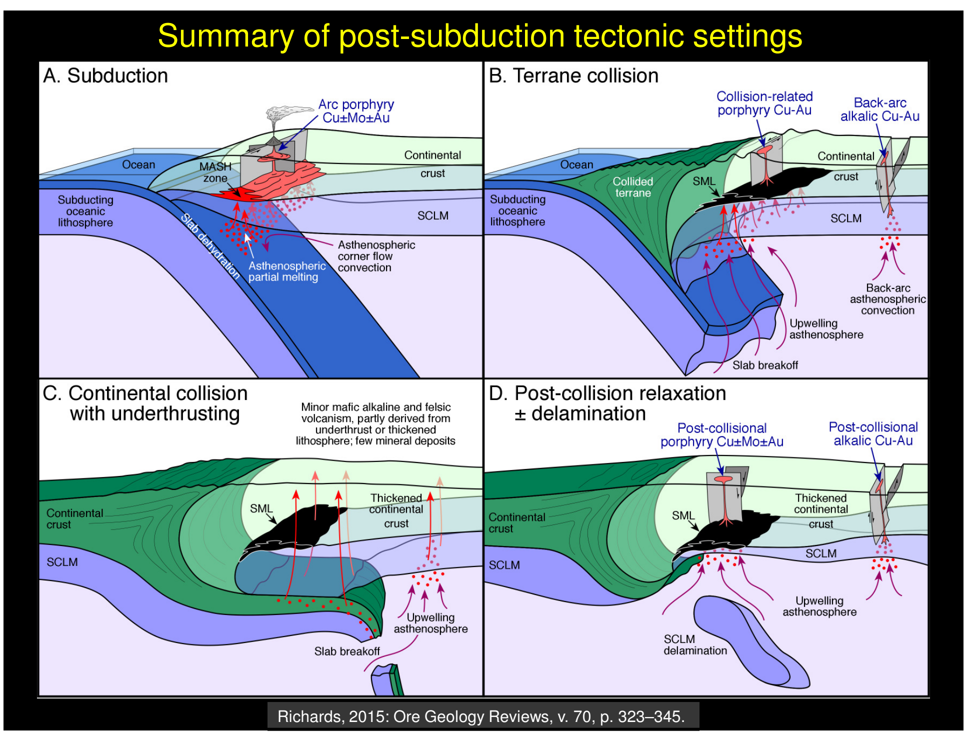
Post-subduction alkalic-type Au deposits:

A number of alkalic-type epithermal Au deposits occur in post-subduction settings in the SW Pacific archipelagos: e.g., Porgera (PNG), Lihir (PNG), Emperor (Fiji). Also Cripple Creek (CO) and Montana.



www.lib.utexas.edu/maps/australia/oceania_ref802646_99.jpg


Alkalic-type low-sulfidation epithermal Au mineralization
Porgera, Papua New Guinea
Bonanza grades over 1000 g/t
CENTIMETRES
INCHES
1 2 3 4 5 6 7


Summary of post-subduction tectonic settings
A. Subduction
Arc porphyry Cu±Mo±Au
Ocean
MASH zone
Continental crust
Subducting oceanic lithosphere
SCLM
Slab dehydration
Asthenospheric corner flow convection
Asthenospheric partial melting
B. Terrane collision
Collision-related porphyry Cu-Au
Back-arc alkalic Cu-Au
Ocean
Collided terrane
SML
Continental crust
Subducting oceanic lithosphere
SCLM
Back-arc asthenospheric convection
Upwelling asthenosphere
Slab breakoff
C. Continental collision with underthrusting
Minor mafic alkaline and felsic volcanism, partly derived from underthrust or thickened lithosphere; few mineral deposits
Continental crust
SML
Thickened continental crust
SCLM
Upwelling asthenosphere
Slab breakoff
D. Post-collision relaxation ± delamination
Post-collisional porphyry Cu±Mo±Au
Post-collisional alkalic Cu-Au
Continental crust
SML
Thickened continental crust
SCLM
Upwelling asthenosphere
SCLM delamination
Richards, 2015: Ore Geology Reviews, v. 70, p. 323–345.

Summary

- Mineralization in convergent margin and collisional settings is ultimately related to the heat and volatile input (and metals) from subduction-generated magmas.
- Subduction-related calc-alkaline magmas are rich in H_2O and SO_2, oxidized, and undepleted in chalcophile elements. They may evolve to generate porphyry Cu and epithermal Cu-Au deposits upon emplacement in the shallow crust.
- Post-subduction magmas generated from second-stage melting of subduction-modified mantle tend to be alkaline, and may generate porphyry Au and alkalic-type epithermal Au deposits.
- Collisional and post-collisional magmas generated from melting of subduction-modified lithosphere are calc-alkaline to mildly alkaline, and may generate porphyry Cu-Au and epithermal Au deposits, not dissimilar to normal arc deposits.