Porphyry and epithermal ore formation in post-subduction tectonic settings

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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


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.

Partitioning of chalcophile metals between magma and sulfide

Cu-rich magmas can form in the presence of up to 1 wt.% S in the mantle source ($R \geq 10^6$).

Au-rich magmas form when residual sulfide abundance falls below ~10 ppm ($R \geq 10^5$).


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.


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 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.

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**Cu-sulfides locally with Au and PGE in Talkeetna amphibole gabbros.**

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Kohistan arc crustal section


Chilas Complex layered gabbros
Small Cu-PGE mine in ultramafic cumulates, Chilas Complex, Kohistan

Approach at own risk!

Cu-Fe-sulfides and moncheite in dunite.
Photo: Ijaz Ahmad

Magmatic sulfides in mafic and ultramafic rocks, Chilas complex, Kohistan

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.

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.
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.

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 as the Neo-Tethyan collided arcs of the Balkans, Turkey, Iran, and Tibet, and the SW Pacific.

References:
- Richards, 2009
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.

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

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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

Major porphyry and epithermal gold deposits in Turkey

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

Geology, genesis, and exploration for magmatic and magmatic-hydrothermal ore deposits

Modified from Shahabpour (1994)
NW Iran (Azerbaijan Province) and Armenia


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


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).

Fine-grained arsenopyrite with invisible Au.

Small grain of Au^+ (40µm) in oxidized stibnite.
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

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.

Sar Cheshmeh mine and smelter
1.1 Gt @ 0.64% Cu, 0.03% Mo
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


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.
Alkaline-type low-sulfidation epithermal Au mineralization
Porgera, Papua New Guinea
Bonanza grades over 1000 g/t

Summary of post-subduction tectonic settings

A. Subduction
- Arc porphyry Cu/Mo/Au
- Subduction oceanic lithosphere
- Continental crust
- Subduction-related porphyry Cu/Au
- Thickened continental crust
- Slab breakoff

B. Terrane collision
- Collision-related porphyry Cu-Au
- Back-arc alkaline Co-Au
- Continental crust
- SCUL
- Subduction of oceanic lithosphere
- Upwelling asthenosphere

C. Continental collision with underthrusting
- Minor mafic alkaline and felsic volcanics, partly derived from underthrust or thickened lithosphere, ten mineral deposits
- Thickened continental crust
- Slab breakoff
- SCUL

D. Post-collision relaxation & delamination
- Post-collisional porphyry Cu/Mo/Au
- Post-collisional alkaline Co-Au
- Continental crust
- SCUL
- Delamination
- Upwelling asthenosphere

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$_2$O 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.