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# Gold (Au) as a by-product of porphyry copper deposit mining

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## Abstract

Au (Gold) is an important by-product of porphyry copper deposits (PCDs) that adds to the overall economic potential of large copper mining projects. PCDs, which develop in subduction zone magmatic-hydrothermal systems, host gold in predominantly sulfide minerals, including chalcopyrite, bornite, and pyrite. Gold grades in PCDs are highly heterogeneous but typically vary from 0.2 to 1.0 g/t. Although gold is largely mined as a by-product, some porphyry systems, like Grasberg in Indonesia and Cadia-Ridgeway in Australia, contain high enough gold grades to qualify as gold-rich deposits. Gold in these deposits is recovered by flotation, smelting, and refining, with cyanide leaching occasionally to recover the remaining gold from tailings. The largest producers of porphyry copper systems in the world are China, Australia, and Russia. Gold is an important component of global trade, industry, and investment, finding uses in electronics, medical technologies, and monetary reserves. Its price varies according to economic performance, geopolitical stability, and supply-demand relations. This paper discusses the geological occurrence, mining, processing, water use, social and environmental effects, waste disposal, and regulatory aspects of gold production from porphyry copper ores and evaluates its viability as a by-product source to satisfy worldwide demand.

**Keywords:** Au (Gold); Porphyry Copper Deposit (PCD); Subduction Zone; Magmatic-Hydrothermal System

## 1. Introduction

Porphyry copper deposits (PCDs) are one of the most important worldwide copper sources and a major by-product gold source (Nuytsia et al., 2017). The deposits develop in magmatic arcs of convergent plate boundaries, and hydrothermal fluids transfer and concentrate metals into giant disseminated ore bodies. The monetary worth of gold as a by-product cannot be overstated, as winning it enhances the profitability of copper mining operations. In some cases, such as the Grasberg deposit in Indonesia and Cadia-Ridgeway in Australia, gold is responsible for a high proportion of the mine revenue (Phillips et al., 2023).

Gold mineralogy in PCDs is polymorphous, and gold is found as gold-bearing tellurides and native gold in veinlets and fractures, electrum (gold and silver alloy), or included in sulfide minerals such as chalcopyrite ($Cues_2$) and bornite ($Cues_4$) (Rees et al., 2015). They are controlled by an interplay of magmatic, hydrothermal, and structural processes that govern metal distribution (Phillips et al., 2023). Gold grade in these systems is generally low and varies from 0.2 to 1.0 g/t, but because of the huge tonnage of porphyry deposits, even low-grade ones make a considerable contribution to total gold production (Tisdall et al., 2009).

Although gold is mostly extracted as a by-product, some porphyry systems are sufficiently gold-rich to be extracted with gold as a co-product. Treatment of these ores is by conventional flotation for sulfide minerals recovery, smelting, and refining for gold and other by-products recovery. Cyanide leaching is used in some instances on tailings for gold remaining recovery (Sun et al., 2016).

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## 2. Occurrence of Gold (Au) in Porphyry Copper Deposits

Gold in porphyry copper deposits is present in several distinct mineralogical forms and is dictated by the physicochemical environment of the hydrothermal regime. It is found principally in three principal mineralogical forms.

- Native gold: Normally occurs as fine-grained particles in quartz veins and stockwork.
- Electrum: A silver-gold alloy that develops as an exsolution product in sulfide minerals.
- Sulfide inclusions: Gold is usually occluded in copper sulfide minerals, i.e., chalcopyrite ($CUFES_2$) and bornite ($CU_5FES_4$), thus rendering its extraction a function of the procedures adopted in copper recovery (Rees et al., 2015).

Gold is included in such minerals because of similar ionic radii and chemical affinities for copper. Gold occurs in some instances in the oxidation zone as a component of supergene enrichment, commonly with secondary chalcocite ($CU_2S$) and iron oxides ($FES_2$) (Hedenquist et al., 2000).

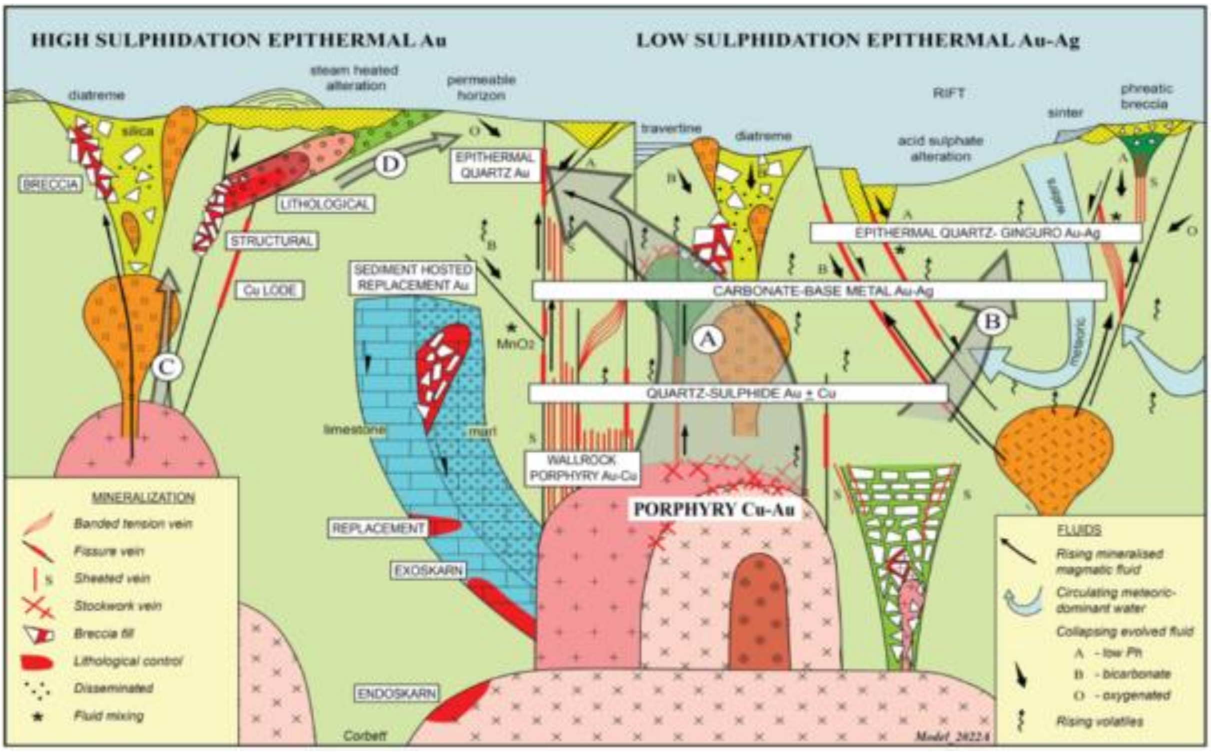


**Figure 1** Schematic cross-section of many structural and host-rock settings of gold and base-metal deposits in a volcanic belt. Source:(Corbett & Leach 1998)

### 2.1. Structural Control on Au Deposits

The occurrence of gold within PCDs is strongly influenced by structural controls, including faults, fractures, and intrusive contacts (Djanet Ey et al., 2025). Fluid pathways created by fault zones provide conduits for metal-bearing hydrothermal fluids, leading to the precipitation of gold and copper minerals along fracture networks (Arias et al., 2021). In some deposits, gold enrichment is localized within dilutional zones, where rapid pressure drops facilitate the precipitation of gold-bearing sulfides and free gold (Klein et al., 2020).

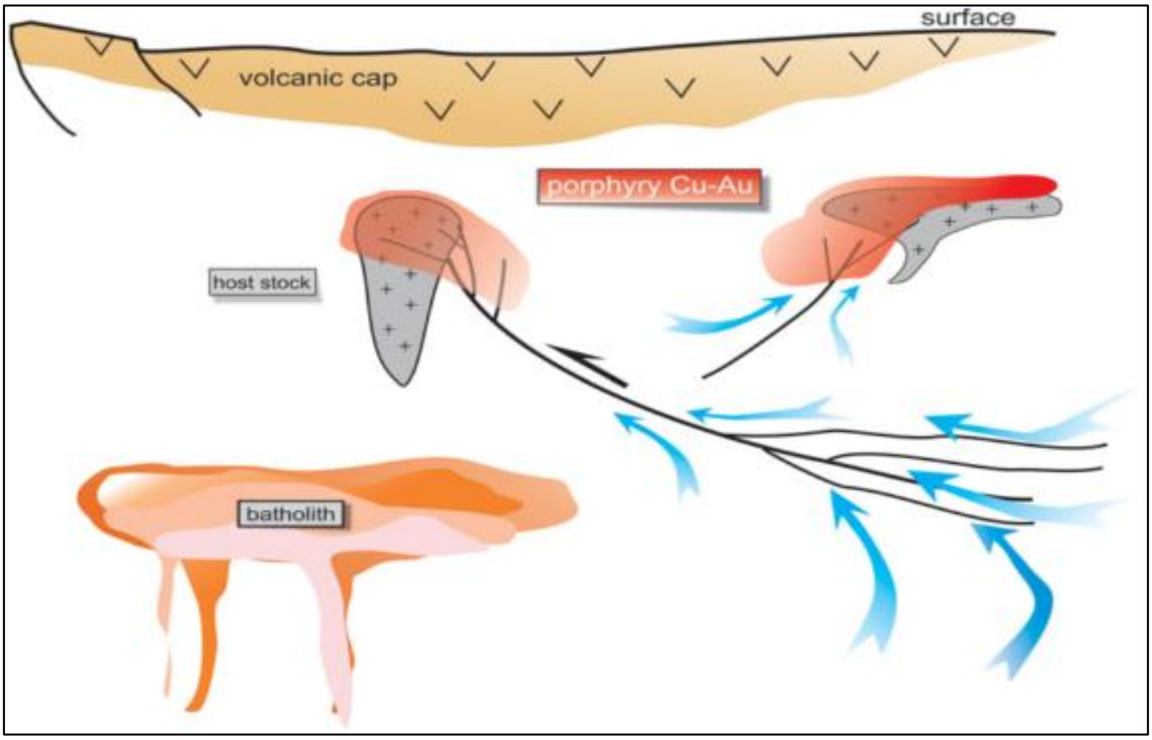


**Figure 2** Conceptual model showing hot, oxidizing Cu–Au fluids derived from large volumes of country rock and migrating along shear zones. Sourced from (Phillips et al., 2023)

### 2.2. Texture, Grain Size, and Shape of Gold (Au)

Gold in porphyry copper deposits occur in various textural modes based on the mineralogical environment. Generally, it exists as inclusions of <10 µm size with subhedral to anhedral shape included in chalcopyrite and bornite (Sun et al., 2016). In certain deposits, gold occurs as disseminated grains in quartz veins with more irregular shape and, at times, well-defined euhedral crystals (Tosdal et al., 2009). The association of gold with sulfide minerals tends to result in a simplistic intergrowth texture, which may influence the recovery efficiency during ore extraction (Klein et al., 2020).

### 2.3. Depth and Zones of Mineralization

Porphyry copper-gold deposits are found 1 to 4 kilometers beneath the Earth's surface, extending vertically for hundreds of meters of mineralization (Phillips et al., 2023). The processes of gold deposition are magmatic fluid evolution-controlled, and precipitation is caused by temperature, pressure, and fluid composition changes. The high-temperature fluids, which are expelled from crystallizing intrusions, enable the transportation of gold in solution, precipitating as the environmental conditions change. (Phillips et al., 2023). Chloride and sulfur complexes enhance the solubility of gold in hydrothermal fluids so that it may be carried for long distances before deposition (Groves et al., 2003). The most common alteration style related to gold mineralization is:

- Potassic alteration is recognized by the presence of K-feldspar, biotite, and magnetite. There is a high concentration of gold in such zones and is often accompanied by bornite and chalcopyrite (Sun et al., 2016).
- Phyllis Alteration: A Quartz-pyrite alteration at a large scale with sericite dominant alteration. Gold remobilization occurs during this phase, forming electrum-bearing quartz veins (Sun et al., 2016).
- Propylitic Alteration: Distal alteration halo that is chlorite, epidote, and carbonate-rich and has minor gold mineralization (Sun et al., 2016).

The highest gold content is found in the deeper part of the deposit, where gold is associated with potassic alteration zones, but the content is lower in overprinted shallower portions because of later hydrothermal fluid activities (Sun et al., 2016). In top-ranked mineral deposits, like Grasberg, mineralization continues to depths of more than 1,500 meters, with gold concentration in late-stage hydrothermal breccias and stockwork veins (Tisdall et al., 2009). The vertical metal distribution is also affected by the presence of deeply seated magmatic systems, which have a significant copper-to-gold ratio at deeper levels (Mudd, 2007).

### 2.4. Geochemical and Mineralogical Associations

Gold is commonly accompanied by copper sulfides, tellurides, and bismuth minerals in porphyry systems. Gold-bearing tellurides, including calaverite ($AuTe_2$) and petzite ($Ag_3AuTe_2$), have been reported to exist in some alkalic porphyry systems, which indicates that late magmatic-hydrothermal fluids are important in gold enrichment (Sun et al., 2016). In some deposits, gold may occur in iron oxides in supergene enrichment zones, where weathering enables the mobilization and reprecipitation of metals at shallow depths (Phillips et al., 2023). Gold is found in association with palladium (Pd) and platinum (Pt) in certain porphyry systems. In Greece and Canada, studies have discovered Pd-Au-Hg signatures in detrital gold grains, pointing to an origin link between porphyry mineralization and PGE enrichment (Chapman et al., 2017).

Porphyry system grades of gold are variable, yet economic extraction is usually viable at as low as 0.2 g/t to 1.0 g/t, while high-grade systems are up to 2 g/t due to the enormous tonnage of these deposits (Sun et al., 2016).

Notable PCDs with large gold endowment are:

- Grasberg, Indonesia: A mega gold-producing PCD containing over 2,800 tons of gold (Phillips et al., 2023).
- Cadia-Ridgeway, Australia: A gold-rich porphyry system with more than 50 million ounces of gold reserves (Phillips et al., 2023).
- Bingham Canyon, USA: A big porphyry copper-gold deposit having a history of gold recovery as a by-product (Phillips et al., 2023).

## 3. Mining Methods

Porphyry copper-gold deposits are mostly mined using open-pit methods. Where the ore body extends to greater depths, underground block caving may be employed (Hedenquist et al., 2000).

Open-pit mining is preferred for several reasons. First, porphyry copper-gold deposits are usually enormous. Second, the grade (i.e., quality) of the ore is comparatively low, which means that more material must be processed to achieve the same amount of saleable metal. Open-pit mining is convenient for removing large quantities of material and hence makes it economically viable to process large quantities of low-grade ore (Phillips et al., 2023).

The geology of porphyry deposits largely determines the use of open-pit mining. Porphyry deposits are found close to the surface (usually less than 1,000 meters deep), are extremely large (sometimes as much as 1 kilometer in diameter), and have large lateral dimensions. Almost all the accessible ore is mined, and production is continuous and efficient from an industrial standpoint (Goldfarb et al., 2001). It also allows for essential economies of scale that are necessary for viable processing of low-grade ores. This process not only allows the recovery of gold and copper but also, at the same time, allows the recovery of associated metals like silver and molybdenum.

In porphyry systems thought to extend to great depths, like the Grasberg mine, we find the block caving method applied. This mining method requires a strong and competent rock mass that can be relied upon to support caving when and where we want it to cave, thereby progressively weakening the ore using gravity. Those are, after all, the essentials of caving. (Hedenquist et al., 2000)

### 3.1. Ore Processing

Extracting gold as a by-product from porphyry copper deposits (PCDs) involves mainly flotation to concentrate the ore and then smelting and refining. The treatment sequence depends on the ore's mineral content and the association of gold with copper sulfides (Tisdall et al., 2009).

### 3.2. Comminution and Liberation

The first step in ore processing involves reducing the ore to the necessary size for separation. For most minerals, this means crushing and then grinding the ore to where it achieves the particle size required for separation. This is where flotation happens, in a slurry of finely ground ore that has lots of theoretical surface area for mineral expression, and hence the easier expression of valuable ore minerals, which is their flotation. (Tosdal et al., 2009).

### 3.3. Floatation

The fine particle-sized ore is mixed with water and chemicals like collectors (e.g., xanthates) and frothers. This mixture is then subjected to flotation. The sulfide minerals are floated off and constitute the flotation concentrate, which contains both gold and copper (Phillips et al., 2023).

### 3.4. Smelting and Refining

The flotation concentrate is treated in a smelter. In this high-temperature operation, copper is produced along with many other metals found with it. The gold, however, is not found with it in significant amounts. Instead, it is found with the copper in the next step, where some of it comes from the golden metal bead produced during fire assay. Once we get the copper, we get the gold. Hedenquist et al. (2000) explain that the purifiers then use electrolysis or some other chemical means to get to the higher standard of purity instead of just refining it, which is what would happen if they were not trying to get to that higher standard.

### 3.5. Leaching

Leaching is generally used to recover additional gold from the concentrate after flotation. The method almost always uses cyanide solutions to do this, which dissolves more of the gold from the ore (Goldfarb et al., 2001).

### 3.6. Recovery techniques

After its leaching, the gold is usually retrieved from the solution by a process like carbon adsorption, where activated carbon is used to adsorb the gold from the cyanide solution. The carbon with the gold on it is then treated to produce the gold, normally by a process called elution, where the gold is stripped from the carbon using a hot caustic solution. This process has very high recovery rates of gold and is economically feasible even for low-grade ores (Cacciuttolo et al., 2023).

### 3.7. Water Demand

Copper-gold porphyry deposits require a significant and complex watershed to meet their demands for mining. Water is required in various phases of the mining operation, from production to ore processing and landscape restoration after mining.

### 3.8. Water utilization during ore processing

Extraction relies on water to help enable the removal of essential minerals from the ore via a method known as flotation. This process may consume large amounts of water, sometimes in millions of liters a day, depending on the size of the operation (Mudd, 2009).

### 3.9. Dust Suppression and Mine Site Operations

Apart from processing, water is also required for dust control on haul roads and in material handling to reduce airborne particulates with associated health effects on workers and nearby communities (Erue et al., 2024). Water is also used for cooling equipment and machinery and processing equipment, again driving demand (Klein et al., 2020). Water is also used in underground mines for drilling activities and cooling to provide safe working conditions for workers (Sun et al., 2016).

### 3.10. Water Recycling and Conservation Techniques

Supply of such water is expected to be difficult, especially where water is a limiting factor itself. Recycling of water and water re-use in the tailings plant is also being considered by some mining companies as alternate supplies to limit freshwater footprint (Amuah et al., 2025). Nevertheless, the use of such forms of technologies means there is an investment in infrastructure as well as on-going maintenance that for some operations is prohibitive (Sun et al., 2016).

## 4. Environmental and Societal Issues

Gold mining as a by-product in PCDs has numerous environmental and social challenges, largely due to extensive land disturbance, water consumption, and waste generation.

- Acid Mine Drainage (AMD): Oxidation of sulfide minerals produces acidic environments, mobilizing heavy metals such as arsenic, lead, and mercury that contaminate aquatic environments and groundwater resources

(Mudd, 2007). Management of AMD includes long-term monitoring, passive and active water treatment systems, and prevention strategies such as encapsulating waste rock to avert sulfide exposure (Klein et al., 2020).
- Water Resource Depletion: Excessive water extraction for operations and disposal of tailings depletes local water supplies, particularly in arid regions where water is increasingly in short supply (Tosdal et al., 2009)
- Risks of Tailings Storage: Improper tailings management may result in catastrophic failure and water pollution.
- Community Displacement: Large-scale mining has been known to cause land conflicts where mining operations overlap with indigenous lands and displacements that can cause loss of livelihood, cultural heritage, and social instability. Where mining operations overlap with Indigenous lands, there are usually conflicts relating to land ownership and resource rights (Sun et al., 2016).
- Energy Consumption: Smelting and refining involve huge energy inputs that lead to carbon emissions (Kumah, 2006).

Sustainable mining processes, including reclamation and waste management, must be adopted to avoid these impacts (Phillips et al., 2023).

### 4.1. Waste Disposal

Porphyry copper-gold mine operations produce waste disposal and gangue material that are major environmental and operational issues. Overburden, waste rock, tailings, and smelting by-products are the main waste streams, each of which must be handled differently to reduce environmental effect and comply with regulations.

### 4.2. Overburden and Waste Rock Disposal

Disposal of waste rock is an environmental issue of concern due to the risk of acid rock drainage (ARD) (Klein et al., 2020). To avert ARD, mining firms practice encapsulation of potentially acid-generating rock in non-reactive material, building-lined storage facilities, and water management systems for managing runoff and leachate generation (Arias et al., 2021).

### 4.3. Tailings Storage and Management

Conventional methods of tailings disposal are based mainly on slurry storage in tailings dams but entail significant safety hazards from catastrophic failure that could result in environmental contamination (Mudd, 2007). More recently developed alternatives such as dry stacking and paste tailings technology are being more frequently adopted to accomplish the dual goals of conserving water and enhancing the structural stability of tailings (Phillips et al., 2023).

### 4.4. Smelting and Refining By-Products

The processes of smelting and refining gold concentrates produce auxiliary wastes like slag, flue dust, and sulfur dioxide emissions. The contemporary practice of smelting involves the use of emission control technologies, such as electrostatic precipitators and scrubbers, that efficiently capture airborne impurities and meet environmental regulations (Klein et al., 2020).

### 4.5. Prevention Strategies for Acid Mine Drainage

To reduce the risk of AMD, preventive measures must be taken. These comprise the use of alkaline additives to neutralize acidity, engineered wetlands for passive treatment, and remediation technologies that use microorganisms. Cleaner production methods aim to minimize AMD risks by controlling exposure to sulfide through the blasting of rocks and careful placement of mining waste to ensure that rocks and materials likely to produce acid when wet don't come into contact with groundwater or surface water. (Phillips et al., 2023).

## 5. Regulations and Permit

The construction and operation of a porphyry copper-gold mine will require extensive regulatory compliance and permitting to ensure the protection of the environment, interaction with local communities, and responsible extraction of minerals. The permits cover a wide range of regulatory concerns, such as environmental impact statement (EIA), water discharge, waste treatment, air pollution, and my reclamation.

### 5.1. Environmental Impact Assessments (EIA)

In most countries, mining operations must perform an EIA. Mining companies are mandated to carry out environmental baseline studies, evaluate the potential risks associated with their projects, and recommend measures to mitigate any potential ecological disturbances that might arise from the proposed project (Sun et al., 2016).

### 5.2. Water Use Permits

These permits regulate the amount of water that may be taken from natural sources, the industrial treatment of water, and the return of wastewater to the environment. In areas with limited water, miners may be compelled to construct desalination plants or recycling facilities in a bid to reduce freshwater consumption (Klein et al., 2020).

### 5.3. Tailings Management and Waste Disposal Permits

Permits for the disposal of waste and for the storage of tailings ensure that mining operators follow the best practices in the storage and handling of waste. The design, site selection, and long-term stability of tailings storage facilities (TSFs) are reviewed by regulators to minimize the potential for dam failure and groundwater contamination (Arias et al., 2021).

### 5.4. Emissions and Air Quality Permits

Environmental regulations mandate that mining operations implement emission controls, dust suppression measures, and monitoring programs to mitigate their impacts on air quality (Phillips et al., 2023).

### 5.5. Land Use and Rehabilitation Permits

Land use permits must be obtained by mining companies prior to the alteration of landscapes for mining operations. Reclamation conditions for the post-mining period are typically included in those permits, and the operators are obligated to those conditions (Erue et al., 2024). They must reclaim ecosystems, restore vegetation, and make the mined land safe for re-us (Tosdal et al., 2009).

### 5.6. Social and community involvement

In addition to obtaining regulatory permits, mining companies must also secure a "social license to operate." This indicates that local communities support and approve of the enterprise. Companies generally achieve this through a three-pronged approach: Public consultations, Benefit-sharing agreements, and Company CSR initiatives (Arias et al., 2021).

### 5.7. Mine Closure and Post-Mining Monitoring

Permitting extends beyond ongoing mining to include mine closure and post-closure monitoring. Regulatory authorities compel companies to develop comprehensive closure plans that address the long-term stability of waste storage facilities, water treatment obligations, and ecological restoration efforts (Sun et al., 2016).

## 6. Conclusion

The presence of gold (Au) in copper porphyry deposits involves a sophisticated interaction of geochemical and geological processes controlling its concentration and extraction. Mining activities, largely open-pit mining, are motivated by economic efficiency in the extraction of valuable resources. Technological advances in mining and processing operations persist in improving the efficiency and sustainability of gold extraction. Nevertheless, the social and hydrological effects of the mining in question here, i.e., water usage and waste disposal, must be strictly controlled to avoid adverse effects. As global demand for copper and gold keeps rising, such an understanding will be central to the sustainable exploitation of porphyry copper-gold deposits.

## Compliance with ethical standards

*Disclosure of conflict of interest*

No conflict of interest to be disclosed.

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