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Silver as a By-Product of Porphyry Copper Deposits: The Geology, Economic Importance and Sustainability

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Abstract

Silver, often regarded as a critical mineral, is one of the major by-products of Porphyry copper deposits (PCDs) which are of great economic importance. Even though copper is the focus of mining activities in PCDs, silver mining is also part of the process as a by-product. The geochemical and mineralogical relationships of silver in PCDs are complex and hence the need for complex ore processing techniques to ensure optimum recovery. This research focuses on reviews and case studies of silver as a by-product in copper mining from PCDs with consideration of the dynamics of the availability of the metal, extraction techniques, and processing. This study takes a critical look into the extraction, processing, market dynamics and the future of silver as a by-product in porphyry copper deposits mining. This study also encompasses an investigation of the global market demand for silver and its use in various sectors such as renewable energy and electronics, and examines the forces affecting the market demand for silver, including price volatility, and geopolitical issues.

Keywords: Critical minerals; Environment; Porphyry copper deposits; Silver extraction and recovery

1. Introduction

Critical minerals are minerals of great importance both in the economic and security of many countries. They are deemed critical because of its limitation of availability and supply coupled with the geopolitical issues affecting its supply (McFall, 2016). Porphyry copper deposits contain significant percentage of gold and silver and are of very high economic value due to the fact that, critical minerals such Rhenium, selenium, Platinum group metals and other important elements are also recovered during extraction (John & Taylor, 2016). Porphyry copper deposits contain significant concentration of Copper and Molybdenum making them among one of the largest ore deposits on Earth and providing about 60% of the world's copper and 95% of Molybdenum (John & Taylor, 2016).

Silver occurs as a by-product porphyry copper deposits and is usually accompanied by other precious metals like gold (Aird et al., 2021). It typically occurs in sulfide minerals like bornite and chalcopyrite, which are known to be the primary copper-bearing minerals in the deposits (John & Taylor, 2016). With mining companies continually evolving operations to maximized production, silver recovery alongside copper has become increasingly significant in its contribution to revenue derived from operations, as well as resource maximization. Porphyry copper deposits being of low-grade large-scale mineralization, its recovery is economically viable when achieved in conjunction with primary copper production methods (John & Taylor, 2016). Over the past decade, the importance of recovering PCDs' silver content has escalated owing to increasing industrial demand, particularly in electronics, photovoltaic cells, and the medical industry (Lo Piano et al., 2019). The complex processes of recovery of silver require a robust processing technology to maximize efficiency of recovery while ensuring environmental sustainability (Crespo et al., 2020). This

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case study addresses geology, mineralogy, mining methods, technical recovery process for silver, market dynamics, and the rising importance of sustainable mining practice in meeting global demand for silver.

2. Geological Setting

Porphyry copper deposits (PCDs) are the most important sources of copper and associated metals (John & Taylor, 2016). They form through complex magmatic-hydrothermal processes and typically in convergent plate environments where subduction-related magmatism is characteristic (Sillitoe, 2010). Their formation is characterized by emplacement of porphyritic stocks into the upper crust with accompanying intense hydrothermal alteration and mineralization. The process takes place at 1 to 5 kilometers depth beneath past volcanic centers, where metal-carrying fluids are liberated from cooling magma chambers. The hydrothermal systems form extensive alteration and mineralization zones, typically a few square kilometers in extent and continuing to great depths (John & Taylor, 2016).

The deposits principally develop in continental and island arc environments, though significant examples are found in the South American Andes, the Philippines, and Indonesia (Sillitoe, 2010). Certain deposits also develop in post-collisional and intracontinental environments, as observed in occurrences in the Tibetan Plateau (Cooke et al., 2017).

The principal host rocks of PCDs are generally intermediate to felsic intrusive kinds, and the intrusions consist of granodiorite, diorite, monzonite, and tonalite (Berger et al., 2008). These intrusions provide the magmatic source of mineralizing fluids. The structural features, which are deeply rooted faults, fractures, and caldera structures, serve as conduits for hydrothermal fluids, thereby enabling ore deposition (Sinclair, 2007). Their formation is characterized by emplacement of porphyritic stocks into the upper crust with accompanying intense hydrothermal alteration and mineralization. The process takes place at 1 to 5 kilometers depth beneath past volcanic centers, where metal-carrying fluids are liberated from cooling magma chambers. The hydrothermal systems form extensive alteration (figure 1) and mineralization zones, typically a few square kilometers in extent and continuing to great depths. The most copper-rich potassic alteration zone, defined by K-feldspar, biotite, and magnetite, carries the highest copper grades, mainly in chalcopyrite and bornite (Sillitoe, 2010). Peripheral to this core, the phyllic zone consists of quartz-sericite-pyrite, and the argillic zone consists of clay minerals such as kaolinite and smectite. The outer propylitic zone, characterized by chlorite, epidote, and carbonate, provides important exploration vectors (Berger et al., 2008).

The mineralization of copper is in the form of disseminated grains and stockwork veins, which owe their origin to hydrothermal metal-rich fluids exsolved from crystallizing magmas (Gustafson, 1978). Molybdenum, gold, and silver are common associated by-products, with some deposits having rhenium and platinum group elements as additional constituents (USGS, 2008). Secondary enrichment through weathering can also elevate copper grades, particularly in supergene environments (Berger et al., 2008).

Some of the major porphyry copper deposits are Escondida in Chile, Grasberg in Indonesia, and Bingham Canyon in the United States, each having distinct geological environments and ore genesis processes (John & Taylor, 2016). The geological setting of PCDs important to understand for exploration, research and resource development.

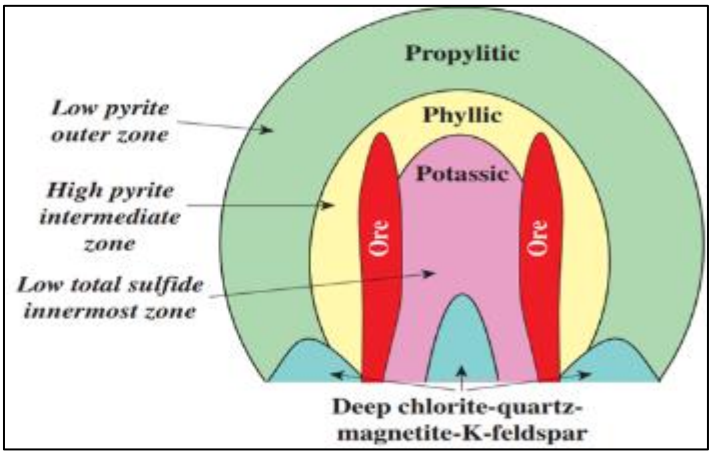

Figure 1 Cross section of a porphyry copper deposit showing idealized alteration Zone (Source; Berger et al., 2008)

3. Mineralogical Occurrence

Silver has a complex and diverse mineralogy as it occurs in different geological settings and mineral species. It mostly occurs in native silver and sulfide ores and is usually associated with zinc, copper and gold mineralization (Palyanova, 2020). Silver is not the principal ore but found as a by-product of polymetallic deposits (Wu et al., 1993). The process of silver mineralization is based on different conditions, mainly hydrothermal, magmatic processes and sedimentary leading to the formation of different silver bearing minerals (Zhuravkova et al., 2017). Silver distribution in ore deposits is based on pressure, temperature, and geochemical conditions. Native silver (Ag) is found as pure metallic silver, commonly in association with other minerals. Acanthite (Ag_2S) and argentite are some silver sulfide minerals that exhibit stability at distinct intervals of temperature (Celep et al., 2015). Silver has also been reported to occur as micro-inclusions of galena (PbS) at Real de Angeles, Mexico, and are accompanied by freibergite and stephanite (Pearson et al., 1988). Similarly, silver is present in minerals like chalcocite, djurleite, and bornite with native silver and stromeyerite as major silver minerals (Bieńko et al., 2023). Silver is formed at comparatively lower temperatures in epithermal environments, in association with minerals such as quartz, calcite, and fluorite (Wu et al., 1993). The polymetallic deposits of China demonstrate that silver is typically concentrated together with lead, zinc, and copper, and usually found in skarns and metasomatic zones (Wu et al., 1993).

Silver mineralogy is also impacted by supergene enrichment processes, in which secondary silver minerals like chlorargyrite are produced through the oxidation of primary sulfide minerals. Such an enrichment process is particularly important under arid climatic conditions, thereby increasing the economic potential of silver deposits (Wu et al., 1993).

4. Grade Distribution

Silver grade distribution depends on the deposit type, mineralogical content, and geochemical processes controlling its concentration. The grade distribution is often related to copper content and major deposits but is not necessarily a linear relationship. In porphyry systems, silver grades are low and are found with chalcopyrite and bornite, as in the case of the Grasberg deposit in Indonesia. The phyllic alteration zone contains moderate grades of silver, commonly with pyrite and tetrahedrite, for example, in Bingham Canyon, USA. Silver enrichment is greater in the supergene zone through oxidation reactions, for example, in Escondida, Chile. Peripheral epithermal veins surrounding porphyry systems are also high-grade in silver, for instance, the El Indio Belt, Chile-Argentina. Porphyry-skarn and carbonate-hosted silver deposits are also characterized by extensive silver mineralization, e.g., the Río Blanco, Chile. Lastly, distal disseminated and replacement deposits such as the Nowa Sól copper–silver deposit, Poland, contain silver in black shales and sedimentary rocks (John & Taylor, 2016; Sinclair, 2007).

Silver is common in porphyry copper deposits, epithermal deposits, and sediment-hosted stratiform deposits, and its grades differ as a function of hydrothermal activity, host rock mineralogy, and enrichment mechanisms (figure 2) (Sillitoe, 2010). Silver grades in porphyry copper deposits generally range from 0.3 to 5.6 g/t, but in some instances, can be as much as 18 g/t (Singer et al., 2008). Statistically comparing well-explored porphyry deposits shows that silver is enriched in Cu-Au and Cu-Mo systems and has a median grade of 4.0 g/t and 3.8 g/t, respectively (Singer et al., 2008). High-grade silver mineralization is typically associated with low-sulfidation environments, wherein metal precipitation is caused by boiling and fluid mixing (Bowell et al., 2023). Sediment-hosted stratiform deposits, exemplified by the Nowa Sól Cu-Ag deposit in Poland, are characterized by extremely high silver enrichment, with local values up to 1000 g/t, and an average annual ore grade of 50 to 52 g/t (Bieńko et al., 2023). Silver in such ores occurs as native silver, silver amalgams, and stromeyerite, commonly together with copper sulfides such as chalcocite and bornite. The greatest concentrations of silver are found in organic-rich shale beds, which are characterized as reducing environments where silver can precipitate (Bieńko et al., 2023). Silver grade distribution is also controlled by supergene processes and depth-related effects. Shallow-depth enrichment due to weathering and secondary mineralization increases silver grades in oxide zones. In general, the heterogeneity of silver grade distribution is high and is controlled by the type of deposit, mineral chemistry, and other geological processes. An understanding of such variations is essential for resource estimation and mine planning, particularly in deposits in which the silver is a by-product (Wu et al., 1993).

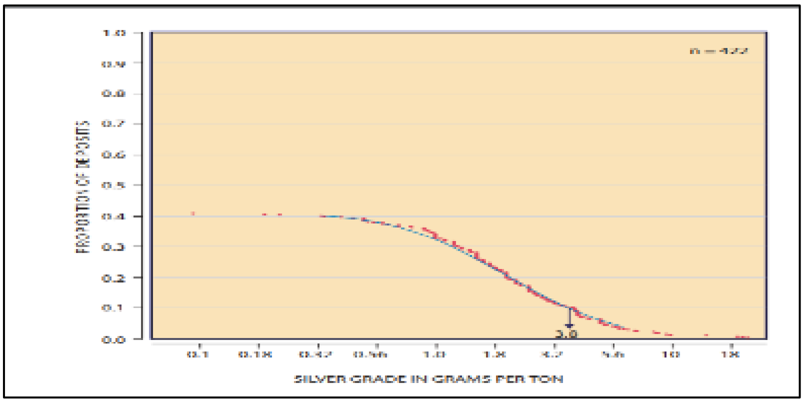

Figure 2 Silver grade model for all PCDs (Source; Singer et al., 2008)

5. Mining Methods

Silver as a by-product of porphyry copper deposits require carefully designed extraction methods due to their size and unusual geological characteristics. The choice of mining method largely depends on factors such as ore body shape, depth, grade distribution, and economics (Djanetey & Yakin, 2025). Silver extraction varies according to the kind of deposit, mineralogy of ore, and feasibility of mining activity. Silver is primarily mined through underground mining and open-pit mining.

5.1. Underground Mining

Underground mining is complex and requires a systematic, multidisciplinary approach to ensure safety and efficiency (Djanetey et al, 2025). Underground mining is frequently employed for extracting high-grade silver deposits situated at considerable depths. Where porphyry deposits are beneath depths at which open-pit mining can be conducted, generally in excess of 600 meters, underground mining must be considered. This technique is used in methods like cut-and-fill mining, room-and-pillar mining, and sublevel stoping which enable effective mining of the ore with minimal waste excavation (Skrzypkowski et al., 2022). Most highly productive silver mines across the globe, particularly those in Mexico, United States and Canada, are underground because of the high-grade nature of the ore. Block caving is used in some instances to large, deeply buried deposits, especially where silver occurs with copper and other base metals (Skrzypkowski et al., 2022).

5.2. Open Pit Mining

Open-pit mining is the most preferred method for low-grade silver deposits in large deposits since it is cost-effective and can be accomplished on a large scale. Open-pit mining involves the extraction of huge volumes of waste rock and ore using heavy machinery through drilling, blasting, and haulage (Erue et al., 2024) . Open-pit mining is most commonly used in porphyry deposits, from which silver is recovered as a by-product of copper and gold mining, for example, the Bingham Canyon Mine in the USA and Escondida in Chile (Sinclair, 2007).

5.3. Processing Methods

Silver extraction varies significantly based on mineralogy, deposit type, and ore complexity. Following silver ore extraction, various metallurgical treatments such as flotation, cyanide leaching, gravity separation, and smelting are employed for metal extraction.

Cyanide leaching is the most common method of silver extraction, particularly for high-grade ores. Silver dissolves in alkaline cyanide solutions to form soluble silver cyanide complexes. Cyanidation is highly effective with silver extraction efficiencies greater than 90% under optimum conditions (Olyaei et al., 2016). Toxicity of cyanide presents severe environmental hazards, but strict regulatory frameworks and advanced treatment methods are required (Bellenfant et al., 2013).

Flotation is very widely practiced for sulfide ores with high silver content, particularly where silver occurs with lead-zinc ores. Gravity separation, assisted by centrifugal concentrators, is used for liberated native silver particles but not for finely disseminated silver (Bellenfant et al., 2013).

Pyrometallurgical treatment involving roasting and smelting is used when silver is present as complicated sulfide ores. It entails the oxidation of sulfide minerals at elevated temperatures to extract silver, and subsequent electrorefining (Sachkov et al., 2019). Despite this, the high energy requirements and release of sulfur dioxide render it less sustainable than hydrometallurgical treatment (Graedel & Eckelman, 2007).

6. Water Management

Silver recovery as a by-product of porphyry copper deposit mining operations has significant water management issues that need to be addressed and planned in a careful manner. Mining operations are likely to consume large volumes of water for processing minerals, dust suppression, and other ancillary activities but this presents scarcity, acid mine drainage and cyanide contamination issues (Armah et., 2025). The Equity Silver Mine in Canada employed sub-aqueous tailings disposal and chemical treatment of water to prevent AMD (Patterson, 1989). Closed-loop water systems are increasingly practiced in areas such as Mexico and Peru, where there is a lack of freshwater resources. Silver mine water pollution is brought about by leachate from tailings ponds, heavy metals dissolved in water, and cyanide residues (Eckelman & Graedel, 2007).

6.1. Waste Management

Silver waste is largely produced from industrial operations, ore processing, and mining activities where silver is used. Silver mining generates large volumes of waste in the form of mine tailings, waste rock, and smelting waste. Tailings contain residual silver, lead, arsenic, and cyanide with long-term environmental effects (Bellenfant et al., 2013). Dry stacking and paste backfilling are preferred to conventional tailings dams as they contain less water and have a lower structural failure risk (Dudeney et al., 2013). There is also the reprocessing of old tailings, and studies show high residual silver recovery (Bellenfant et al., 2013). Several industries are now adopting closed-loop recycling programs, through which silver is reclaimed from waste and subsequently recycled into the manufacturing process (Suah et al., 2019).

With the demand for silver still on the rise, it is essential that industries implement sustainable waste management strategies to minimize environmental degradation and optimize resource utilization.

6.2. Social and Environmental Impacts of Silver Mining

Silver mining also results in environmental hazards such as deforestation, habitat destruction, soil erosion, and metal toxic pollution. The oxidation of sulfide minerals results in acid mine drainage (AMD), which triggers long-term release of lead, cadmium, and mercury into water bodies (Eckelman & Graedel, 2007).

Social issues involve land displacement, Indigenous rights violations, and health problems brought about by the mining activities. Many mining nations have seen protests over mining activities that affect water sources and agricultural fields. Formulation of sustainable mining policies is critical in reducing community conflicts and promoting equitable sharing of resources.

7. Trends in Global Market and Production

The world's largest producing region of silver is located in the Americas with Mexico being the leading producer together with Chile and Peru supply about 40% of the world’s silver, followed by China, Russia, and Australia, supplying about 33% of the world’s silver (Cremona & Mestl, 2023). Silver is extracted primarily as a by-product, in contrast to gold, and therefore its supply depends on base metal demand (Eckelman & Graedel, 2007). The global silver market is propelled by industrial demand, investment demand, and geopolitical factors. The move to renewable sources of energy has brought about a sharp increase in the utilization of silver, particularly in the manufacture of solar panels. Industrial demand for silver is on the rise with its use in photovoltaics, electric vehicles, and medical technology (Lo Piano et al., 2019).

7.1. The Future of Silver Mining

The path of silver mining is expected to be shaped by technological advancements, regulatory policies, and sustainability initiatives. It is expected that AI-enabled exploration, mechanized mining methods, and bio-mining technologies will enhance extraction efficiency and, at the same time, minimize environmental damage (Lo Piano et al., 2019). Silver recycling from solar panels and electronic waste is important in supplementing the primary supply. The shift to a circular economy, in which recovery and reuse are ongoing processes with silver, is vital to long-term resource security (Eckelman & Graedel, 2007).

The future trend of silver production and its corresponding market will likely be influenced by technological innovation, green energy promotion policies, and shifting investment patterns. Further, the increasing demand for electric vehicles and the rollout of 5G technology is expected to further increase the value of silver in industrial applications.

Even with such positive trends, some of the issues such as ore depletion, stricter environmental regulations, and geopolitical uncertainties may affect silver supply.

8. Conclusion

Silver is considered as one of the major and economically viable by-products of Porphyry copper deposits. It is a critical mineral and industrial strategic metal, supporting renewable energy, electronics, and healthcare equipment. But environmental concerns, declining ore grades, and geopolitical risk threaten its sustainable production. Advances in recycling, green leach technologies, and AI-powered resource exploration will be critical to ensure the long-term sustainability of silver. The future of silver mining hinges on the industry's capacity to conform to environmental regulations, embrace sustainable mining methods, and develop policies that will promote its utilization.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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