EPITHERMAL LITHOCAPS, HIGH-SULFIDATION GOLD DEPOSITS, AND TRANSITION TO TOPS OF PORPHYRY DEPOSITS: POTENTIAL FOR PORPHYRY CU-AU DISCOVERY IN PERU

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INTRODUCTION

Most of the significant porphyry copper deposits in Peru that are now mines or in advanced stages of development are located in the south. These are associated with Paleocene and, to the north, middle Eocene to early Oligocene (Apurimac) magmatic belts that continue south into northern Chile. Porphyry copper (as well as related skarn) deposits and their ages include Cuajone (53 Ma), Toquepala (56 Ma) and Cerro Verde (58 Ma) in the Paleocene belt, and Cotobambas (36 Ma), Las Bambas (36 Ma), Los Chancas (32 Ma), Haquira (34 Ma), Antapaccay (~35 Ma) and Tintaya (~33 Ma) in the younger belt; these trends appear to end to the northwest at the northeast-trending Abancay deflection. In northern Peru the porphyry deposits are Miocene in age, with some approaching the size of older deposits in southern Peru, including La Granja and Cerro Corona (14 Ma), Kupfertal (10.7 Ma), Perol (15.8 Ma), Galeno (17 Ma) and Michquillay (20 Ma). This belt extends to the La Libertad district and La Arena (26.1 Ma) and on to central Peru, with the Magistral (15 Ma), Antamina (10 Ma) and Toromocho (7 Ma) deposits; to the northwest, the belt similarly terminates at a northeast deflection, Huancabamba.

Major epithermal deposits in southern Peru (Cardozo, 2006, 2012) formed in the middle to latest Miocene, including the silver-gold intermediate-sulfidation vein deposits of Orcopampa and Caylloma (17-18 Ma), Selene (14 Ma) and Arcata (5.4 Ma), and the high-sulfidation gold deposits at Santa Rosa and Tucari in the Aruntani district, further south (6.4 to 4.7 Ma). These deposits are significantly younger than the Paleocene and Eocene-Oligocene porphyry belts exposed by erosion to the south and north of the Miocene volcanic trend. By contrast, the porphyry and epithermal deposits in northern Peru are closer in location and age. The major high-sulfidation deposits, from north to south, are Yanacocha (a series of deposits formed at 13.6 to 8.2 Ma), Lagunas Norte (~17 Ma), Calaorco (La Arena; 25.8 Ma) and Pierina (14.5 Ma), with the intermediate (to high-) sulfidation veins of Quiruvilca near Lagunas Norte formed at 15 Ma. The porphyry deposits ~10 km east of Yanacocha formed at 21 to 16 Ma, and were eroded to the upper portions of their stockwork quartz veins. By contrast, the younger lithocaps (14-8 Ma) immediately to the west at Yanacocha that host shallow-formed high-sulfidation gold-(copper) deposits are preserved, although they have been supergene oxidized; here the lithocap level is still preserved, capping the porphyry environment (e.g., Kupfertal, 10.7 Ma).

CAUSES OF PORPHYRY AND EPITHERMAL LINKAGE

The linkage between porphyry and volcanic arc-hosted epithermal deposits, particularly those of the high- and intermediate-sulfidation style, has been well demonstrated in South America, the southwest Pacific and elsewhere (Sillitoe, 1973, 2010; Hedenquist et al., 1998). This relationship starts with a degassing intrusion that forms the potassic alteration stage of a porphyry deposit plus the overlying lithocap of advanced argillic alteration; both alteration types have the same age. The potassic-stage brine is dense, but a low-salinity vapor rich in gases such as SO_2 and HCl is buoyant and ascend toward the surface, with a portion discharging as high-temperature volcanic fumaroles. However, part also condenses into meteoric water to form an acidic liquid (pH~1; Hedenquist and Taran, 2013). The shallow vapor condensate causes complete leaching of the host, leaving residual quartz with a halo of quartz-alunite, as well as kaolinite, dickite and, in the hotter feeder zone, pyrophyllite, diaspore, etc.; this alteration stage is anomalous but barren of significant metal concentration (e.g., <50-100 ppb Au; Chang et al., 2011). Where advanced argillic alteration has a strong stratigraphic control, this alteration is called a lithocap, although there is always a structure-related feeder zone proximal to the deep parental intrusion. A lower salinity liquid causes the subsequent overprint of chlorite and white mica (muscovite or illite) alteration, and if this intermediate sulfidation-state liquid rises to the level of the lithocap, it will evolve to high-sulfidation state due to cooling in the residual quartz (Einaudi et al., 2003). Copper will deposit principally as enargite along with gold to form a lithocap-hosted high-sulfidation deposit. By contrast, if the same phyllic-stage liquid ascends along structures away from the lithocap, hosted by fresh rock or propylitic alteration, the deep white mica- and chalcopyrite-stable liquid may form quartz veins with intermediate-sulfidation chalcopyrite, tennantite and low-Fe sphalerite plus silver minerals and gold.

The most intense zones of silicic and advanced argillic alteration of lithocaps, whether barren or mineralized, tend to occur on the shoulders of deeper porphyry intrusions, rather than directly over the porphyry, due to two causes. The first is the common presence of volcanic edifice(s) associated with the deep intrusion(s), and this relief causes a hydraulic gradient away from the surface projection of the intrusion, commonly influenced by regional structures. Secondly, the leaching and formation of residual quartz starts to occur at a temperature below ~220 ºC, where the sulfuric and hydrochloric acids are more dissociated and hence increasingly reactive (Hedenquist and Taran, 2013). This generation of reactive acid at lower temperature, coupled with lateral flow away from the structurally controlled feeder zone along the hydraulic gradient in a horizon of lithologic permeability, causes the common asymmetric distribution of advanced argillic alteration relative to the surface projection of the deep intrusion. Subsequent mineralization of the silicic lithocap inherits this asymmetry.

EXAMPLES OF LINKED PORPHYRY AND EPITHERMAL DEPOSITS

These relationships are well illustrated in the Mankayan district, northern Luzon, Philippines, at the Far Southeast porphyry Cu-Au (~20 Moz Au, 5 Mt Cu) and overlying Lepanto high-sulfidation Cu-Au (4 Moz Au, 1 Mt Cu) deposits, which are closely associated in terms of location, time (1.4-1.3 Ma; and genesis (Hedenquist et al., 1998). There is also an adjacent intermediate-sulfidation vein deposit of Au-Ag-Cu-Zn at Victoria (~2 Mt Au), less than 1 km south of the porphyry deposit, of similar age (1.4-1.2 Ma; Chang et al., 2011). The Far Southeast deposit is associated with a negative magnetic anomaly about 1500 x 700 m in size, due to the potassic-stage magnetite having been destroyed by the phyllic-stage overprint to ~900 m below the present surface, as well as the more shallow advanced argillic alteration; there are limited outcrops of alteration over the porphyry. The advanced argillic alteration of the lithocap extends for over 4 km away from the porphyry center to the northwest along the Lepanto fault, well exposed by river erosion through the unconformity that controlled the distribution of the lithocap. The mineralogy of alteration that outcrops does not show any systematic variation, whereas the mineral chemistry of alunite has a distinct change, from Na-alunite near the porphyry to K-alunite in a distal position (Chang et al., 2011), due to the stability of Na-alunite at higher temperature (Hedenquist and Taran, 2013). This composition can be assessed in the field by short wave infrared equipment (SWIR, e.g. TerraSpec).

Recently there have been several porphyry deposits discovered with outcropping stockwork veins <1 km from the margin of higher elevation (a few 100s m) advanced argillic lithocaps. The porphyry discoveries have occurred while assessing the lithocap for possible high sulfidation-style gold mineralization. The Cocañez lithocap in the Minas Conga district, Peru, ~10 km east of the Yanacocha high-sulfidation district, was first assessed in the 1980s for gold mineralization but found to be barren (<100 ppb Au). Subsequent follow-up of stream-sediment anomalies by another company led to the fortuitous identification of sheeted quartz veins in a swamp, below the level of the lithocap base, about 1 km to the south. The Perol porphyry deposit has a resource of 641 Mt at 0.3% Cu and 0.7 g/t Au, with top close to the surface. Another porphyry discovery was made adjacent to the Calaorco high-sulfidation gold deposit in La Libertad, Peru, where 690 koz Au has been produced since 2011, with proven and probable reserves of 103 Mt at 0.39 to 0.47 g/t Au, respectively. The zone of advanced argillic alteration is located ~400 m from the outcropping La Arena Cu-Au porphyry, with gold-mineralized advanced argillic alteration at Calaorco extending below the top of the adjacent 0.5 wt% Cu contour of the porphyry deposit, the latter associated with a sericite overprint of earlier potassic alteration. The measured and indicated resource of the La Arena porphyry is 274 Mt at 0.24 g/t Au and 0.33 wt% Cu.

EXPLORATION FOR BURIED PORPHYRY DEPOSITS

Where porphyry systems (Sillitoe, 2010) are eroded beneath the level of lithocap alteration and stockwork veins are exposed, the vein style (early, related to potassic alteration, to late, related to phyllic alteration), the vein occurrence of Cu sulfides, and vein distribution plus density must be mapped. Such information provides indications on the location of the center of the deeper mineralized intrusion. In addition, syn-mineral collapse of the hydrothermal system with time (Sillitoe, 2010) may cause the level of advanced argillic alteration to occur below the top of the porphyry deposit, including level of stockwork veins.

Shallower levels of erosion, with portions of the lithocap still preserved, commonly expose alteration that defines a transition from the lithocap to the top of the porphyry. Patchy pyrophyllite replacement of residual quartz (or dickite, diaspore and/or alunite, plus pyrite) is common throughout Peru, and indicates the roots of the epithermal lithocap and thus proximity to the underlying porphyry. Since pyrophyllite is the shallow, lower temperature equivalent of muscovite, it forms from muscovite on cooling, with pyrophyllite deriving silica from the rock (Watanabe and Hedenquist, 2001), hence the distinctive nodular pyrophyllite patches of residual quartz replacement near the base of silicic alteration.

A good example of patchy pyrophyllite replacement of the silicic lithocap is well exposed in the Yanacocha district in the Kupfertal valley, with the San Jose high-sulfidation deposit (alunite ~10.7 Ma) sitting on its shoulder. About 100 m below the level of the San Jose deposit and extending to the valley floor, 300 m below the San Jose deposit, there is well-developed patchy pyrophyllite replacement, grading to a gusano (wormy) texture in the valley bottom, with outcrops of porphyry vein stockwork plus sericite alteration. Drilling discovered the Kupfertal porphyry Cu-Au deposit (biotite ~10.7 Ma) at depths of 200-400 m below the valley floor, with grades up to 0.4 wt% Cu and 0.4 g/t Au, largely below the valley that bisects this world-class high-sulfidation district (>50 Moz Au produced and in oxide reserves).

In addition to the potential for porphyry deposits to occur sub-adjacent to mineralized or barren lithocaps, there is also the potential for significant intermediate-sulfidation veins within 1-2 km of the mineralized lithocap. The recent discovery of the diatreme-related intermediate-sulfidation deposit at Canahuire, southern Peru, ~2 km from the barren lithocap of Chucapaca, highlights this relationship. The dacite dome-hosted barren lithocap was first assessed, followed by a joint-venture partner examining adjacent (pseudo)gossan for the zinc potential in altered sedimentary horizons. Zinc was not found, but in the last of six drill holes, gold mineralization was encountered, 140 m at 2 g/t associated with siderite, ankerite and rhodochrosite. The intermediate-sulfidation deposit now has a resource of over 7 Moz Au equivalent, illustrating that it is essential to assess the margins of mineralized as well as barren lithocaps for whatever mineralization style may be present, epithermal or, at depth, porphyry.

POTENTIAL FOR THE DISCOVERY OF MIOCENE PORPHYRY CU-AU DEPOSITS IN PERU

The preservation of relatively young (Miocene age) lithocaps of advanced argillic alteration throughout Peru, from north to south and some barren, others well mineralized, indicates the potential for porphyry deposits, albeit deeper and in most cases blind. Exceptions are where erosion has exposed veins in the tops of the porphyry deposits in valleys eroded below the quartz-alunite lithocap, such as at La Arena (26.1 Ma) next to the mineralized lithocap of Calaorco (25.8 Ma), Perol (15.8 Ma) adjacent to the barren Cerro Cocañez lithocap (16.1 Ma), and Kupfertal (10.73±0.05 Ma) in a valley between the lithocap-hosted ore deposits of San Jose (10.73±0.1 Ma) and Corimayo (10.75±0.15 Ma). Otherwise, there may be few if any subtle clues at present erosion levels for the location of the deep porphyry intrusion and potential copper deposit, particularly if lying beneath post-mineral cover.

In addition to areas of outcropping epithermal alteration, many Peruvian mineral districts have significant cover due to the presence of post-mineral volcanic deposits or alluvial fill, the latter due to local post-mineral down-faulting. These areas should also be considered for their buried porphyry potential if there are remnants of hypogene advanced argillic alteration, particularly resistant lithocaps (e.g., Marcapunta and Quicay) extending above or lying on the margins of the cover, as a blind intrusion-centered hydrothermal system is indicated.

Understanding the relationship between lithocaps - whether mineralized or barren - and the parental intrusion with its possible porphyry mineralization, is essential during exploration and assessment of volcanic districts with a relatively shallow level of erosion. Future discoveries of porphyry Cu-Au deposits are predicted in Peru, particularly in Miocene volcanic belts, albeit at depths most likely requiring underground mining operations.

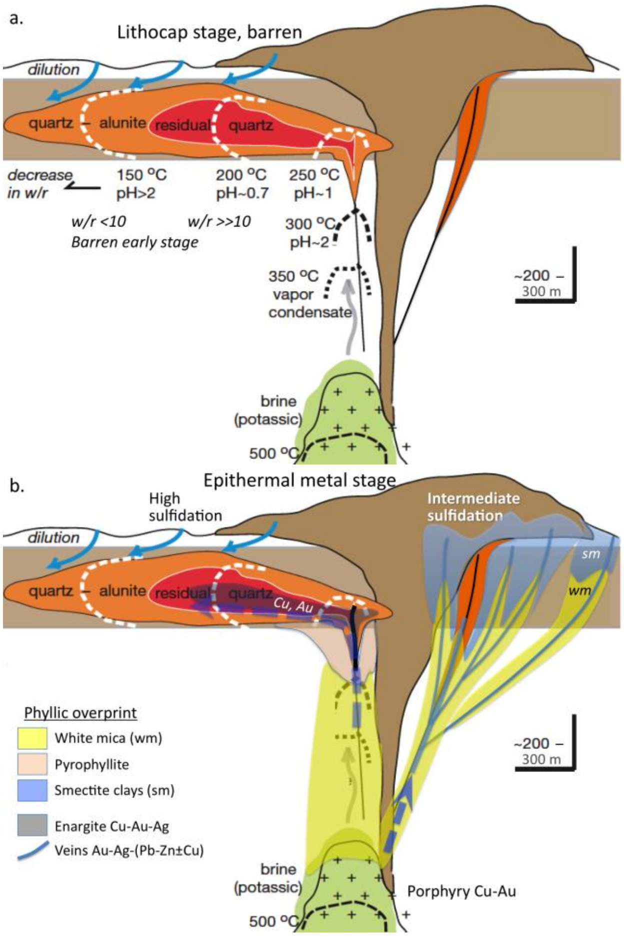

Fig. 1. a) Early-stage porphyry development, deep potassic alteration coupled with shallow advanced argillic alteration, the latter formed by an acidic condensate of magmatic vapor. Hydraulic gradients plus higher reactivity at lower temperature cause the asymmetric formation of residual quartz lithocaps with halos of advanced argillic alteration on the shoulders of the causative intrusion. At this stage, the lithocap is barren. b) Subsequent mineralization stage of the lithocap, caused by ascent of phyllic-stage liquid to epithermal levels; cooling of the intermediate-sulfidation phyllic-stage liquid causes evolution to high sulfidation-state stability in the residual quartz due to lack of rock buffer (Einaudi et al., 2003), resulting in deposition of enargite plus gold. If this magmatic liquid rises from the porphyry along structures that cut fresh or propylitic-altered rock, intermediate-sulfidation epithermal veins may form with halos of white mica (locally advanced argillic) alteration. Modified from Hedenquist and Taran (2013).

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