Geology of the Josemaría Porphyry Copper-Gold Deposit, Argentina: Formation, Exhumation, and Burial in Two Million Years

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Abstract
The Josemaría porphyry copper-gold deposit is located in the Frontal Cordillera of San Juan Province, Argentina, near the present-day northern limit of the Chilean-Pampean flat-slab segment of the central Andes, and midway between the Maricunga and El Indio metallogenic belts. The deposit is centered on small, multiphase dacite porphyry intrusions that were emplaced at the contact between rhyolitic volcanic and tonalitic plutonic rocks of Late Permian to Triassic age. The earlier, more intensely quartz ± magnetite-veined porphyry phases and contiguous wall rocks display a telescoped sequence of alteration-mineralization zones, from shallow advanced argillic (mainly quartz-pyrophyllite) and underlying sericitic to deeper chlorite-sericite and minor remnant potassic. All the alteration types are mineralized, but the highest copper and gold grades are present as a low-arsenic, high-sulfidation assemblage in the quartz-pyrophyllite and sericitic zones. The outermost parts of the copper-gold zone are overlapped by a pronounced molybdenum-bearing annulus.

New U-Pb zircon ages show that the deposit was formed at ~25 to 24.5 Ma, partially unroofed during continued NNE-striking, high-angle reverse faulting, and then unconformably overlain by red-bed conglomerate and sandstone capped by andesitic and dacitic tuff and lava. The andesite reported an age of ~22.35 Ma. A second, discrete pulse of currently undated, advanced argillic alteration, accompanied by minor high-sulfidation enargite mineralization, locally affected the southern periphery of the deposit, including its postmineral cover. Following erosional removal of the volcano-sedimentary strata from the northern and central parts of the deposit, the NNE-trending fault zone underwent minor normal displacement and localized economically significant supergene chalcocite enrichment. However, probably because of the rapidity of deposit unroofing, supergene processes were barely able to keep pace with erosion, resulting in a thin supergene profile over much of the exposed deposit. The southern part of the deposit remains beneath the postmineral cover and, hence, escaped the enrichment.

Josemaría is unusual among the many central Andean porphyry copper deposits formed during rapid uplift because it preserves evidence for not only alteration-mineralization telescoping but also exceptionally rapid postmineral exhumation and subsequent burial beneath thick volcano-sedimentary cover. Unroofing of porphyry copper deposits in 1 to 2 m.y. is more typical of the high erosion rates that characterize pluvial tropical climates than the semiarid conditions that prevailed during and since the formation of Josemaría.

Introduction
Josemaría is a porphyry copper-gold deposit located 4,400 to 4,800 m above sea level in the Frontal Cordillera of San Juan Province, Argentina, ~8 km east of the border with Chile (lat 28°26’S, long 69°32’W). The Frontal Cordillera—the main Andean mountain range at this latitude—is a fault-bounded massif consisting of late Paleozoic to Triassic basement and partially preserved cover sequences (Ramos, 1999). Josemaría lies roughly midway between the porphyry and high-sulfidation epithermal deposits of the Maricunga and El Indio metallogenic belts and, along with nearby porphyry copper deposits and several early-stage prospects, effectively links the two (Paneteleyev and Cravero, 2001; Mpodozis and Kay, 2003; Jones and Martínez, 2007; Rode and Carrizo, 2007; Fig. 1a).

The Josemaría deposit was discovered in 2004 by Desarrollo de Prospectos Mineros S.A. (Deprominsa), the Argentinian

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Fig. 1. a. Location of the Josemaría porphyry copper-gold deposit in the late Oligocene-Miocene volcanic belt of northern Chile and contiguous Argentina, showing the age assignment of the main porphyry and epithermal deposits. Insets show the location of the flat-slab portion of the subducted Nazca plate (contours from Cahill and Isacks, 1992) and position of Figure 1a in South America. b. More detailed geology of the Josemaría area and vicinity. Volcanic rocks compiled mainly from Maksaev et al. (1984), Mpodozis et al. (1995), Faúndez (2001), Fanteleiev and Cravero (2001), Zappettini et al. (2001, 2008), SERNAGEOMIN (2003), Sanguinetti (2006), Martínez et al. (2015a), Mpodozis et al. (2018), and C. Mpodozis (writ. commun., 2018). The age of older volcanic rocks west of the Los Helados fault is uncertain, but between Paleocene and Oligocene. Deposit age assignments based on Sillitoe et al. (1991, 2013, 2016), Kay et al. (1994), Mpodozis et al. (1995), Bissig et al. (2001), Mpodozis and Kay (2003), Perelló et al. (2012), Maydagán et al. (2014), Cáceres (2015), Y. Kapusta in Rode et al. (2015), Yoshie et al. (2015), Holley et al. (2016), Astorga et al. (2017), and NGEx Resources Inc. (unpub. data). Background shaded-relief image from Esri (2014 version).
subsidiary of Tenke Mining Corporation—a Lundin Group company, during a regional program to explore the apparently poorly mineralized gap between the Maricunga and El Indio belts (Jones, 2007). Follow-up of a LANDSAT TM false-color anomaly, first defined a decade earlier by Norwest Mine Services, Inc. on behalf of the Secretaría de Minería de la Nación of Argentina (Decker, 1994), led to definition of a promising 400-×-400-m, talus-fines geochemical copper-gold-molybdenum anomaly and eventual drill testing (Rode and Carrizo, 2007). Since then, Josemaría has been the subject of a series of drilling campaigns, for a total of 61,100 m in 142 holes, culminating in the 2016 announcement by NGEx Resources Inc.—a successor company to Tenke Mining Corporation—of an indicated sulfide mineral resource of 835 Mt at 0.35% Cu and 0.25 g/t Au, at a 0.3% Cu equiv cutoff, for 6,500 Mlb of copper and 6.6 Moz of gold (Ovalle et al., 2016).

In the context of its geographic location, the Josemaría deposit displays several interesting geologic features, including its age, localized supergene enrichment, and limited time spanning deposit formation, exhumation, and subsequent burial beneath postmineral volcano-sedimentary rocks. These topics are the main focus of this paper, which is based on detailed field mapping, drill core logging, and supporting petrography and U-Pb zircon geochronology. The paper builds on an extended abstract presented previously (Ortiz et al., 2015).

Regional Geologic Setting

The Josemaría deposit is situated near the northern limit of the present-day amagmatic Chilean-Pampean flat-slab segment of the Andean Cordillera (~28°–33°S), which is characterized by low-angle subduction of the Nazca plate beneath South America (Jordan et al., 1983; Cahill and Isacks, 1992; Kay and Mpodozis, 2002; Ramos et al., 2002; Fig. 1a, inset). Josemaría is an integral part of a N-trending, late Oligocene to Miocene magmatic arc, containing numerous porphyry and epithermal deposits and prospects, which spans the northern transition zone between the Chilean-Pampean flat-slab segment and the central Andean steep slab, including the Maricunga belt to the north (Fig. 1a). In the Maricunga and El Indio belts, volcanic rocks are widespread whereas between them, where Josemaría is situated, the volcanic pile is rather less extensive, possibly because of erosional removal during kilometer-scale Miocene uplift to expose the late Paleozoic to Triassic basement (Ribbà et al., 1988; Mpodozis and Kay, 1992, 2003; Fig. 1a).

The late Oligocene to early Miocene (~26–20 Ma) part of the volcanic arc was constructed during relatively steep subduction, which since ~18 Ma became progressively shallower and, south of latitude 28°S, evolved to the current flat-slab geometry (Kay and Mpodozis, 2002; Kay et al., 2014). The slab shallowing is generally attributed to subduction of the Juan Fernández aseismic ridge, a bathymetric high, resulting in increased interplate mechanical coupling and consequent contraction, thick-skinned reverse faulting, and crustal shortening and thickening (Jordan et al., 1983; Gutscher et al., 2000; Horton, 2018). Nonetheless, one of the anomalous geologic features of the transition zone between the flat-slab segment and steeper slab to the north, at least along the eastern side of the Maricunga belt around latitude 27°–28°S, is an important earlier pulse of compressive deformation at ~26 to 25 Ma (Mpodozis and Clavero, 2002; Mpodozis et al., 2018) that is thought likely to have extended at least as far south as Josemaría.

Most porphyry and epithermal deposits in the flat-slab segment were formed during the process of flattening, from ~18 to 5 Ma (Bissig et al., 2001; Mpodozis and Kay, 2003; Y. Kapusta in Rode et al., 2015; Yoshie et al., 2015; Holley et al., 2016; Sillitoe et al., 2016; Astorga et al., 2017, Fig. 1a). The only known exceptions, emplaced prior to slab flattening, are Josemaría and several prospects near the Caserones porphyry copper deposit (Perelló et al., 2003a; Yoshie et al., 2015, Fig. 1a). However, north of the flat-slab segment, in the main part of the Maricunga belt, several deposits and prospects formed during the 26 to 20 Ma interval, most notably the Caspiche porphyry gold-copper, Refugio (Maricunga) porphyry gold, and La Coipa, Esperanza (Nueva Esperanza), and La Pepa high-sulfidation epithermal gold-silver deposits (Sillitoe et al., 1991, 2013; Kay et al., 1994; Mpodozis et al., 1995; Fig. 1a).

Deposit Geology

Premineral lithologies

The Josemaría deposit is located within a 25-km-wide, fault-bounded block of volcanic and plutonic basement rocks (Fig. 1b), the former considered Late Permian in age by Marcos et al. (1971). These volcanic rocks are now assigned to the Guanaco Sonso Formation, of Late Permian-Early Triassic age (Martin et al., 1999; Coloma et al., 2017), which is widespread along the Chilean side of the international border, west of Josemaría (Martínez et al., 2015a). In the western parts of the Josemaría area, the Guanaco Sonso Formation comprises rhylitic volcaniclastic rocks, including welded ignimbrite flows (Figs. 2, 3), although systematic subdivision is difficult because of the masking effects of hydrothermal alteration.

East of and locally intruded beneath the rhylitic sequence is an equigranular hornblende-biotite tonalite pluton (Figs. 2, 3), which consists of several phases distinguishable on the basis of grain size and total quartz content. A granodioritic phase is also present north of the deposit (Fig. 3) and melanocratic diorite was encountered by drilling to the southeast. A U-Pb zircon age of 259.11 ± 0.21 Ma was obtained for a sample of the tonalite from the southern part of the deposit, using the chemical abrasion, isotope dilution, thermal ionization mass spectrometry (CA-TIMS) technique on single grains, as detailed in Scoates and Friedman (2008) and the Electronic Appendix. This result makes it part of the regionally extensive Montosa-El Potro Plutonic Complex of Late Permian to Early Triassic age (265–245 Ma; Martínez et al., 2015a). The tonalite is cut by N- to NE-trending, andesite to basaltic dikes (Fig. 3), most too narrow to be shown in the figures. Such dikes are a typical feature of many Permo-Triassic plutons in the Frontal Cordillera (e.g., Martin et al., 1999).

These Late Permian to Triassic volcanic and plutonic rocks are currently considered to represent the shallow and deep parts, respectively, of igneous complexes emplaced during crustal extension induced by either a hiatus in subduction (Mpodozis and Kay, 1992) or slow subduction with slab rollback (del Rey et al., 2016).
Pre- and synmineral structure

The main premineral feature at Josemaría is the contact between the tonalite pluton and rhyolitic volcanic rocks. Although this contact is inferred to be generally subhorizontal, there is a suggestion from three-dimensional modeling of the immediate deposit area that it may be marked by a steep, N-striking, premineral fault that was plugged by porphyry intrusions, although the evidence is largely obscured by postmineral faulting (Fig. 3). Judging by the northerly elongation of the porphyry intrusions, the suspected fault may have influenced their emplacement (Fig. 3). Furthermore, the Josemaría deposit lies at the southern end of a >16-km-long, N-trending alteration corridor, within which there are at least two additional porphyry copper-gold prospects (Fig. 1b), including N-trending porphyry dikes, suggesting that the putative structure could be regionally significant.

At the time of and immediately following deposit formation, and broadly contemporaneous with the 26 to 25 Ma compressive tectonism (Mpodozis et al., 2018), a slightly oblique, NNE-trending fault zone transected the Josemaría area and acted as an east-over-west reverse structure, thereby accounting for preservation of the rhyolitic volcanic rocks and shallow-level alteration features (see below) on its western footwall side (Fig. 3). Similarly oriented faults, showing most recent W-vergent reverse displacement, are mapped in the region; some of them had early normal motion during late Eocene extension when a major parallel structure, the Mogotes fault, ~5 km east of Josemaría, was active along the western margin of the Macho Muerto basin (C. Mpodozis, writ. commun., 2018; Fig. 1b).

Porphyry intrusions

The Josemaría porphyry copper-gold deposit is centered on several small dacite porphyry intrusions, which are subdivided into early, inter-, and late-mineral phases. All the phases are characterized by 60 to 80 vol % of well-formed plagioclase, hornblende, and biotite phenocrysts, the last as well-formed “books,” along with scattered quartz phenocrysts in a fine-grained groundmass.

The early porphyry phases are intensely quartz veined and well mineralized, whereas the intermineral phases are noticeably less strongly veined; both phases were originally potassic altered. In contrast, the late-mineral phases display propylitic alteration, have few quartz veinlets, and are essentially barren. The porphyry phases were distinguished using standard geologic criteria (Sillitoe, 2000, 2010; Proffett, 2003), particularly the presence near intrusive contacts of quartz veinlet xenoliths (Fig. 4) in combination with quartz veinlet intensities and copper and gold contents.

The greatest volume of intrusive porphyry occupies the central parts of the deposit, where the largest body of the early phase is flanked to the northeast and southwest by the largest late and intermineral bodies, respectively (Figs. 2, 3). Farther north still, the porphyries are confined to steep dikes, with the early and intermineral phases only a few meters wide.

The early and intermineral porphyries (Fig. 3) returned U-Pb zircon ages of 24.98 ± 0.04 Ma (youngest grain) and 24.66 ± 0.04 Ma (MSWD = 1.12), respectively, employing the same CA-TIMS method; analytical details are given in the Electronic Appendix.

Hypogene Alteration and Mineralization

Five alteration types—potassic, chlorite-sericite, sericitic, advanced argillic, and late propylite—are systematically recognized within the Josemaría deposit, each with its own distinctive sulfide assemblage where not subjected to supergene oxidation. Together, these define an alteration footprint measuring 4 km north-south and 2 km east-west (Fig. 5).
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Fig. 3. Geology of the Josemaría porphyry copper-gold deposit and environs, simplified from 1:5,000-scale mapping by the second author (FAMD). Also shown is the surface projection of the deposit at a >0.3% Cu equiv cutoff (after Ovalle et al., 2016).
The Josemaría deposit is broadly centered on an exposed chlorite-sericite alteration zone, approximately 800 m across, which gives way westward and, below postmineral cover, southward to sericitic and advanced argillic alteration (Figs. 5, 6b, 7b). The chlorite-sericite assemblage formed at the expense of preexisting potassic alteration, which is preserved at depths of anywhere between 400 and 600 m below the present surface and as a steeply inclined, roughly cylindrical body, up to 200 m across, which extends to the surface alongside the dikes in the central-northern part of the deposit (Figs. 5, 6b). Approach to the potassic zone is heralded by weakening of the chlorite-sericite overprint and presence of remnant biotite.

Results of the surface mapping show that the alteration zone is much larger than the deposit itself, with advanced argillic and sericitic alteration extending 700 m west and >1,500 m north and south; to the east, this distal alteration is concealed beneath postmineral cover (Fig. 5). The advanced argillic alteration occupies the highest ground, dominates the rhyolitic volcanic rocks (see below), and transitions downward to and overprints the sericitic zone or, where the latter is absent, the chlorite-sericite or potassic zones. The sericitic zone is encircled by a weakly developed propylitic halo (Fig. 5).

**Potassic alteration**

The potassic alteration is preserved at depth in the tonalite as well as in the preporphyry andesitic to basaltic dikes and early and intermineral dacite porphyry intrusions that cut it (Fig. 6b). The preporphyry dikes can display potassic alteration even where enclosing tonalite was overprinted by chlorite-sericite alteration, reflecting their greater contents of hydrothermal biotite and fine-grained, relatively impermeable nature.

Hydrothermal biotite defines the potassic zone (Fig. 8a), although apparently unaltered magmatic biotite is also present. Plagioclase is bleached white in parts of the potassic zone as a result of replacement by albite associated in part with K-feldspar, an assemblage denominated sodic-potassic by Lang et al. (2013). Hydrothermal magnetite constitutes up to 5 vol % or more of the potassic-altered tonalite and early and intermineral porphyries, in veinlets with or without quartz as well as in disseminated form.

Multidirectional quartz veinlets were introduced during the potassic event and become less abundant as the porphyries become younger and, in their host rocks, with distance from the core of the deposit; they attain ~15 vol % of the early porphyry and were everywhere preserved during the superposition of the chlorite-sericite, sericitic, and advanced argillic alteration (Fig. 8b, d). The more prominent exposed quartz veinlets are mapped in Figure 5. The outer limit of appreciable quartz veining acts as a useful proxy for the external limit of copper-gold mineralization (Fig. 6b). Following the classification of Gustafson and Hunt (1975), the quartz veinlets in the potassic zone are mainly A-type (Figs. 4, 8a), containing varied amounts of chalcopyrite ± magnetite, but molybdenite-bearing B-type quartz and D-type quartz-pyrite veinlets (Fig. 8c) are also present. Where not dissolved by cool descendant groundwater under supergene conditions (see below), anhydrite is present in the potassic zone, most of it in monomineralic veinlets that were introduced late during deposit formation.

The potassic alteration is characterized by veinlet and disseminated chalcopyrite, with little or no accompanying pyrite. The relatively low-sulfidation state of the sulfide zone is further emphasized by the local presence, mainly in the A-type quartz veinlets, of minor bornite. Chalcopyrite/bornite ratios are estimated to be >30:1.

**Chlorite-sericite alteration**

The chlorite-sericite alteration is dominant throughout the tonalite and early and intermineral porphyry intrusions in the northern and central parts of Josemaría where it is transitional to and overprints the potassic alteration; however, farther south in the deposit it is present mainly at depth. Plagioclase is wholly or partially replaced by sericite, and biotite and hornblendes by chlorite (Fig. 8b). On the margins of the chlorite-sericite zone, the sericite gives way in places to pale-green illite. Magnetcite is largely transformed to hematite, either as pseudomorphic martite or specularite. Anhydrite veining is similar to that in the potassic alteration. The low-sulfidation chalcopyrite ± bornite assemblage in the potassic alteration is variably reconstituted to pyrite-chalcopyrite in the chlorite-sericite zone, typically giving rise to pyrite/chalcopyrite ratios of ~3 to 10:1.

**Sericitic alteration**

The sericitic alteration is present in the shallower levels of the deposit and commonly underlies the advanced argillic alteration, a relationship best seen in the southern parts. However, as illustrated by Figure 6b, it can be volumetrically subordinate to advanced argillic alteration in the rhyolitic volcanic rocks. Sericite-bordered, D-type veinlets are a characteristic feature of the sericitic zone (Fig. 8c).

The sericitic alteration within the copper-gold deposit is characterized by a prominent high-sulfidation sulfide assemblage in which disseminated grains of pyrite are surrounded by black sulfide rims composed of intergrown hypogene chalcocite, bornite, and/or covellite along with trace amounts of tennantite and enargite. All preexisting magnetite and hematite were pyritized and pyrite/copper sulfide ratios are roughly 10:1. Downward, the sericitic alteration and high-sulfidation mineralization are observed in places to grade into the pyrite- and chalcopyrite-bearing, chlorite-sericite zone.
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Josemaría porphyry system alteration

LATE OLIGOCENE (~25 Ma)

Basaltic plug (unaltered)

Hydrothermal breccia (alunite & kaolinite cement)

Postporphyry cover rocks

Advanced argillic

Sericitic (strong/moderate)

Propylitic

Chlorite-sericite

Potassic

EARLY MIOCENE (~22 Ma)

Quartz veinlets

MIOCENE (post - 22 Ma)

Volcanic rocks

Redbed sandstone/conglomerate

Fig. 5. Hydrothermal alteration of the Josemaría porphyry copper-gold deposit and environs. Also shown is the surface projection of the deposit at a >0.3% Cu equiv cutoff (after Ovalle et al., 2016).
Fig. 6. Representative sections at 5,600N, approximately the middle of the Josemaría copper-gold deposit. a. Lithologies. b. Hydrothermal alteration. c. Supergene profile. Section line shown in Figures 3 and 5.
Fig. 7. Representative sections at 5,000N, in the southern part of the Josemaría copper-gold deposit where it is concealed beneath postmineral rocks. a. Lithologies. b. Hydrothermal alteration. c. Supergene profile. Note the position of the dated tonalite sample in (a). Section line shown in Figures 3 and 5.
Advanced argillic alteration

The advanced argillic alteration is largely but not exclusively restricted to the rhyolitic volcanic unit (Fig. 6b) although, locally, narrow, structurally controlled zones penetrate the underlying tonalite to depths of up to 350 m. The advanced argillic alteration preferentially affected the rhyolite because of its silicic nature and consequent low acid-buffering capacity relative to the other lithologies present. The zone is dominated by quartz and pyrophyllite (Fig. 8d) although in places, at shallow depths, alunite rather than pyrophyllite replaces plagioclase phenocrysts. Other minerals typical of the advanced argillic alteration include dickite, observed together with pyrite filling a few veinlets, dumortierite, in the form of tiny pale-blue rosettes, and diaspore, identified only in thin sections.

The advanced argillic alteration contains the same high-sulfidation sulfide assemblage as the sericitic zone and is similarly pyrite rich and devoid of magnetite and hematite. Native sulfur coats fractures in places, accompanied locally by crystalline, hypogene covellite.

Propylitic alteration

In addition to the weakly developed propylitic halo to the Josemaría deposit (Fig. 5), the late-mineral dacite porphyry intrusions are also pervasively albeit weakly propylitized (Figs. 5, 6b), with all mafic minerals altered to chlorite and plagioclase containing replacive patches of epidote. The late propylitization, in common with that in late-mineral porphyry copper intrusions in general (e.g., Sillitoe, 2000), barely affects the enclosing rocks. Pyrite contents of both the early halo and late-mineral porphyry propylitization are low, typically <1 vol %.

The propylitic halo, thought to have formed contemporaneously with the potassic zone (e.g., Proffett, 2003), is not distinguished from this late-stage propylitization of the late-mineral porphyry in Figures 5 and 6b because of their mineralogic similarity.

Grade distribution

Using a >0.3% Cu equiv cutoff projected to surface, the copper-gold zone at Josemaría measures a maximum of ~1,500 m north-south and ~1,000 m east-west (Figs. 3, 5, 9). Within this zone, the highest hypogene copper and gold values lie in its southern part, eccentrically with respect to the deposit outline (Fig. 9). The external parts of the copper-gold deposit are overlapped by a molybdenum-rich annulus, with >50 ppm Mo, which is higher in grade around the northern and eastern sides (Fig. 9). Although the molybdenite in the annulus formed during potassic alteration, as shown by much of it occurring in B-type quartz veinlets, it was retained during the subsequent alteration overprints.

The hypogene copper and gold values generally correlate reasonably well in all the alteration-mineralization types, suggesting joint introduction and precipitation of the two metals during the early potassic event and their continued close association during the alteration-mineralization overprinting. However, the Cu-Au correlation coefficient for the entire deposit is only 0.57, at least in part due to mobility of copper in the central and northern parts of the deposit during supergene
Fig. 9. Horizontal slices through the Josemaría porphyry copper-gold deposit at 4,500-, 4,300-, and 4,100-m elevations, showing distributions of hypogene gold (>0.3 g/t) and molybdenum (>50 ppm) and hypogene plus supergene copper (>0.2%). Note the well-formed molybdenum annulus. The progressive northward deepening of the highest copper values reflects the fault-localized supergene chalcocite enrichment. Grade boundaries are interpolated from downhole assay values.
processes. The overall similarity of copper (~0.35%) and gold (~0.2 g/t) contents in the potassic and chlorite-sericite zones suggests that there was little metal addition or removal during the reconstitution of the chalcopyrite ± bornite assemblage to pyrite-chalcopyrite.

At the deposit scale, the highest hypogene grades, particularly of copper but, in the south, also of gold, tend to occur in the advanced argillic and sericitic zones in which they are present in the high-sulfidation sulfide assemblage; this clearly gave rise to hypogene enrichment, defined as a grade increase relative to the preexisting potassic and chlorite-sericite alteration (Fig. 8a, b). In the south, average copper and gold values of ~0.6% and ~0.7 g/t are attained locally, accounting for the highest grade part of the deposit. The minor tennantite and enargite result in arsenic values typically between 10 and 100 ppm. Distinction of the hypogene enrichment from that of supergene origin at Josemaría is not straightforward. Nonetheless, hypogene-enriched zones are commonly cut by pristine pyrite veinlets lacking copper-bearing sulfide minerals, whereas such veinlets are the preferred sites for supergene chalcocite enrichment (see below).

Postmineral Volcano-Sedimentary Cover

The southern part of the Josemaría deposit is unconformably overlain by a volcano-sedimentary sequence, much of which is completely unaltered and devoid of sulfide minerals (Figs. 5, 7b). Contacts between the porphyry copper alteration and mineralization and postmineral sequence are abrupt and readily mappable at surface and in drill core (Figs. 2, 3, 5). The sequence, which comprises lower sedimentary and upper volcanic components (Fig. 10a), thickens dramatically southeastward to ~500 m, much of it attributable to the sedimentary unit (Fig. 7a). The paleotopography upon which the sediments were deposited dips southeast at ~30°, steepening farther southeastward (Fig. 7a). The fact that the porphyry intrusions are subvertical strongly suggests that this is an original slope angle rather than a product of postmineral tilting.

The lower part of the postmineral sequence is entirely composed of stratified siliciclastic rocks, both polymict, clast-supported, cobble-pebble conglomerate and immature, poorly bedded, quartz-rich sandstone, the latter becoming more abundant eastward (Figs. 3, 7a). Clasts vary from well rounded to subangular, with the term breccia perhaps more appropriate where the latter predominate. These lithofacies suggest deposition in a proximal alluvial fan environment (e.g., Blair and McPherson, 1994). Above the southern part of the deposit, the conglomerate horizon

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**Fig. 10.** Postmineral features near the Josemaría porphyry copper-gold deposit. 

- **a.** Hematitic basal conglomerate overlain by felsic ignimbrite. Note the thin jarosite layer along the contact. 
- **b.** Hematitic polymict conglomerate, with the largest clast being hyaloclastic rock containing chalcopyrite (cpy). 
- **c.** Hematitic (hem) conglomerate cut by pyrite veinlets with kaolinitized halos (kao) containing disseminated pyrite (py). Note that pyrite overprints and destroys the hematite. 
- **d.** Advanced argillic-altered conglomerate impregnated with quartz (q), pyrite (py), and enargite (en); kaolinite (kao) fills cavities. 
- **e.** Hematitic (hem) conglomerate overprinted by supergene jarosite (jar) after former disseminated pyrite. Note the A-type quartz (Aq) veinlet in the centrally located clast. Scribe tip for scale in (b), (c), (d), and (e).
and a thinner conglomerate bed intercalated in the overlying volcanic unit have a hematite-impregnated matrix and are considered as red-bed sediments (Figs. 7a, 10b). At surface, the main hematitic horizon can be traced continuously for 2,300 m along the base of the postmineral sequence (Fig. 3). The conglomerate clasts consist mainly of rhyolitic volcanic rocks, some displaying advanced argillitic alteration, but clasts containing A-type quartz veinlets (Fig. 10c) or specular hematite are also present. Pyrite, chalcopyrite, and high-sulfidation sulfide mineralization occur in many incompletely oxidized or unoxidized clasts (Fig. 10b). Indeed, the unaltered conglomerate contains elevated copper and gold values, typically ~50 to 500 ppm and 0.1 to 0.2 g/t, respectively, which are assumed to be contributed by the mineralized clasts. Local concentrations of detrital magnetite grains also occur in places. These lithologic and geochemical features support a local source contribution from the eroding Josemaría deposit.

The upper, volcanic part of the postmineral sequence comprises andesitic and dacitic lavas underlain by poorly welded, lithic-rich and -poor ignimbrites (Figs. 7a, 10a). An andesite sample, collected at surface (Fig. 3), returned a U-Pb zircon age of 22.35 ± 0.03 Ma (MSWD = 1.3; Electronic Appendix), in keeping with the postmineral timing of the volcano-sedimentary sequence. Based on this age, the postmineral volcano-sedimentary rocks may be correlated with the Río La Gallina-Refugio sequence along the eastern side of the southern Maricunga belt, between latitude 27°30’ and 28°S (26–21 Ma; Mendoza et al., 2018) and the Tilito Formation of the Doña Ana Group in the El Indio belt (24.1–21 Ma; Maksay et al., 1984; Kay et al., 1988; Bissig et al., 2001; C. Mpodozis, pers. commun., 2019).

### Postmineral Normal Faults

A series of NW-striking, high-angle faults transect the eastern parts of the deposit, stepping the postmineral volcano-sedimentary rocks down to the northeast but also accommodating some sinistral motion (Fig. 3). The NW faults appear to terminate at the NNE-striking reverse fault zone within the deposit, which was reactivated at this time as a series of normal faults. The reactivated faults are marked by 5 to 10 cm of gouge surrounded by damage zones a few meters wide. East-side-down displacement on the easternmost of the three main reactivated faults is on the order of 120 m (Fig. 6a).

The age of this post ~22 Ma normal faulting is unconstrained, although it could have been broadly synchronous with the postmineral red-bed sedimentation and volcanism and, therefore, correlative with the regional extension that accompanied deposition of the Doña Ana Group in the El Indio belt (24.1–17.5 Ma; Bissig et al., 2001; C. Mpodozis, writ. commun., 2019). Alternatively, it could have been in the mid-Miocene when extension affected the eastern side of the southern Maricunga belt around latitude 27°–28°S (Mpodozis et al., 2018).

#### Younger Hypogene Alteration and Mineralization

The upper, volcanic part of the postmineral cover sequence is everywhere little altered except for weak propylitization of the andesitic units; however, part of the siliciclastic red-bed sequence unconformably overlying the Josemaría deposit, particularly the hematitic basal conglomerate, is pervasively kaolinized and pyritized (Fig. 7b). Although most of this later alteration and mineralization lies beyond the Josemaría deposit, it did affect it locally along faults but with minimal addition to grade.

Hydrothermal breccia dikes, 1 to 50 m wide and cemented by chalcedony, alunite, kaolinite, pyrite, and enargite, are prominent just south of the Josemaría deposit. The main dike at surface strikes west to northwest and is ~2 km long (Figs. 3, 5). Locally, the advanced argillitic alteration and mineralization associated with this breccia dike invade fault zones, with a particular affinity for the NW faults, as well as the hematitic conglomerate at the base of the postmineral sequence (Fig. 5), causing the latter to undergo bleaching and hematite destruction. In drill core, pyrite veinlets cutting the conglomerate have kaolinized halos containing disseminated pyrite, which clearly overprints and sulfidizes the hematitic matrix (Fig. 10e). The conglomerate in several places, including that at the base of one of the thickest siliciclastic intervals, is cut by a stockwork of quartz, pyrite, and enargite associated with cavity-filling kaolinite and lesser alunite (Figs. 7b, 10d), with all former hematite entirely destroyed. Importantly, this arsenic-rich copper mineralization lacks accompanying gold (<40 ppb), thereby making it not only temporally but also geochemically distinct from the high-sulfidation mineralization in the upper parts of the Josemaría deposit.

#### Supergene Oxidation and Enrichment

The supergene profile at Josemaría is generally thin, but in the central and northern parts of the deposit it can attain a thickness of 400 m over widths of <200 m because of downward extension along the three main NNE-striking, steeply E-dipping, normal postmineral faults (Figs. 2, 7c, 9). The supergene profile consists of a jarosite- and goethite-dominated leached capping—which within 43 Mt average 0.32 g/t Au (at a 0.2 g/t Au cutoff; Ovalle et al., 2016)—underlain by a northward-deepening, chalocite enrichment blanket, ranging from 100 to 200 m thick (Fig. 6c). In places, however, where the oxidation affected pyrite-poor potassic alteration, there are zones containing oxide copper minerals (Fig. 6c), mainly fracture-coating malachite and neotocite. Nonetheless, the leached capping is generally depleted in copper, typically reporting <0.1%, in marked contrast to the underlying enrichment with typical values of 0.8 to 1.5% Cu.

In the concealed southern parts of the deposit, the postmineral volcano-sedimentary rocks overlie a 30- to 140-m-thick, E-thinning supergene profile, comprising mainly leached and partially leached zones; underlying chalcocite enrichment is minimal (Fig. 7c). The leached and partially leached zones contain more supergene hematite than the leached capping farther north, the reason for which is uncertain. The southern part of the supergene profile and its host rocks may be disrupted by the NW-striking normal faults, which may also have facilitated groundwater circulation (Figs. 3, 7e).

In places, where the postmineral hematitic conglomerate was affected by the later pyritization (Fig. 10c), supergene oxidation gave rise to formation of jarosite. Since hematite is stable in the weathering environment, the oxidation of
partially pyritized zones resulted in jarosite veining of the hematite-cemented conglomerate (Fig. 10e). The unaltered and pyrite-free conglomerate and overlying volcanic rocks were incapable of developing leached capping, thereby giving the erroneous impression that they postdate all leached-capping development (Fig. 7c).

The Josemaría deposit is characterized in places by an abrupt sulfate front: the boundary between gypsum ± anhydrite-cemented rock below and sulfate-free rock above (Sillitoe, 2005). The anhydrite is an abundant hypogene mineral, probably formerly present in all the alteration types described above, with the possible exception of the propylitic halo. The gypsum is its supergene hydration product, which persists until it is eventually dissolved by continued descent of cool groundwater, leaving open cavities. Although the anhydrite front is typically deeper than 600 m, the lower limit of drilling, it occurs locally at relatively shallow depths in the northern and central parts of the deposit. There, pillars of impermeable, sulfate-cemented rock exist as shallowly as the base of the leached capping, a situation that effectively prevents the downward passage of supergene solutions and development of chalcoite enrichment (Fig. 6c).

Discussion

Evolution of Josemaría hypogene mineralization

Josemaría displays the main attributes of porphyry copper-gold deposits worldwide, including elevated hydrothermal magnetite content, reasonably good copper-gold correlation, and a molybdenum-rich halo to the central copper-gold zone (Sillitoe, 1979, 2000). Furthermore, notwithstanding their very different host rocks, these features, along with the telescoped nature of the alteration and mineralization zoning, are shared with the contemporaneous Caspiche porphyry gold-copper deposit at the southern end of the Maricunga belt (Sillitoe et al., 2013; Fig. 1a).

In combination, various lines of evidence, including the trend of elongate porphyry bodies and dikes (Fig. 3), suggest that the Josemaría porphyry copper-gold deposit, along with the two prospects farther north (Fig. 1b), was localized by a N-striking zone of structural weakness in the late Paleozoic to Triassic basement (Fig. 11a). This basement feature was transected by a slightly oblique, NNE-striking reverse fault zone, which underwent reverse motion following and probably also during deposit formation at ~25 to 24.5 Ma (Fig. 11b), in general accord with the timing of compressive tectonism along

Fig. 11. Evolutionary schema for the Josemaría porphyry copper-gold deposit. a. Premineral development of N-striking zone of basement weakness, possibly followed by normal faulting. The Mogotes normal fault was active at this time along the western margin of the Macho Muerto basin (C. Mpodozis, writ. commun., 2018; Fig. 1b). b. Initiation of compression, NNE-striking reverse faulting, and emplacement of dacite porphyry intrusions and associated porphyry copper system. c. Continued compression, telescoping of alteration and copper-gold mineralization, unroofing, and deposition of red-bed siliciclastic sequence. d. Accumulation of dacitic and andesitic volcanic rocks. e. Localized post-Josemaría hydrothermal brecciation, advanced argillic alteration, and high-sulfidation copper mineralization. f. Reexhumation of the deposit and supergene copper enrichment, probably later than the normal motion on the NNE-striking fault zone. g. Further erosion, particularly during Pleistocene glaciation.
the eastern side of the southern Maricunga belt (26–25 Ma; Mpodozis et al., 2018) and elsewhere in the Andean backarc at latitude ~27°–28°S (late Oligocene onward; Kraemer et al., 1999; Carrapa et al., 2005; Zhou et al., 2017).

As a direct result of the late Oligocene-early Miocene compressive deformation and consequent uplift, Josemaría underwent synmineral erosion, resulting in progressive paleo-surface lowering and alteration-mineralization telescoping (cf. Sillitoe, 1994; Fig. 11c). This caused extensive reconstitution of early potassic by lower temperature chlorite-sericite alteration, which, in turn, was widely and deeply overprinted by sericitic and, at shallower levels, advanced argillic alteration. Although there was little obvious grade change during the conversion of potassic to chlorite-sericite alteration, the superposition of the high-sulfidation sulfide assemblage during the sericitic and advanced argillic events gave rise to hypogene enrichment of copper and, less extensively, also gold. A significant proportion of the copper and gold in the high-sulfidation assemblage appears to have been inherited from the preexisting chlorite-sericite zone: a conclusion supported by the consistently higher grade of the early compared to intermineral porphyries where both host high-sulfidation mineralization.

Once hydrothermal activity had ceased, the Josemaría deposit continued to be eroded until concealment beneath the synorogenic red-bed sediments that constitute the lower unit of the postmineral cover sequence (Fig. 11c). The rhyolitic volcanic rocks appear to have contributed much of the detritus. The steep slopes existing at the time (Fig. 6) would have favored mass wasting and accumulation of the coarse conglomerate and breccia. The local presence at surface of potassic alteration and A-type quartz veinlets along with the quartz-pyrophyllite dominance of the advanced argillic alteration suggests that relatively deep parts of a formerly more areally extensive lithocap are currently exposed; this likely implies erosional removal of at least 1,000 m of shallower, probably more silicic and alunitic advanced argillic alteration that may have been hosted by coeval volcanic rocks and contained higher grade, high-sulfidation epithermal gold mineralization (cf. Sillitoe, 2010; Hedenquist and Taran, 2013). However, such material is not abundant in the observed hematitic conglomerate, suggesting that, if ever present, it was not transported in a southeasterly direction or deposited nearby Josemaría.

The duration of deposit exhumation cannot be precisely determined on the basis of current data. Nonetheless, the fact that the early and intermineral porphyries, separated by only ~0.3 m.y., are followed first by postmineral red-bed sediments (Fig. 11c) and then, <2.4 m.y. later, by the volcanic rocks (Fig. 11d) shows that it was a short-lived event that is unlikely to have exceeded ~2 m.y.

Post-Josemaría copper mineralization

After concealment of the Josemaría deposit beneath the postmineral volcano-sedimentary cover, advanced argillic alteration and minor high-sulfidation copper mineralization affected mainly the area south and southeast of the deposit (Figs. 5, 7b, 10d, 11e). The event has not yet been radiometrically dated but must be >2.4 m.y. later than formation of the Josemaría deposit. Some of the NW-striking faults cutting the postmineral sequence guided ascent of the high-sulfidation fluid, with the siliciclastic sediments, probably poorly consolidated at the time, providing the permeability for more widespread fluid ingress (Figs. 7b, 11e).

Although at least 2 m.y. of erosion, sedimentation, and volcanism intervened between the main porphyry copper-gold and late high-sulfidation epithermal events, their proximity suggests that the latter is the product of delayed resurgence of the Josemaría system, presumably linked to a currently undocumented intrusion.

Supergene development at Josemaría

The supergene chalcocite enrichment at Josemaría was preferentially developed in the central and northern parts of the deposit and most deeply within the reactivated, NNE-striking, postmineral normal fault zone (Figs. 6c, 9), which appears to have acted as a channelway for focused descent of copper-charged solutions. In contrast, the rest of the deposit, especially its southern part, has much thinner leached and partially leached zones beneath which there is negligible chalcocite enrichment despite the presence of apparently suitable hypogene pyrite and copper contents (Fig. 7c). Furthermore, in places, the oxidation also affected pyritized parts of the postmineral siliciclastic sedimentary rocks (Figs. 7c, 10e).

In combination, these features strongly suggest that the supergene profile developed since the postmineral cover sequence was deposited, but after it was eroded from the central and northern parts of the deposit (Fig. 11f). However, precisely when the cover sequence was removed is unknown although it could potentially have been relatively recently, depending upon its original thickness and the erosion rate. Percolation of water along the top and base of the hematitic conglomerate horizon and down the normal faults (Fig. 7c) could have caused the weak sulfide oxidation that affected the southern part of the deposit, a possibility supported by the jarosite layer along the top contact (Fig. 10a). The steepness of the topography that existed during unroofing of Josemaría (Fig. 7) and the fact that many mineralized clasts in the conglomerate are sulfidic suggest that little sulfide oxidation took place during initial deposit exhumation, prior to concealment beneath the postmineral cover, probably because of the rapidity of the unroofing process.

Erosional stripping of the postmineral volcano-sedimentary cover from the northern and central parts of the deposit and initiation of the oxidation and enrichment must have taken place during the continued Miocene uplift of the 25-km-wide block of late Paleozoic to Triassic basement in which Josemaría is located, facilitated by major displacements on the El Potro and subsidiary Los Helados faults (Fig. 1b). Nonetheless, as noted above, an extensional episode must have intervened either before or during the active enrichment. The erosional dissection would have progressively lowered paleogroundwater tables, resulting in exposure of the Josemaría sulfide mineralization to the effects of oxidation and the generation of subjacent chalcocite enrichment. Nonetheless, the overall thinness and immaturity of the supergene profile over much of the Josemaría deposit suggests that supergene processes may have barely kept pace with the rapid erosion, resulting in confinement of appreciable chalcocite enrichment to the permeable NNE-striking fault zone. Preservation of the shallow,
anhydrite-cemented rock volumes (Fig. 6c) further supports the notion of supergene immaturity.

An alternative possibility is that much of the supergene profile, except for the more deeply developed parts in the NNE-striking fault zone, was removed during the Pleistocene when the high altitude (>4,350 m) parts of the region underwent intense glacial and periglacial dissection (Ammann et al., 2001; Perucca and Angillieri, 2005). Since then, and notwithstanding ongoing active sulfide oxidation and enrichment in this high elevation Andean region (Sillitoe, 2005), insufficient time has elapsed to redevelop a deep supergene profile if, indeed, one ever existed.

### Rapidity of porphyry copper exhumation

Advanced argillic lithocaps are widely distributed in the Maricunga and El Indio belts and the transition zone between them. Some contain high-sulfidation epithermal gold ± silver deposits (Fig. 1a), whereas many are largely barren (Bissig et al., 2001) even where they flank or overlie known porphyry gold and gold-copper deposits (e.g., Cerro Casale and Marte; Vila and Sillitoe, 1991; Vila et al., 1991; Fig. 1a). The abundance of lithocaps provides firm evidence that erosion levels are generally relatively shallow (say, <0.5–1 km; Sillitoe 2010; Bissig et al., 2015) throughout large parts of these belts, notwithstanding the Miocene Miocene (post-18 Ma) compressive tectonism and concomitant rock uplift and denudation south of approximately latitude 28°S (e.g., Martínez et al., 2015a, b; Rossel et al., 2018). In the absence of dated postmineral cover—and approximations based on either radiometric age of supergene minerals (Sillitoe, 2005) or thermochronometry (McInnes et al., 2005)—the only available constraint on the timing of erosional unroofing is provided by the formational ages of the deposits themselves, one of the youngest being El Indio (~8–5 Ma; Bissig et al., 2001, 2015; Fig. 1a). Therefore, Josemaría is the standout exception because the partly preserved postmineral cover can be used to show that initial exposure and subsequent burial were accomplished within ~2 m.y. of deposit formation. Accepting the removal of at least 1,000 m of overlying lithocap prior to deposit burial, the erosion rate could at times have exceeded 0.5 km/m.y.

Rapidity of exhumation is assured where exposed porphyry copper deposits are extremely young (<3 Ma), with Ok Tedi in the Papua New Guinea Highlands being arguably the best example because it was formed at 1.1 to 1.2 Ma (K-Ar; Page and McDougall, 1972), an age confirmed by U-Pb zircon dating (1.187 ± 0.022 Ma; Large et al., 2018). There is no evidence that Ok Tedi was ever concealed beneath more recent deposits, the erosion rate are maximized immediately following pulses of Andean uplift (Carretier et al., 2015), in accord with the limited time has elapsed to redevelop a deep supergene profile if, indeed, one ever existed.

### Paleoclimatic context

Yanites and Kesler (2015) showed that the world’s youngest exposed porphyry copper deposits occur in tropical regions where rainfall is higher and erosion rates generally faster than in other climatic regimes. Nonetheless, exhumation of the Josemaría deposit was just as fast as that of porphyry deposits in tropical regions, such as the southwestern Pacific island arcs, notwithstanding the semiarid conditions that prevailed in this region of the Andes during the late Oligocene-early Miocene, as documented by widespread vegetation-free alluvial fan, evaporitic playa, and eolian deposits (M. Song et al., 2018). Nonetheless, extremely rapid unroofing was documented at the Late Devonian Hugo Dumnett porphyry copper-gold deposit in the Oyu Tolgoi district, Mongolia, where as little as 1 m.y. could have separated deposit formation and an unconformably overlying volcano-sedimentary sequence within which polymictic conglomerate and breccia contain mineralized clasts (Wainwright et al., 2017). Furthermore, the postmineral sequence, including the advanced argillic alteration that affected it, is cut by weakly altered and mineralized, late mineral porphyry intrusions, showing conclusively that exhumation took place during the waning stages of the magmatic-hydrothermal system (Wainwright et al., 2017).
from the rapid erosion responsible for deposit telescoping (~25–24.5 Ma) and subsequent unroofing (24.5–22.3 Ma) at Josemaría.

Therefore, although few porphyry copper deposits worldwide possess (or at least preserve) direct geologic evidence bearing on their exhumation histories, it is clear that deposits in magmatic arc terranes subject to compressive tectonism and rapid rock uplift can be unroofed in 1 to 2 m.y. Although this is most common under the tropical climatic conditions that prevailed during the unroofing at Ok Tedi, Bougain-Bayuyo, Tombulilito, and probably also Oyu Tolgoi, given its low-latitudinal Devonian position (Copper and Scotese, 2003), the Josemaría deposit demonstrates that it is also possible in semiarid, mountainous terrain.

Conclusions

The Josemaría porphyry copper-gold deposit is located in a reverse fault-bounded block of Permian to Triassic igneous basement that forms part of the Frontal Cordillera of westernmost Argentina. The deposit is genetically related to small, multiphase dacite porphyry intrusions that were emplaced in a reverse fault zone concurrently with compression and contemporaneous uplift in the late Oligocene (~25–24.7 Ma). A telescoped sequence of alteration zones, from early potassic to a late advanced argillic lithocap, is broadly centered on the porphyry intrusions and, together, host the potentially economic copper-gold mineralization.

During continued compressive tectonism and uplift, the deposit was unroofed, with some of the resultant detritus contributing to a nearby red-bed conglomerate, breccia, and sandstone sequence. These strata and overlying volcanic rocks, dated at ~22.3 Ma, eventually buried the Josemaría deposit. The postmineral volcano-sedimentary package was then locally subjected to weakly developed, high-sulfidation epithermal copper mineralization, which, in marked contrast to the high-sulfidation mineralization in the lithocap, is gold deficient. The deposit was subsequently reexhumed from beneath its volcanic-sedimentary cover and, during or after minor extensional reactivation of the reverse fault zone, underwent supergene sulfide oxidation and enrichment, with the highest grades confined to the proximity of the fault.

Many porphyry copper deposits in the central Andes were formed during uplift resulting from the crustal shortening and thickening that accompanied compressive tectonism (e.g., Maksae and Zentilli, 1999; Perelló et al., 2003b; Sillitoe and Perelló, 2005; Maksae et al., 2009) and, as a consequence, are likely to have been rapidly exhumed; however, Josemaría is the only known example in which the presence of postmineral cover allows estimation of the actual time required, ~2 m.y., for the unroofing to take place. Josemaría joins several other porphyry copper-gold deposits, predominantly in the western Pacific region, that were exhumed extremely rapidly, in 1 to 2 m.y., and then protected from further erosion by concealment beneath postmineral cover. However, Josemaría appears currently to be unique in that the erosion took place under semiarid rather than high-rainfall, tropical conditions.

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